National Aeronautics and Space Administration

SMALL BUSINESS
INNOVATION RESEARCH (SBIR)
&
SMALL BUSINESS
TECHNOLOGY TRANSFER (STTR)

Fiscal Year 2020 General Solicitation

Opening Date: January 21, 2020
Closing Date: April 20, 2020

Amended: April 17, 2020

This amendment is issued to incorporate the below language in Section 1.7 I-Corps™ of the solicitation.

> The I-Corps™ Program may be extended and offered to firms applying for SBIR/STTR Post-Phase II opportunities. Please refer to the NASA SBIR/STTR website to stay up to date on latest details at www.sbir.nasa.gov.

Amended: April 13, 2020

The NASA SBIR/STTR Program continues to closely monitor the situation with the novel coronavirus (COVID-19).

1) Due to uncertainty around travel and large gatherings, the Innovation and Opportunity Conference (IOC) will not be held as an in-person event in 2020; therefore, **the below opportunity is no longer applicable**.

> ***Travel in Phase I***
>
> *Due to the intent and short period of performance of the Phase I contracts along with their limited budget, travel during the Phase I contract is highly discouraged unless it is required to successfully complete the proposed effort. If the purpose of the meeting cannot be accomplished via videoconference or teleconference, the offeror must provide rationale for the trip in the proposal budget form. All travel must be approved by the Contracting Officer and concurred by the Technical Monitor.*
>
> *However, during this solicitation, Phase I offerors may propose up to $1,500.00 for one person per firm for travel to attend the Innovation & Opportunity Conference (IOC) tentatively scheduled for fall 2020 with location to be determined. For additional information on the IOC, see the Noteworthy Changes section at the front of this solicitation. This request for travel funding shall not be used for travel other than attending the IOC meeting. If an offeror plans to submit multiple proposals, it is recommended that the offeror request up to $1,500.00 for travel to the IOC per proposal, however NASA will only allow up to $1,500.00 of travel funds to be provided to a single firm that receives multiple awards under this solicitation to attend the IOC meeting.*

- For those firms that have not yet completed their proposals, please do not include IOC travel funds in your budget request.
- For firms that have already completed their proposals, if you proposed travel to the IOC, we recommend updating your budget accordingly, resubmitting, and re-endorsing. Otherwise, during contract negotiations, this funding request will be denied.

2) NASA will accept STTR proposal packages that do not include (1) Research Agreements and/or (2) Research Institute (RI) budgets and have not been endorsed by the RI. Firms who do not include these items will not be penalized during evaluation. Research Agreements and/or RI budgets shall instead be submitted within ten days of the notification of selection.

3) NASA will accept SBIR/STTR proposal packages that do not include signed letters of commitment from subcontractors or consultants. Firms who do not include these items will not be penalized during evaluations. Signed letters of commitment from subcontractors and/or consultants shall instead be submitted within ten days of the notification of selection.

NASA will provide additional guidance on how Small Business Concerns (SBC) and RIs can provide these documents and endorsements at https://sbir.nasa.gov/content/covid-19-impact-nasa-sbirsttr-program.

Amended: March 20, 2020

Due to the Coronavirus Disease 2019 (COVID-19), NASA is modifying its 2020 SBIR/STTR submission deadline and process as follows, notwithstanding any provisions to the contrary in this solicitation:

- NASA is extending the 2020 SBIR/STTR submission deadline to **5:00pm ET on April 20, 2020.**

Amended: March 16, 2020

Due to the Coronavirus Disease 2019 (COVID-19), NASA is modifying its 2020 SBIR/STTR submission deadline and process as follows, notwithstanding any provisions to the contrary in this solicitation:

- NASA is extending the 2020 SBIR/STTR submission deadline to **5:00pm ET on March 23, 2020.**
- Because of widespread university closures, NASA will provisionally accept SBIR submissions that do not include (1) Research Agreements and/ or (2) Research Institution budgets and that have not been endorsed by the Research Institute provided that NASA receives all such documents no later than **5:00pm ET on April 3, 2020.**
- NASA will provisionally accept SBIR submissions that do not include signed letters of commitment from subcontractors or consultants provided that NASA receives all such documents no later than **5:00pm ET on April 3, 2020.**

NASA will provide additional guidance on how SBCs and RIs can provide these documents and endorsements on https://sbir.nasa.gov.

Fiscal Year 2020 SBIR/STTR Solicitation Noteworthy Changes

Research Topics for SBIR and STTR

The STTR subtopics will appear in an integrated list with the SBIR subtopics again this year. They will be clearly marked as STTR subtopics so that offerors will know that the additional Research Institution (RI) partnership is required before submitting a proposal. This will assist Firms in seeing related subtopics across both programs.

Updated Certifications

The certifications collected at time of proposal, time of award, and during the lifecycle have been revised to match those required in the latest SBIR and STTR Policy Directives located at https://www.sbir.gov/. These certifications will look similar to those you may have seen in the past from NASA's SBIR and STTR programs, but with some updated language. You will see one set of certifications twice. Once at time of proposal and again at time of award. The purpose of presenting these certifications at time of proposal is to speed up the award timeline by preparing you for what will be asked of your company by the Contracting Officer at time of award.

Understanding the Patent Landscape

Offerors should indicate in the proposal that a comprehensive patent review has been completed to ensure that there is no existing patent or perceived patent infringement based on the innovation proposed. The U.S. Patent and Trade Office (USPTO) has an online patent search tool that can found at https://www.uspto.gov/patents-application-process/search-patents.

Suggested Page Limits

Within the technical proposal guidelines in sections 3.2.4 and 3.4.4 are suggested page limits for each part of the technical proposal. These are guidelines and are not strict requirements. Offerors are still required to meet the total page limit requirements as described within this solicitation.

Phase I STTR Pilot Purchase Card Program

NASA is considering initiating a pilot program to provide payments to Phase I STTR awardees utilizing a purchase card. The goal of the program is to reduce the time it takes to provide payments to the awardee. Offerors that are selected for an STTR Phase I award would be contacted by the NASA Shared Services Center (NSSC) and would be provided an opportunity to opt out of the Pilot Purchase Card Program. Awardees would be provided additional instructions and information during the negotiation of the contract on how to participate in the program.

Travel to the Innovation and Opportunity Conference (IOC)

NASA is implementing an additional outreach opportunity to small businesses, with the purpose of providing networking and knowledge sharing opportunities focused on the innovations being developed under the NASA SBIR/STTR program. The Innovation and Opportunity Conference (IOC), brings together NASA and other government agency experts, small businesses, startups, research institutions and large businesses/prime contractors for a technology and commercialization event. The IOC provides opportunities for companies at every stage of maturity, from those just starting out with a great idea, to experienced innovators looking to expand and actively participate in tomorrow's aerospace and defense industries. For more information on the IOC see https://innovation-opportunity-conference.com.

During this solicitation, ~~Phase I and~~ Phase II offerors may propose up to $1,500.00 for one person per firm for travel to attend the IOC tentatively scheduled for fall 2020 with location to be determined. For additional information on requesting travel funds and restrictions refer to the appropriate budget sections found in Chapter 3 of this solicitation.

Moon to Mars Campaign

Working with U.S. companies and international partners, NASA will push the boundaries of human exploration forward to the Moon and on to Mars. NASA is working to establish a permanent human presence on the Moon within the next decade to uncover new scientific discoveries and lay the foundation for private companies to build a lunar economy. Right now, NASA is taking steps to begin this next era of exploration. It all starts with delivery services to the lunar surface from U.S. companies for scientific instruments and technology demonstrations as well as a spaceship, called the Gateway, in orbit around the Moon that will support human missions to the surface with reusable lander elements for decades to come. The Gateway will, for the first time, give NASA and its partners access to more of the lunar surface than ever before, supporting both human and robotic missions. The agency's powerful Space Launch System rocket and Orion spacecraft will be the backbone to build the Gateway and transport astronauts to and from Earth. (See https://www.nasa.gov/topics/moon-to-mars/overview).

NASA has plans to purchase services for delivery of payloads to the Moon through the Commercial Lunar Payload Services (CLPS) contract. Under this subtopic, proposals may include efforts to develop payloads for flight demonstration of relevant technologies in the lunar environment. The CLPS payload accommodations will vary depending on the particular service provider and mission characteristics. Additional information on the CLPS program and providers can be found at this link: https://www.nasa.gov/content/commercial-lunar-payload-services. CLPS missions will typically carry multiple payloads for multiple customers. Smaller, simpler, and more self-sufficient payloads are more easily accommodated and would be more likely to be considered for a NASA-sponsored flight opportunity. Commercial payload delivery services may begin as early as 2020 and flight opportunities are expected to continue well into the future. In future years it is expected that larger and more complex payloads will be accommodated. Selection for award under this solicitation will not guarantee selection for a lunar flight opportunity.

Due to this emerging new commercial payload delivery service, a highlight in this year's solicitation is that a number of the subtopics are encouraging proposers to consider the potential for developing a lunar payload as part of their technology development effort. Where appropriate, the technology development project may consider a lunar payload as a deliverable by the end of Phase II (or perhaps in a post Phase II effort). While not all proposals from those subtopics are expected to produce a payload as their deliverable, suitable payloads which are developed may be eligible (through subsequent competitive selection) for delivery to the lunar surface at no cost. However, selection for an SBIR award will not guarantee selection for a future lunar payload flight opportunity.

Rights in Data Developed Under SBIR Funding Agreements

SBA is adopting a 20-year protection period for appropriately marked SBIR/STTR Data and SBA intends that this much longer, finite protection period, even with the elimination of extensions to such period, will preserve the incentives for small business concerns to participate in the SBIR/STTR programs. SBA is confident that 20 years will be sufficient to provide data rights protection during the entire development and commercialization process for most technologies in most industries that participate in the SBIR/STTR programs. Additionally, the adoption of a 20-year protection period provides greater consistency with the 20-year protection period that the Government provides for patents issued by the U.S. Patent and Trademark Office. For a detailed explanation of the data rights see section 5.7 Rights in Data Developed under SBIR Funding Agreements.

Space Technology Roadmap Technology Areas (TAs) vs, the New NASA Technology Taxonomy

The 2020 NASA Technology Taxonomy is part of an evolution that began with technology roadmaps and the Technology Area Breakdown Structure (TABS) drafted in 2010, followed by updates in 2012 and 2015. The 2020 NASA Technology Taxonomy provides a structure for articulating the technology development disciplines needed to enable future space missions and support commercial air travel. The 2020 revision is comprised of 17 distinct technical discipline based Taxonomies (TX) that provide a breakdown structure for each technology area. The taxonomy uses a three-level hierarchy for grouping and organizing technology types. Level 1 represents the technology area, which is the title of that area (e.g. TX01: Propulsion Systems). Level 2 is a list of the subareas (e.g. TX01.1 Chemical Space Propulsion). Level 3 categorizes the types of technologies within the subareas (e.g. TX1.1.1 Integrated Systems and Ancillary Technologies). The taxonomy is a foundational element of NASA's technology management process. NASA's mission directorates reference the taxonomy to solicit proposals and to inform decisions on NASA's technology policy, prioritization, and strategic investments.

The subtopics in this solicitation will still reference the previous Space Technology Roadmap Technology Areas (TAs) in the subtopic descriptions. They will be cross-referenced to the new Technology Taxonomy in Appendix B: SBIR/STTR and the Space Technology Roadmaps/Technology Taxonomy. The 2015 NASA Technology Roadmaps will be archived and remain accessible via their current internet address (https://www.nasa.gov/offices/oct/home/roadmaps/index.html) as well as via the new 2020 NASA Technology Taxonomy Internet page. (https://www.nasa.gov/sites/default/files/atoms/files/2020_nasa_technology_taxonomy_lowres.pdf)

"Pointers" to Assist You in Finding the Appropriate Subtopic

Subtopic pointers are used to indicate subtopics that are asking for related technologies. Where applicable, these pointers will appear in the subtopic headers to assist proposers with identifying those related subtopics that potentially seek related technologies for different customers or applications. Pointers in conjunction with the focus area listings of subtopics will make it easier for proposers to find all subtopics that may be of interest.

CCRPP Is Back For 2020

The Civilian Commercialization Readiness Pilot Program (CCRPP) is an additional funding opportunity available to small businesses, with the purpose of accelerating the transition of SBIR and STTR funded technologies to commercialization. The funding is a combination of additional SBIR/STTR Program investment and NASA or non-NASA entity investment. The program will match between $500,000 and $1 million of external investment. The primary objective of the NASA CCRPP is an infusion or commercialization, not an incremental improvement in technology maturation alone. Technology maturation without infusion or commercialization will not be accepted for CCRPP. For additional information, please see https://sbir.nasa.gov/content/post-phase-ii-initiatives#CCRPP.

Table of Contents

1. Program Description

1.1 Introduction

This document includes instructions for two NASA program solicitations with separate subtopics under which small business concerns (SBCs) are invited to submit proposals: the Small Business Innovation Research (SBIR) Program and the Small Business Technology Transfer (STTR) Program. While the SBIR and STTR subtopics appear in an integrated list in Chapter 9, each subtopic will indicate its program of origin. Program background information, eligibility requirements for participants, information on the three program phases, and information for submitting responsive proposals are contained herein. The fiscal year 2020 Solicitation period for Phase I proposals begins January 21, 2020 and ends April 20, 2020.

The NASA SBIR and STTR Programs do not fund proposals solely directed towards system studies, market research, routine engineering, development of existing product(s), proven concepts, or modifications of existing products without substantive innovation.

It is anticipated that some SBIR and STTR Phase I proposals will be selected for negotiation of firm-fixed-price contracts approximately during the month of June 2020. Historically, 24 percent of SBIR Phase I proposal submissions receive awards, while 35 percent of STTR Phase I proposals receive awards. About 41 percent of the completed Phase I projects receive funding for Phase II development.

Under this Solicitation NASA will not accept more than 10 proposals to either program from any one firm (20 total) in order to ensure the broadest participation of the small business community. NASA does not plan to award more than 5 SBIR contracts and 2 STTR contracts (7 total) to any offeror. See section 3.1.

Proposals including all relevant documentation must be submitted online via the Proposal Submissions Electronic Handbook at http://sbir.nasa.gov. Unsolicited proposals will not be accepted.

1.2 Program Management and Alignment

The Space Technology Mission Directorate (STMD) provides overall policy direction for implementation of the NASA SBIR/STTR Programs. The NASA SBIR/STTR Program Management Office, which operates the programs in conjunction with NASA mission directorates and centers, is hosted at the NASA Ames Research Center. NASA Shared Services Center (NSSC) provides the overall procurement management for the programs.

For the SBIR Program, NASA research and technology areas to be solicited are identified annually by the agency's mission directorates. The directorates identify high priority research problems and technology needs for their respective programs and projects. The range of problems and technologies is broad, and the list of topics and subtopics vary in content from year to year to maintain alignment with current interests.

The STTR Program is aligned with the priorities of NASA's Space Technology Roadmaps, as well as the associated core competencies of the NASA centers. Again, the range of technologies is broad, and the list of topics and subtopics vary in content from year to year to maintain alignment with current interests.

For information regarding the mission directorates and the NASA centers see section 7.1.

For details on the research subtopic descriptions by Focus Area please see section 9.

1.3 Three-Phase Program

Both the SBIR and STTR Programs are divided into three funding and development stages. These three phases are described in detail on the NASA SBIR/STTR website: http://sbir.nasa.gov/content/nasa-sbirsttr-basics.

Phase I and II

Maximum value and period of performance for Phase I and Phase II contracts:

Phase I Contracts	**SBIR**	**STTR**
Maximum Contract Value	$125,000	$125,000
Period of Performance	6 months	13 months
Phase II Contracts	**SBIR**	**STTR**
Maximum Contract Value	$750,000	$750,000
Maximum Period of Performance	24 months	24 months

Post-Phase II Opportunities for Continued Technology Development

The NASA SBIR/STTR Program has two initiatives for supporting its small business partners beyond the basic Phase II award. These are the Phase II Extended (Phase II-E) contract option and the Civilian Commercialization Readiness Pilot Program (CCRPP) contract.

Please refer to http://sbir.nasa.gov/content/post-phase-ii-initiatives for eligibility, application deadlines, matching requirements and further information.

Phase III

Phase III is the commercialization of innovative technologies, products and services resulting from either a Phase I or Phase II contract. This includes further development of technologies for transition into NASA programs, other government agencies or the private sector. Phase III contracts are funded from sources other than the SBIR and STTR programs and may be awarded without further competition.

Please refer to http://sbir.nasa.gov/content/post-phase-ii-initiatives for Phase III information.

1.4 Availability of Funds

All Phase I, Phase II and post-Phase II awards are subject to availability of funds. NASA has no obligation to make any specific number of awards based on this solicitation, and may elect to make several or no awards in any specific technical topic or subtopic.

1.5 Eligibility Requirements

1.5.1 Small Business Concern

To receive SBIR/STTR funds, each Awardee of a Phase I or Phase II award must qualify as an SBC at the time of award and at any other time set forth in SBA's regulations at 13 CFR 121.701-121.705. Each Phase I and Phase II.

Awardee must submit a certification stating that it meets the size, ownership and other requirements of the SBIR or STTR program at the time of award, and at any other time set forth in SBA's regulations at 13 CFR 121.701-

121.705. Socially and economically disadvantaged and women-owned SBCs are particularly encouraged to propose.

1.5.2 Place of Performance

Research/Research & Development (R/R&D) must be performed in the United States (See: http://sbir.nasa.gov/content/nasa-sbirsttr-program-definitions). However, based on a rare and unique circumstance (for example, if a supply, material or other item or project requirement is not available in the United States), NASA may allow a particular portion of the research or R&D work to be performed or obtained in a country outside of the United States. Proposals must clearly indicate if any work will be performed outside the United States, including subcontractor performance, and justification must be provided. Prior to award, approval by the Contracting Officer for such specific condition(s) must be in writing.

Note: NASA will not approve purchases from or work with countries that appear on the list of Designated Countries. For reference, please visit https://oiir.hq.nasa.gov/nasaecp/ - Designated Countries List

1.5.3 Principal Investigator (PI) Employment Requirement

The primary employment of the Principal Investigator (PI) shall be with the SBC under the SBIR Program, while under the STTR Program, either the SBC or Research Institution (RI) shall employ the PI. Primary employment means that more than 50% of the PI's total employed time (including all concurrent employers, consulting and self-employed time) is spent with the SBC or RI at time of award and during the entire period of performance. Primary employment with a small business concern precludes full-time employment at another organization. If the PI does not currently meet these primary employment requirements, then the offeror must explain how these requirements will be met if the proposal is selected for contract negotiations that may lead to an award. Co-Principal Investigators are not allowed.

Note: NASA considers a full-time workweek to be nominally 40 hours and we consider a 19.9-hour or more workweek elsewhere to be in conflict with this rule. In rare occasions, minor deviations from this requirement may be necessary; however, any minor deviation must be approved in writing by the Contracting Officer after consultation with the NASA SBIR/STTR Program Manager/Business Manager.

Requirements	**SBIR**	**STTR**
Primary Employment	PI shall be primarily employed with the SBC	PI shall be primarily employed with the RI or SBC
Employment Certification	The offeror must certify in the proposal that the primary employment of the PI will be with the SBC at the time of award and during the conduct of the project	The offeror must certify in the proposal that the primary employment of the PI will be with the SBC or the RI at the time of award and during the conduct of the project
Co-PIs	Not Allowed	Not Allowed
Misrepresentation of Qualifications	Shall result in rejection of the proposal or termination of the contract	Shall result in rejection of the proposal or termination of the contract
Substitution of PIs	Requires a prior approval from NASA	Requires a prior approval from NASA

1.5.4 Restrictions on Venture Capital-owned Businesses

At the current time, small businesses owned in majority part by multiple venture capital operating companies, hedge funds or private equity firms are not eligible to submit proposals to the NASA SBIR/STTR Solicitation.

1.5.5 Joint Ventures and Limited Partnerships

Both joint ventures and limited partnerships are permitted, provided the entity created qualifies as an SBC in accordance with the definition of an SBC here: http://sbir.nasa.gov/content/nasa-sbirsttr-program-definitions. A statement of how the workload will be distributed, managed and charged should be included in the proposal. A copy or comprehensive summary of the joint venture agreement or partnership agreement should be included on the Technical Proposal upload page.

1.5.6 Required Benchmark Transition Rate

The Phase I to Phase II Transition Rate requirement applies only to SBIR and STTR Phase I applicants that have received more than 20 (21 or more) Phase I awards over the past 5 fiscal years, excluding the most recent year. These companies must meet the required benchmark rate of transition from Phase I to Phase II. The current Transition Rate requirement, agreed upon and established by all 11 SBIR agencies and published for public comment at 77 FR 63410 in October 2012 and amended at 78 FR 30951 in May 2013, is that an awardee must have received an average of one Phase II for every four Phase I awards received during the most recent 5-year time period (which excludes the most recently-completed fiscal year) to be eligible to submit a proposal for a new Phase I (or Direct-to-Phase II) award. That is, the ratio of Phase II to Phase I awards must be at least 0.25.

On June 1 of each year, the SBA assesses SBIR/STTR awardees using SBIR and STTR award information across all federal agencies reported on www.sbir.gov to determine if they meet the benchmark requirements. Companies that failed to meet the transition rate benchmark on June 1, 2019 are not eligible to submit a Phase I proposal during the period June 1, 2019 through May 31, 2020. Companies were notified by the SBA if they failed to meet the benchmark and can find their status at any time on www.sbir.gov. .

More information on the Transition Rate requirements is available at https://www.sbir.gov/faqs/performance-benchmarks.

1.6 NASA Technology Available (TAV) for SBIR/STTR Use

Offerors have the option of using technology developed by NASA (Technology Available (TAV)) related to the subtopic to which they are proposing. NASA has over 1400 patents available for licensing in its portfolio, including many sensors and materials related patents. NASA has over 1000 available software codes/tools listed in its Software Catalog (software.nasa.gov). While NASA scientists and engineers conduct breakthrough research that leads to innovations, the range of NASA's effort does not extend to commercial product development in any of its intramural research areas. Additional work is often necessary to exploit these NASA technologies (TAVs) for either infusion or commercial viability and likely requires innovation on behalf of the private sector. These technologies can be searched via the NASA Technology Transfer Portal, http://technology.nasa.gov, and may be a NASA owned patent and/or computer software. Use of a TAV requires a patent license or Software Usage Agreement from NASA. TAVs are available for use during both Phase I and Phase II award periods, including any extensions. NASA provides these technologies "as is" and makes no representation or guarantee that additional effort will result in infusion or commercial viability.

Whether or not a firm proposes the use of a NASA patent or computer software within their proposed effort will not in any way be a factor in the selection for award.

Use of NASA Software

If an offeror intends to use NASA software, a Software Usage Agreement (SUA), on a non-exclusive, royalty-free basis, is necessary, and the clause at 48 C.F.R. 1852.227-88, “Government-Furnished Computer Software and Related Technical Data,” will apply to the contract. A Software Usage Agreement (SUA) shall be requested from the appropriate NASA Center Software Release Authority (SRA), after contract award.

Use of NASA Patent

All offerors submitting proposals including the use of a NASA patent must submit an application for a non-exclusive, royalty-free evaluation license. Once a firm has identified a patent to license in the NASA patent portfolio (http://technology.nasa.gov), there is a link on the patent webpage that says “Click Here to License this Technology”. Firms will be directed to NASA’s Automated Licensing System (ATLAS) to finalize their license with the appropriate field center technology transfer office. The completed evaluation license application must be uploaded on the EHB Proposal Certifications page. Such grant of non-exclusive evaluation license will be set forth in the successful offeror’s SBIR/STTR contract. The evaluation license will automatically terminate at the end of the SBIR/STTR contract. License applications will be treated in accordance with federal patent licensing regulations as provided in 37 CFR Part 404.

In addition to an evaluation license, if the proposed work includes the making, using or selling of products or services incorporating a NASA patent, successful awardees will be given the opportunity to negotiate a non-exclusive commercialization license or, if available, an exclusive commercialization license to the NASA patent. Commercialization licenses are also provided in accordance with 37 CFR Part 404.

An SBIR/STTR awardee that has been granted a non-exclusive, royalty-free evaluation license to use a NASA patent under the SBIR/STTR award may, if available and on a non-interference basis, also have access to NASA personnel knowledgeable about the NASA patent. Licensing Executives located at the appropriate NASA field center will be available to assist awardees requesting information about a patent that was identified in the SBIR/STTR contract and, if available and on a non-interference basis, provide access to the inventor or surrogate for the purpose of knowledge transfer.

Note: Access to the inventor for the purpose of knowledge transfer will require the requestor to enter into a Non-Disclosure Agreement (NDA), or other agreement, such as a Space Act Agreement. The awardee may be required to reimburse NASA for knowledge transfer activities. For Phase I proposals this is a time-consuming process and is not recommended.

1.7 I-Corps™

The NASA SBIR/STTR Program is partnering with the National Science Foundation (NSF) to offer the NSF Innovation Corps Program (I-Corps ™) (hereinafter I-Corps). I-Corps focuses on educating teams on how to translate technologies from the laboratory into the marketplace. Participation in I-Corps will require selected contractors to conduct either 30 interviews (shortened version for the SBIR Program) or 100 interviews (full version for the STTR Program) to enable contractors to understand the commercial potential of their ideas. Selected contractors will be awarded training grants, separate from their Phase I contract, that must be completed prior to the conclusion of Phase I contracts. The program is described further at http://sbir.nasa.gov/content/I-Corps. The application process for I-Corps is described in Section 3.3.6. NASA will conduct an abbreviated competition for I-Corps after it selects offerors for Phase I SBIR and STTR contracts. NASA anticipates awarding a total of approximately 35 grants to SBIR and STTR Phase I contractors. The distribution is expected to be approximately 10 STTR teams and 25 SBIR teams. The amount of funding is up to $25,000 for the full I-Corps Program for STTR firms, and up to $10,000 for the shortened version for SBIR firms.

The I-Corps™ Program may be extended and offered to firms applying for SBIR/STTR Post-Phase II opportunities. Please refer to the NASA SBIR/STTR website to stay up to date on latest details at www.sbir.nasa.gov.

1.8 Technical and Business Assistance (TABA)

SEC. 854(c) of H.R.5515 - John S. McCain National Defense Authorization Act for Fiscal Year 2019 revised the requirements of the 2011 SBIR Reauthorization for Direct Technical Assistance to awardees. The 2019 NDAA contained language that each agency "may" implement a Technical and Business Assistance (TABA) program and revised the amount agencies may make available for this assistance. At this time, NASA is allowing Phase II companies to request TABA assistance at a maximum of $5,000 per year per Phase II project while NASA evaluates how to implement an expanded Phase II TABA program for future year solicitations. Requesting TABA funding does not count toward the maximum award size of your Phase II contract. Phase I companies are not permitted to request TABA funding at this time; however, NASA is currently evaluating how to implement an expanded Phase I TABA program for the future.

In accordance with the Small Business Act, NASA may authorize the recipient of a Phase II SBIR/STTR award to purchase technical and business assistance services through one or more outside vendors. The offeror may also seek business-related services aimed at improving its commercialization success from an entity, such as a public or private organization or an agency of or other entity established or funded by a State that facilitates or accelerates the commercialization of technologies or assists in the creation and growth of private enterprises that are commercializing technology

These services may, as determined appropriate, include access to a network of non-NASA scientists and engineers engaged in a wide range of technologies, assistance with product sales, intellectual property protections, market research, market validation, and development of regulatory plans and manufacturing plans, or access to technical and business literature available through online databases, for the purpose of assisting such concerns in:

1. Making better technical decisions concerning such projects.
2. Solving technical problems which arise during the conduct of such projects.
3. Minimizing technical risks associated with such projects.
4. Commercializing new commercial products and processes resulting from such projects, including intellectual property protections.

If you are interested in proposing the use of a vendor for technical and business assistance, you must complete the Technical and Business Assistance section located under Other Direct Costs (ODCs) in the Proposal Budget form. You must provide the vendor name and contact information, the proposed amount not to exceed $5,000 per year per Phase II project and a detailed explanation of the services to be provided. You must also upload a price quote from the vendor including their DUNS number. Technical and business assistance does not count toward the maximum award size of your Phase II. Approval of technical and business assistance is not guaranteed and is subject to review by the Contracting Officer.

A description of any technical and business assistance obtained under this section and the benefits and results of the technical or business assistance provided will be a required deliverable of your Phase II contract.

1.9 NASA Mentor-Protégé Program (MPP)

The purpose of the NASA Mentor-Protégé Program (MPP) is to provide incentives to NASA contractors, performing under at least one active approved subcontracting plan negotiated with NASA, to assist protégés in enhancing their capabilities to satisfy NASA and other contract and subcontract requirements. The NASA MPP, established under the authority of Title 42, U.S.C., 2473(c)(1) and managed by the Office of Small Business Programs (OSBP), includes an Award Fee Pilot Program. Under the Award Fee Pilot Program, a mentor is eligible to receive an award fee at the end of the agreement period based upon the mentor's performance of providing developmental assistance to an active SBIR/STTR Phase II contractor in a NASA Mentor-Protégé agreement (MPA).

The evaluation criterion is based on the amount and quality of technology transfer and business development skills that will increase the protégé's Technology Readiness Levels (TRLs). TRLs measure technology readiness on a scale of 1 to 9. A mentor should attempt to raise the TRL of the protégé and outline the goals and objectives in the MPA and the award fee plan. A separate award fee review panel set up by NASA OSBP will use the semiannual reports, annual reviews and the award fee plan in order to determine the amount of award fee given at the end of the performance period of the agreement.

For more information on the Mentor-Protégé Program please visit: http://www.osbp.nasa.gov/mpp/index.html.

1.10 NASA Procurement Ombudsman Program

The NASA Procurement Ombudsman Program is available under this solicitation as a procedure for addressing concerns and disagreements. The clause at NASA FAR Supplement (NFS) 1852.215-84 ("Ombudsman") is incorporated into this solicitation.

The cognizant ombudsman is:

William Roets
Deputy Assistant Administrator for Procurement
Office of Procurement
NASA Headquarters
Washington, DC 20546-0001
Telephone: 202-358-4483
Fax: 202-358-3082
Email: agency-procurementombudsman@nasa.gov

1.11 General Information

1.11.1 Means of Contacting NASA SBIR/STTR Program

1. NASA SBIR/STTR Website: http://sbir.nasa.gov

2. Help Desk: The NASA SBIR/STTR Help Desk can answer any questions regarding clarification of proposal instructions and any administrative matters. The Help Desk may be contacted by:

    a. Email: sbir@reisystems.com
    b. Telephone: 301-937-0888 between 9:00 a.m.-5:00 p.m. (Mon.-Fri., Eastern Time)

c. The requestor must provide the name and telephone number of the person to contact, the organization name and address, and the specific questions or requests.

3. NASA SBIR/STTR Program Manager: Specific information requests that could not be answered by the Help Desk should be emailed to: ARC-SBIR-PMO@mail.nasa.gov

1.11.2 Questions about this Solicitation

To ensure fairness, questions relating to the intent and/or content of research topics in this Solicitation cannot be addressed during the open solicitation period. Only questions requesting clarification of proposal instructions and administrative matters will be addressed.

The cut-off date and time for receipt of Phase I solicitation procurement related questions and answers is 5:00 p.m. Eastern, April 13, 2020.

The cut-off date and time for receipt of Phase II solicitation procurement related questions and answers is seven calendar days prior to the end of the Phase I contract.

1.11.3 NASA Electronic Handbook (EHB)

NASA uses the EHB for all proposal submissions. See section 6 for more information.

1.12 Definitions

A comprehensive list of definitions related to the SBIR and STTR Programs is available at: http://sbir.nasa.gov/content/nasa-sbirsttr-program-definitions. These definitions include those from the SBIR and STTR policy directives, as well as terms specific to NASA. Offerors are strongly encouraged to review these prior to submitting a proposal.

2. Certifications and Other Proposal Information

2.1 SBA Firm Registry

Each Applicant must register in SBA's Company Registry Database at www.SBIR.gov and submit a .pdf document of the registration and any required certifications with its application if the information cannot be transmitted automatically to the SBIR/STTR Agencies from www.SBIR.gov.

Applicants must have updated their information on the Company Registry no more than 6 months prior to the date of a proposal submission.

Each SBC applying for a Phase II award is required to update its Commercialization information on www.SBIR.gov for all of its prior Phase II awards.

In the NASA SBIR/STTR Proposal Submissions Electronic Handbook (EHB), the SBC must provide their unique SBC Control ID that gets assigned by SBA upon completion of the Company Registry registration, as well as upload the PDF document validating their registration. This information is submitted to NASA via the Firm Certifications form and is applicable across all proposals submitted by the SBC for that specific solicitation.

2.2 System for Award Management (SAM) Registration

Offerors should be aware of the requirement to register in SAM prior to selection for award.

Note: To avoid a potential delay in contract award, offerors are required to register prior to submitting a proposal. To be eligible for SBIR/STTR awards firms must be registered under the applicable NAICS code. SBIR/STTR Phase I and II awards use NAICS codes 541713 or 541715. Offerors that are not registered should consider applying for registration immediately upon receipt of this solicitation. Offerors and contractors may obtain information on SAM registration and annual confirmation requirements at https://www.sam.gov/SAM or by calling (866) 606-8220. SAM registration and updates to SAM registration have required a processing period of several weeks.

SAM is the primary repository for contractor information required for the conduct of business with NASA. It is maintained by the Department of Defense. To be registered in SAM, all mandatory information, which includes the Data Universal Numbering System (DUNS) or DUNS+4 number, and a Commercial and Government Entity (CAGE) code, must be validated in SAM.

- The DUNS number is a 9-digit number assigned by Dun and Bradstreet Information Services to identify unique business entities. The DUNS+4 is similar, but includes a 4-digit suffix that may be assigned by a parent (controlling) business concern. To obtain a DUNS number please follow instructions at http://www.dnb.com.
- The CAGE code is assigned by the Defense Logistics Information Service (DLIS) to identify a commercial or government entity. If an SBC does not have a CAGE code, one will be assigned during the SAM registration process.

Note: It is recommended to list Purpose of Registration as "All Awards" on your SAM Registration.

2.3 FAR Certifications

SAM contains required certifications offerors may access at https://www.acquisition.gov/browsefar as part of required registration (see FAR 4.1102). Offerors must complete these certifications to be eligible for award.

Offerors should be aware that SAM requires all offerors provide representations and certifications electronically via the website, and to update the representations and certifications as necessary, but at least annually, to keep them current, accurate and complete. NASA will not enter into any contract wherein the Contractor is not compliant with the requirements stipulated herein.

2.3.1 52.222-37 Employment Reports on Special Disabled Veterans, Veterans of the Vietnam-Era and Other Eligible Veterans

In accordance with Title 38, United States Code, Section 4212(d), the U.S. Department of Labor (DOL) Veterans' Employment and Training Service (VETS) collects and compiles data on the Federal Contractor Program Veterans' Employment Report (VETS-4212 Report) from federal contractors and subcontractors who receive federal contracts that meet the threshold amount of $150,000. The VETS-4212 reporting cycle begins annually on August 1 and ends September 30. Any federal contractor or prospective contractor that has been awarded or will be awarded a federal contract with a value of $150,000 or greater must have a current VETS-4212 report on file. Please visit the DOL VETS-4212 website at https://www.dol.gov/agencies/vets/programs/vets4212. NASA will not enter into any contract wherein the firm is not compliant with the requirements stipulated herein.

2.4 Certifications

Offerors must complete the Firm and Proposal Certifications section in the Electronic Handbook, answering Yes or No to certifications as applicable.

Firms should carefully read each of the certification statements. The federal government relies on the information to determine whether the business is eligible for a SBIR or STTR Program award. A similar certification will be used to ensure continued compliance with specific program requirements at time of award and during the life of the funding agreement. The definitions for the terms used in this certification are set forth in the Small Business Act, SBA regulations (13 C.F.R. Part 121), the SBIR and STTR Policy Directives and any statutory and regulatory provisions referenced in those authorities.

> For Phase I awards, in addition to the final invoice certification and as a condition for payment of the final invoice, a life cycle certification shall be completed in the EHB. The life cycle certification is pre-set in the EHB and it shall be completed along with the final invoice certification before uploading the final invoice in IPP.
>
> For Phase II awards, two life cycle certifications shall be completed in the EHB. A life cycle certification shall be completed along with the second invoice certification as a condition of payment of the second invoice. Another life cycle certification shall be completed along with the final invoice certification as a condition of payment of the final invoice. The life cycle certifications are pre-set in the EHB.

If the Contracting Officer believes that the business may not meet certain eligibility requirements at the time of award, they are required to file a size protest with the U.S. Small Business Administration (SBA), who will determine eligibility. At that time, SBA will request further clarification and supporting documentation in order to assist in the eligibility determination. Additionally, the Contracting Officer may request further clarification and supporting documentation regarding eligibility to determine whether a referral to SBA is required.

2.5 NASA Clauses

The following NASA clauses are necessary to implement restrictions in NASA appropriations. Offerors must comply with these clauses to be eligible for award.

1852.203-71 Requirement to Inform Employees of Whistleblower Rights (Aug 14)

(a) The Contractor shall inform its employees in writing, in the predominant native language of the workforce, of contractor employee whistleblower rights and protections under 10 U.S.C. 2409, as described in subpart 1803.9 of the NASA FAR Supplement.
(b) The Contractor shall include the substance of this clause, including this paragraph (b), in all subcontracts.

1852.225-72 Restriction on funding Activity with China – Representation.

(a) Definition - "China" or "Chinese-owned" means the People's Republic of China, any company owned by the People's Republic of China or any company incorporated under the laws of the People's Republic of China.
(b) Public Laws 112-10, Section 1340(a) and 112-55, Section 536, restrict NASA from contracting to participate, collaborate, or coordinate bilaterally in any way with China or a Chinese-owned company with funds appropriated on or after April 25, 2011. Contracts for commercial and non-developmental items are excepted from the prohibition as they constitute purchase of goods or services that would not involve participation, collaboration, or coordination between the parties.
(c) Representation. By submission of its offer, the offeror represents that the offeror is not China or a Chinese-owned company.

2.6 False Statements

Note: Knowingly and willfully making any false, fictitious or fraudulent statements or representations may be a felony under the Federal Criminal False Statement Act (18 U.S.C. Sec 1001), punishable by a fine and imprisonment of up to five years in prison. The Office of the Inspector General (OIG) has full access to all proposals submitted to NASA.

Pursuant to NASA policy, any company representative who observes crime, fraud, waste, abuse, or mismanagement or receives an allegation of crime, fraud, waste, abuse or mismanagement from a federal employee, contractor, grantee, contractor or grantee employee, or any other source will report such observation or allegation to the OIG. NASA contractor employees and other individuals are also encouraged to report crime, fraud, waste and mismanagement in NASA's programs to the OIG. The OIG offers several ways to report a complaint:

NASA OIG Hotline: 1-800-424-9183 (TDD: 1-800-535-8134)

NASA OIG Cyber Hotline: http://oig.nasa.gov/cyberhotline.html

Or by mail:
NASA Office of Inspector General
P.O. Box 23089
L'Enfant Plaza Station
Washington, DC 20026

2.7 Software Development Standards

Offerors proposing projects involving the development of software may be required to comply with the requirements of NASA Procedural Requirements (NPR) 7150.2A, “NASA Software Engineering Requirements” which are available online at http://nodis3.gsfc.nasa.gov/displayDir.cfm?t=NPR&c=7150&s=2.

2.8 Human and/or Animal Subject

Offerors should be aware of the requirement that an approved protocol by a NASA Review Board is required if the proposed work includes human or animal subject. An approved protocol shall be provided to the Contracting Officer prior to the initiation of any human and/or animal subject research. Offerors shall identify the use of human or animal subject in the Proposal Certifications form. For additional information, contact the NASA SBIR/STTR Program Management Office at ARC-SBIR-PMO@mail.nasa.gov. Reference 14 CFR 1230 and 1232.

Note: Due to the complexity of the approval process, use of human and/or animal subjects is not allowed for Phase I contracts.

2.9 HSPD-12

Firms that require access to federally controlled facilities or access to a federal information system (federally controlled facilities and federal information system are defined in FAR 2.101(b)(2)) for six consecutive months or more must adhere to Homeland Security Presidential Directive 12 (HSPD-12), “Policy for a Common Identification Standard for Federal Employees and Contractors”, and Federal Information Processing Standards Publication (FIPS PUB) Number 201, “Personal Identity Verification (PIV) of Federal Employees and Contractors,” which require agencies to establish and implement procedures to create and use a government-wide secure and reliable form of identification no later than October 27, 2005. See: https://nvlpubs.nist.gov/nistpubs/FIPS/NIST.FIPS.201-2.pdf. In accordance with the FAR clause 52.204-9, “Personal Identity Verification of Contractor Personnel,” which states in part that the contractor shall comply with the requirements of this clause and shall ensure that individuals needing such access shall provide the personal background and biographical information requested by NASA.

Note: Additional information regarding PIV credentials can be found at https://csrc.nist.gov/Projects/PIV.

3. Proposal Preparation Instructions and Requirements

3.1 Fundamental Considerations

3.1.1 Multiple Proposal Submissions

Each proposal submitted must be based on a unique innovation, must be limited in scope to just one subtopic and shall be submitted only under that one subtopic within each program. An offeror shall not submit more than 10 proposals to each of the SBIR or STTR Programs (20 total). An offeror may submit more than one unique proposal to the same subtopic; however, an offeror shall not submit the same (or substantially equivalent) proposal to more than one subtopic. Submitting substantially equivalent proposals to several subtopics may result in the rejection of all such proposals. In order to enhance SBC participation, NASA does not plan to select more than 5 SBIR proposals and 2 STTR proposals from any one offeror under this solicitation (7 total).

3.1.2 Understanding the Patent Landscape

Offerors should indicate in the proposal that a comprehensive patent review has been completed to ensure that there is no existing patent or perceived patent infringement based on the innovation proposed. The U.S. Patent and Trade Office (USPTO) has an online patent search tool that can found at https://www.uspto.gov/patents-application-process/search-patents.

3.2 Proprietary Information in the Proposal Submission

The Government, except solely for proposal review purposes, shall not use or disclose, or authorize any other person or entity to use or disclose, all proprietary information, regardless of type, submitted in a contract proposal or grant application for a Funding Agreement under the SBIR/STTR programs. This information must be clearly marked by the applicant as confidential proprietary information.

Information contained in unsuccessful proposals will remain the property of the applicant. However, the government will retain copies of all proposals.

3.2.1 Release of Certain Proposal Information

In submitting a proposal, the offeror agrees to permit the government to disclose publicly the information contained in the Contact Information form, Proposal Summary form and Briefing Chart. Other proposal data is considered to be the property of the offeror, and NASA will protect it from public disclosure to the extent permitted by law including requests submitted under the Freedom of Information Act (FOIA).

3.3 Phase I Proposal Requirements

3.3.1 General Requirements

A competitive proposal will clearly and concisely: (1) describe the proposed innovation relative to the state of the art; (2) address the scientific, technical, and commercial merit and feasibility of the proposed innovation, and its relevance and significance to NASA interests as described in section 9 of this solicitation; and (3) provide a preliminary strategy that addresses key technical, market and business factors pertinent to the successful development, demonstration of the proposed innovation, and its transition into products and services for NASA mission programs, the commercial aerospace industry, and other potential markets and customers.

3.3.2 Format Requirements

Note: The government administratively screens all proposals and reserves the right to reject any proposal that does not conform to the following formatting requirements. Offerors that repeatedly violate solicitation formatting instructions are at higher risk of rejection for nonconformance on subsequent SBIR/STTR proposals.

Page Limitations and Margins

Note: Technical proposal uploads with any page(s) going over the required page limit will not be accepted. Any page(s) going over the required page limit will be deleted and omitted from the proposal review.

A Phase I technical proposal shall not exceed a total of 19 standard 8 1/2 x 11 inch (21.6 x 27.9 cm) pages. Proposals uploaded with more than 19 pages will prompt a warning which will prevent the completed proposal from being submitted. Each page shall be numbered consecutively at the bottom. Margins shall be 1.0 inch (2.5 cm). The space allocated to each part of the technical content will depend on the project chosen and the offeror's approach. The additional forms required for proposal submission will not count against the 19-page limit.

Suggested Page Limits

Within section 3.3.4 are suggested page limits for each part of the technical proposal. These are guidelines and are not strict requirements. Offerors are still required to meet the total page limit requirements as described above.

Type Size

No type size smaller than 10 point shall be used for text or tables, except as legends on reduced drawings. Proposals prepared with smaller font sizes may be rejected without consideration.

Header/Footer Requirements

Header must include firm name, proposal number and project title. Footer must include the page number and proprietary markings if applicable. Margins can be used for header/footer information.

Classified Information

NASA does not accept proposals that contain classified information.

Project Title

The proposal project title shall be concise and descriptive of the proposed effort. The title should not use acronyms or words like "Development of" or "Study of." The NASA research subtopic title must not be used as the proposal title.

Proposal Package

Each complete proposal package submitted shall contain the following items:

1. Proposal Contact Information (3.3.3.1)
2. Proposal Certifications, electronically endorsed. (3.3.3.2)
3. Proposal Summary (must not contain proprietary data). (3.3.3.3)
4. Proposal Budget (including letters of availability for facilities and subcontractors/consultants, if applicable) (3.3.3.4)
5. Technical Proposal - 10 parts in the order specified in section 3.3.4, and not to exceed 19 pages (both SBIR and STTR), including all graphics, with a table of contents. (3.3.4)

6. Research Agreement between the SBC and RI (STTR only). (3.3.5)
7. Briefing Chart (must not contain proprietary data). (3.3.7)
8. NASA Evaluation License Application, only if TAV is being proposed. (1.6)
9. I-Corps Opt-In Form (3.3.6)

Note: Letters expressing general technical interest or letters of funding support commitments (for Phase I) are not required or desired and will not be considered during the review process. However, if submitted, such letter(s) will count against the page limit.

Firm Level Forms

In addition to the above items, each offeror must submit the following firm level forms, which must be filled out once during each submission period and are applicable to all firm proposal submissions:

1. Firm Certifications (3.3.8)
2. Audit Information (3.3.9)
3. Prior Awards Addendum (3.3.10)
4. Commercial Metrics Survey (3.3.11)

Previews of all forms and certifications are available via the NASA SBIR/STTR Firm Library, located at: http://sbir.gsfc.nasa.gov/sbir/firm_library/index.html.

Note: The systems will not allow the upload of relevant technical papers, product samples, videotapes, slides or other ancillary items and they will not be considered during the review process.

3.3.3 Forms

All form submissions shall be completed electronically, and do not count towards the 19-page limit for the technical proposal.

3.3.3.1 Proposal Contact Information

A sample Contact Information form is provided in the NASA SBIR/STTR Firms Library http://sbir.gsfc.nasa.gov/sbir/firm_library/index.html. The offeror shall provide complete information for each contact person and submit the form as required in section 6.

Note: Contact Information is public information and may be disclosed.

3.3.3.2 Proposal Certifications

A sample Proposal Certifications form is provided in the NASA SBIR/STTR Firms Library http://sbir.gsfc.nasa.gov/sbir/firm_library/index.html. The offeror shall provide complete information for each item and submit the form as required in section 6.

3.3.3.3 Proposal Summary

A sample Proposal Summary form is provided in the NASA SBIR/STTR Firms Library http://sbir.gsfc.nasa.gov/sbir/firm_library/index.html. The offeror shall provide complete information for each item and submit the form as required in section 6.

Note: The Proposal Summary, including the Technical Abstract, is public information and may be disclosed. Do not include proprietary information in this form.

3.3.3.4 Proposal Budget

A sample of the Proposal Budget form is provided in the NASA SBIR/STTR Firms Library http://sbir.gsfc.nasa.gov/sbir/firm_library/index.html. The offeror shall complete the Proposal Budget following the instructions provided with the sample form. The total requested funding for the Phase I effort shall not exceed $125,000. Contextual help is provided on the electronic budget form for additional explanation. Information shall be submitted to explain the offeror's plans for use of the requested funds to enable NASA to determine whether the proposed price is fair and reasonable.

Note: The government is not responsible for any monies expended by the firm before award of any contract.

In addition, the following additional uploads, must be submitted in the Proposal Budget form, as applicable:

Proposal Requirements for Use of Federal Services, Facilities or Equipment:

In cases where an offeror seeks to use NASA or another federal department or agency services, equipment or facilities, the offeror shall provide the following:

1. Statement, signed by the appropriate government official at the effected federal department or agency, verifying that the resources should be available during proposed period of performance.
2. Signed letter on company letterhead from the contractor's Small Business Official explaining why the SBIR/STTR research project requires the use of federal services, equipment or facilities, including data that verifies the absence of non-federal facilities or personnel capable of supporting the research effort, a statement confirming that the facility proposed is not a federal laboratory, if applicable, and the associated cost estimate.

Note: Use of federal laboratories/facilities for Phase I contracts is highly discouraged. Approval for use of federal facilities and labs, for a Phase I proposal, requires Program Executive approval during negotiations if selected for award.

See Part 8 of the Technical Proposal for additional information on use of federal facilities.

Use of Subcontractors and Consultants:

Subject to the restrictions set forth below, the SBC may establish business arrangements with other entities or individuals to participate in performance of the proposed R/R&D effort. Subcontractors' and consultants' work has the same place of performance restrictions as stated in section 1.5.2.

Note:

1. ***Offerors should list consultants by name and specify, for each, the number of hours and hourly costs.***
2. ***Breakdown of subcontractor budget should mirror the SBC's own breakdown in the Proposal Budget form and include breakdowns of direct labor, other direct costs, profit, as well as indirect rate agreements.***
3. ***A signed letter of commitment is required for each subcontractor and/or consultant. For educational institutions, the letter must be from the institution's Office of Sponsored Programs.***

STTR: The RI's budget must be submitted at the time of proposal submission and if the RI is an educational institution, they must submit a letter from the institution's Office of Sponsored Programs.

The following restrictions apply to the use of subcontracts/consultants and the formula below must be used in preparing budgets with subcontractors/consultants:

SBIR Phase I Subcontracts/Consultants	STTR Phase I Subcontracts/Consultants
The proposed subcontracted business arrangements, including consultants, must not exceed 33 percent of the research and/or analytical work [as determined by the total cost of the proposed subcontracting effort (to include the appropriate OH and G&A) in comparison to the total effort (total contract price including cost sharing, if any, less profit if any)]. Occasionally, deviations from these SBIR requirements may occur, and must be approved in writing by the Funding Agreement officer after consultation with the agency SBIR/STTR Program Manager.	A minimum of 40 percent of the research or analytical work must be performed by the proposing SBC and minimum of 30 percent must be performed by the RI. Any subcontracted business effort other than that performed by the RI, shall not exceed 30 percent of the research and/or analytical work [as determined by the total cost of the subcontracting effort (to include the appropriate OH and G&A) in comparison to the total effort (total contract price including cost sharing, if any, less profit if any)]. Deviations from these STTR requirements are not allowed, as the performance of work requirements are specified in statute at 15 USC 638(e).

Example:	Total price to include profit	- $99, 500
	Profit	- $3,000
	Total price less profit	- $99,500 - $3,000 = $96,500
	Subcontractor cost	- $29,500
	G&A	- 5%
	G&A on subcontractor cost	- $29,500 x 5% = $1,475
	Subcontractor cost plus G&A	- $29,500 + $1,475 = $30,975
	Percentage of subcontracting effort	**- $30,975 / $96,500 = 32.1%**
	– Subcontractor cost plus G&A / total price less profit	

- For an SBIR Phase I this is acceptable since it is below the limitation of 33%.
- For an STTR Phase I, where there is a subcontract with a company other than the RI, this is unacceptable since it is above the 30% limitation.

See Part 9 of the Technical Proposal for additional information on the use of Subcontractors and Consultants.

Travel in Phase I

Due to the intent and short period of performance of the Phase I contracts along with their limited budget, travel during the Phase I contract is highly discouraged unless it is required to successfully complete the proposed effort. If the purpose of the meeting cannot be accomplished via videoconference or teleconference, the offeror must provide rationale for the trip in the proposal budget form. All travel must be approved by the Contracting Officer and concurred by the Technical Monitor.

~~However, during this solicitation, Phase I offerors may propose up to $1,500.00 for one person per firm for travel to attend the Innovation & Opportunity Conference (IOC) tentatively scheduled for fall 2020 with location to be determined. For additional information on the IOC, see the Noteworthy Changes section at the front of this solicitation. This request for travel funding shall not be used for travel other than attending the IOC meeting. If an offeror plans to submit multiple proposals, it is recommended that the offeror request up to $1,500.00 for travel to the IOC per proposal, however NASA will only allow up to $1,500.00 of travel funds to be provided to a single firm that receives multiple awards under this solicitation to attend the IOC meeting.~~

3.3.4 Technical Proposal

This part of the submission should not contain any budget data and must consist of all ten (10) parts listed below in the given order. All ten parts of the technical proposal must be numbered and titled. Parts that are not applicable must be included and marked "Not applicable." A proposal omitting any part will be considered non-responsive to this solicitation and may be rejected during administrative screening. The required table of contents is provided below:

Phase I Table of Contents

Part 1:	Table of Contents……………………………………………………………………Page 1
Part 2:	Identification and Significance of the Innovation
Part 3:	Technical Objectives
Part 4:	Work Plan
Part 5:	Related R/R&D
Part 6:	Key Personnel and Bibliography of Directly Related Work
Part 7:	Potential Future Applications and Relationship with Future R/R&D
Part 8:	Facilities/Equipment
Part 9:	Subcontracts and Consultants
Part 10:	Related, Essentially Equivalent and Duplicate Proposals and Awards

Part 1: Table of Contents *(Suggested Page Limit – 0.5 Page)*

The technical proposal shall begin with a brief table of contents indicating the page numbers of each of the parts of the proposal.

Part 2: Identification and Significance of the Proposed Innovation *(Suggested Page Limit – 5 Pages)*

Succinctly describe:

- The proposed innovation.
- The relevance and significance of the proposed innovation to an interest, need or needs, within a subtopic described in section 9.
- The proposed innovation relative to the state of the art.

Part 3: Technical Objectives *(Suggested Page Limit – 1 Page)*

State the specific objectives of the Phase I R/R&D effort as it relates to the problem statement(s) posed in the subtopic description and the types of innovations being requested by the subtopic manager(s).

Proposed Deliverables: Indicate the proposed deliverables at the end of the Phase I effort. These may include, but are not limited to, required contract deliverables, test reports, software, or hardware, etc.

Note: All offerors submitting proposals who are planning to use NASA Intellectual Property (IP) must describe their planned developments with the IP. The NASA Evaluation License Application should be added as an attachment in the Proposal Certifications form (see section 1.6).

Part 4: Work Plan *(Suggested Page Limit – 5 Pages)*

Include a detailed description of the Phase I R/R&D plan to meet the technical objectives. The plan should indicate what will be done, where it will be done and how the R/R&D will be carried out. Discuss in detail the methods planned to achieve each task or objective. Task descriptions, schedules, resource allocations, estimated task hours for each key personnel and planned accomplishments including project milestones shall be included. Offerors should ensure that the estimated task hours provided in the work plan for key personnel are consistent with the hours reported in the Proposal Budget form. If the offeror is a joint venture or limited partnership, a statement of how the workload will be distributed, managed and charged should be included here.

STTR: In addition, the work plan will specifically address the percentage and type of work to be performed by the SBC and the RI. The plan will provide evidence that the SBC will exercise management direction and control of the performance of the STTR effort, including situations in which the PI may be an employee of the RI.

Part 5: Related R/R&D *(Suggested Page Limit – 1 Page)*

Describe significant current and/or previous R/R&D that is directly related to the proposal including any conducted by the PI or by the offeror. Describe how it relates to the proposed effort and any planned coordination with outside sources. The offeror must persuade reviewers of his or her awareness of key recent R/R&D conducted by others in the specific subject area.

Part 6: Key Personnel and Bibliography of Directly Related Work *(Suggested Page Limit – 2.5 Pages)*

Identify all key personnel involved in Phase I activities whose expertise and functions are essential to the success of the project. Provide bibliographic information including directly related education and experience. Where vitae are extensive, summaries that focus on the most relevant experience or publications are desired and may be necessary to meet proposal size limitation.

The PI is considered key to the success of the effort and must make a substantial commitment to the project. The following requirements are applicable:

Functions: The functions of the PI are: planning and directing the project, leading it technically and making substantial personal contributions during its implementation, serving as the primary contact with NASA on the project and ensuring that the work proceeds according to contract agreements. Competent management of PI functions is essential to project success. The Phase I proposal shall describe the nature of the PI's activities and the amount of time that the PI will personally apply to the project. The amount of time the PI proposes to spend on the project must be acceptable to the Contracting Officer.

Qualifications: The qualifications and capabilities of the proposed PI and the basis for PI selection are to be clearly presented in the proposal. NASA has the sole right to accept or reject a PI based on factors such as education, experience, demonstrated ability and competence, and any other evidence related to the specific assignment.

Eligibility: This part shall also establish and confirm the eligibility of the PI, and indicate the extent to which other proposals recently submitted or planned for submission in Fiscal Year 2020 and existing projects commit the time of the PI concurrently with this proposed activity. Any attempt to circumvent the restriction on PIs working more than half time for an academic or a nonprofit organization by substituting an ineligible PI will result in rejection of the proposal. However, for an STTR the PI can be primarily employed by either the SBC or the RI. Please see section 1.5.3 for further explanation.

Part 7: The Market Opportunity *(Suggested Page Limit – 1 Page)*

Phase I applicants should describe both NASA and Non-NASA markets and addressable markets for the innovation. Discuss the business economics and market drivers in the target industry. How has the market opportunity been validated? Describe your customers and your basic go to market strategy to achieve the market opportunity. Describe the competition. How do you expect the competitive landscape may change by the time your innovation enters the market? What are the key risks in bringing your innovation to market? Describe your commercialization approach. Discuss the potential economic benefits associated with your innovation, and provide estimates of the revenue potential, detailing your underlying assumptions. Describe the resources you expect will be needed to implement your commercialization approach.

Note: Companies with no SBIR/STTR awards or fairly recent awards will not be penalized under past performance for the lack of past SBIR/STTR commercialization.

Part 8: Facilities/Equipment *(Suggested Page Limit – 1 Page)*

Offerors must describe the necessary instrumentation and facilities to be used to perform the proposed work. Offerors must ensure the resources are adequate and address any reliance on external sources, such as government furnished equipment or facilities. In cases where an offeror seeks to use NASA or another federal department or agency services, equipment or facilities, the offeror shall describe in this part why the use of government furnished equipment or facilities is necessary. See section 3.3.3.4 and 5.14 for additional requirements when proposing use of federal facilities. The narrative description of facilities and equipment should support the proposed approach and documentation in the Proposal Budget form.

Note: Use of federal laboratories/facilities for Phase I contracts is highly discouraged. Approval for use of federal facilities and labs, for a Phase I proposal, requires Program Executive approval during negotiations if selected for award.

Part 9: Subcontracts and Consultants *(Suggested Page Limit – 1 Page)*

The offeror must describe all subcontracting or other business arrangements and identify the relevant organizations and/or individuals with whom arrangements are planned. The expertise to be provided by the entities must be described in detail, as well as the functions, services and number of hours. Offerors are responsible for ensuring that all organizations and individuals proposed to be utilized are actually available for the time periods proposed. Subcontract costs shall be documented in the Subcontractors/Consultants section of the Proposal Budget form and supporting documentation should be uploaded for each (appropriate documentation is specified in the form). The narrative description of subcontracts and consultants in the technical proposal should support the proposed approach and documentation in the Proposal Budget form.

Part 10: Related, Essentially Equivalent, and Duplicate Proposals and *Awards (Suggested Page Limit – 1 Page)*

WARNING – While it is permissible with proper notification to submit identical proposals or proposals containing a significant amount of essentially equivalent work for consideration under numerous federal program solicitations, it is unlawful to enter into funding agreements requiring essentially equivalent work.

If an applicant elects to submit identical proposals or proposals containing a significant amount of essentially equivalent work under other federal program solicitations, a statement must be included in each such proposal indicating:

1. The name and address of the agencies to which proposals were submitted or from which awards were received.
2. Date of proposal submission or date of award.
3. Title, number and date of solicitations under which proposals were submitted or awards received.
4. The specific applicable research topics for each proposal submitted or award received.
5. Titles of research projects.
6. Name and title of principal investigator or project manager for each proposal submitted or award received.

Offerors are at risk for submitting essentially equivalent proposals and therefore are strongly encouraged to disclose these issues to the soliciting agency to resolve the matter prior to award.

A summary of essentially equivalent work information, as well as related research and development on proposals and awards is also required on the Proposal Certifications form (if applicable).

3.3.5 Research Agreement (Applicable for STTR proposals only)

STTR: The Research Agreement (different from the Allocation of Rights Agreement, see: http://sbir.nasa.gov/content/nasa-sbirsttr-program-definitions) is a single-page document electronically submitted and endorsed by the SBC and RI. A model agreement is provided, or firms can create their own custom agreement. The Research Agreement shall be submitted as required in section 6.

All STTR Phase I proposals must provide sufficient information to convince NASA that the proposed SBC/RI cooperative effort represents a sound approach for converting technical information resident at the RI into a product or service that meets a need described in a Solicitation research topic.

3.3.6 Applications to I-Corps

Firms proposing to this solicitation will be allowed to also propose participation in the SBIR/STTR I-Corps Program using the following submittal process. I-Corps awards will be made separately from the Phase I contract as a training grant.

3.3.6.1 Step 1: Opt-In Form

Phase I SBIR/STTR offerors must complete a short I-Corps Opt-In Form as part of their Phase I proposal submission. Representations in the form will determine an offeror's eligibility to participate in I-Corp. The form also asks that offerors provide a brief summary explaining the value of I-Corps to their companies. In the event a large number of offerors express interest, the government reserves the right to limit the number of offerors invited to submit I-Corps proposals based upon the government's assessment of the initial summary statements.

3.3.6.2 Step 2: I-Corps Proposal

To be qualified to submit an I-Corps proposal: 1) offerors must have submitted the I-Corps Opt-In Form as part of their Phase I proposals; 2) offerors must be qualified to participate in I-Corps and 3) offerors must be selected for a

Phase I award. Participating offerors must form a team composed of three main members: The Principal Investigator, the Entrepreneurial Lead and the Mentor, as described in http://sbir.nasa.gov/content/I-Corps. The I-Corps proposal shall follow the same format requirements as the SBIR/STTR Phase I proposal, shall be limited to six pages and shall include the following sections in order to be considered complete:

- I-Corps Team and Commercialization Plan (limited to five pages).
  - I-Corps Team: Biographical sketches of I-Corps team members and their commitment to participate in I-Corps (limited to one page per team member).
  - Commercialization Plan (limited to one page). This shall include:
    - Composition and roles (Principal Investigator, Entrepreneurial Lead and Mentor) of the team members proposing to undertake the commercialization feasibility research.
    - Building off the commercialization information provided in the Phase I proposal, include an additional, brief description of the potential non-NASA commercial impacts of the project, what types of customer discovery the firm hopes to accomplish through I-Corps and what steps the company will take to move the project closer to commercialization.
- I-Corps Proposal Budget (limited to one page).
  - Capped at $10,000 for each SBIR team and $25,000 for each STTR team.
  - Only recovery of certain direct costs associated with participation in I-Corps is allowed, no recovery of indirect costs is allowed.
  - The budget should include the following five components:
    - Maximum of $5,500 for Entrepreneurial Lead stipend (no stipend for the Principal Investigator or I-Corps Mentor)
    - An estimate for the travel costs associated with team member participation in required kick-off and close out/lessons learned meetings (i.e., airfare, per diem costs). Suggested limit is $5,500 per team.
    - Costs for workshop registration fees that will be paid to the instruction service (logistics) providers. This is expected to be $4,500 per team.
    - Estimated costs for travel associated with the three team members traveling as a group to conduct customer interviews (30 interviews for SBIR participants and 100 interviews for STTR participants). Suggested limits are $2,550 for SBIR teams and $10,000 for STTR teams.

The I-Corps proposal will be due one week after formal notification that the firm has been selected for negotiation of a Phase I SBIR or STTR contract. The firm shall submit their I-Corps proposal into the Proposal Submissions EHB, which shall be re-opened for those firms which have met the three qualifications identified above.

Note: Proposals for I-Corps have separate page limitations outside the page limitations for the technical proposal.

3.3.7 Briefing Chart

The one-page briefing chart is required to assist in the ranking and advocacy of proposals prior to selection and contains the following sections with summary information:

- Identification and Significance of Innovation
- Technical Objectives
- Proposed Deliverables
- NASA Applications
- Non-NASA Applications
- Graphic

It shall not contain any proprietary data or ITAR restricted data. An electronic form will be provided during the submissions process.

Note: The briefing chart is public information and may be disclosed. Do not include proprietary information in this form.

3.3.8 Firm Certifications

Firm certifications that are applicable across all proposal submissions submitted to this solicitation must be completed via the Firm Certifications section of the Proposal Submissions Electronic Handbook. The offeror shall answer Yes or No as applicable. An example of the certifications can be found in the NASA SBIR/STTR Firms Library http://sbir.gsfc.nasa.gov/sbir/firm_library/index.html. An electronic form will be provided during the submissions process.

Note: The designated Firm Admin, typically the first person to register your firm, is the only individual authorized to update the certifications.

3.3.9 Audit Information

Although firms are not required to have an approved accounting system, knowledge that a firm has an approved accounting system facilitates NASA's determination that rates are fair and reasonable. To assist NASA, the SBC shall complete the questions in the Audit Information form regarding the firm's rates and upload the federal agency audit report or related information that is available from the last audit. There is a separate "Audit Information" section in the Proposal Budget form that shall also be completed. If your firm has never been audited by a federal agency, then answer "No" to the first question and you do not need to complete the remainder of the form. An electronic form will be provided during the submissions process.

The Contracting Officer will use this Audit Information to assist with negotiations if the proposal is selected for award. The Contracting Officer will advise offerors what is required to determine reasonable cost and/or rates in the event the Audit Information is not adequate to support the necessary determination on rates.

Note: The designated firm admin, typically the first person to register your firm, is the only individual authorized to update the audit information.

3.3.10 Prior Awards Addendum

If the SBC has received more than 15 Phase II awards in the prior 5 fiscal years, submit name of awarding agency, solicitation year, phase, date of award, funding agreement/contract number, and topic or subtopic title for each Phase II. If your firm has received any SBIR or STTR Phase II awards, even if it has received fewer than 15 in the last 5 years, it is still recommended that you complete this form for those Phase II awards your firm did receive. This information will be useful when completing the Commercialization Metrics Survey, and in tracking the overall success of the SBIR and STTR Programs. Any NASA Phase II awards your firm has received will be automatically populated in the electronic form, as well as any Phase II awards previously entered by the SBC during prior submissions (you may update the information for these awards). An electronic form will be provided during the submissions process.

Note: The designated firm admin, typically the first person to register your firm, is the only individual authorized to update the addendum information.

3.3.11 Commercial Metrics Survey

NASA has instituted a comprehensive commercialization survey/data gathering process for firms with prior NASA SBIR/STTR awards. If the SBC has received any Phase III awards resulting from work on any NASA SBIR or STTR awards, provide the related Phase I or Phase II contract number, name of Phase III awarding agency, date of award, funding agreement number, amount, project title and period of performance. The survey will also ask for firm financial, sales and ownership information, as well as any commercialization success the firm has had as a result of SBIR or STTR awards. This information must be updated annually during proposal submission via the EHB. This information allows firms to demonstrate their ability to carry SBIR/STTR research through to achieve commercial success, and allow agencies to track the overall commercialization success of their SBIR and STTR Programs. The survey should be limited to information requested above. An electronic form will be provided during the submissions process.

Note: Information received from SBIR/STTR awardees completing the survey is kept confidential, and will not be made public except in broad aggregate, with no firm-specific attribution.

The Commercialization Metrics Survey is a required part of the proposal submissions process and must be completed via the Proposal Submissions Electronic Handbook. Also, Companies with no SBIR/STTR awards or only fairly recent awards will not be penalized under past performance for the lack of past SBIR/STTR commercialization.

3.3.12 Allocation of Rights Agreement (STTR awards only)

An SBC, before receiving an STTR award, must negotiate a written agreement between the SBC and the partnering Research Institution, allocating Intellectual Property rights, if any, to carry out follow-on research, development, or Commercialization which has been signed by authorized representatives of the SBC, RI, and subcontractors and consultants, as applicable. A sample ARA is available in the NASA SBIR/STTR Firm Library http://sbir.gsfc.nasa.gov/sbir/firm_library/index.html of this Solicitation.

The SBC should submit this agreement with the proposal by uploading it in in the Proposal Budget form. This will help to expedite contract negotiations.

3.4 Phase II Proposal Requirements

3.4.1 General Requirements

The Phase I contract will serve as a request for proposal (RFP) for the Phase II follow-on project. Phase II proposals are more comprehensive than those required for Phase I. Submission of a Phase II proposal is in accordance with Phase I contract requirements and is voluntary. NASA assumes no responsibility for any proposal preparation expenses.

A competitive Phase II proposal will clearly and concisely (1) describe the proposed innovation relative to the state of the art and the market, (2) address Phase I results relative to the scientific, technical merit and feasibility of the proposed innovation and its relevance and significance to the NASA interests and (3) provide the planning for a focused project that builds upon Phase I results and encompasses technical, market, financial and business factors relating to the development and demonstration of the proposed innovation, and its transition into products and services for NASA mission programs, other government agencies and non-government markets.

3.4.2 Format Requirements

Note: The government administratively screens all proposals and reserves the right to reject any proposal that does not conform to the following formatting requirements.

Page Limitations and Margins

Note: Technical proposal uploads with any page(s) going over the required page limit will not be accepted. Any page(s) going over the required page limit will be deleted and omitted from the proposal review.

A Phase II technical proposal shall not exceed a total of 46 standard 8 1/2 x 11 inch (21.6 x 27.9 cm) pages. Proposals uploaded with more than 46 pages will prompt a warning which will prevent the completed proposal from being submitted. Each page shall be numbered consecutively at the bottom. Margins shall be 1.0 inch (2.5 cm). The space allocated to each part of the technical content will depend on the project chosen and the offeror's approach. The additional forms required for proposal submission will not count against the 46-page limit.

Suggested Page Limits

Within section 3.4.4 are suggested page limits for each part of the technical proposal. These are guidelines and are not strict requirements. Offerors are still required to meet the total page limit requirements as described above.

Type Size

No type size smaller than 10 point shall be used for text or tables, except as legends on reduced drawings. Proposals prepared with smaller font sizes may be rejected without consideration.

Header/Footer Requirements

Header must include firm name, proposal number and project title. Footer must include the page number and proprietary markings if applicable. Margins can be used for header/footer information.

Classified Information

NASA does not accept proposals that contain classified information.

Project Title

The proposal project title shall be concise and descriptive of the proposed effort. The title should not use acronyms or words like "Development of" or "Study of." The NASA research topic title must not be used as the proposal title.

Proposal Package

Each complete proposal package submitted shall contain the following items:

1. Proposal Contact Information. (3.4.3.1)
2. Proposal Certifications, electronically endorsed. (3.4.3.2)
3. Proposal Summary (must not contain proprietary data). (3.4.3.3)
4. Proposal Budget. (3.4.3.4)
5. Technical Content - 10 Parts in the order specified in section 3.4.4, not to exceed 46 pages (for SBIR AND STTR), including all graphics, and starting with a table of contents. (3.4.4)
6. Research Agreement between the SBC and RI (STTR only). (3.4.5)

7. Briefing Chart (must not contain proprietary data). (3.4.7)
8. NASA Evaluation License Application, only if TAV is being proposed. (1.6)
9. Capital Commitments Addendum Supporting Phase II and Phase III (optional). (3.4.6)

Note: Letters expressing general technical interest are not required or desired and will not be considered during the review process. However, if submitted, such letter(s) will count against the page limit. Letters of funding support commitments are allowable for Phase II proposals but will be considered only under Factor 4 - Commercial Potential and Feasibility. Letters of funding support commitments should be submitted as part of the Capital Commitments Addendum.

Firm Level Forms

In addition to the above items, each offeror must submit the following firm level forms, which must be filled out once during each submission period and are applicable to all firm proposal submissions:

1. Firm Certifications (3.4.8)
2. Audit Information (3.4.9)
3. Prior Awards Addendum (3.4.10)
4. Commercial Metrics Survey (3.4.11)

Previews of all forms and certifications are available via the NASA SBIR/STTR Firm Library, located at: http://sbir.gsfc.nasa.gov/sbir/firm_library/index.html.

Note: The systems will not allow the upload of relevant technical papers, product samples, videotapes, slides or other ancillary items and they will not be considered during the review process.

3.4.3 Forms

All form submissions shall be done electronically, and do not count towards the 46-page limit.

3.4.3.1 Contact Information

A sample Contact Information form is provided in the NASA SBIR/STTR Firms Library http://sbir.gsfc.nasa.gov/sbir/firm_library/index.html. The offeror shall provide complete information for each contact person and submit the form as required in section 6.

Note: Contact Information, is public information and may be disclosed.

3.4.3.2 Proposal Certifications

A sample Proposal Certifications form is provided in the NASA SBIR/STTR Firms Library http://sbir.gsfc.nasa.gov/sbir/firm_library/index.html. The offeror shall provide complete information for each item and submit the form as required in section 6.

3.4.3.3 Proposal Summary

A sample Proposal Summary form is provided in the NASA SBIR/STTR Firms Library http://sbir.gsfc.nasa.gov/sbir/firm_library/index.html. The offeror shall provide complete information for each item and submit the form as required in section 6.

Note: The Proposal Summary, including the Technical Abstract, is public information and may be disclosed. Do not include proprietary information in this form.

3.4.3.4 Proposal Budget

A sample of the Proposal Budget form is provided in the NASA SBIR/STTR Firms Library http://sbir.gsfc.nasa.gov/sbir/firm_library/index.html. The offeror shall complete the Budget Summary following the instructions provided with the sample form. The total requested funding for the Phase II effort shall not exceed $750,000. Contextual help is provided on the electronic budget form for additional explanation. Information shall be submitted to explain the offeror's plans for use of the requested funds to enable NASA to determine whether the proposed price is fair and reasonable.

Note: The government is not responsible for any monies expended by the firm before award of any contract.

In addition, the following additional uploads, must be submitted in the Proposal Budget form, as applicable:

Proposal Requirements for Use of Federal Services, Facilities or Equipment:

In cases where an offeror seeks to use NASA or another federal department or agency services, equipment or facilities, the offeror shall provide the following:

1. Statement, signed by the appropriate government official at the effected federal department or agency, verifying that the resources should be available during the proposed period of performance. Offerors must upload this letter in the Proposal Budget form.
2. Signed letter on company letterhead from the contractor's Small Business Official explaining why the SBIR/STTR research project requires the use of federal services, equipment or facilities, including data that verifies the absence of non-federal facilities or personnel capable of supporting the research effort, a statement confirming that the facility proposed is not a federal laboratory, if applicable, and the associated cost estimate. Offerors must upload this letter in the Proposal Budget form.

See Part 8 of the Technical Proposal for additional information on use of federal Facilities.

Use of Subcontractors and Consultants:

Subject to the restrictions set forth below, the SBC may establish business arrangements with other entities or individuals to participate in performance of the proposed R/R&D effort.

Note:

1. ***Offerors should list consultants by name and specify, for each, the number of hours and hourly costs.***
2. ***Breakdown of subcontractor budget should mirror the SBC's own breakdown in the Proposal Budget form and include breakdowns of direct labor, other direct costs, profit, as well as indirect rate agreements.***
3. ***A signed letter of commitment is required for each subcontractor and/or consultant. For educational institutions, the letter must be from the institution's office of sponsored programs.***

STTR: The RI's budget must be submitted at the time of proposal submission and if the RI is an educational institution, they must submit a letter from the institution's Office of Sponsored Programs.

Subcontractors' and consultants' work has the same place of performance restrictions as stated in section 1.5.2.

The following restrictions apply to the use of subcontracts/consultants and the formula below must be used in preparing budgets with subcontractors/consultants:

SBIR Phase II Subcontracts/Consultants	**STTR Phase II Subcontracts/Consultants**
The proposed subcontracted business arrangements including consultants, must not exceed 50 percent of the research and/or analytical work [as determined by the total cost of the proposed subcontracting effort (to include the appropriate OH and G&A) in comparison to the total effort (total contract price including cost sharing, if any, less profit if any)]. Occasionally, deviations from these SBIR requirements may occur, and must be approved in writing by the Funding Agreement officer after consultation with the agency SBIR/STTR Program Manager.	A minimum of 40 percent of the research or analytical work must be performed by the proposing SBC and minimum of 30 percent must be performed by the RI. Any subcontracted business effort other than that performed by the RI, shall not exceed 30 percent of the research and/or analytical work [(as determined by the total cost of the subcontracting effort (to include the appropriate OH and G&A) in comparison to the total effort (total contract price including cost sharing, if any, less profit if any)]. Deviations from these STTR requirements are not allowed, as the performance of work requirements are specified in statute at 15 USC 638(e).

Example:	Total price to include profit	- $725,000
	Profit	- $21,750
	Total price less profit	- $725,000 - $21,750 = $703,250
	Subcontractor cost	- $250,000
	G&A	- 5%
	G&A on subcontractor cost	- $250,000 x 5% = $12,500
	Subcontractor cost plus G&A	- $250,000 + $12,500 = $262,500
	Percentage of subcontracting effort – Subcontractor cost plus G&A / total price less profit	**- $262,500 / $703,250 = 37.3%**

- For an SBIR Phase II this is acceptable since it is below the limitation of 50%.
- For an STTR Phase II, where there is a subcontract with a company other than the RI, this is unacceptable since it is above 30% limitation.

See Part 9 of the Technical Proposal for additional information on the use of Subcontractors and Consultants.

Travel to the Innovation & Opportunity Conference (IOC) in Phase II

NASA does not normally limit the ability for Phase II awardees to propose travel that supports their project during the project period of performance. Under this solicitation NASA is encouraging Phase II awardees to plan to attend the Innovation & Opportunity Conference (IOC) tentatively scheduled for fall 2020 with a location to be determined. Under a Phase II proposal, NASA is encouraging that any firms that wish to attend the IOC propose up to $1,500.00 for one person per firm for travel to attend the IOC. This request to attend the IOC is over and above any additional travel that may be requested for other meetings or activities that fall within the scope of the Phase II project. NASA will only allow up to $1,500.00 of travel funds to be provided to a single firm that receives multiple Phase II awards under this solicitation to attend the IOC. For additional information on the IOC, see the Noteworthy Changes section at the front of this solicitation.

Milestone Plan

For Phase II, offerors shall submit a proposed quarterly milestone plan with the Proposal Budget form. The milestone plan shall be in accordance with the proposed work plan outlining the work to be accomplished each quarter and the cost proposed associated with each of the quarterly milestones. The cost breakdown shall be similar to the Proposal Budget form for each of the proposed quarterly milestones (i.e., each milestone should include the labor, supplies, travel and profit associated with those tasks to be accomplished that quarter). The proposed cost associated with each quarterly milestone must be realistic for the work to be accomplished but is not required to be equally distributed across each quarter.

3.4.4 Technical Proposal

This part of the submission shall not contain any budget data and must consist of all ten (10) parts listed below in the given order. All ten parts of the technical proposal must be numbered and titled. Parts that are not applicable must be included and marked "Not applicable." A proposal omitting any part will be considered non-responsive to this Solicitation and may be rejected during administrative screening. The required table of contents is provided below:

Phase II Table of Contents

Part 1: Table of Contents *(Suggested Page Limit – 0.5 Page)*

The technical proposal shall begin with a brief table of contents indicating the page numbers of each of the parts of the proposal.

Part 2: Identification and Significance of the Innovation and Results of the Phase I Award *(Suggested Page Limit – 15 Pages)*

Please provide a summary of your Phase I results and building on those results succinctly describe the Phase II proposed work including:

- The proposed innovation.
- The relevance and significance of the proposed innovation to an interest, need or needs within the subtopic.
- The proposed innovation relative to the state of the market, the state of the art and its feasibility.

Please be advised that the evaluators may review the Phase I final technical report to verify accuracy of this summary. However proposers shouldn't rely on this and should include relevant results in the Phase II proposal.

Part 3: Technical Objectives *(Suggested Page Limit – 2 Pages)*

State the specific objectives of the Phase I R/R&D effort as it relates to the problem statement(s) posed in the subtopic description and the types of innovations being requested by the subtopic manager(s).

Proposed Deliverables: Indicate the proposed deliverables at the end of the Phase II effort. These may include, but are not limited to, required contract deliverables, test reports, software, or hardware, etc.

Note: All offerors submitting proposals who are planning to use NASA IP must describe their planned developments with the IP. The NASA Evaluation License Application should be added as an attachment under Proposal Certifications (see section 1.6).

Part 4: Work Plan *(Suggested Page Limit – 10 Pages)*

Include a detailed description of the Phase II R/R&D plan to meet the technical objectives. The plan should indicate what will be done, where it will be done and how the R/R&D will be carried out. Discuss in detail the methods planned to achieve each task or objective. Task descriptions, schedules, resource allocations, estimated task hours for each key personnel and planned accomplishments including project milestones shall be included. Offerors should ensure that the estimated task hours provided in the work plan for key personnel are consistent with the hours reported in the Proposal Budget form. If the offeror is a joint venture or limited partnership, a statement of how the workload will be distributed, managed and charged should be included in the proposal.

STTR: In addition, the work plan will specifically address the percentage and type of work to be performed by the SBC and the RI. The plan will provide evidence that the SBC will exercise management direction and control of the performance of the STTR effort, including situations in which the PI may be an employee of the RI.

Part 5: Related R/R&D *(Suggested Page Limit – 1 Page)*

Describe significant current and/or previous R/R&D that is directly related to the proposal including any conducted by the PI or by the offeror. Describe how it relates to the proposed effort and any planned coordination with outside sources. The offeror must persuade reviewers of his or her awareness of key recent R/R&D conducted by others in the specific subject area.

Part 6: Key Personnel and Bibliography of Directly Related Work *(Suggested Page Limit – 5 Pages)*

Identify all key personnel involved in Phase II activities whose expertise and functions are essential to the success of the project. Provide bibliographic information including directly related education and experience. Where vitae are extensive, summaries that focus on the most relevant experience or publications are desired and may be necessary to meet proposal size limitation.

The PI is considered key to the success of the effort and must make a substantial commitment to the project. The following requirements are applicable:

Functions: The functions of the PI are: planning and directing the project, leading it technically and making substantial personal contributions during its implementation, serving as the primary contact with NASA on the project and ensuring that the work proceeds according to contract agreements. Competent management of PI functions is essential to project success. The Phase II proposal shall describe the nature of the PI's activities and the amount of time that the PI will personally apply to the project. The amount of time the PI proposes to spend on the project must be acceptable to the Contracting Officer.

Qualifications: The qualifications and capabilities of the proposed PI and the basis for PI selection are to be clearly presented in the proposal. NASA has the sole right to accept or reject a PI based on factors such as education, experience, demonstrated ability and competence, and any other evidence related to the specific assignment.

Eligibility: This part shall also establish and confirm the eligibility of the PI, and indicate the extent to which other proposals recently submitted or planned for submission in the year and existing projects commit the time of the PI concurrently with this proposed activity. Any attempt to circumvent the restriction on PIs working more than half time for an academic or a nonprofit organization by substituting an ineligible PI will result in rejection of the proposal. However, for an STTR the PI can be primarily employed by either the SBC or the RI. Please see section 1.5.3 for further explanation.

Note: If the Phase II PI is different than that proposed under the Phase I, please provide rationale for the change.

Part 7: Phase III Efforts, Commercialization and Business Planning *(Suggested Page Limit – 8 Pages)*

The Commercialization Plan should complement, through narrative, the data provided by the applicant in the proposal briefing chart (see section 3.4.7) and the data provided to the Commercialization Metrics Survey (CMS) (see section 3.4.11). The CMS data is intended to support the company's claims about their ability to achieve the proposed innovation's commercialization for firms that have previously received SBIR/STTR awards, and provide a level of confidence regarding the SBC's future and financial viability.

Commercial Potential – Market

1. Describe the market segment and potential commercial Total Addressable Market (TAM) that is appropriate to the proposed innovation.
    a. Indicate how the market was validated and what assumptions were used in the analysis;
    b. Indicate the market size by providing the scope in dollars if possible;
    c. Indicate market segmentation and/or TAM in dollars if possible; and
    d. Indicate the projected percentage of the offeror's market share in 2-3 years after entry into the identified market.
2. Describe the proposed innovation in terms of target customers (e.g., NASA, other federal agency, commercial enterprise); and
3. Describe the competitive landscape, by identifying potential competitors.
    a. Indicate potential competitors by company name within the identified market;
    b. Discuss the barriers to entry and how many years it would take a competitor to enter this segment in terms of capitalization, technology, and people; and
    c. Describe how the proposed innovation is different from current and future competitors.

Commercial Intent – Plan

1. Describe the commercial development plan by providing a development timeline to bring the innovation to market.
2. Describe the applicable business model (spin-out, license, OEM, etc.) the offeror would use to bring the innovation to market.
    a. Indicate the channels of distribution (direct sales, distributors, etc.) that would be used in bringing the innovation into the identified market;
    b. Indicate the pro-forma 2-3 year revenue dollar projections based on the proposed innovation's penetration of the identified market; and
    c. Describe any follow-on development (long term > 5 years) plans to expand your proposed innovation's market presence.

3. Describe the risks to the commercial development plan and what mitigations, if any, can be taken over a reasonable period of time to lessen the risks.

Commercial Capability – Execution

1. Describe the current and future company capitalization efforts by;
    a. Discussing the technical, operations/manufacturing and business staff conducting the project;
    b. Describing the physical plant, including facilities and the capital equipment, tooling and test equipment used to conduct the investigation;
    c. Discussing consultants, incubators and research institutions that will be utilized to achieve commercialization; and
    d. Indicate how the innovation will enter into production (i.e., in house or through a licensee) and what changes (if any) will be made to company capitalization for commercialization;
2. As applicable, describe the approach, path to market and revenues from past commercialization(s) resulting from SBIR/STTR awards disclosed in the CMS. (Companies with no SBIR/STTR awards or only fairly recent SBIR/STTR awards will not be penalized under past performance for the lack of past SBIR/STTR commercialization.)

Intellectual Property

1. Describe how you will protect the intellectual property that results from your innovation.
    a. Note any actions you may consider to attain at least a temporary competitive advantage.
    b. What is the company's prior record in this area?
    c. Comment on the company's strategy to build a sustainable business through protection of intellectual property.

Assistance and Mentoring

1. Describe the existing and future business relationships in terms of any formal Partnerships, Joint Ventures, Licensing Agreements with other companies/organizations;
2. Describe the plans for securing needed technical or business assistance through mentoring, partnering, or through arrangements with State assistance programs, SBDCs, Federally-funded research laboratories, Manufacturing Extension Partnership centers, Federal programs or other assistance providers.

Show you have a plan for this funding in one or more of the following ways:

1. A letter of commitment* for follow-on funding;
2. A letter of commitment* for matching funding to be provided for a future Phase II/E application;
3. A letter of intent* or evidence of negotiations to provide funding, should the Phase II project be successful and the market need still exists; and
4. A specific plan to secure Phase III funding.

****Note: Letters of funding support commitments should be submitted as part of the Capital Commitments Addendum found in section 3.4.6 and will be considered only under Factor 4 - Commercial Potential and Feasibility (section 4). Any formal letters of commitment or intent submitted will not count towards the page limits of the application*.***

Part 8: Facilities/Equipment *(Suggested Page Limit – 2 Pages)*

Offerors must describe the necessary instrumentation and facilities to be used to perform the proposed work. Offerors must ensure the resources are adequate and address any reliance on external sources, such as government furnished equipment or facilities. In cases where an offeror seeks to use NASA or another federal department or agency services, equipment or facilities, the offeror shall describe in this part why the use of government furnished equipment or facilities is necessary. See section 3.4.3.4 and 5.14 for additional requirements when proposing use of federal facilities.

Part 9: Subcontracts and Consultants *(Suggested Page Limit – 2 Pages)*

The offeror must describe all subcontracting or other business arrangements, and identify the relevant organizations and/or individuals with whom arrangements are planned. The expertise to be provided by the entities must be described in detail, as well as the functions, services, number of hours and labor rates. Offerors are responsible for ensuring that all organizations and individuals proposed to be utilized are actually available for the time periods proposed. Subcontract costs shall be documented in the Subcontractors/Consultants section of the Proposal Budget form and supporting documentation should be uploaded for each (appropriate documentation is specified in the form). The narrative description of subcontracts and consultants in the technical proposal should support the proposed approach and documentation in the Proposal Budget form.

Part 10: Related, Essentially Equivalent, and Duplicate Proposals and Awards *(Suggested Page Limit – 0.5 Page)*

WARNING – While it is permissible with proposal notification to submit identical proposals or proposals containing a significant amount of essentially equivalent work for consideration under numerous federal program solicitations, it is unlawful to enter into funding agreements requiring essentially equivalent work.

If an applicant elects to submit identical proposals or proposals containing a significant amount of essentially equivalent work under other federal program solicitations, a statement must be included in each such proposal indicating:

1. The name and address of the agencies to which proposals were submitted or from which awards were received.
2. Date of proposal submission or date of award.
3. Title, number and date of solicitations under which proposals were submitted or awards received.
4. The specific applicable research topics for each proposal submitted for award received.
5. Titles of research projects.
6. Name and title of principal investigator or project manager for each proposal submitted or award received.

Offerors are at risk for submitting essentially equivalent proposals and therefore, are strongly encouraged to disclose these issues to the soliciting agency to resolve the matter prior to award.

A summary of essentially equivalent work information, as well as related research and development on proposals and awards is also required on the Proposal Certifications form (if applicable).

3.4.5 Research Agreement (Applicable for STTR proposals only)

STTR: The Research Agreement (different from the Allocation of Rights Agreement, see: http://sbir.nasa.gov/content/nasa-sbirsttr-program-definitions) is a single-page document electronically submitted and endorsed by the SBC and RI. A model agreement is provided, or firms can create their own custom agreement. The Research Agreement shall be submitted as required in section 6.

All STTR Phase I proposals must provide sufficient information to convince NASA that the proposed SBC/RI cooperative effort represents a sound approach for converting technical information resident at the RI into a product or service that meets a need described in a Solicitation research topic.

3.4.6 Capital Commitments Addendum Supporting Phase II and Phase III

Letters of capital commitment act as an indication of market validation for the proposed innovation and add significant credibility to the proposed effort. Although, NASA can be a future stakeholder and possibly issue a Phase III contract for the innovation to be infused in a future mission, it should be understood that NASA's goal under the SBIR/STTR program is for small businesses to commercialize innovations in markets that are larger than just NASA. Letters of capital commitment should demonstrate that the company has initiated dialogue with relevant non-NASA stakeholders (potential customers, end users, strategic partners, investors, etc.) for the proposed innovation and that a legitimate business opportunity may exist should the innovation prove feasible outside of NASA. Additionally, NASA offers a Phase II/E program where a funded Phase II company can obtain additional NASA funding for the innovation. A Phase II/E application requires matching funding from an outside source in order to qualify. Applicants are encouraged to provide letters of capital commitment that can provide matching funds for a future Phase II/E application and should start this process at the onset of the first Phase II project.

The letter(s) must not exceed 2 pages in length, should come directly from potential customers, end users, strategic partners, investors, etc., and must contain affiliation information and contact information for the signatory stakeholder. Letters and supporting documents that only support the development of the innovation with no capital funding commitment as described above will not be reviewed. Letters and supporting documents from State, Local and Congressional representatives, are NOT considered letters of capital commitment and should not be submitted as part of the application and will not be reviewed.

If letters of capital commitment are not appropriate for this stage of an innovation, due to business considerations, then the applicant must clearly justify why letters of capital commitment are not being included in the application. The justification should relate to the technical and commercial considerations of the innovation proposed in the application.

3.4.7 Briefing Chart

A one-page briefing chart is required to assist in the ranking and advocacy of proposals prior to selection and contains the following sections:

- Identification and Significance of Innovation
- Technical Objectives
- Proposed Deliverables
- NASA Applications
- Non-NASA Applications
- Graphic

The briefing chart shall not contain any proprietary data or ITAR restricted data. An electronic form will be provided during the submissions process.

Note: The briefing chart is public information and may be disclosed. Do not include proprietary information in this form.

3.4.8 Firm Certifications

Firm certifications that are applicable across all proposal submissions submitted to this solicitation must be completed via the Firm Certifications section of the Proposal Submissions Electronic Handbook. The offeror shall answer Yes or No as applicable. An example of the certification can be found in the NASA SBIR/STTR Firm Library http://sbir.gsfc.nasa.gov/sbir/firm_library/index.html.

Note: The designated firm admin, typically the first person to register your firm, is the only individual authorized to update the certifications.

3.4.9 Audit Information

Although firms are not required to have an approved accounting system, knowledge that a firm has an approved accounting system facilitates NASA's determination that rates are fair and reasonable. To assist NASA, the SBC shall complete the questions in the Audit Information form regarding the firm's rates and upload the federal agency audit report or related information that is available from the last audit. There is a separate "Audit Information" section in the Proposal Budget form that shall also be completed. If your firm has never been audited by a federal agency, then answer "No" to the first question and you do not need to complete the remainder of the form. An electronic form will be provided during the submissions process.

The Contracting Officer will use this Audit Information to assist with negotiations if the proposal is selected for award. The Contracting Officer will advise offerors what is required to determine reasonable cost and/or rates in the event the Audit Information is not adequate to support the necessary determination on rates.

Note: The designated firm admin, typically the first person to register your firm, is the only individual authorized to update the audit information.

3.4.10 Prior Awards Addendum

If the SBC has received more than 15 Phase II awards in the prior 5 fiscal years, submit name of awarding agency, solicitation year, phase, date of award, funding agreement/contract number, and topic or subtopic title for each Phase II. If your firm has received any SBIR or STTR Phase II awards, even if it has received fewer than 15 in the last 5 years, it is still recommended that you complete this form for those Phase II awards your firm did receive. This information will be useful when completing the Commercialization Metrics Survey, and in tracking the overall success of the SBIR and STTR Programs. Any NASA Phase II awards your firm has received will be automatically populated in the electronic form, as are any Phase II awards previously entered by the SBC during prior submissions (you may update the information for these awards). An electronic form will be provided during the submissions process.

Note: The designated firm admin, typically the first person to register your firm, is the only individual authorized to update the addendum information.

3.4.11 Commercial Metrics Survey (CMS)

NASA has instituted a comprehensive commercialization survey/data gathering process for firms with prior NASA SBIR/STTR awards. If the SBC has received any Phase III awards resulting from work on any NASA SBIR or STTR awards, provide the related Phase I or Phase II contract number, name of Phase III awarding agency, date of award, funding agreement number, amount, project title and period of performance. The survey will also ask for firm financial, sales and ownership information, as well as any commercialization success the firm has had as a result of SBIR or STTR awards. This information must be updated annually during proposal submission via the EHB. This information will allow firms to demonstrate their ability to carry SBIR/STTR research through to achieve commercial success, and allow agencies to track the overall commercialization success of their SBIR and STTR Programs. The survey should be limited to information requested above. An electronic form will be provided during the submissions process.

Note: Information received from SBIR/STTR awardees completing the survey is kept confidential, and will not be made public except in broad aggregate, with no firm-specific attribution.

The Commercialization Metrics Survey is a required part of the proposal submissions process and must be completed via the Proposal Submissions Electronic Handbook. Also, Companies with no SBIR/STTR awards or only fairly recent SBIR/STTR awards will not be penalized under past performance for the lack of past SBIR/STTR commercialization.

3.4.12 Contractor Responsibility Information

No later than 10 business days after the notification of selection for negotiations, the offeror shall provide a signed statement from your financial institution(s), on its letterhead, stating whether or not your firm is in good standing and how long you have been with the institution.

3.4.13 Allocation of Rights Agreement (STTR awards only)

An SBC, before receiving an STTR award, must negotiate a written agreement between the SBC and the partnering Research Institution, allocating Intellectual Property rights, if any, to carry out follow-on research, development, or Commercialization which has been signed by authorized representatives of the SBC, RI, and subcontractors and consultants, as applicable. A sample ARA is available in the NASA SBIR/STTR Firm Library http://sbir.gsfc.nasa.gov/sbir/firm_library/index.html of this Solicitation.

The SBC should submit this agreement with the proposal by uploading it in in the Proposal Budget form. This will help to expedite contract negotiations.

4. Method of Selection and Evaluation Criteria

4.1. Access to Proprietary Data by Non-NASA Personnel

4.1.1 Non-NASA Reviewers

In addition to government personnel, NASA, at its discretion and in accordance with 1815.207-71 of the NASA FAR Supplement, may utilize individuals from outside the government with highly specialized expertise not found in the government in the proposal review process. Any decision to obtain an outside evaluation shall take into consideration requirements for the avoidance of organizational or personal conflicts of interest and the competitive relationship, if any, between the prospective contractor or subcontractor(s) and the prospective outside evaluator. Any such evaluation will be under agreement with the evaluator that the information (data) contained in the proposal will be used only for evaluation purposes and will not be further disclosed. Such requests for non-NASA Reviewers must be approved by the NASA SBIR/STTR Program Manager.

4.1.2 Non-NASA Access to Confidential Business Information

In the conduct of proposal processing and potential contract administration, the agency may find it necessary to provide proposal access to other NASA contractor and subcontractor personnel. NASA will provide access to such data only under contracts that contain an appropriate NFS 1852.237-72 Access to Sensitive Information clause that requires the contractors to fully protect the information from unauthorized use or disclosure.

4.2 Phase I Proposals

All proposals will be evaluated and ranked on a competitive basis. Proposals will be initially screened to determine responsiveness. Proposals determined to be responsive to the administrative requirements of this Solicitation and having a reasonable potential of addressing a NASA interest, as evidenced by the technical abstract included in the Proposal Summary form, will be technically evaluated by NASA personnel to determine the most promising technical and scientific approaches. Each proposal will be reviewed on its own merit. NASA is under no obligation to fund any proposal or any specific number of proposals in a given subtopic. It also may elect to fund several or none of the proposed approaches to the same subtopic.

4.2.1 Evaluation Process

Proposals shall provide all information needed for complete evaluation. Evaluators will not seek additional information. NASA scientists and engineers will perform evaluations. Also, qualified experts outside of NASA (including industry, academia and other government agencies) may assist in performing evaluations as required to determine or verify the merit of a proposal. Offerors should not assume that evaluators are acquainted with the firm, key individuals, or with any experiments or other information. Any pertinent references or publications should be noted in Part 5 of the technical proposal.

4.2.2 Phase I Evaluation Criteria

NASA intends to select for award those proposals that offer the most advantageous research and development, deliver technological innovation that contribute to NASA's missions, provide societal benefit and grow the US economy. NASA will give primary consideration to the scientific and technical merit and feasibility of the proposal and its benefit to NASA interests. Each proposal will be evaluated and scored on its own merits using the factors described below:

Factor 1: Scientific/Technical Merit and Feasibility

The proposed R/R&D effort will be evaluated on whether it offers a clearly innovative and feasible technical approach to the described NASA problem area. Proposals must clearly demonstrate relevance to the subtopic as well as one or more NASA mission and/or programmatic needs. Specific objectives, approaches and plans for developing and verifying the innovation must demonstrate a clear understanding of the problem and the current state of the art. The degree of understanding and significance of the risks involved in the proposed innovation must be presented.

Factor 2: Experience, Qualifications and Facilities

The technical capabilities and experience of the PI, project manager, key personnel, staff, consultants and subcontractors, if any, are evaluated for consistency with the research effort and their degree of commitment and availability. The necessary instrumentation or facilities required must be shown to be adequate and any reliance on external sources, such as government furnished equipment or facilities, addressed (section 3.3.4, part 8).

Factor 3: Effectiveness of the Proposed Work Plan

The work plan will be reviewed for its comprehensiveness, effective use of available resources, labor distribution and the proposed schedule for meeting the Phase I objectives. The methods planned to achieve each objective or task should be discussed in detail. Please see Factor 5 for price evaluation criteria.

STTR: The clear delineation of responsibilities of the SBC and RI for the success of the proposed cooperative R/R&D effort will be evaluated. The offeror must demonstrate the ability to organize for effective conversion of intellectual property into products and services of value to NASA and the commercial marketplace.

Factor 4: Commercial Potential and Feasibility

The proposal will be evaluated for the commercial potential and feasibility of the proposed innovation and associated products and services for NASA mission programs, other government agencies and non-government markets. The offeror’s experience and record in technology commercialization, co-funding commitments from private or non-SBIR/non-STTR funding sources, existing and projected commitments for Phase III funding, investment, sales, licensing, and other indicators of commercial potential and feasibility will be considered along with the initial commercialization strategy for the innovation.

Factor 5: Price Reasonableness

The offeror’s cost proposal will be evaluated for price reasonableness based on the information provided in the Proposal Budget form. NASA will comply with the FAR and NASA FAR Supplement (NFS) to evaluate the proposed price/cost to be fair and reasonable.

The Contracting Officer shall submit a recommendation for award to the Source Selection Official after completion of evaluation for price reasonableness and determination of responsibility.

Scoring of Factors and Weighting

Factors 1, 2 and 3 will be scored numerically with Factor 1 worth 50 percent and Factors 2 and 3 each worth 25 percent. The sum of the scores for Factors 1, 2 and 3 will comprise the Technical Merit score. The evaluation for Factor 4, Commercial Potential and Feasibility, will be in the form of an adjectival rating (Excellent, Very Good, Good, Fair, Poor). For Phase I proposals, Technical Merit is more important than Commercial Merit. Factors 1 - 4 will be evaluated and used in the selection of proposals for negotiation. Factor 5 will be evaluated and used in the award decision, i.e., NASA will only make award when the price is fair and reasonable.

4.2.3 Prioritization

In prioritizing proposals recommended for negotiations NASA will also consider other factors including recommendations from the program, centers and mission directorates regarding such things as overall NASA priorities, program balance, and available funding. Programmatic balance considerations may include: first time awardees/participants, historically underrepresented communities, geographic distribution, balance across ideation/point solutions/market stimulation; and mission directorate/center balance.

4.2.4 Selection

Proposals recommended for negotiations will be forwarded to the Program Management Office for analysis and presented to the Source Selection Official and Mission Directorate Representatives. The Source Selection Official has the final authority for choosing the specific proposals for contract negotiation. Each proposal selected for negotiation will be evaluated for cost/price reasonableness, the terms and conditions of the contract will be negotiated and a responsibility determination made. The Contracting Officer will advise the Source Selection Official on matters pertaining to cost reasonableness, responsibility and known past performance issues.

The list of proposals selected for negotiation will be posted on the NASA SBIR/STTR website (http://sbir.nasa.gov). All firms will receive a formal notification letter. A Contracting Officer will negotiate an appropriate contract to be signed by both parties before work begins.

4.3 I-Corps

For awardees invited to submit an I-Corps proposal pursuant to section 3.3.6.2, NASA will provide a programmatic assessment of firms and their technologies to include:

- Number of previous SBIR/STTR awards received by the firm and the firm’s commercialization success rate.
- Potential for commercialization of the selected Phase I research/solution to non-NASA markets (distinct from integration/transition into NASA programs).
- Technical relevance to NASA.

Based on these assessments, STTR offerors will be selected to participate in phone interviews conducted by the NASA SBIR/STTR PMO and the NSF-provided I-Corps instructors. NASA will use these interviews to determine the dynamics of the teams and gauge their level of commitment to meeting requirements for I-Corps to make the final selection. NASA will make the final selections for I-Corps based upon its initial assessments of the I-Corps proposals and the assessments of the phone interviews.

NASA anticipates a total of approximately 42 SBIR/STTR firms will be selected for participation in the I-Corps program for Phase I.

4.4 Phase II Proposals

All Phase II proposals will be evaluated and ranked on a competitive basis. Proposals will be initially screened to determine responsiveness. Proposals determined to be responsive to the administrative requirements of this solicitation and having a reasonable potential of meeting a NASA need, as evidenced by the technical abstract included in the Proposal Summary form, will be technically evaluated by NASA personnel to determine the most promising technical and scientific approaches. Each proposal will be reviewed on its own merit. NASA is under no obligation to fund any proposal or any specific number of proposals in a given subtopic. It also may elect to fund several or none of the proposed approaches to the same subtopic.

4.4.1 Evaluation Process

The Phase II evaluation process is similar to the Phase I process. Each proposal will be reviewed by NASA scientists and engineers and by qualified experts outside of NASA as needed. In addition, the proposals will be reviewed for commercial merit. NASA may use a peer review panel to evaluate commercial merit. Panel membership may include non-NASA personnel with expertise in business development and technology commercialization.

4.4.2 Phase II Evaluation Criteria

NASA intends to select for award those proposals that offer the most advantageous research and development, deliver technological innovation that contributes to NASA's missions, provides societal benefit and grows the US economy. NASA will give primary consideration to the scientific and technical merit and feasibility of the proposal and its benefit to NASA interests. Each proposal will be evaluated and scored on its own merits using the factors described below:

Note: Past performance will not be a separate evaluation factor but will be evaluated under Factors 1 (with respect to performance in Phase I) and 4 (with respect to commercialization past performance, as applicable) below.

Factor 1: Scientific/Technical Merit and Feasibility

The proposed R/R&D effort will be evaluated on its originality, the feasibility of the innovation and potential technical value. In addition, past performance of Phase I will be evaluated to determine the degree to which Phase I objectives were met, and whether the Phase I results indicate a Phase II project is appropriate. The evaluators may review the Phase I final technical report to verify the Phase I results.

Factor 2: Experience, Qualifications and Facilities

The technical capabilities and experience of the PI or project manager, key personnel, staff, consultants and subcontractors, if any, are evaluated for consistency with the research effort and their degree of commitment and availability. The necessary instrumentation or facilities required must show to be adequate and any reliance on external sources, such as government furnished equipment or facilities, addressed (section 3.4.4, Part 8).

Factor 3: Effectiveness of the Proposed Work Plan

The work plan will be reviewed for its comprehensiveness, effective use of available resources, labor distribution and the proposed schedule for meeting the Phase II objectives. The methods planned to achieve each objective or task should be discussed in detail. The proposed path beyond Phase II for further development and infusion into a NASA mission or program will also be reviewed. Please see Factor 5 for price evaluation criteria.

STTR: The clear delineation of responsibilities of the SBC and RI for the success of the proposed cooperative R/R&D effort will be evaluated. The offeror must demonstrate the ability to organize for effective conversion of intellectual property into products and services of value to NASA and the commercial marketplace.

Factor 4: Phase III Efforts, Commercialization and Business Planning

The proposal will be evaluated for the commercial potential and feasibility of the proposed innovation and associated products and services as described in Part 7. Evaluation of the commercialization plan and the overall proposal will include consideration of the following areas:

1. **Commercial Potential - Market:** This includes assessment of:
    a. The market segmentation and the commercial Total Addressable Market (TAM);
    b. The proposed innovation in terms of target customers (e.g., NASA, other federal agency, commercial enterprise);
    c. The competitive landscape, by identifying potential competitors.

2. **Commercial Intent – Plan:** This includes assessing:
    a. The commercial development plan by providing a development timeline to bring the innovation to market;
    b. The applicable business model (spin-out, license, OEM, etc.) the offeror would use to bring the innovation to market;
    c. The risks to the commercial development plan and what mitigations, if any, can be taken over a reasonable period of time to lessen the risks.

3. **Commercial Capability – Execution:** This includes assessment of:
    a. The current and future company capitalization efforts;
    b. As applicable, the description of the approach, path to market and revenues from past commercialization(s) resulting from SBIR/STTR awards disclosed in the CMS.

4. **Intellectual Property:** This includes assessment of:
    a. How the offeror will protect the intellectual property that results from the innovation.

5. **Assistance and Mentoring:** This includes assessment of:
    a. The existing and future business relationships in terms of any formal Partnerships, Joint Ventures, Licensing Agreements with other companies/organizations;
    b. The plans for securing needed technical or business assistance through mentoring, partnering, or through arrangements with State assistance programs, SBDCs, Federally-funded research laboratories, Manufacturing Extension Partnership centers, Federal programs or other assistance providers.

6. **Capital Commitments Addendum:** This includes assessment of:

a. Any letters of commitment describing follow-on funding, matching funding to be provided for a future Phase II/E application, letter of intent or evidence of negotiations to provide funding should the Phase II project be successful and the market need still exists and a specific plan to secure Phase III funding.
b. The justification from the offeror that obtaining letters of commitment are not appropriate for this stage of an innovation, due to business considerations.

Factor 5: Price Reasonableness

The offeror's cost proposal will be evaluated for price reasonableness based on the information provided in the Proposal Budget form. NASA will comply with the FAR and NASA FAR Supplement (NFS) to evaluate the proposed price/cost to be fair and reasonable.

The Contracting Officer shall submit a recommendation for award to the Source Selection Official after completion of evaluation for price reasonableness and determination of responsibility.

Scoring of Factors and Weighting

Factors 1, 2, 3 and 4 will be scored numerically with Factor 1 worth 45 percent, Factors 2 and 3 each worth 25 percent and Factor 4 worth five percent. The sum of the scores for Factors 1, 2, 3 and 4 will comprise the Technical Merit score. Factors 1 - 4 will be evaluated and used in the selection of proposals for negotiation. Factor 5 will be evaluated as part of the award decision, i.e., NASA will only make award when the price is fair and reasonable.

4.4.3 Prioritization

In prioritizing proposals recommended for negotiations NASA will also consider other factors including recommendations from the program, centers and mission directorates regarding such things as overall NASA priorities, program balance, and available funding. Programmatic balance considerations may include: first time awardees/participants, historically underrepresented communities, geographic distribution, balance across ideation/point solutions/market stimulation; and mission directorate/center balance.

4.4.4 Selection

Proposals recommended for negotiations will be forwarded to the Program Management Office for analysis and presented to the Source Selection Official and Mission Directorate Representatives. The Source Selection Official has the final authority for choosing the specific proposals for contract negotiation. Each proposal selected for negotiation will be evaluated for cost/price reasonableness. After completion of evaluation for cost/price reasonableness and a determination of responsibility the Contracting Officer will submit a recommendation for award to the Source Selection Official.

The list of proposals selected for negotiation will be posted on the NASA SBIR/STTR website (http://sbir.nasa.gov). All firms will receive a formal notification letter. A Contracting Officer will negotiate an appropriate contract to be signed by both parties before work begins.

4.5 Debriefing of Unsuccessful Offerors

After Phase I and Phase II selections for negotiation have been announced, debriefings will be available to the offeror's corporate official or designee via email. Written debriefings will be sent only to the Business Official designated in the proposal. Debriefings will not disclose the identity of the proposal evaluators, proposal scores, the content of, or comparisons with other proposals. The debriefing process for Phase I and Phase II proposals are described below.

Note: Due to the competitive nature of the program and limited funding, recommendations to fund or not fund a proposal will be final and the decision cannot be contested by the offeror. Debriefings are not opportunities to reopen selection decisions and telephone requests for debriefings will not be accepted. Applicants are encouraged to use the written debriefing as a way to understand the outcome from the review of their proposal and to develop plans to strengthen the proposal for a future submission.

4.5.1 Phase I Debriefings

Debriefings will be automatically emailed to the designated Business Official within 60 days of the announcement of selection for negotiation. If you have not received your debriefing by this time, contact the SBIR/STTR Program Support Office at ARC-SBIR-PMO@mail.nasa.gov.

4.5.2 Phase II Debriefings

For Phase II, offerors must send a debriefing request via email to the SBIR/STTR Program Office at ARC-SBIR-PMO@mail.nasa.gov within 60 days after the selection announcement. Late requests will not be honored.

5. Considerations

5.1 Requirement for Contracting

Upon award of a Funding Agreement, the Awardee will be required to make certain legal commitments through acceptance of numerous clauses in Phase I Funding Agreements. The outline that follows is illustrative of the types of clauses to which the contractor would be committed. This list is not a complete list of clauses to be included in Phase I Funding Agreements, and is not the specific wording of such clauses. Copies of complete terms and conditions are available upon request.

Although the SBIR/STTR Policy Directive provides the above language for Phase I, NASA also includes these clauses in the Phase II contracts.

To simplify making contract awards and to reduce processing time, all contractors selected for Phase I and Phase II contracts shall ensure that:

1. All information in your proposal is current, e.g., your address has not changed, the proposed PI is the same, etc. If changes have occurred since submittal of your proposal, notify the Contracting Officer immediately.
2. Your firm is registered with System for Award Management (SAM) (section 2.2).
3. Your firm is in compliance with the VETS-4212 requirement (section 2.3.1). Confirmation of that the report has been submitted to the Department of Labor is current shall be provided to the Contracting Officer within 10 business days of the notification of selection for negotiation.
4. Your firm HAS NOT proposed a Co-Principal Investigator.
5. No more than 10 business days after the notification of selection for negotiation, the offeror should provide to the Contracting Officer, a completed Allocation of Rights Agreement (ARA), which has been signed by authorized representatives of the SBC, RI, and subcontractors and consultants, as applicable.
6. Your firm is required to provide timely responses to all communications from the NSSC Contracting Officer.
7. All proposed cost is supported with documentation such as a quote, previous purchase order, published price lists, etc. All letters of commitment are dated and signed by the appropriate person with contact information. If a University is proposed as a subcontractor or a RI, the signed letter shall be on the University letterhead from the Office of Sponsored Programs. If an independent consultant is proposed, the signed letter should not be on a University letterhead. If the use of government facility or equipment is proposed, your firm shall submit a signed letter from the government facility stating the availability, cost if any, and authorizing the use of it, and a signed letter from your firm justifying the need to use the facility.

From the time of proposal notification of selection for negotiation, until the award of a contract, all communications shall be submitted electronically to NSSC-SBIR-STTR@nasa.gov.

Note: Costs incurred prior to and in anticipation of award of a contract are entirely the risk of the contractor in the event that a contract is not subsequently awarded. A notification of selection for negotiation is not to be misconstrued as an award notification to commence work.

5.2 Awards

5.2.1 Award Conditions

NSSC will distribute the NASA SBIR/STTR award with the following for each phase. NASA awards are electronically signed by a NASA Contracting Officer and transmitted electronically to the organization via e-mail.

Phase I:

- SF26 - Contract Cover Sheet
- Contract Terms and Conditions – to include reference to the proposal and budget
- Attachment 1: Contract Distribution List
- Attachment 2: Example of the Final Summary Chart
- Attachment 3: IT Security Management Plan Template
- Attachment 4: Applicable Documents List
- Negotiation Confirmation
- Phase I Frequently Asked Questions (FAQs)

Phase II:

- SF26 - Contract Cover Sheet
- Contract Terms and Conditions – to include reference to the proposal and budget
- Contract Distribution List
- Final Summary Chart and Instructions
- IT Security Management Plan
- Applicable Documents List (ADL)
- Phase II Frequently Asked Questions (FAQs)

5.2.2 Type of Contract

NASA SBIR/STTR Phase I and Phase II awards are made as Firm Fixed Price contracts.

5.2.3 Model Contracts

An example of the Phase I and II contracts can be found in the NASA SBIR/STTR Firm Library: http://sbir.gsfc.nasa.gov/sbir/firm_library/index.html.

Note: Model contracts are subject to change.

5.3 Reporting and Required Deliverables

An IT Security Management Plan is required at the beginning of the contract. Contractors interested in doing business with NASA and/or providing IT services or solutions to NASA should use the list found at the website of the Office of the Chief Information Officer (OCIO) as a reference for information security requirements -

https://www.nasa.gov/content/security-requirements-policies. An example of the IT Security Management Plan can be found in the NASA SBIR/STTR Firm Library: http://sbir.gsfc.nasa.gov/sbir/firm_library/index.html. For more information see NASA FAR Supplement clause 1852.204-76

All contracts shall require the delivery of technical reports that present: (1) the work and results accomplished; (2) the scientific, technical and commercial merit and feasibility of the proposed innovation, and project results; (3) its relevance and significance to one or more NASA interests (section 9); and (4) the strategy for development, transition of the proposed innovation, and project results into products and services for NASA mission programs and other potential customers. Deliverables may also include the demonstration of the proposed innovation and/or the delivery of a prototype or test unit, product or service for NASA testing and utilization.

The technical reports and other deliverables are required as described in the contract and are to be provided to NASA. These reports shall document progress made on the project and activities required for completion. Periodic certification for payment will be required as stated in the contract. A final report must be submitted to NASA upon completion of the Phase I or Phase II R/R&D effort in accordance with applicable contract provisions.

A final New Technology Summary Report (NTSR) is due at the end of the contract, and New Technology Report(s) (NTR) are required if technology(ies) are developed under the award, prior to submission of the final invoice. For additional information on NTSR and NTR requirements and definitions see section 1.12 and 5.8.

Report deliverables shall be submitted electronically via the EHB. For any reports that require an upload NASA requests the submission in PDF or MS Word format.

Note: To access contract management in the EHB you will be required to have an identity in the NASA Account Management System (NAMS). This is the agency's centralized system for requesting and maintaining accounts for NASA IT systems and applications. The system contains user account information, access requests and account maintenance processes for NASA employees, contractors, and remote users such as educators and foreign users. A basic background check is required for this account. Instructions will be provided during contract negotiations.

It is recommended that you begin this process immediately upon notification as this access will be required to submit deliverables and invoices so prompt attention is requested.

5.4 Payment Schedule

All NASA SBIR and STTR contracts are firm-fixed-price contracts. The exact payment terms will be included in the contract.

Although invoices are submitted electronically through the Department of Treasury's Invoice Processing Platform (IPP), as a condition for payment, invoice certifications shall be completed in the EHB for each individual invoice. The certification is pre-set in the EHB and it shall be completed before uploading each invoice in IPP. Upon completion of the certification, a link to IPP is automatically provided in the EHB.

5.5 Profit or Fee

Contracts may include a reasonable profit. The reasonableness of proposed profit is determined by the Contracting Officer during contract negotiations. Reference FAR 15.404-4.

5.6 Cost Sharing

Cost sharing is permitted for proposals under this Program Solicitation; however, cost sharing is not required. Cost sharing will not be an evaluation factor in consideration of your proposal.

5.7 Rights in Data Developed Under SBIR Funding Agreements

The SBIR/STTR Protection Period begins with award of an SBIR/STTR Funding Agreement and ends twenty years, or longer at the discretion of the Participating Agency, from the date of award of an SBIR/STTR Funding Agreement (either Phase I, Phase II, or Federally-funded SBIR/STTR Phase III) unless subsequent to the award, the agency and the SBC negotiate for some other protection period for the SBIR/STTR Data.

SBIR/STTR Data Rights Clause

(a) Definitions.

(1) Computer Software. Computer programs, source code, source code listings, object code listings, design details, algorithms, processes, flow charts, formulae, and related material that would enable the software to be reproduced, recreated, or recompiled. Computer Software does not include Computer Databases or Computer Software Documentation.

(2) Data. All recorded information, regardless of the form or method of recording or the media on which it may be recorded. The term does not include information incidental to contract or grant administration, such as financial, administrative, cost or pricing or management information.

(3) Form, Fit, and Function Data. Data relating to items, components, or processes that are sufficient to enable physical and functional interchangeability, and data identifying source, size, configuration, mating and attachment characteristics, functional characteristics, and performance requirements. For Computer Software it means data identifying source, functional characteristics, and performance requirements, but specifically excludes the source code, algorithms, processes, formulas, and flow charts of the software.

(4) Government Purpose. Any activity in which the United States Government is a party, including cooperative agreements with international or multi-national defense organizations or sales or transfers by the United States Government to foreign governments or international organizations. Government Purposes include competitive procurement, but do not include the rights to use, modify, reproduce, release, perform, display, or disclose Technical Data or Computer Software for commercial purposes or authorize others to do so.

(5) Operations, Maintenance, Installation, or Training Purposes (OMIT) Data. Data that is necessary for operation, maintenance, installation, or training purposes (but not including detailed manufacturing or process data).

(6) SBIR/STTR Computer Software Rights. The Federal Government's rights during the SBIR/STTR Protection Period in specific types of SBIR/STTR Data that are Computer Software.

(A) The Federal Government may use, modify, reproduce, release, perform, display, or disclose SBIR/STTR Data that are Computer Software within the Government. The Federal Government may exercise SBIR/STTR Computer Software Rights within the Government for:

(1) Use in Federal Government computers;

(2) Modification, adaptation, or combination with other Computer Software, provided that the Data incorporated into any derivative software are subject to the rights in § 3(ee) of the SBIR/STTR Policy Directive and that the derivative software is marked as containing SBIR/STTR Data;

(3) Archive or backup; or

(4) Distribution of a computer program to another Federal agency, without further permission of the Awardee, if the Awardee is notified of the distribution and the identity of the recipient prior to the distribution, and a copy of the SBIR/STTR Computer Software Rights included in the Funding Agreement is provided to the recipient.

(B) The Federal Government shall not release, disclose, or permit access to SBIR/STTR Data that is Computer Software for commercial, manufacturing, or procurement purposes without the written permission of the Awardee. The Federal Government shall not release, disclose, or permit access to SBIR/STTR Data outside the Government without the written permission of the Awardee unless:

(i) The non-Governmental entity has entered into a non-disclosure agreement with the Government that complies with the terms for such agreements outlined in § 8 of the SBIR/STTR Policy Directive; and

(ii) The release or disclosure is—

(I) To a Federal Government support service contractor or their subcontractor for purposes of supporting Government internal use or activities, including evaluation, diagnosis and correction of deficiencies, and adaptation, combination, or integration with other Computer Software provided that SBIR/STTR Data incorporated into any derivative software are subject to the rights in § 3(ee) of the SBIR/STTR Policy Directive; or

(II) Necessary to support certain narrowly-tailored essential Government activities for which law or regulation permits access of a non-Government entity to a contractors' data developed exclusively at private expense, non-SBIR/STTR Data, such as for emergency repair and overhaul.

(7) SBIR/STTR Data. All Data developed or generated in the performance of an SBIR or STTR award, including Technical Data and Computer Software developed or generated in the performance of an SBIR or STTR award. The term does not include information incidental to contract or grant administration, such as financial, administrative, cost or pricing or management information.

(8) SBIR/STTR Data Rights. The Federal Government's license rights in properly marked SBIR/STTR Data during the SBIR/STTR Protection Period are as follows: SBIR/STTR Technical Data Rights in SBIR/STTR Data that are Technical Data or any other type of Data other than Computer Software; and SBIR/STTR Computer Software Rights in SBIR/STTR Data that is Computer Software. Upon expiration of the protection period for SBIR/STTR Data, the Federal Government has a royalty-free license to use, and to authorize others to use on its behalf, these data for Government Purposes, and is relieved of all disclosure prohibitions and assumes no liability for unauthorized use of these data by third parties, except that any such data that is also protected under a subsequent SBIR/STTR award shall remain protected through the protection period of that subsequent award. The Federal Government receives Unlimited Rights in Form Fit, and Function Data, OMIT Data, and all unmarked SBIR/STTR Data.

(9) SBIR/STTR Protection Period. The period of time during which the Federal Government is obligated to protect SBIR/STTR Data against unauthorized use and disclosure in accordance with SBIR/STTR Data Rights. The SBIR/STTR Protection Period begins at award of an SBIR/STTR Funding Agreement and ends not less than twenty years from that date (See § 8(b)(4) of the SBIR/STTR Policy Directive).

(10) SBIR/STTR Technical Data Rights. The Federal Government's rights during the SBIR/STTR Protection Period in SBIR/STTR Data that are Technical Data or any other type of Data other than Computer Software.

(A) The Federal Government may, use, modify, reproduce, perform, display, release, or disclose SBIR/STTR Data that are Technical Data within the Government; however, the Government shall not use, release, or disclose the data for procurement, manufacturing, or commercial purposes; or release or disclose the SBIR/STTR Data outside the Government except as permitted by paragraph (B) below or by written permission of the Awardee.

(B) SBIR/STTR Data that are Technical Data may be released outside the Federal Government without any additional written permission of the Awardee only if the non-Governmental entity or foreign government has entered into a non-disclosure agreement with the Federal Government that complies with the terms for such agreements outlined in § 8 of the SBIR/STTR Policy Directive and the release is:

(i) Necessary to support certain narrowly-tailored essential Government activities for which law or regulation permits access of a non-Government entity to a contractors' data developed exclusively at private expense, non-SBIR/STTR Data, such as for emergency repair and overhaul;

(ii) To a Government support services contractor in the performance of a Government support services contract for internal Government use or activities, including evaluation, diagnosis or modification, provided that SBIR/STTR Technical Data incorporated into any derivative Data are subject to the rights in § 3(ii) of the SBIR/STTR Policy Directive, and the release is not for commercial purposes or manufacture;

(iii) To a foreign government for purposes of information and evaluation if required to serve the interests of the U.S. Government; or

(iv) To non-Government entities or individuals for purposes of evaluation.

(11) Technical Data. Recorded information, regardless of the form or method of the recording, of a scientific or technical nature (including Computer Software Documentation and Computer Databases). The term does not include Computer Software or financial, administrative, cost or pricing, or management information, or other data incidental to contract or grant administration. The term includes recorded Data of a scientific or technical nature that is included in Computer Databases.

(12) Unlimited Rights. The Government's rights to access, use, modify, prepare derivative works, reproduce, release, perform, display, disclose, or distribute Data in whole or in part, in any manner and for any purpose whatsoever, and to have or authorize others to do so.

(b) Allocation of SBIR/STTR Data Rights.

(1) An SBC retains ownership of all SBIR/STTR Data it develops or generates in the performance of an SBIR/STTR award. The SBC retains all rights in SBIR/STTR Data that are not granted to the Federal Government in accordance with the SBIR/STTR Policy Directive. These rights of the SBC do not expire.

(2) During the SBIR/STTR Protection Period, the Federal Government receives SBIR/STTR Technical Data Rights in appropriately marked SBIR/STTR Data that is Technical Data or any other type of Data other than Computer Software; and SBIR/STTR Computer Software Rights in appropriately marked SBIR/STTR Data that is Computer Software.

(3) After the protection period, the Federal Government may use, and authorize others to use on its behalf, for Government Purposes, SBIR/STTR Data that was protected during the SBIR/STTR Protection Period. Awards issued by the U.S. Department of Energy are subject to Unlimited Rights after the expiration of the SBIR/STTR Protection Period.

(4) The Federal Government receives Unlimited Rights in Form Fit, and Function Data, OMIT Data, and all unmarked SBIR/STTR Data

(c) Identification and Delivery of SBIR/STTR Data. Any SBIR/STTR Data delivered by the Awardee, and in which the Awardee intends to limit the Federal Government's rights to SBIR/STTR Data Rights, must be delivered with restrictive markings. The Federal Government assumes no liability for the access, use, modification, reproduction, release, performance, display, disclosure, or distribution of SBIR/STTR Data without markings. The Awardee or its subcontractors or suppliers shall conspicuously and legibly mark all such SBIR/STTR Data with the appropriate legend.

(1) The authorized legend shall be placed on each page of the SBIR/STTR Data. If only portions of a page are subject to the asserted restrictions, the SBIR/STTR Awardee shall identify the restricted portions (e.g.,

by circling or underscoring with a note or other appropriate identifier). With respect to SBIR/STTR Data embodied in Computer Software, the legend shall be placed on: (1) the printed material or media containing the Computer Software; or (2) the transmittal document or storage container. The legend shall read as follows:

"SBIR/STTR DATA RIGHTS
Funding Agreement No.
Award Date
SBIR/STTR Protection Period
SBIR/STTR Awardee
SBIR/STTR Awardee Address

This is SBIR/STTR Data (or is Computer Software or a Prototype that embodies or includes SBIR/STTR Data) to which the SBIR/STTR Awardee has SBIR/STTR Data Rights and to which the Federal

Government has received SBIR/STTR Technical Data Rights (or SBIR/STTR Computer Software Rights) during the SBIR/STTR Protection Period and rights of use for Government Purposes after the

SBIR/STTR Protection Period, as those terms are defined in the SBIR/STTR Funding Agreement. Awards issued by the U.S. Department of Energy are subject to Unlimited Rights after the SBIR/STTR Protection

Period, as that term is defined in the SBIR/STTR Funding Agreement. Any reproduction of SBIR/STTR Data or portions of such data marked with this legend must also reproduce the markings."

(End of Legend)

(2) Data submitted without correct or appropriate markings may be corrected within 6 months from the date the data is delivered.

d) Relation to patents. Nothing regarding SBIR/STTR Data Rights in this clause shall imply a license to or imply a requirement to license to the Federal Government any patent to a Subject Invention (as defined under the Bayh-Dole Act implemented at 37 CFR 401) made under an SBIR/STTR award.

5.8 Copyrights

The contractor may copyright and publish (consistent with appropriate national security considerations, if any) material developed with NASA support. NASA receives a royalty-free license for the federal government and requires that each publication contain an appropriate acknowledgment and disclaimer statement.

5.9 Invention Reporting, Election of Title, Patent Application Filing and Patents

Consistent with the SBIR/STTR Program requirements, the Contractor shall complete their electronic submission of the New Technology Report (NTR), for any new subject inventions; and the New Technology Summary Report (NTSR) for the interim and final contract periods, via the SBIR/STTR EHB at http://sbir.nasa.gov under the Handbooks section.

NASA SBIR and STTR contracts will includes FAR 52.227-11 Patent Rights – Ownership by the Contractor and NFS 1852.227-11 Patent Rights – Ownership by the Contractor (APR 2015), which requires SBIR/STTR contractors to disclose all subject inventions to NASA within two (2) months of the inventor's report to the contractor. A subject invention means any invention of the Contractor made in the performance of work under this contract. Once the contractor discloses a subject invention, the contractor has up to 2 years to notify the government whether it elects to retain title to the subject invention. If the contractor elects to retain title, a patent application covering the subject invention must be initiated within the 1 year statutory period. If the contractor fails to do any of these within time specified periods, the government has the right to obtain title.

Small business concerns normally may elect to retain ownership of any subject invention. In such circumstances, the government shall have a nonexclusive, nontransferable, irrevocable, royalty-free license for federal government use. Further, the government reserves the right to require the patent holder to license others in certain circumstances and may require that anyone exclusively licensed to sell the invention in the United States must normally manufacture it domestically. To the extent authorized by 35 U.S.C. 205, the government will not make public any information disclosing a government-supported invention for a minimum 4-year period (that may be extended by subsequent SBIR funding agreements) to allow the contractor a reasonable time to pursue a patent.

5.10 1852.225-70 Export Licenses

The contractor shall comply with all U.S. export control laws including Export Administration Regulations (EAR) and International Traffic in Arms Regulations (ITAR). Offerors are responsible for ensuring that all employees who will work on this contract are eligible under export control laws, EAR and ITAR. Any employee who is not a U.S. citizen or a permanent resident may be restricted from working on this contract if the technology is restricted under export control laws, ITAR, or EAR unless the prior approval of the Department of State or the Department of Commerce is obtained via a technical assistance agreement or an export license. Violations of these regulations can result in criminal or civil penalties.

For additional information on ITAR, please visit the Code of Federal Regulations at https://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title22/22cfr120_main_02.tpl. For additional information on EAR, please visit https://www.bis.doc.gov/index.php/regulations/export-administration-regulations-ear. For additional training, refer to http://sbir.gsfc.nasa.gov/content/training-resources. For additional assistance contact the NASA SBIR helpdesk at sbir@reisystems.com.

5.11 Government Furnished and Contractor Acquired Property

Under the Act, the Federal Government may transfer title to property provided by the SBIR/STTR Participating Agency to the Awardee or acquired by the Awardee for the purpose of fulfilling the contract where such transfer would be more cost effective than recovery of the property.

Note: Use of government facilities is covered in section 5.13 Use of Federal Services, Facilities or Equipment.

5.12 Essentially Equivalent Awards and Prior Work

If an award is made pursuant to a proposal submitted under either SBIR or STTR Solicitations, the firm will be required to certify with every invoice that it has not previously been paid nor is currently being paid for essentially equivalent work by any agency of the federal government. **Failure to report essentially equivalent or duplicate efforts can lead to the termination of contracts and/or civil or criminal penalties.**

5.13 Additional Information

5.13.1 Precedence of Contract over Solicitation

This Program Solicitation reflects current planning. If there is any inconsistency between the information contained herein and the terms of any resulting SBIR/STTR contract, the terms of the contract take precedence over the solicitation.

5.13.2 Evidence of Contractor Responsibility

In addition to the information required to be submitted for Phase II proposals as stated in in section 3.4.12, before award of an SBIR or STTR contract, the government may request the offeror to submit certain organizational, management, personnel and financial information to establish responsibility of the offeror. Contractor responsibility includes all resources required for contractor performance, i.e., financial capability, work force and facilities.

5.14 Use of Federal Services, Facilities or Equipment

Federal Departments and Agencies

Use of SBIR funding for unique federal/non-NASA services, equipment or facilities from a federal department or agency which does not meet the definition of a federal laboratory as defined in the SBA Policy Directive on the SBIR/STIR Program, requires a waiver from the SBA. Proposals requiring waivers must include an explanation of why the waiver is appropriate. NASA will provide the offeror’s request, along with an explanation to SBA during the negotiation process. NASA cannot guarantee that a waiver can be obtained from SBA. Specific proposal instructions to request use of Federal Services, Facilities or Equipment are in section 3.3 of the solicitation.

Note: NASA Facilities qualify as Federal Laboratories.

Agreement to Use Any Federal Facility

All offerors selected for award that require the use of any federal facility shall, within twenty (20) business days of notification of selection for negotiations, provide to the NASA Shared Services Center Contracting Officer an agreement by and between the Contractor and the appropriate federal facility, executed by the government official authorized to approve such use. The Agreement must delineate the terms of use, associated costs, facility responsibilities and liabilities. Having a signed agreement for use of federal facilities is a requirement for award.

An executed SBIR/STTR Use Agreement, available in the Firm Library (http://sbir.gsfc.nasa.gov/sbir/firm_library/index.html), is required before a contractor can use NASA services, facilities, or equipment. Offerors should not include an executed SBIR/STTR Use Agreement in the proposals. NASA expects selected offerors to execute the SBIR/STTR Use Agreement during their negotiations with NSSC. The information required in the proposals should facilitate executing the SBIR/STTR Use Agreement.

Contractor Responsibilities for Costs

In accordance with the Federal Acquisition Regulations (FAR) Part 45, it is NASA's policy not to provide services, equipment or facilities (resources) [capital equipment, tooling, test and computer facilities, etc.] for the performance of work under SBIR/STTR contracts. Generally, any contractor will furnish its own resources to perform the proposed work on the contract.

In all cases, the Contractor shall be responsible for any costs associated with services, equipment or facilities provided by NASA or another federal department or agency, and such costs shall result in no increase in the price of this contract.

Note: The Facility Use Agreement has been updated to include additional requirements related to NASA IT Security under Section C. Terms and Conditions (of the Facility Use Agreement).

3. If Contractor's use of NASA facilities, equipment, and/or services includes use of or access to NASA Information Technology (IT) resources, the Contractor will at all times remain in compliance with and adhere to all NASA IT security requirements and processes, including those set forth in the Contractor's IT Security Plan. The Contractor's failure to do so may result in NASA's unilateral termination of this Use Agreement.

6. Submission of Proposals

6.1 Submission Requirements

NASA uses electronically supported business processes for the SBIR/STTR Programs. An offeror must have Internet access and an email address. Paper submissions are not accepted.

The EHB for submitting proposals is located at http://sbir.nasa.gov under the Handbooks section. The Proposal Submissions EHB guides the firms through the steps for submitting an SBIR/STTR proposal. All EHB submissions are through a secure connection. Communication between NASA's SBIR/STTR Programs and the firm is primarily through a combination of EHBs and email.

6.2 Submission Process

New SBCs must register in the EHB to begin the submission process. Returning firms can use the same account that they have used for previous submissions. Firms are encouraged to start the proposal process early, to allow for sufficient time to complete the submissions process. It is recommended that the Business Official, or an authorized representative designated by the Business Official, be the first person to register for the SBC. The SBC's Employer Identification Number (EIN)/Taxpayer Identification Number is required during registration.

Note: The designated firm admin, typically the first person to register your firm, is the only individual authorized to update and change the firm level forms.

For successful proposal submission, SBCs shall complete all forms online, upload their technical proposal in an acceptable format, and have the Business Official and Principal Investigator electronically endorse the proposal. Electronic endorsement of the proposal is handled online with no additional software requirements. The term "technical proposal" refers to the part of the submission as described in section 3.3.4 for Phase I proposals or 3.4.4 for Phase II proposals.

STTR: The Research Institution is required to electronically endorse the Research Agreement prior to the SBC endorsement of the completed proposal submission.

6.2.1 What Needs to Be Submitted

The entire proposal package must be submitted via the Submissions EHB located on the NASA SBIR/STTR website.

Note: Other forms of submissions are not acceptable.

The proposal package includes:

1. Proposal Contact Information
2. Proposal Certifications
3. Proposal Summary
4. Proposal Budget
5. Technical Proposal (upload)
6. Research Agreement (STTR only)
7. Briefing Chart
8. NASA Evaluation License Application (only if TAV is being proposed)

9. I-Corps Opt-In (Phase I only) or Capital Commitments Addendum (Phase II only, optional)
10. Firm Level Forms (completed once for all proposals submitted to a single Solicitation)
    a. Firm Certifications
    b. Audit Information
    c. Prior Awards Addendum
    d. Commercial Metrics Survey

6.2.2 Technical Proposal Submissions

NASA converts all technical proposal files to PDF format for evaluation. Therefore, NASA requests that technical proposals be submitted in PDF format.

Note: Embedded animation or video, as well as reference technical papers for "further reading" will not be considered for evaluation.

Virus Check

The offeror is responsible for performing a virus check on each submitted technical proposal. As a standard part of entering the proposal into processing, NASA will scan each submitted electronic technical proposal for viruses.

Note: The detection, by NASA, of a virus on any electronically submitted technical proposal, may cause rejection of the proposal.

6.2.3 Technical Proposal Uploads

Firms will upload their proposals using the Submissions EHB. Directions will be provided to assist users. All transactions via the EHB are encrypted for security. Firms cannot submit security/password protected technical proposal and/or supporting documentation, as reviewers may not be able to open and read the files.

You may upload the technical proposal multiple times, with each new upload replacing the previous version, but only the final uploaded and electronically endorsed version will be considered for review. Before you can submit the proposal package, you must download the entire proposal package and certify that you have reviewed it to ensure that you have uploaded the correct materials.

6.3 Deadline for Phase I Proposal Receipt

All Phase I proposal submissions shall be received no later than *5:00 p.m. EDT on Monday, April 20, 2020* via the NASA SBIR/STTR website (http://sbir.nasa.gov), under the Handbooks section.

The EHB will not allow submissions after this deadline, but firms will have read-only access to the materials they have already submitted.

Note: Offerors are strongly encouraged to start the submission process early in order to allow sufficient time for completing their proposal package.

6.4 Deadline for Phase II Proposal Receipt

All Phase II proposal submissions shall be received no later than 5:00 p.m. EST the last day of the Phase I contract original period of performance, via the NASA SBIR/STTR website (http://sbir.nasa.gov) under the Handbooks section.

The EHB will be available for submissions approximately 6 weeks prior to completion date of Phase I contracts. Receipt of Phase II proposals are due on the last day of performance under SBIR/STTR Phase I contracts. The EHB will not be available for submissions after this deadline, but firms will have read-only access to the materials they have already submitted.

6.5 Acknowledgment of Proposal Receipt

The final proposal submission includes successful completion of all firm level forms, Contact Information, Proposal Certifications, Proposal Budget, Proposal Summary, the Technical Proposal upload, the Briefing Chart, the I-Corps Opt-In (if applicable in Phase I), and electronic endorsement by the SBC Official and Principal Investigator. For STTR submissions, it also includes the Research Agreement and endorsement of this agreement by the Research Institution official. NASA will acknowledge receipt of electronically submitted proposals upon endorsement by the SBC Official to the SBC Official's email address as provided on the proposal cover sheet, as well as to the user who created the proposal, if different. If a proposal acknowledgment is not received, the offeror should contact the NASA SBIR/STTR Program Support Office at 301-937-0888 or sbir@reisystems.com.

6.6 Withdrawal of Proposals

Prior to the close of submissions, proposals may be withdrawn via the Proposal Submissions Electronic Handbook hosted on the NASA SBIR/STTR website (http://sbir.nasa.gov) under the Handbooks section. In order to withdraw a proposal after the deadline, the designated SBC Official must send written notification via email to sbir@reisystems.com.

6.7 Service of Protests

For any concerns or disagreements, see Section 1.10.

Copies of any protests, as defined in section 33.101 of the FAR, shall be served on the Contracting Officer by obtaining written and dated acknowledgement of receipt from the NASA SBIR/STTR Program contact listed below:

Theresa Stanley
NASA Shared Services Center
Building 1111, Jerry Hlass Road
Stennis Space Center, MS 39529
Agency-SBIR-STTRSolicitation@mail.nasa.gov

The copy of any protest shall be received within one calendar day of filing a protest with the GAO.

7. Proposal, Scientific and Technical Information Sources

7.1 NASA Websites

General sources relating to organizational and programmatic information at NASA is available via the following websites:

NASA Budget Documents, Strategic Plans and Performance Reports:
http://www.nasa.gov/about/budget/index.html
NASA Organizational Structure: http://www.nasa.gov/centers/hq/organization/index.html
NASA SBIR/STTR Programs: http://sbir.nasa.gov

Information regarding the mission directorates and the NASA centers can be obtained at the following websites:

Office of the Chief Technologist	
Space Technology Roadmaps	http://www.nasa.gov/offices/oct/home/roadmaps/index.html

NASA Mission Directorates	
Aeronautics Research	http://www.aeronautics.nasa.gov/
Human Exploration and Operations	http://www.nasa.gov/directorates/heo/home/
Science	http://nasascience.nasa.gov
Space Technology	http://www.nasa.gov/directorates/spacetech/home/index.html

NASA Centers	
Armstrong Flight Research Center (AFRC)	http://www.nasa.gov/centers/armstrong/home/index.html
Ames Research Center (ARC)	http://www.nasa.gov/centers/ames/home/index.html
Glenn Research Center (GRC)	http://www.nasa.gov/centers/glenn/home/index.html
Goddard Space Flight Center (GSFC)	http://www.nasa.gov/centers/goddard/home/index.html
Jet Propulsion Laboratory (JPL)	http://www.nasa.gov/centers/jpl/home/index.html
Johnson Space Center (JSC)	http://www.nasa.gov/centers/johnson/home/index.html
Kennedy Space Center (KSC)	http://www.nasa.gov/centers/kennedy/home/index.html
Langley Research Center (LaRC)	http://www.nasa.gov/centers/langley/home/index.html
Marshall Space Flight Center (MSFC)	http://www.nasa.gov/centers/marshall/home/index.html
Stennis Space Center (SSC)	http://www.nasa.gov/centers/stennis/home/index.html
NASA Shared Services Center (NSSC)	https://www.nssc.nasa.gov/

7.2 United States Small Business Administration (SBA)

The Policy Directives for the SBIR/STTR Programs may be obtained from the following source. SBA information can also be obtained at: http://www.sbir.gov.

U.S. Small Business Administration
Office of Technology – Mail Code 6470
409 Third Street, S.W.
Washington, DC 20416
Phone: 202-205-6450

7.3 National Technical Information Service

The National Technical Information Service is an agency of the Department of Commerce and is the federal government's largest central resource for government-funded scientific, technical, engineering and business-related information. For information regarding their various services and fees, call or write:

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
Phone: 703-605-6000
URL: http://www.ntis.gov

7.4 Other Sources of Assistance

The U.S. Government invests in a wide variety of resources designed to aid and assist small business owners and their employees. A variety of websites containing these resources and links to additional resources can be found at: http://sbir.nasa.gov/content/additional-sources-assistance.

8. Submission Forms

Note: Previews of all forms and certifications are available via the NASA SBIR/STTR Firm Library, located at: http://sbir.gsfc.nasa.gov/sbir/firm_library/index.html.

8.1 SBIR Phase I Check List

For assistance in completing your Phase I proposal, use the following checklist to ensure your submission is complete.

1. The proposal and innovation is submitted for one subtopic only (section 3.1).
2. The entire proposal package is submitted consistently with the requirements outlined in section 3.3.
    a. Proposal Contact Information
    b. Proposal Certifications
    c. Proposal Summary
    d. Proposal Budget
    e. Technical Proposal
    f. Briefing Chart
    g. I-Corps Opt-In
    h. Firm Level Forms (completed once for all proposals submitted to a single Solicitation)
        i. Firm Certifications
        ii. Audit Information
        iii. Prior Awards Addendum
        iv. Commercialization Metrics Survey
3. **The technical proposal shall not exceed a total of 19 8.5 x 11 inch pages and follow the format requirements (section 3.3.2).**
4. The technical proposal contains all ten parts in order (section 3.3.4).
5. Any additional required letters/documentation.
    a. A letter of commitment from the facility manager, if the research or R&D effort requires use of federal facilities (section 3.3.3.4).
    b. Letters of commitment from Subcontractors/Consultants.
    c. If the firm is an eligible joint ventures and limited partnership, a copy or comprehensive summary of the joint venture agreement or partnership agreement is included.
    d. NASA Evaluation License Application if proposing the use of NASA Technology (TAV).
    e. Supporting documentation of budgeted costs.
6. Proposed funding does not exceed $125,000 (section 1.3).
7. Proposed project duration does not exceed 6 months (section 1.3).
8. Proposal package electronically endorsed by the SBC Official and the PI.
9. **Proposals must be received no later than 5:00 p.m. EDT on April 20, 2020 (section 6.3).**

8.2 STTR Phase I Check List

For assistance in completing your Phase I proposal, use the following checklist to ensure your submission is complete.

1. The proposal and innovation is submitted for one subtopic only (section 3.1).
2. The entire proposal package is submitted consistently with the requirements outlined in section 3.3.
    a. Proposal Contact Information
    b. Proposal Certifications
    c. Proposal Summary
    d. Proposal Budget
    e. Technical Proposal
    f. Research Agreement (STTR only)
    g. Briefing Chart
    h. I-Corps Opt-In
    i. Firm Level Forms (completed once for all proposals submitted to a single Solicitation)
        i. Firm Certifications
        ii. Audit Information
        iii. Prior Awards Addendum
        iv. Commercialization Metrics Survey
3. **The technical proposal shall not exceed a total of 19 8.5 x 11 inch pages and follow the format requirements (section 3.3.2).**
4. The technical proposal contains all ten parts in order (section 3.3.4).
5. Any additional required letters/documentation.
    a. A letter of commitment from the facility manager, if the research or R&D effort requires use of federal facilities (section 3.3.3.4).
    b. Letters of commitment from Subcontractors/Consultants.
    c. If the firm is an eligible joint ventures and limited partnership, a copy or comprehensive summary of the joint venture agreement or partnership agreement is included.
    d. NASA Evaluation License Application if proposing the use of NASA Technology (TAV).
    e. Supporting documentation of budgeted costs.
6. Proposed funding does not exceed $125,000 (section 1.3).
7. Proposed project duration does not exceed 13 months (section 1.3).
8. Research Agreement electronically endorsed by both the SBC Official and the RI (section 3.3.5, 6.2).
9. Proposal package electronically endorsed by the SBC Official and the PI.
10. Signed Allocation of Rights Agreement.
11. **Proposals must be received no later than 5:00 p.m. EDT on April 20, 2020 (section 6.3).**

8.3 SBIR Phase II Check List

For assistance in completing your Phase II proposal, use the following checklist to ensure your submission is complete.

1. The proposal and innovation is submitted for one subtopic only (section 3.1).

2. The entire proposal package is submitted consistently with the requirements outlined in section 3.4.
    a. Proposal Contact Information
    b. Proposal Certifications
    c. Proposal Summary
    d. Proposal Budget
    e. Technical Proposal
    f. Briefing Chart
    g. Capital Commitments Addendum (if applicable)
    h. Firm Level Forms (completed once for all proposals submitted to a single Solicitation)
        i. Firm Certifications
        ii. Audit Information
        iii. Prior Awards Addendum
        iv. Commercialization Metrics Survey

3. **The technical proposal shall not exceed a total of 46 8.5 x 11 inch pages and follow the format requirements (section 3.4.2).**

4. The technical proposal contains all ten parts in order (section 3.4.4).

5. Any additional required letters/documentation
    a. A letter of commitment from the facility manager, if the research or R&D effort requires use of federal facilities (section 3.4.4).
    b. Letters of commitment from Subcontractors/Consultants.
    c. Letters in support of Capital Commitments Addendum.
    d. If the firm is an eligible joint ventures and limited partnership, a copy or comprehensive summary of the joint venture agreement or partnership agreement is included.
    e. NASA Evaluation License Application if proposing the use of NASA Technology (TAV).
    f. Supporting documentation of budgeted costs.

6. Proposed funding does not exceed $750,000, excluding the $5,000/year Technical and Business Assistance, if requested (section 1.8).

7. Proposed project duration does not exceed 24 months (section 1.3).

8. Proposal package electronically endorsed by the SBC Official and the PI.

9. **Phase II proposal submissions will be due the last day of the Phase I contract (section 6.4).**

8.4 STTR Phase II Check List

For assistance in completing your Phase II proposal, use the following checklist to ensure your submission is complete.

1. The proposal and innovation is submitted for one subtopic only (section 3.1).
2. The entire proposal package is submitted consistently with the requirements outlined in section 3.4.
    a. Proposal Contact Information
    b. Proposal Certifications
    c. Proposal Summary
    d. Proposal Budget
    e. Technical Proposal
    f. Research Agreement
    g. Briefing Chart
    h. Capital Commitments Addendum (if applicable)
    i. Firm Level Forms (completed once for all proposals submitted to a single Solicitation)
        i. Firm Certifications
        ii. Audit Information
        iii. Prior Awards Addendum
        iv. Commercialization Metrics Survey
3. **The technical proposal shall not exceed a total of 46 8.5 x 11 inch pages and follow the format requirements (section 3.4.2).**
4. The technical proposal contains all ten parts in order (section 3.4.4).
5. Any additional required letters/documentation
    a. A letter of commitment from the facility manager, if the research or R&D effort requires use of federal facilities (section 3.4.4).
    b. Letters of commitment from Subcontractors/Consultants.
    c. Letter in support of Capital Commitments Addendum.
    d. If the firm is an eligible joint ventures and limited partnership, a copy or comprehensive summary of the joint venture agreement or partnership agreement is included.
    e. NASA Evaluation License Application if proposing the use of NASA Technology (TAV).
    f. Supporting documentation of budgeted costs.
6. Proposed funding does not exceed $750,000 excluding the $5,000/year Technical and Business Assistance, if requested (section 1.8).
7. Proposed project duration does not exceed 24 months (section 1.3).
8. Research Agreement electronically endorsed by both the SBC Official and the RI (section 3.4.5, 6.2).
9. Proposal package electronically endorsed by the SBC Official and the PI.
10. Signed Allocation of Rights Agreement.
11. **Phase II proposal submissions will be due the last day of the Phase I contract (section 6.4).**

9. Research Topics for SBIR and STTR

Introduction

The SBIR and STTR subtopics are organized into groupings called “Focus Areas”. Focus Areas are a way of grouping NASA interests and related technologies with the intent of making it easier for proposers to understand related needs across the agency and thus identify subtopics where their research and development capabilities may be a good match.

Note: The SBIR and STTR Subtopics will appear in one combined listing. The STTR subtopics will begin with a “T” and will be clearly marked so that offerors will know that the additional Research Institution (RI) partnership is required before submitting a proposal.

Subtopic numbering conventions from previous year’s solicitations have been maintained for traceability of like-subtopics from previous solicitations. The mapping is as follows:

A – Aeronautics Research Mission Directorate (ARMD)
H – Human Exploration and Operations Mission Directorate (HEOMD)
S – Science Mission Directorate (SMD)
Z – Space Technology Mission Directorate (STMD)
T – Small Business Technology Transfer (STTR)

Proposers should think of the Subtopic Lead Mission Directorates and Lead/Participating Centers as potential customers for their proposals. Multiple Mission Directorates and Centers may have interests across the subtopics within a Focus Area.

Related subtopic pointers are identified when applicable in the subtopic headers to assist proposers with identifying related subtopics that also potentially seek related technologies for different customers or applications. As stated in section 3.1, an offeror shall not submit the same (or substantially equivalent) proposal to more than one subtopic. It is the offeror’s responsibility to select which subtopic to propose to.

Moon to Mars Campaign

NASA is implementing a program for the exploration and utilization of the Moon followed by missions to Mars and other destinations, called the Moon to Mars campaign (see https://www.nasa.gov/topics/moon-to-mars/overview). Working with U.S. companies and international partners, NASA will push the boundaries of human exploration forward to the Moon and on to Mars. NASA is working to establish a permanent human presence on the Moon within the next decade to uncover new scientific discoveries and lay the foundation for private companies to build a lunar economy.

An early element of the exploration campaign is the delivery of payloads to the Moon for scientific study and the advancement of technology capabilities to support sustained lunar surface operations. There are many subtopics where proposals may include efforts to develop payloads for flight demonstration of relevant technologies in the lunar environment.

All subtopics with lunar relevance will be marked by a moon. For additional information on the Moon to Mars Campaign please see the Notable Changes section at the front of this solicitation.

Focus Area 1: In-Space Propulsion Technologies

Lead MD: STMD

Participating MD(s): STTR

NASA is interested in technologies for advanced in-space propulsion systems to reduce travel time, increase payload mass, reduce acquisition costs, reduce operational costs, and enable new science capabilities for exploration and science spacecraft. The future will require demanding propulsive performance and flexibility for more ambitious missions requiring high duty cycles, more challenging environmental conditions, and extended operation. This focus area seeks innovations for NASA propulsion systems in chemical, electric, nuclear thermal and advanced propulsion systems related to human exploration and science missions. Propulsion technologies will focus on a number of mission applications including ascent, descent, orbit transfer, rendezvous, station keeping, proximity operations and deep space exploration.

T2.04: Advanced in-space propulsion (STTR)

Lead Center: MSFC

Participating Center(s): GRC

Technology Area: 2.0.0 In-Space Propulsion Technologies

Related Subtopic Pointer(s): H10.01 S3.03 Z4.04 Z10.03

This subtopic is seeking small business - non-profit research institution partnerships to advance subsystem elements of three important, next generation in-space propulsion technologies: the Electrostatic Solar Sail, Freeform additive fabrication for propulsion elements, and Nuclear Thermal Propulsion low cost fuel testing.

Scope Title

Electrostatic Solar Sail (E-Sail) Advancement

Scope Description

The E-Sail is a propellant-less in-space propulsion system that utilizes electrostatic repulsion of solar wind (off of an electrically biased tether) to generate thrust. Preliminary studies indicate several advantages of this technology, including enabling access to interstellar space with transit times significantly faster than state-of-the-art (SOA) technologies. For this year's E-Sail investments, concepts to advance the Technology Readiness Level (TRL) of the E-sail guidance, navigation, and control system and/or robust models for spacecraft dynamics both during deployment as well as during operation are solicited. Marshall Space Flight Center (MSFC) is currently conceptualizing a 6-12U, ~10km total tether length E-Sail demonstration. Neither a specific architecture nor specific requirements have yet been detailed, however, responders should focus efforts in their proposed work towards this size spacecraft while keeping eventual scaling to as much as a 10x larger spacecraft in mind.

Expected TRL or TRL range at completion of the project: 3 to 6

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Software, and/or Research

Desired Deliverables Description

Phase I proof of concept and/or preliminary guidance, navigation & control (GN&C) designs and/or models that will lead to Phase II medium to high fidelity prototypes ready for system infusion (in case of hardware), system analysis (in case of models), and/or advanced TRL testing (space environments testing) to support a MSFC led technology demonstration mission. Beyond Phase II, infusion into the planned E-Sail Technology Demonstration Missions (TDM) via a Phase III, IIE, directed work, etc. or additional development/test via an Announcement of Collaborative Opportunity (ACO) may be potential opportunities.

State of the Art and Critical Gaps

The E-Sail concept has potential to enable practical access to interstellar space and fast travel beyond our solar system. The E-Sail has several open technology gaps. NASA is systematically reducing known risks of full system implementation prior to a flight demonstration. State of the Art GN&C systems and modeling have limitations due to the complex and changing dynamics of an E-Sail system. A critical gap is robust and high fidelity GN&C modeling and/or concepts for control of the E-Sail vehicle.

Relevance / Science Traceability

An Electrostatic Sail E-Sail is a propellant-less advanced propulsion system that harnesses solar wind by electrostatic repulsion. Note, this contrasts Solar Sails, which utilize optical reflection of solar photons. E-Sail is comprised of thin tethers, which are electrically biased to form large electric fields. These fields create a virtual sail that repels solar ions and generates thrust. A key advantage is this mechanism better maintains thrust as it moves away from the sun – falling off at only 1/distance, substantially better than the solar sail 1/d^2. E-Sail will rapidly improve transit time within and to the edge of the solar system as well as enable out of plan maneuvers not currently possible.

References

https://www.nasa.gov/centers/marshall/news/news/releases/2016/nasa-begins-testing-of-revolutionary-e-sail-technology.html (as of 8/2/2019)

Scope Title

Large Scale Freeform Additive Fabrication using GRCop-42 and Gradient Alloys

Scope Description

NASA is interested in soliciting proposals to develop a process for large scale freeform fabrication using additive manufacturing of GRCop-42 and functional gradient materials. Components such as rocket nozzles and heat exchangers are actively-cooled with internal channel features and require high performance materials in the extreme environment. Typically these components are made from a monolithic alloy, although various alloys and functional gradient materials could increase performance and optimize the overall system. The objective of this solicitation is to complete process development (i.e., directed energy deposition, coldspray, etc.) to fabricate a freeform component that incorporates thin-wall integral channels into a structure. This process should focus on GRCop-42 (Cu-Cr-Nb) and transition to an alternate material using a functional gradient process. The proposer should provide a technique and approach to axially transition from the GRCop-42 to alternate alloy (Superalloy, Stainless, High Entropy Alloys) providing a compatible functional gradient joint to minimize stresses. A thorough development approach would include process development, initial characterization and testing of the GRCop-42 and functional gradient alloys, process demonstration of manufacturing technology demonstrators (MTD), and trade study and/or planning to increase the scale to several feet in diameter.

Expected TRL or TRL range at completion of the project: 3 to 6

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, and/or Research

Desired Deliverables Description

Phase I: Develop a process for fabricating (using directed energy deposition, coldspray, etc.) a freeform structure that incorporates thin-wall integral channels targeting a heat exchanger, combustion chamber, rocket nozzle, channel-cooled structure and provide a trade on combination of compatible materials, with NASA inputs.

Leading to Phase II: Complete fabrication of process development samples using GRCop-42 and functional gradient alloys (Superalloy, High Entropy Alloys) to change the material axially along the component; and complete process characterization, mechanical testing, materials evaluation to provide first order design data. Fabricate manufacturing demonstrator components with integral channels with materials selected. Provide components that NASA could perform benchtop, flow, and/or hot-fire testing. Demonstrate a manufacturing technology component with integral channels and that is larger than 16” diameter with the GRCop-42 and functionally gradient alloys. Provide scale-up to >40” diameter.

State of the Art and Critical Gaps

NASA has been developing various additive manufacturing technologies in GRCop-42 using laser powder bed fusion (L-PBF) and currently working to mature large-scale (>3 ft dia) blown powder directed energy deposition (DED) process using NASA HR-1 and JBK-75. These technologies have been limited to monolithic materials though. Additional development has included bimetallic cladding (radial deposition) to provide superalloy jackets on copper-alloy combustion chambers under the Low Cost Upper Stage Propulsion (LCUSP) project, however this technology is not easily accessible at service companies. While the technology exist to fabricate components at sizes <16” diameter using laser powder bed fusion (L-PBF) using GRCop-42, this is limited to a monolithic material in the axial direction. There are also no current additive techniques to rapidly fabricate GRCop-42 structures larger than this scale.

There are also additional challenges in this approach with a binary transition from one alloy to another. Optimized structures for heat exchanges and combustion devices would include the ability to fabricate large structures with complex internal features and vary/transition alloys along the axial length of a component (not just radial). This would allow for a more compliant bond between a copper-alloy and alternate material instead of a drastic change in alloys. This would reduce risk of joints. A further gap is the ability to produce copper-alloys, such as GRCop-42, in scales larger than 16” diameter. This provides new solutions for designers of large engines and structures providing higher thermal margins on the walls with the use of copper. The copper technology using additive manufacturing does not exist using directed energy deposition (DED) or other technologies at this scale.

Relevance / Science Traceability

Applications to: Propulsion and energy, Liquid rocket engines, Small thrusters, Additive Manufacturing, and Advanced Manufacturing.

References

Gradl, P., Greene, S., Wammen, T. “Bimetallic Channel Wall Nozzle Development and Hot-fire Testing using Additively Manufactured Laser Wire Direct Closeout Technology”. 55th AIAA/SAE/ASEE Joint Propulsion Conference, AIAA Propulsion and Energy Forum. August 19-21, Indianapolis, IN. AIAA-2019.

Gradl, P., Protz, C., Wammen, T. "Additive Manufacturing Development and Hot-fire Testing of Liquid Rocket Channel Wall Nozzles using Blown Powder Directed Energy Deposition Inconel 625 and JBK-75 Alloys". 55th AIAA/SAE/ASEE Joint Propulsion Conference, AIAA Propulsion and Energy Forum. August 19-21, Indianapolis, IN. AIAA-2019

https://gameon.nasa.gov/projects/rapid-analysis-and-manufacturing-propulsion-technology-rampt/

Gradl, P. "Rapid Fabrication Techniques for Liquid Rocket Channel Wall Nozzles." AIAA-2016-4771, Paper presented at 52nd AIAA/SAE/ASEE Joint Propulsion Conference, July 27, 2016. Salt Lake City, UT.

Scope Title

Nuclear Thermal Propulsion (NTP) Advancement fuel testing

Scope Description

The NTP concept is similar to a liquid chemical propulsion system, except instead of combustion in the thrust chamber, a monopropellant is heated with a fission reactor (heat exchanger) in the thrust chamber and exposes the engine components and surrounding structures to a radiation environment. NTP thrust is ~25,000 lbf with ~29 lbs/sec flow of hydrogen through the fuel elements. Current fuel element designs are based on cermet (ceramic metal) or carbon with low enriched uranium.

The scope is open to university/Small Business Concern (SBC) partners to propose key innovation on how to best test NTP fuel pieces in the university nuclear reactors that come close to meeting the following test goals:

- Neutron/gamma radiation fluence approximating NTP operation.
- Heat NTP fuel test piece up to 2700K.
- Power density of 5 MW/L.
- Test piece exposed to hydrogen (if possible).
- Maintain steady state up to 15 minutes (or fluence equivalent).

Expected TRL or TRL range at completion of the project: 3 to 6

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, and Research

Desired Deliverables Description

The STTR team provides the following for Phase I and II:

- Irradiation capsule design and thermal analysis predictions to handle a variety of fuel test pieces in the university reactor.
- Instrumentation required to determine how best the fuel performed and validate analysis predictions.
- Development plan for Phase II including a description of the reactor test arrangement and fuel pieces to be irradiated. Start-off with irradiating a surrogate test piece during phase II. Conclude phase II with irradiating a fuel test piece with High Assay Low Enriched Uranium. Include a description of post-test examinations to be performed.

State of the Art and Critical Gaps

Testing various fuel concepts in the same environment as an NTP engine at low cost is not easy. Many current irradiation test facilities can test sample pieces to only a few of the NTP environment conditions.

Relevance / Science Traceability

Research could have a significant positive impact on the design and development of NTP systems. NTP potentially useful for both science and exploration missions.

References

Multiple publicly available references, see for example:

https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20120003776.pdf (as of 9/30/2019)

https://apps.dtic.mil/dtic/tr/fulltext/u2/a430931.pdf (as of 9/30/2019)

Z10.01: Cryogenic Fluid Management (SBIR)

Lead Center: GRC

Participating Center(s): JSC, MSFC

Technology Area: 2.0.0 In-Space Propulsion Technologies

Related Subtopic Pointer(s): Z10.03 T2.05 Z8.09

Scope Description

This subtopic seeks technologies related to cryogenic propellant (e.g. hydrogen, oxygen, methane) storage and transfer to support NASA's space exploration goals. This includes a wide range of applications, scales, and environments consistent with future NASA missions. Such missions include, but are not limited to upper stages, ascent and descent stages, refueling elements or aggregation stages, nuclear thermal propulsion, and in-situ resource utilization. Anticipated outcome of Phase 1 proposals are expected to deliver proof of the proposed concept with some sort of basic testing or physical demonstration. Proposals shall include plans for a prototype and demonstration in a defined relevant environment (with relevant fluids) at the conclusion of Phase II.

Desired technology concepts are listed below in order of priority:

- Develop cryogenic mass flow meters applicable to liquid oxygen and methane, having a volumetric flow measurement capacity of 1 - 20 L/min (fluid line size of approximately ½ inch), of rugged design that is able to withstand launch-load vibrations (e.g., 20g rms), with remote powered electronics (not attached to the flowmeter), able to function accurately in microgravity and vacuum environment, and having measurement error less than +/- 0.5% of the mass flow rate reading. Ability to measure bi-directional flow, compatibility with liquid hydrogen, and ability to measure mass flow rate during two-phase flows is also desired. Designs that can tolerate gas flow without damage to the flowmeter are also desired. Goal is Proof of concept end of Phase 1. Working prototype flow meter end of Phase 2.
- Broad area cooling methods for cryogenic composite propellant tanks (reduced and/or zero boil-off applications or liquefaction): Design and integration concepts must exhibit low mass, high-heat transfer between cooling fluid and propellant in tank, high heat exchanger efficiency (>90%), and operate in reduced gravity environments (10-6 g worse case). Proposers should consider structural and pressure vessel implications of the proposed concept. Target applications include liquid oxygen liquefaction system (16 g/s neon gas, 85K < T < 90K, pressure drop < 0.25 psia, 2.6m diameter, 3m tall tank) and reduced and/or zero boil off liquid hydrogen nuclear thermal propulsion system (3.5 g/s helium gas, 20K < T < 24K, 7m diameter, 8m tall tank).
- Cryogenic liquid/vapor phase separators capable of delivering single-phase liquid flow at least up to 10 gallons per minute, void fractions up to 30%, with an emphasis on minimizing pressure drop across the separator. Devices should be able to maintain performance (phase separation at highest flow rate) after multiple (> 15) thermal cycles (room temperature to 77K and back). Phase separator

should tolerate transient (transfer line and separator are chilling down). Phase 1 concept should yield a proof of concept using liquid cryogens. Phase 2 should focus on minimizing phase separator pressure drop, overall integration of phase separator into transfer system (i.e. where to route the vapor), and development a unit to test in liquid hydrogen.

NASA has plans to purchase services for delivery of payloads to the Moon through the Commercial Lunar Payload Services (CLPS) contract. Under this subtopic, proposals may include efforts to develop payloads for flight demonstration of relevant technologies in the lunar environment. The CLPS payload accommodations will vary depending on the particular service provider and mission characteristics. Additional information on the CLPS program and providers can be found at this link: https://www.nasa.gov/content/commercial-lunar-payload-services. CLPS missions will typically carry multiple payloads for multiple customers. Smaller, simpler, and more self-sufficient payloads are more easily accommodated and would be more likely to be considered for a NASA-sponsored flight opportunity. Commercial payload delivery services may begin as early as 2020 and flight opportunities are expected to continue well into the future. In future years it is expected that larger and more complex payloads will be accommodated. Selection for award under this solicitation will not guarantee selection for a lunar flight opportunity.

References

1. Johnson et al. “Investigation into Cryogenic Tank Insulation Systems for the Mars Surface Environment” 2018 Joint Propulsion Conference Cincinnati, OH, July, 2018. Paper.

2. Plachta, D., et al. "Zero Boil-Off System Testing" NASA TP 20150023073.

3. Hartwig, J.W., "Liquid Acquisition Devices for Advanced In-Space Cryogenic Propulsion Systems" Elsevier, Boston, MA, November, 2015.

Expected TRL or TRL range at completion of the project 2 to 4

Desired Deliverables of Phase II

Hardware, Software

Desired Deliverables Description

Phase I proposals should at minimum deliver proof of the concept, including some sort of testing or physical demonstration, not just a paper study. Phase II proposals should provide component validation in a laboratory environment preferably with hardware deliverable to NASA.

State of the Art and Critical Gaps

Cryogenic Fluid Management is a cross-cutting technology suite that supports multiple forms of propulsion systems (nuclear and chemical), including storage, transfer, and gauging, as well as liquefaction of ISRU (In-Situ Resource Utilization) produced propellants. STMD (Space Technology Mission Directorate) has identified that Cryogenic Fluid Management (CFM) technologies are vital to NASA's exploration plans for multiple architectures, whether it is hydrogen/oxygen or methane/oxygen systems including chemical propulsion and nuclear thermal propulsion. Several recent Phase IIs have resulted from CFM subtopics, most notably for advanced insulation, cryocoolers, and liquid acquisition devices.

Relevance / Science Traceability

STMD strives to provide the technologies that are needed to enable exploration of the solar system, both manned and unmanned systems; cryogenic fluid management is a key technology to enable exploration. Whether liquid oxygen/liquid hydrogen or liquid oxygen/liquid methane is chosen by HEO (Human Exploration and Operations) as the main in-space propulsion element to transport humans, CFM will be required to store propellant for up to 5 years in various orbital environments. Transfer will also be required, whether to engines or other tanks (e.g. depot/aggregation), to enable the use of cryogenic propellants that have been stored. In conjunction with ISRU, oxygen will have to be produced, liquefied, and stored, the latter two of which are CFM functions for the surface of the Moon or Mars. ISRU and CFM liquefaction drastically reduces the amount of mass that has to be landed.

Z10.03: Nuclear Thermal Propulsion (SBIR)

Lead Center: MSFC

Participating Center(s): GRC, SSC

Technology Area: 2.0.0 In-Space Propulsion Technologies

Related Subtopic Pointer(s): H10.01 T2.04 Z10.04 Z10.01

Scope Title
Reactor and Fuel System

Scope Description

The focus is on highly stable materials for nuclear fuels and non-fuel reactor components (i.e., moderator tie tubes, etc.) that can heat hydrogen to temperatures greater than 2600K without undergoing significant dimensional deformation, cracking, or hydrogen reactions. Current technology hurdles related to ceramic metal fuels center around refractory metal processing and manufacturing (i.e., welding of refractories, refractory metal coatings, etc.). The development of refractory alloys with enhanced/targeted material properties are of key interest (i.e., tungsten or molybdenum with increased ductility, or dispersion strengthen Mo/W alloys). Current technology hurdles with carbide fuels include embedding carbide kernels with coatings in a carbide matrix with potential for total fission product containment and high fuel burn-up. Manufacturing and testing of the insulator and reflector materials are also critical to the success of a Nuclear Thermal Propulsion (NTP) reactor.

Technologies being sought include:

- Low Enriched Uranium reactor fuel element designs with high temperature (> 2600K), high power density (>5 MW/L) to optimize hydrogen propellant heating.
- New advanced manufacturing processes to quickly manufacture the fuel with uniform channel coatings and/or claddings that reduce fission product gas release and reactor particulates into the engines exhaust stream.
- High temperature fuels that build on experience from AGR (Advanced Gas Reactor) TRISO (Tristructural-isotropic) design and testing. Potentially enable NTP with Isp> 900 seconds.

Fuels focused on Ceramic-metallic (cermet) designs:

- Fabrication technique for full length W/UN or W/UO2 fuel elements with greater than 60% volume ceramic loading

Fuels focused on carbide designs:

- Compatibility with high temperature hydrogen.
- High thermal conductivity and other properties (e.g., ductility) needed for high power density operation (~5MW/l).
- Kernel diameters, including coatings for fission product containment, which allow the fuel element to be fabricated with adequate strength for high temperature and high-power density operation.

Insulator design (one application is for tie tubes and the other is for interface with the pressure vessel) which has very low thermal conductivity and neutron absorption, withstands high temperatures, compatible with hot hydrogen and radiation environment, and light weight.

Expected TRL or TRL range at completion of the project: 2 to 5

Desired Deliverables of Phase II

Prototype hardware is desired.

Desired Deliverables Description

Desired deliverables for this technology would include research that can be conducted to determine technical feasibility of the proposed concept during Phase I and show a path toward a Phase II hardware demonstration. Testing the technology in a simulated (as close as possible) NTP environment as part of Phase II is preferred. Delivery of a prototype test unit at the completion of Phase II allows for follow-up testing by NASA.

Phase I Deliverables - Feasibility analysis and/or small-scale experiments proving the proposed technology to develop a given product (TRL 2-3). The final report includes a Phase II plan to raise the TRL. The Phase II plan includes a verification matrix of measurements to be performed at the end of Phase II, along with specific quantitative pass-fail ranges for each quantity listed.

Phase II Deliverables - A full report of component and/or breadboard validation measurements, including populated verification matrix from Phase I (TRL 4-5). Also delivered is a prototype of the proposed technology for NASA to do further testing if Phase II results show promise for NTP application. Opportunities and plans should also be identified and summarized for potential commercialization of the proposed technology.

State of the Art and Critical Gaps

The SOA (State-Of-the-Art) is reactor fuel developed for the Rover/NERVA program in the 1960's and early 1970's. The fuel was carbon based and had what is known as "mid-ban" corrosion, which effected the fuel endurance. Switching over to cermet (metal and ceramics) or advance carbide fuels shows promise, but has fabrication challenges.

Solid core NTP has been identified as an advanced propulsion concept which could provide the fastest trip times with fewer SLS (Space Launch System) launches than other propulsion concepts for human missions to Mars over a variety of mission years. NTP had major technical work done between 1955-1973 as part of the Rover and Nuclear Engine for Rocket Vehicle Application (NERVA) programs. A few other NTP programs followed including the Space Nuclear Thermal Propulsion (SNTP) program in the early 1990's. The NTP concept is similar to a liquid chemical propulsion system, except instead of combustion in the thrust chamber, a monopropellant is heated with a fission reactor (heat exchanger) in the thrust chamber and exposes the engine components and surrounding structures to a radiation environment.

Focus is on a range of modern technologies associated with NTP using solid core nuclear fission reactors and technologies needed to ground test the engine system and components. The engines are pump fed ~25,000 lbf with a specific impulse goal of 900 seconds (using hydrogen), and are used individually or in clusters for the spacecraft's primary propulsion system. The NTP can have multiple start-ups (>4) with cumulative run time >100 minutes in a single mission, which can last a few years. The Rover/NERVA program ground tested a variety of engine sizes, for a variety of burn durations and start-ups with the engine exhaust released to the open air. Current regulations require exhaust filtering of any radioactive noble gases and particulates. The NTP primary test requirements can have multiple start-ups (>8) with the longest single burn time ~50 minutes.

Relevance / Science Traceability

STMD (Space Technology Mission Directorate) is supporting the NTP project.

Future mission applications:

- Human Missions to Mars
- Science Missions to Outer Planets
- Planetary Defense

Some technologies may have applications for fission surface power systems.

Scope Title
Ground Test Technologies

Scope Description

Included in this area of technology development needs are identification and application of robust materials, advanced instruments and monitoring systems capable of operating in extreme temperature, pressure and radiation environments. Specific areas of interest include:

- Devices for measurement of radiation, pressure, temperature and strain in a high temperature and radiation environment.
- Non-intrusive diagnostic technology to monitor engine exhaust for fuel element erosion/failure and release of radioactive particulates.

Expected TRL or TRL range at completion of the project: 2 to 5

Desired Deliverables of Phase II

Prototype hardware is desired

Desired Deliverables Description

Desired deliverables for this technology would include research to determine the technical feasibility during Phase I and show a path toward a Phase II hardware demonstration. Determine a prototype instrument arrangement which can be strategically positioned to monitor NTP operation as good as possible. To monitor fuel degradation in the exhaust stream, the optimum position of the sensors must account for anomalies near an operating reactor core and have the ability to withstand the radiation and heat environment. Testing the technology in a simulated (as close as possible) NTP environment as part of phase II is preferred. Delivery of a prototype test unit at the completion of phase II allows for follow-up testing by NASA.

Phase I Deliverables - Feasibility analysis and/or small-scale experiments proving the proposed technology to develop a given product (TRL 2-3). The final report includes a Phase II plan to raise the TRL. The Phase II plan includes a verification matrix of measurements to be performed at the end of Phase II, along with specific quantitative pass-fail ranges for each quantity listed.

Phase II Deliverables - A full report of component and/or breadboard validation of sensor measurements, including populated verification matrix from Phase I (TRL 4-5). Also delivered is a prototype of the proposed technology for NASA to do further testing if phase II results show promise for NTP application. Opportunities and plans must also be identified and summarized for potential commercialization of the proposed technology.

State of the Art and Critical Gaps

The SOA NTP ground testing involved open air testing in the 1960's and early 1970's. The current regulations require an exhaust treatment system to avoid release of significant quantities of fission products into the air. Validating various exhaust treatment concepts requires a subscale simulation of NTP hot hydrogen, the cooling system, filtering, and special instrumentation to monitor what is coming out in the hydrogen exhaust, which could lead to shutdown.

Solid core NTP has been identified as an advanced propulsion concept which could provide the fastest trip times with fewer SLS launches than other propulsion concepts for human missions to Mars over a variety of mission years. NTP had major technical work done between 1955-1973 as part of the Rover and Nuclear Engine for Rocket Vehicle Application (NERVA) programs. A few other NTP programs followed including the Space Nuclear Thermal Propulsion (SNTP) program in the early 1990's. The NTP concept is similar to a liquid chemical propulsion system, except instead of combustion in the thrust chamber, a monopropellant is heated with a fission reactor (heat exchanger) in the thrust chamber and exposes the engine components and surrounding structures to a radiation environment.

Focus is on a range of modern technologies associated with NTP using solid core nuclear fission reactors and technologies needed to ground test the engine system and components. The engines are pump fed ~25,000 lbf with a specific impulse goal of 900 seconds (using hydrogen), and are used individually or in clusters for the spacecraft's primary propulsion system. The NTP can have multiple start-ups (>4) with cumulative run time >100 minutes in a single mission, which can last a few years. The Rover/NERVA program ground tested a variety of engine sizes, for a variety of burn durations and start-ups with the engine exhaust released to the open air. Current regulations require exhaust filtering of any radioactive noble gases and particulates. The NTP primary test requirements can have multiple start-ups (>8) with the longest single burn time ~50 minutes.

Relevance / Science Traceability

STMD (Space Technology Mission Directorate) is supporting NTP project.
Future mission applications:

- Human Missions to Mars
- Science Missions to Outer Planets
- Planetary Defense

Z10.04: Manufacturing Processes Enabling Lower-Cost, In-Space Electric Propulsion Thrusters (SBIR)

Lead Center: GRC

Participating Center(s):

Technology Area: 2.0.0 In-Space Propulsion Technologies

Related Subtopic Pointer(s): S3.03 Z10.03

Electric propulsion for space applications has demonstrated tremendous benefit to a variety of NASA, military, and commercial missions. During recent flight thruster development projects, NASA has identified manufacturing issues that have resulted in significant costs to achieve performance repeatability and hardware reliability. Without addressing the process and materials issues, both the production of existing thrusters and the development of new thrusters will continue to face the prospect of high costs that limit the commercial viability of these technologies. NASA thus seeks proposals that address improved fabrication processes or materials to reduce the total life cycle cost of electric propulsion thrusters. For example, a proposed component or assembly manufacturing process that improves fabrication reliability could permit reductions in the scope of acceptance testing and thus lower the overall cost of the technology.

Critical NASA needs have been identified in the scope areas detailed below. Proposals outside the described scope shall not be considered. Proposers are expected to show an understanding of the current state-of-the-art (SOA) and quantitatively (not just qualitatively) describe improvements over relevant SOA processes and materials that substantiate NASA investment. Prospective proposers in fields outside of electric propulsion are highly encouraged to apply if they have experiences with manufacturing processes that may be suitable for this solicitation.

Scope Title

Material joining in hollow cathodes

Scope Description

SOA hollow cathodes in thrusters are complex assemblies with metal-to-ceramic (e.g., alumina, magnesium oxide, etc.) and metal-to-metal joints where dissimilar materials may have large thermal expansion mismatches. In such cathodes, operating temperatures can range from 1000 - 1700 °C (necessitating the use of refractory metals such as molybdenum, rhenium, tantalum, tungsten, etc.), and material joints must be able to survive in excess of 10,000 thermal on-off cycles without failure. Existing material joining processes used to construct Hall-effect and ion thruster cathodes have demonstrated inconsistencies in joint strength and the presence of impurities that may degrade cathode performance during vacuum operations. Efforts to mitigate these issues have to date contributed to the high cost for the integrated cathode assembly and thruster; thus, making them less attractive for commercial usage, particularly for small satellite propulsion applications. Proposed material joining processes to this area must be compatible with critical high-temperature materials; be performed readily, reliably, and with some economy; demonstrate structural integrity at typical cathode operating conditions; and avoid contaminant release that could degrade the performance of common cathode emitter materials such as barium oxide (BaO) and lanthanum hexaboride (LaB6).

References:

- M.J. Patterson, "Robust Low-Cost Cathode for Commercial Applications", NASA/TM 2007-214984.
- AWS C3.2M/C3.2:2008, "Standard Method for Evaluating the Strength of Brazed Joints".

Scope Title

High-temperature electromagnets

Scope Description

Thermal management of integrated electric propulsion systems is often challenging, especially for compact micro-propulsion devices or high-power-density systems. For thrusters with electromagnetic coils, such as Hall-effect thrusters or plasma thrusters utilizing magnetic nozzles, these magnetic circuits may experience operational temperatures in excess of 500 ºC due to coil self-heating and close proximity to plasma-wetted surfaces; such magnetic circuits, may also need to survive in excess of 10,000 thermal on-off cycles without failure. High wire packing density is frequently desirable to achieve high magnetomotive forces (i.e., high ampere-turns). This is facilitated by small wire diameters with thin insulation, with the drawback of being more susceptible to heating and insulation failure. Existing processes for manufacturing and potting magnetic wire have exhibited instances of insulation and potting degradation during thruster operations that can lead to early thruster failure; however, the associated extensive acceptance testing required to ensure high reliability contributes to the current high cost of thrusters. Proposed solutions to this scope area must be compatible with high ampere-turn, multi-layer electromagnets; be fray-resistant; and avoid performance degradation at the operational conditions indicated above. Any formation of volatile materials under operational conditions, particularly if binders or potting materials are used (e.g., for electrical insulation between wire layers or for thermal management), must be limited so as to preserve the insulating materials' dielectric strength and to remain compliant with general NASA material outgassing guidelines (i.e., < 1% total mass loss and < 0.1% collected volatile condensable material).

References:

- J. Myers et al., "Hall Thruster Thermal Modeling and Test Data Correlation", AIAA 2016-4535.

- ASTM E595-15, "Standard Test Method for Total Mass Loss and Collected Volatile Condensable Materials from Outgassing in a Vacuum Environment".

Scope Title

Robust ceramics for Hall-effect thruster discharge channels

Scope Description

State-of-the-art Hall-effect thrusters make use of hot-pressed, hexagonal boron nitride (BN) or derivative ceramics, for the machined discharge channel in which plasma is generated and accelerated. The discharge channel (typically with outer diameters between 2 and 14 inches depending on the thruster's power level) must maintain electrical isolation between the thruster electrodes while being subjected to an energetic plasma environment, large thermal gradients and transients, and back-sputtered material from other thruster components or the vacuum test facility. To date, these materials have exhibited substantial lot-to-lot variability in key material properties (including mechanical strength, moisture sensitivity, and thermal conductivity and emissivity) that have resulted in discharge channel damage during vibration, shock, and thermal testing of the assembled thruster. Such material property inconsistencies have thus necessitated costly thruster design features to improve survivability margins against mechanical and thermal shock. Proposed processes to improve the lot-to-lot consistency should focus on the BN family of materials or similar ceramics compatible (i.e., exhibiting low ion-bombardment sputtering yields) with a Hall-effect thruster's discharge plasma.

References

H. Kamhawi et al., "Performance, Stability, and Plume Characterization of the HERMeS Thruster with Boron Nitride Silica Composite Discharge Channel", IEPC-2017-392.

ASTM C1424-04, "Standard Test Method for Monotonic Compressive Strength of Advanced Ceramics at Ambient Temperature".

ASTM E1461-13, "Standard Test Method for Thermal Diffusivity by the Flash Method".

ASTM E1933-14, "Standard Practice for Measuring and Compensating for Emissivity Using Infrared Imaging Radiometers".

Desired Deliverables

Phase I: In addition to a final report with supporting analysis, awardees shall deliver NASA material samples from the effort that can be utilized for independent verification of claimed improvements over SOA technologies.

Phase II: In addition to a final report with supporting analysis, awardees shall demonstrate functionality of components derived from the effort when integrated with operating thruster hardware. Partnering with electric propulsion developers may be required.

Expected TRL or TRL range at completion of the project: 2 to 6

Relevance / Science Traceability

Both NASA's Science Mission Directorate (SMD) and Human Exploration and Operations Mission Directorate (HEOMD) need spacecraft with demanding propulsive performance and greater flexibility for more ambitious missions requiring high duty cycles and extended operations under challenging environmental conditions. Planetary spacecraft need the ability to rendezvous with, orbit, and conduct *in situ* exploration of planets, moons, and other small bodies (i.e., comets, asteroids, near-Earth objects, etc.) in the solar system; furthermore, mission priorities are outlined in the decadal surveys for each of the SMD divisions (https://science.nasa.gov/about-us/science-strategy/decadal-surveys). For HEOMD, higher-power electric propulsion is a key element (e.g., the Power and Propulsion Element of the Lunar Gateway) in supporting sustained human exploration of cis-lunar space.

This subtopic seeks innovations to meet future SMD and HEOMD propulsion requirements in electric propulsion systems related to such missions. The innovations would enable lower-cost electric propulsion systems for small spacecraft, Discovery-class missions, and low-power NEP (nuclear electric propulsion) missions while improving the reliability and robustness of higher-power electric propulsion systems to support human missions. The roadmap for such in-space propulsion technologies is covered under the 2015 NASA Technology Roadmap TA-2 (In-Space Propulsion Technologies).

Focus Area 2: Power, Energy and Storage

Lead MD: STMD

Participating MD(s): SMD

Power is a ubiquitous technology need across many NASA missions. Within the SBIR Program, power is represented across a broad range of topics in human exploration, space science, space technology and aeronautics. New technologies are needed to generate electrical power and/or store energy for future human and robotic space missions and to enable hybrid electric aircraft that could revolutionize air travel. A key goal is to develop technologies that are multi-use and cross-cutting for a broad range of NASA mission applications. In aeronautics, power technologies are needed to supply large-scale electric power and efficiently distribute the power to aircraft propulsors (see Focus Area 18 – Air Vehicle Technologies). In the space power domain, mission applications include planetary surface power, large-scale spacecraft prime power, small-scale robotic probe power, and smallsat/cubesat power. Applicable technology options include photovoltaic arrays, radioisotope power systems, nuclear fission, thermal energy conversion, motor/generators, fuel cells, batteries or other energy storage devices, power management, transmission, distribution and intelligent control. An overarching objective is to mature technologies from analytical or experimental proof-of-concept (TRL3) to breadboard demonstration in a relevant environment (TRL5). Successful efforts will transition into NASA Projects where the SBIR/STTR deliverables will be incorporated into ground testbeds or flight demonstrations.

S3.01: Power Generation and Conversion (SBIR)

Lead Center: GRC

Participating Center(s): ARC, JPL

Technology Area: 3.0.0 Space Power and Energy Storage

Related Subtopic Pointer(s): S3.02 H5.01

Scope Title

Photovoltaic Energy Conversion

Scope Description

Photovoltaic cell and blanket technologies that lead to significant improvements in overall solar array performance by increasing photovoltaic cell efficiency greater than 30%, increasing array mass specific power greater than 300W/ kg, decreased stowed volume, reduced initial and recurring costs, long- term operation in radiation environments, high power arrays and a wide range of space environmental operating conditions are solicited.

Photovoltaic Energy Conversion: advances in, but not limited to, the following: (1) Photovoltaic cell and blanket technologies capable of low intensity, low-temperature operation applicable to outer planetary (low solar intensity) missions, (2) Photovoltaic cell, and blanket technologies that enhance and extend performance in lunar applications including orbital, surface and transfer, (3) Solar arrays to support Extreme Environments Solar Power type missions, including long-lived, radiation tolerant, cell and blanket technologies applicable to Jupiter missions, and (4) Lightweight solar array technologies applicable to science missions using solar electric propulsion.

Current missions being studied require solar arrays that provide 1 to 20 kilowatts of power at 1 AU, greater than 300 watts/kilogram specific power, operation in the range of 0.7 to 3 AU, low stowed volume, and the ability to provide operational array voltages up to 300 volts to enable direct drive electric propulsion systems for science missions.

References

Solar Power Technologies for Future Planetary Science Missions, found at: https://solarsystem.nasa.gov/resources/548/solar-power-technologies-for-future-planetary-science-missions/

Scope Title

Photovoltaic Energy Conversion

Scope Description

Photovoltaic cell and blanket technologies that lead to significant improvements in overall solar array performance by increasing photovoltaic cell efficiency greater than 30%, increasing array mass specific power greater than 300W/ kg, decreased stowed volume, reduced initial and recurring costs, long- term operation in radiation environments, high power arrays and a wide range of space environmental operating conditions are solicited.

Photovoltaic Energy Conversion: advances in, but not limited to, the following: (1) Photovoltaic cell and blanket technologies capable of low intensity, low-temperature operation applicable to outer planetary (low solar intensity) missions, (2)Photovoltaic cell, and blanket technologies that enhance and extend performance in lunar applications including orbital, surface and transfer, (3) Solar arrays to support Extreme Environments Solar Power type missions, including long-lived, radiation tolerant, cell and blanket technologies applicable to Jupiter missions, and (4) Lightweight solar array technologies applicable to science missions using solar electric propulsion.

Current missions being studied require solar arrays that provide 1 to 20 kilowatts of power at 1 AU, greater than 300 watts/kilogram specific power, operation in the range of 0.7 to 3 AU, low stowed volume, and the ability to provide operational array voltages up to 300 volts to enable direct drive electric propulsion systems for science missions.

References

Solar Power Technologies for Future Planetary Science Missions, found at: https://solarsystem.nasa.gov/resources/548/solar-power-technologies-for-future-planetary-science-missions/

NASA outlines New Lunar Science, Human Exploration Missions, found at: https://www.nasa.gov/feature/nasa-outlines-new-lunar-science-human-exploration-missions

NASA Science Missions, found at: https://science.nasa.gov/missions-page?field_division_tid=All&field_phase_tid=3951

Expected TRL or TRL range at completion of the project 3 to 5

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Research

Desired Deliverables Description

Phase I deliverables include detailed reports with proof- of- concept and key metrics of components tested and verified.
Phase II deliverables include detailed reports with relevant test data along with proof- of- concept hardware and components developed.

State of the Art and Critical Gaps

State of the Art photovoltaic array technology consists of high efficiency, multijunction cell technology on thick honeycomb panels. Lightweight arrays are just beginning to be developed. There are very limited demonstrated technology for High Intensity High Temperature (HIHT), Low Intensity Low Temperature (LILT), Solar Electric Propulsion (SEP) missions and Lunar orbital, surface or transfer applications.

Significant improvements in overall solar array performance are needed to address the current gaps between SOA (Sate of the Art) and many mission requirements for photovoltaic cell efficiency greater than 30%, array mass specific power greater than 300W/ kg, decreased stowed volume, reduced initial and recurring costs, long- term operation in radiation environments, high power arrays and a wide range of space, lunar, and planetary environmental operating conditions.

Relevance / Science Traceability

These technologies are relevant to any space science, earth science, planetary surface, or other science mission that requires affordable high-efficiency photovoltaic power production for orbiters, flyby craft, landers and rovers. Specific requirements can be found in the references listed above, but include many future Science Mission Directorate (SMD) missions. Specific requirements for orbiters and flybys to Outer planets include: LILT capability (>38% at 10 AU and <−140°C), radiation tolerance (6e15 1 MeV e-cm^2), high power (>50 kW at 1 AU), low mass (3× lower than SOP), low volume (3× lower than SOP), long life (>15 years), and high reliability.

These technologies are relevant and align to any Space Technology Mission Directorate (STMD) or Human Exploration and Operations Mission Directorate (HEOMD) mission that requires affordable high-efficiency photovoltaic power production.

NASA outlines New Lunar Science, Human Exploration Missions, found at:
https://www.nasa.gov/feature/nasa-outlines-new-lunar-science-human-exploration-missions

NASA Science Missions, found at:
https://science.nasa.gov/missions-page?field_division_tid=All&field_phase_tid=3951

NASA has plans to purchase services for delivery of payloads to the Moon through the Commercial Lunar Payload Services (CLPS) contract. Under this subtopic, proposals may include efforts to develop payloads for flight demonstration of relevant technologies in the lunar environment. The CLPS payload accommodations will vary depending on the particular service provider and mission characteristics. Additional information on the CLPS program and providers can be found at this link: https://www.nasa.gov/content/commercial-lunar-payload-services. CLPS missions will typically carry multiple payloads for multiple customers. Smaller, simpler, and more self-sufficient payloads are more easily accommodated and would be more likely to be considered for a NASA-sponsored flight opportunity. Commercial payload delivery services may begin as early as 2020 and flight opportunities are expected to continue well into the future. In future years it is expected that larger and more complex payloads will be accommodated. Selection for award under this solicitation will not guarantee selection for a lunar flight opportunity.

S3.02: Dynamic Power Conversion (SBIR)

Lead Center: GRC

Participating Center(s):

Technology Area: 3.0.0 Space Power and Energy Storage

Related Subtopic Pointer(s): Z2.01 S3.01 Z1.03

Scope Description

NASA is developing Dynamic Radioisotope Power Systems (DRPS) for unmanned robotic missions to the moon, and other solar system bodies of interest. This technology directly aligns with the Science Mission Directorate (SMD) strategic technology investment plan for space power and energy storage and could be infused into a highly efficient RPS for missions to dark, dusty, or distant destinations where solar power is not practical. Current work in dynamic radioisotope power systems is focused on novel Stirling, Brayton, or Rankine convertors that would be integrated with one or more 250 watt-thermal General Purpose Heat Source (GPHS) modules or 1 watt-thermal Light Weight Radioisotope heater Unit (RHU) to provide high thermal-to-electric efficiency, low mass, long life, and high reliability for planetary spacecraft, landers, and rovers. Heat is transferred from the radioisotope heat source assembly to the power convertor hot end using conductive or radiative coupling. Power convertor hot end temperatures would generally range from 300-500 °C for RHU applications and 500-800 °C for GPHS applications. Waste heat is removed from the cold end of the power convertor at temperatures ranging from 20-175 °C, depending on the application, using conductive coupling to radiator panels. The NASA projects target power systems able to produce a range of electrical power output levels based on the available form factors of space rated fuel sources. These include a very low range of 0.5-2.0 watt-electric that would utilize one or more RHU, a moderately range of 40-70 watt-electric that would utilize a single GPHS Step-2 module, and a high range of 100-500 watt-electric that would utilize multiple GPHS Step-2 modules. For these power ranges, one or more power convertors could be used to improve overall system reliability. The current solicitation is focused on innovations that enable efficient and robust power conversion systems. Areas of interest include:

1. Robust, efficient, highly reliable, and long-life thermal-to-electric power convertors that would be used to populate a generator of a prescribed electric power output range.
2. Electronic controllers applicable to Stirling, Brayton, or Rankine power convertors.
3. Multi-Layered Metal Insulation (MLMI) for minimizing environmental heat losses and maximizing heat transfer from the radioisotope heat source assembly to the power convertor.
4. Advanced dynamic power conversion components and RPS integration components, including efficient alternators able to survive extended exposure to 200 °C, robust high-temperature tolerant Stirling regenerators, robust highly effective recuperators, integrated heat pipes, and radiators that improve system performance, and improving the margin, reliability, and fault tolerance for existing components.

NASA has plans to purchase services for delivery of payloads to the Moon through the Commercial Lunar Payload Services (CLPS) contract. Under this subtopic, proposals may include efforts to develop payloads for flight demonstration of relevant technologies in the lunar environment. The CLPS payload accommodations will vary depending on the particular service provider and mission characteristics. Additional information on the CLPS program and providers can be found at this link: https://www.nasa.gov/content/commercial-lunar-payload-services. CLPS missions will typically carry multiple payloads for multiple customers. Smaller, simpler, and more self-sufficient payloads are more easily accommodated and would be more likely to be considered for a NASA-sponsored flight opportunity. Commercial payload delivery services may begin as early as 2020 and flight opportunities are expected to continue well into the future. In future years it is expected that larger and more complex payloads will be accommodated. Selection for award under this solicitation will not guarantee selection for a lunar flight opportunity.

References

Radioisotope Power Systems (RPS): https://rps.nasa.gov/about-rps/overview/

Oriti, Salvatore, "Dynamic Power Convertor Development for Radioisotope Power Systems at NASA Glenn Research Center," AIAA Propulsion and Energy (P&E) 2018, AIAA 2018-4498.

Wilson, Scott D., "NASA Low Power Stirling Convertor for Small Landers, Probes, and Rovers Operating in Darkness," AIAA P&E 2018, AIAA 2018-4499.

Wong, Wayne, "Advanced Stirling Convertor (ASC) Technology Maturation," AIAA P&E 2015, AIAA 2015-3806.

Expected TRL or TRL range at completion of the project: 3 to 5

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Research

Desired Deliverables Description

The desired deliverables include prototype hardware that has demonstrated basic functionality in a laboratory environment and the appropriate research and analysis used to develop the hardware. Deliverables also include maturation options for flight designs.

State of the Art and Critical Gaps

Radioisotope Power Systems are critical for long duration NASA missions in dark, dusty, or harsh environments. Thermoelectric systems have been used on the very successful RPS flown in the past, but are limited in efficiency. Dynamic thermal energy conversion provides significantly higher efficiency and through proper engineering of the non-contact moving components, can eliminate wear mechanisms and provide long life. While high efficiency performance of dynamic power convertors has been proven, reliable and robust systems tolerant of off-nominal operation is needed. In addition to convertors appropriate for General Purpose Heat Source (GPHS) RPS, advances in much smaller and lower power dynamic power conversion systems are sought that can utilize Radioisotope Heater Units (RHU) for applications such as distributed sensor systems, small spacecraft, and other systems that take advantage of lower power electronics for the exploration of surface phenomenon on icy moons and other bodies of interest. While the power convertor advances are essential, to develop reliable and robust systems for future flight, advances in convertor components as well as RPS integration components are also needed. These would include efficient alternators able to survive 200 C, robust high-temperature tolerant regenerators, robust high efficiency recuperators, heat pipes, radiators, and controllers applicable to Stirling flexure-bearing, Stirling gas-bearing, or Brayton convertors. Similar scope and content was previously included as part of the broader S3.01 subtopic last year. This nomination is for dynamic power conversion as a stand-alone subtopic under S3.

Relevance / Science Traceability

This technology directly aligns with the Science Mission Directorate - Planetary Science Division for space power and energy storage. Investments in more mature technologies through the Radioisotope Power System Program is ongoing. This SBIR subtopic scope provides a lower TRL technology pipeline for advances in this important power capability that improves performance, reliability, and robustness.

S3.03: Energy Storage for Extreme Environments (SBIR)

Lead Center: GRC

Participating Center(s): JPL

Technology Area: 3.0.0 Space Power and Energy Storage

Related Subtopic Pointer(s): Z10.04 T2.04 Z1.03

Scope Description

NASA's Planetary Science Division is working to implement a balanced portfolio within the available budget and based on a decadal survey that will continue to make exciting scientific discoveries about our solar system. This balanced suite of missions shows the need for low mass/volume energy storage that can effectively operate in extreme environments for future NASA Science Missions.

Future science missions will require advanced primary and secondary battery systems capable of operating at temperature extremes from -200° C for outer planet missions to 400 to 500° C for Venus missions, and a span of -230° C to +120° C for missions to the Lunar surface. Operational durations of 60 days for Titan and 14 days for the Moon are of interest. Advancements to battery energy storage capabilities that address operation at extreme temperatures combined with high specific energy and energy density (>200 Wh/kg and >200 Wh/l) are of interest in this solicitation.

In addition to batteries, other advanced energy storage/load leveling technologies designed to the above mission requirements, such as mechanical or magnetic energy storage devices, are of interest. These technologies have the potential to minimize the size and mass of future power systems.

NASA has plans to purchase services for delivery of payloads to the Moon through the Commercial Lunar Payload Services (CLPS) contract. Under this subtopic, proposals may include efforts to develop payloads for flight demonstration of relevant technologies in the lunar environment. The CLPS payload accommodations will vary depending on the particular service provider and mission characteristics. Additional information on the CLPS program and providers can be found at this link: https://www.nasa.gov/content/commercial-lunar-payload-services. CLPS missions will typically carry multiple payloads for multiple customers. Smaller, simpler, and more self-sufficient payloads are more easily accommodated and would be more likely to be considered for a NASA-sponsored flight opportunity. Commercial payload delivery services may begin as early as 2020 and flight opportunities are expected to continue well into the future. In future years it is expected that larger and more complex payloads will be accommodated. Selection for award under this solicitation will not guarantee selection for a lunar flight opportunity.

References

- NASA Science: https://science.nasa.gov/
- Solar Electric Propulsion: https://www1.grc.nasa.gov/space/sep/

Expected TRL or TRL range at completion of the project: 3 to 5

Desired Deliverables of Phase II

Prototype

Desired Deliverables Description

Research should be conducted to demonstrate technical feasibility during Phase I and show a path toward a Phase II, and when possible, deliver a demonstration unit for NASA testing at the completion of the Phase II contract. Phase II emphasis should be placed on developing and demonstrating the technology under relevant test conditions. Additionally, a path should be outlined that shows how the technology could be commercialized or further developed into science-worthy systems.

State of the Art and Critical Gaps

State-of the-art primary and rechargeable cells are limited in both capacity and temperature range. Typical primary Li-SO_2 and Li-$SOCl_2$ operate within a max temperature range of -40 to 80 deg C but suffer from capacity loss, especially at low temperatures. At -40 deg C, the cells will provide roughly half the capacity available at room temperature. Similarly, rechargeable Li-ion cells operate within a narrow temperature range of -20 to 40 C and also suffer from capacity loss at lower temperatures. The lower limit of temperature range of rechargeable cells can be extended through the use of low temperature electrolytes, but with limited rate capability and concerns over lithium plating on charge. There is currently a gap that exists for high temperature batteries, primary and rechargeable, that can operate at Venus atmospheric temperatures. This solicitation is aimed at the development of cells that can maintain performance at extreme temperatures so as to minimize or eliminate the need for strict thermal management of the batteries, which adds complexity and mass to the spacecraft.

Relevance / Science Traceability

These batteries are applicable over a broad range of science missions. Low temperature batteries are needed for potential NASA decadal missions to Ocean Worlds (Europa, Enceladus, and Titan) and the Icy Giants (Neptune, Uranus). These batteries are also needed for science missions on the lunar surface. Low temperature batteries developed under this subtopic would enhance these missions and could be potentially enabling if the missions are mass or volume limited. There is also significant interest in a Venus surface mission that will require primary and/or rechargeable batteries that can operate for 60+ days on the surface of Venus. A high temperature battery that can meet these requirements is enabling for this class of missions.

Z1.03: Kilowatt-Class Energy Conversion for Small Fission Reactors (SBIR)

Lead Center: GRC

Participating Center(s): JPL

Technology Area: 3.0.0 Space Power and Energy Storage

Related Subtopic Pointer(s): Z1.05 Z2.01 S3.03 H5.01 S3.02

Scope Title

Kilowatt-Class Fission Energy Conversion

Scope Description

NASA is considering the use of kilowatt class Fission Power Systems for surface missions to the moon and Mars. This technology directly aligns with the Space Technology Mission Directorate (STMD) roadmap for space power and energy storage. Prior work in fission power systems had focused on a 1kWe ground demonstration, however, NASA desires to scale-up the system and components for a flight demo mission to the lunar surface, so component technologies that support a 10kWe-class fission power system are sought that address the following technical challenges:

- Robust, efficient, highly reliable, and long-life thermal-to-electric power conversion in the range of 1-10kWe. Stirling, Brayton, and thermoelectric convertors that can be coupled to Kilopower reactors are of interest.
- Freeze tolerant heat pipe radiators that can operate through lunar night (-173 ºC) and day (127 ºC) temperature swings. Heat pipes must start-up from lunar night temperature and begin transferring heat within several thermal cycles.
- Radiation shield materials selection, design, and fabrication for mixed neutron and gamma environments, with consideration for mass effectiveness, manufacturability, and cost.
- Radiation tolerant generator control electronics designed to withstand an induced radiation environment in addition to the ambient environment in space. These electronics can include: source control and generation, high voltage outputs with dynamic response needed to meet power quality standards, short term heating prior to startup, shunt control to manage excess power production, and source monitoring for power management. Target dose tolerance ranges for fission power system electronics are between 1E11 to 1E13 n/cm^2 total neutron fluence, and between 100 kRad (Si) and

1000kRad (Si) total ionizing gamma dose. Natural space environment should also be considered, with specific attention to Single Event Effect susceptibility.

The desired deliverables are primarily prototype hardware, research, and analysis to demonstrate concept feasibility and a TRL range of 3 to 5. The prototype hardware may include one (or more) of the following:

- Power convertor (hot-end temperature = 800 ºC, cold-end temperature = 100 to 200 ºC)
- Heat pipe radiator (for up to 30 kW heat rejection)
- Radiation shield (reduce radiation down to 1E11 to 1E13 n/cm^2 neutron fluence and 100 to 1000 kRad TID at minimum mass)
- Control electronics (capable of surviving the radiation environment that passes through the radiation shield)

NASA has plans to purchase services for delivery of payloads to the Moon through the Commercial Lunar Payload Services (CLPS) contract. Under this subtopic, proposals may include efforts to develop payloads for flight demonstration of relevant technologies in the lunar environment. The CLPS payload accommodations will vary depending on the particular service provider and mission characteristics. Additional information on the CLPS program and providers can be found at this link: https://www.nasa.gov/content/commercial-lunar-payload-services. CLPS missions will typically carry multiple payloads for multiple customers. Smaller, simpler, and more self-sufficient payloads are more easily accommodated and would be more likely to be considered for a NASA-sponsored flight opportunity. Commercial payload delivery services may begin as early as 2020 and flight opportunities are expected to continue well into the future. In future years it is expected that larger and more complex payloads will be accommodated. Selection for award under this solicitation will not guarantee selection for a lunar flight opportunity.

References

Kilopower (https://www.nasa.gov/directorates/spacetech/kilopower).

Gibson, M.A., et al., "The Kilopwer Reactor Using Stirling TechnologY (KRUSTY) Nuclear Ground Test Results and Lessons Learned," AIAA P&E 2018, AIAA-2018-4973.

Mason, Lee S., "A Comparison of Energy Conversion Technologies for Space Nuclear Power Systems," AIAA P&E 2018, AIAA-2018-4977.

Chaiken, M.F., et al., "Radiation Tolerance Testing of Electronics for Space Fission Power Systems," Nuclear and Emerging Technologies for Space 2018, Paper No. 24146.

Gibson, M.A., et al., "NASA's Kilopower Reactor Development and the Path to Higher Power Missions," 2017 IEEE Aerospace Conference, 4-11 March 2017, Big Sky, MT.

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Expected TRL or TRL range at completion of the project: 3 to 5

Desired Deliverables of Phase II

Hardware, Analysis, and Research

Desired Deliverables Description

We are primarily looking for component and/or breadboard hardware to demonstrate concept feasibility in a lab or relevant environment. The appropriate research and analysis required to develop the hardware are also desired.

State of the Art and Critical Gaps

Kilowatt-class fission power generation is an enabling technology for lunar and Mars surface missions that require day and night power for long-duration surface operations, and may be the only viable power option to achieve a sustained human presence. The surface assets that could benefit from a continuous and reliable fission power supply include landers, rover recharge stations, science platforms, mining equipment, ISRU (In-Situ Resource Utilization) propellant production, and crew habitats. Compared to solar arrays with energy storage, nuclear fission offers considerable mass savings, greater simplicity of deployment, improved environmental tolerance, and superior growth potential for increasing power demands. Fission power is also one of very few technologies that can be used on either the moon or Mars with the same basic design. A first-use on the moon provides an excellent proving ground for future Mars systems, on which the crew will be highly dependent for their survival and return propellant. The technology is also extensible to outer planet science missions with power requirements that exceed the capacity of radioisotope generators, including nuclear electric propulsion spacecraft that could enable certain science missions that might otherwise be impossible.

Current work on fission power systems has focused on a 1kWe design using a highly enriched Uranium-Molybdenum reactor core with a Beryllium oxide reflector. Depleted uranium, tungsten, and lithium hydride provide shielding of gamma rays and neutrons to the power conversion system, control electronics, payload, and habitat. Heat is removed from the core at approximately 800° C using sodium heat pipes and delivered to the power conversion system. Waste heat is removed from the power conversion system at approximately 100 to 200° C using water heat pipes coupled to aluminum or composite radiator panels.

Reliable, robust, and long life power conversion is highly desirable in fission systems. There are currently not enough vendors or enough long duration reliability data for power conversion technologies under these operating conditions and environments. More work is needed in this area to expand the supplier base, and to increase the TRL of power conversion technology. The reactor core must be isolated from the Martian environment to prevent oxidation. However, simply canning the core may not be an option since increased distance between the core and reflector can have large negative effects on system mass. Canning the reflector and core together is the simplest option; however, the increased temperature of the reflector results in reduced reactivity and increased mass. Innovations are necessary to provide isolation while reducing the negative effect due to the neutronics.

Total Ionizing Dose (TID) effects, Displacement Damage Dose (DDD) effects, and Single Event Effect (SEE) transients are well studied for the standard space radiation environment composed of charged particles and electromagnetic radiation of either solar or galactic origin. Aerospace electronics vendors offer high reliability product lines that have been qualified using standard irradiation testing procedures. These procedures do not typically cover the neutron environment of a nuclear fission reactor. Further qualification in a reactor radiation environment is needed for components and systems that will be used in a space fission power system.

Relevance / Science Traceability

This technology directly aligns with the STMD roadmap for space power and energy storage. This technology could be infused into the Kilopower Project to enhance performance or reliability.

Z1.05: Lunar & Planetary Surface Power Management & Distribution (SBIR)

Lead Center: GRC

Participating Center(s): GSFC, JSC

Technology Area: 3.0.0 Space Power and Energy Storage

Related Subtopic Pointer(s): Z1.03 Z1.06 S4.04 Z13.01

Scope Title

Innovative ways to transmit high power for lunar & Mars surface missions

Scope Description

The Global Exploration Roadmap (January 2018) and the Space Policy Directive (December 2017) detail NASA's plans for future human-rated space missions. A major factor in this involves establishing bases on the lunar surface and eventually Mars. Surface power for bases is envisioned to be located remotely from the habitat modules and must be efficiently transferred over significant distances. The International Space Station (ISS) has the highest power (100kW), and largest space power distribution system with eight interleaved micro-grids providing power functions similar to a terrestrial power utility. Planetary bases will be similar to the ISS with expectations of multiple power sources, storage, science, and habitation modules, but at higher power levels and with longer distribution networks providing interconnection. In order to enable high power (>100kW) and longer distribution systems on the surface of the moon or Mars, NASA is in need of innovative technologies in the areas of lower mass/higher efficiency power electronic regulators, switchgear, cabling, connectors, wireless sensors, power beaming, power scavenging, and power management control. The technologies of interest would need to operate in extreme temperature environments, including lunar night, and could experience temperature changes from -153C to 123C for lunar applications, and -125C to 80C for Mars bases. In addition to temperature extremes, technologies would need to withstand (have minimal degradation from) lunar dust/regolith, Mars dust storms, and space radiation levels.

While this subtopic would directly address the lunar and Mars base initiatives, technologies developed could also benefit other NASA Mission Directorates including SMD (Science Mission Directorate) and ARMD (Aeronautics Research Mission Directorate). Specific projects which could find value in the technologies developed herein include Gateway, In-Situ Resource Utilization (ISRU), Advanced Modular Power Systems (AMPS), In-Space Electric Propulsion (ISP), planetary exploration, and Hybrid Gas Electric Propulsion. The power levels may be different, but the technology concepts could be similar, especially when dealing with temperature extremes and the need for electronics with higher power density and efficiency.

Specific technologies of interest would need to address the lunar or Mars environment, and include:

- Application of wide bandgap electronics in DC-DC isolating converters with wide temperature (-70ºC to 150ºC), high power density (>2 kW/kg), high efficiency (>96%) power electronics and associated drivers for voltage regulation.
- Low mass, highly conductive wires and terminations that provide reliable small gauges for long distance power transmission in the 1-10kW range, low mass insulation materials with increased dielectric breakdown strength and void reductions with 600 V or greater ratings, and low loss/low mass shielding.
- Power beaming concepts to enable highly efficient flexible/mobile power transfer in the 100-1,000W range, including the fusion of power/communication/navigation.

(See Z13.02 - Dust Tolerant Mechanisms subtopic to propose power connection/termination related technologies that are impervious to environmental dust and enable robotic deployment, such as robotically-enabled high voltage connectors and/or near-field wireless power transfer in the 1-10kW range.)

References

The Global Exploration Roadmap, January 2018: https://www.nasa.gov/sites/default/files/atoms/files/ger_2018_small_mobile.pdf

Space Policy Directive, December 2017: https://www.nasa.gov/topics/moon-to-mars/overview

Expected TRL or TRL range at completion of the project 3 to 6

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Research

Desired Deliverables Description

Typically, deliverables under Phase I proposals are geared towards a technology concept with associated analysis and design. A final report usually suffices in summarizing the work. Phase II hardware prototypes will have opportunities for infusion into NASA technology testbeds and commercial landers.

State of the Art and Critical Gaps

While high power terrestrial distribution systems exist, there is no equivalent to a lunar or planetary base. Unique challenges must be overcome in order to enable a realistic power architecture for these future applications, especially when dealing with the environmental extremes which will be encountered. The temperature swings will be a critical requirement on any technology developed, from power converters to cabling or power beaming concepts. In addition, proposals will have to consider lunar regolith and Mars dust storms.

Relevance / Science Traceability

This subtopic would directly address the lunar and Mars surface initiatives. There are potential infusion opportunities with SMD (Science Mission Directorate) Commercial Lander Payload Services and HEOMD (Human Exploration and Operations Mission Directorate) Flexible Lunar Exploration (FLEx) Landers. In addition, technologies developed could benefit other NASA missions including Gateway. The power levels may be different, but the technology concepts could be similar, especially when dealing with temperature extremes.

Z1.06: Radiation Tolerant High-Voltage, High-Power Electronics (SBIR)

Lead Center: GSFC

Participating Center(s): GRC, JPL, LaRC

Technology Area: 3.0.0 Space Power and Energy Storage

Related Subtopic Pointer(s): S4.04 Z1.05

Scope Description

NASA's directives for space exploration and habitation require high-performance, high-voltage transistors and diodes capable of operating without damage in the natural space radiation environment. Recently, significant progress has been made in the research community in understanding the mechanisms of heavy-ion radiation induced damage and catastrophic failure of wide bandgap power transistors and diodes. This subtopic seeks to facilitate movement of this understanding into the successful development of radiation-hardened high voltage transistors and rectifiers to meet NASA mission power needs reliably in the space environment. These needs include:

- High-voltage, high-power solutions: Technology Area (TA) 3.3.3, Power Management and Distribution (PMAD) Distribution and Transmission calls out the need for development of radiation-hardened, high-voltage, extreme- temperature components for power distribution systems. NASA has a core need for diodes and transistors that meet the following specifications:
    - Diodes: minimum 1200 V, 40 A, with fast recovery < 50 ns;
    - Transistors: minimum 600 V, 40 A, with < 24 mohm on-state drain-source resistance.
- High-voltage, low-power solutions: In support of TA 8.1 (Remote Sensing Instruments and Sensors), radiation-hardened, high-voltage transistors are needed for low-mass, low-leakage, high-efficiency applications such as LIDAR Q-switch drivers, mass spectrometers, and electrostatic analyzers. High-

voltage, fast-recovery diodes are needed to enhance performance of a variety of heliophysics and planetary science instruments.

- Transistors: minimum 1000 V, < 40 ns rise and fall times;
- Diodes: 2 kV to 5 kV, < 50 ns recovery time.

- High-voltage, low- to medium-power solutions: In support of peak-power solar tracking systems for planetary spacecraft and small satellites, transistors and diodes are needed to increase buck converter efficiencies through faster switching speeds.
  - Transistors: minimum 600 V, < 50 ns rise and fall times, current ranging from low to > 20 A.

Successful proposal concepts should result in the fabrication of transistors and/or diodes that meet or exceed the above performance specifications without susceptibility to damage due to the heavy-ion space radiation environment (single-event effects resulting in permanent degradation or catastrophic failure). These diodes and/or transistors will form the basis of innovative, high-efficiency, low mass and volume systems and therefore must significantly improve upon the electrical performance available from existing heavy-ion radiation-tolerant devices. Proposals must state the initial state of the art for the proposed technology and justify the expected final performance metrics. Well-developed plans for validating the tolerance to heavy-ion radiation must be included, and the expected total ionizing dose tolerance should be indicated and justified. Target radiation performance levels will depend upon the device structure due to the interaction of the high electric field with the ionizing particle:

- For vertical-field power devices: No heavy-ion induced permanent destructive effects upon irradiation while in blocking configuration (in powered reverse-bias/off state) with ions having a silicon-equivalent surface incident Linear Energy Transfer (LET) of 40 MeV-cm^2/mg and sufficient energy maintain a rising LET level throughout the epitaxial layer(s).
- For all other devices: No heavy-ion induced permanent destructive effects upon irradiation while in blocking configuration (in powered reverse-bias/off state) with ions having a silicon-equivalent surface-incident Linear Energy Transfer (LET) of 75 MeV-cm^2/mg and sufficient energy to fully penetrate the active volume prior to the ions reaching their maximum LET value (Bragg peak).

Other innovative heavy-ion radiation-tolerant high-power, high-voltage discrete device technologies will be considered that offer significant electrical performance improvement over state-of-the art heavy-ion radiation-tolerant power devices.

References

The following is only a partial listing of relevant references:

1. S. Kuboyama*, et al.*, "Thermal Runaway in SiC Schottky Barrier Diodes Caused by Heavy Ions," *IEEE Transactions on Nuclear Science,* vol. 66, pp. 1688-1693, 2019.
2. D. R. Ball, *et al.*, “Ion-Induced Energy Pulse Mechanism for Single-Event Burnout in High-Voltage SiC Power MOSFETs and Junction Barrier Schottky Diodes,” IEEE Nuclear and Space Radiation Effects Conference, San Antonio, TX, July 2019.
3. J. McPherson, *et al.*, "Mechanisms of Heavy Ion Induced Single Event Burnout in 4H-SiC Power MOSFETs," International Conference on Silicon Carbide and Related Materials (ICSCRM), Kyoto, Japan, to be presented, September, 2019.
4. C. Abbate*, et al.*, "Gate Damages Induced in SiC Power MOSFETs during Heavy-Ion Irradiation--Part I," *IEEE Transactions on Electron Devices,* to be published, 2019. [see also Part II]

5. J.-M. Lauenstein, “Getting SiC Power Devices Off the Ground: Design, Testing, and Overcoming Radiation Threats,” Microelectronics Reliability and Qualification Working (MRQW) Meeting, El Segundo, CA, February 2018. https://ntrs.nasa.gov/search.jsp?R=20180006113
6. E. Mizuta*, et al.*, "Single-Event Damage Observed in GaN-on-Si HEMTs for Power Control Applications," *IEEE Transactions on Nuclear Science,* vol. 65, pp. 1956-1963, 2018.
7. M. Zerarka*, et al.*, "TCAD Simulation of the Single Event Effects in Normally-OFF GaN Transistors after Heavy Ion Radiation," *IEEE Transactions on Nuclear Science,* vol. 64, pp. 2242-2249, 2017.
8. J. Kim*, et al.*, "Radiation damage effects in Ga_2O_3 materials and devices," *Journal of Materials Chemistry C,* vol. 7, pp. 10-24, 2019.
9. S. J. Pearton*, et al.*, "Perspective: Ga_2O_3 for ultra-high power rectifiers and MOSFETS," *Journal of Applied Physics,* vol. 124, p. 220901, 2018.

Expected TRL or TRL range at completion of the project: 5 to 6

Desired Deliverables of Phase II

Prototype, Analysis, Hardware

Desired Deliverables Description

Deliverables in Phase II shall include prototype and/or production-ready semiconductor devices (diodes and/or transistors), device electrical and radiation performance characterization (device electrical performance specifications and heavy-ion radiation test results and total dose radiation analyses).

State of the Art and Critical Gaps

A prior version of this subtopic, "High-Power, High-Voltage Electronics" was active in 2016-2017 and paused for two years to give time for funded proposals and a similar Early Stage Innovation topic designed to understand the radiation-induced failure mechanisms in wide bandgap semiconductors to mature. This pause has allowed these studies to mature and it is now time to re-open this subtopic to provide a means for applying the knowledge gained toward fabrication of radiation hardened power devices that are tailored to meet performance criteria of a number of NASA technology needs.

High voltage silicon power devices are limited in current ratings and have limited power efficiency and higher losses than do commercial Wide Bandgap (WBG) power devices. Efforts to space-qualify WBG power devices to take advantage of their tremendous performance advantages revealed they are very susceptible to damage from the heavy ion space radiation environment (galactic cosmic rays) that cannot be shielded against. Higher voltage devices are more susceptible to these effects; as a result, to date, there are space qualified GaN (Gallium Nitride) transistors now available but these are limited to 300 V. Recent radiation testing of 600 V and higher GaN transistors have shown failure susceptibility at about 50% of the rated voltage, or less. Silicon carbide power devices have undergone several generation advances commercially, improving their overall reliability, but catastrophically fail at less than 50% of their rated voltage. NASA has funded modeling and experimental efforts to understand the silicon carbide's susceptibility to heavy-ion radiation. Re-opening of this topic will provide a path for development and fabrication of hardened designs based upon this research, and encourage progress in other wide bandgap technologies such as higher voltage GaN, gallium oxide, and possibly diamond.

Specific needs in STMD (Space Technology Mission Directorate) and SMD (Science Mission Directorate) areas have been identified for spacecraft PMAD and science instrument power applications and device performance requirements to meet these needs are included in this subtopic nomination. In all cases, there is no alternative solution that can provide the mass and power savings sought to enable game-changing capability. Current PPUs (Power Processing Unit's) and instrument power systems rely on older silicon technology with many stacked devices and efficiency penalties. In NASA's move to do more with less (smaller satellites), the technology of this subtopic nomination is truly enabling.

A phase I funded SBIR under the S4.04 Extreme Environments Technology, was awarded (https://sbir.nasa.gov/SBIR/abstracts/19/sbir/phase1/SBIR-19-1-S4.04-3611.html) in 2019 to develop low-defect gallium oxide (Ga_2O_3) based high-voltage power diodes grown on commercially available bulk Ga_2O_3 substrates via a thin-film deposition technique. The S4.04 Subtopic Manager serves as a participating subtopic manager on this Z1 subtopic to foster good leveraging and to avoid duplication of efforts. The S4.04 subtopic solicits development of technology for extreme temperatures and high total ionizing dose radiation primarily.

Other non-NASA funded efforts include:

Vertical GaN diode development has been a focus of ARPA-E PNDIODE and (previous) SWITCHES programs. Diodes developed under the SWITCHES program were shown by Sandia National Lab to have good switching reliability, but another Italian team has found they may degrade under high current stress. Heavy-ion radiation susceptibility has not been assessed and is not expected to be robust without design alteration.

DoD (Department of Defense) has two funded Ga_2O_3 technology SBIRs that focus on development of manufacturing capabilities as opposed to device design itself.

Relevance / Science Traceability

Power transistors and diodes form the building blocks of numerous power circuits for spacecraft and science instrument applications. This subtopic therefore feeds a broad array of space technology hardware development activities by providing single-event effect (heavy ion) radiation-hardened state-of-the-art device technologies that achieve higher voltages with lower power consumption and greater efficiency than presently available.

TA 3.3.3, Power Management and Distribution (PMAD) Distribution and Transmission calls out the need for development of radiation-hardened, high-voltage, extreme-temperature components for power distribution systems. This subtopic will serve as a feeder to the subtopic Z1.05 - Lunar & Planetary Surface Power Management & Distribution" in which wide bandgap circuits for PMAD applications are solicited. The solicited developments in this subtopic will also feed systems development for Kilopower due to the savings in size/mass combined with radiation hardness. In addition, power distribution for lunar and Martian habitats will benefit from power circuits adopting this subtopic through significantly improved power efficiencies and radiation hardness.

TA 8.1, Remote Sensing Instruments and Sensors, radiation-hardened, high-voltage transistors are needed for low-mass, low-leakage, high-efficiency applications such as LIDAR Q-switch drivers, mass spectrometers, and electrostatic analyzers. These applications are aligned with science objectives including Earth Science LIDAR needs, Jovian moon exploration, and Saturn missions. Finally, mass spectrometers critical to planetary and asteroid research and in the search for life on other planets such as Mars require high voltage power systems and will thus benefit from mass and power savings from this subtopic's innovations.

Focus Area 3: Autonomous Systems for Space Exploration

Lead MD: HEOMD

Participating MD(s): SMD, STTR

The exploration of space requires the best of the nation's technical community to provide the technologies that will enable human and robotic exploration beyond Low Earth Orbit (LEO): to establish a lunar presence, to visit asteroids, to extend human reach to Mars, and for increasingly ambitious robotic missions such as a Europa Lander. Autonomous Systems technologies provide the means of migrating mission control from Earth to spacecraft, habitats, and robotic explorers. This is enhancing for missions in the Earth-Lunar neighborhood and enabling for deep space missions. Long light-time delays, for example up to 42 minutes round-trip between Earth and Mars, require time-critical control decisions to be closed on-board autonomously, rather than through round-trip communication to Earth mission control. For robotic explorers this will be done through automation, while for human missions this will be done through astronaut-automation teaming.

Long-term crewed spacecraft and habitats, such as the International Space Station, are so complex that a significant portion of the crew's time is spent keeping it operational even under nominal conditions in low-Earth orbit, while still requiring significant real-time support from Earth. The considerable challenge is to migrate the knowledge and capability embedded in current Earth mission control, with tens to hundreds of human specialists ready to provide instant knowledge, to on-board automation that teams with astronauts to autonomously manage spacecraft and habitats. For outer planet robotic explorers, the opportunity is to autonomously and rapidly respond to dynamic environments in a timely fashion.

The “Deep Neural Network Accelerator and Neuromorphic Computing” subtopic addresses extrapolating new terrestrial computing paradigms related to machine learning to the space environment. For machine inferencing and learning computing hardware proposals, metrics related to energy expenditure per operation (e.g., multiply-add) and throughput acceleration in a space environment are especially relevant.

The subtopic on swarms of space vehicles addresses technologies for control and coordination of planetary rovers, flyers, and in-space vehicles in dynamic environments. Co-ordinated swarms can provide a more robust and sensor-rich approach to space missions, allowing simultaneous recording of sensor data from dispersed vehicles and co-ordination especially in challenging environments such as cave exploration.

Fault management is an integral part of space missions. The fault management subtopic spans the lifecycle of fault management for space missions from design through verification and validation to operations. In the past, the predominant operational approach to detected faults has been to safe the spacecraft, and then rely on Earth mission control to determine how to proceed. New mission concepts require future spacecraft to autonomously decide how to recover from detected anomalies and continue the mission. The fault management subtopic solicits proposals that advance fault management technology across architectures, design tools, verification and validation, and operations.

The “Artificial Intelligence for the Lunar Orbital Platform-Gateway” subtopic solicits autonomy, artificial intelligence and machine learning technologies to manage and operate engineered systems to facilitate long-duration space missions, with the goal of testing proposed technologies on Gateway. The Gateway is a planned lunar-orbit spacecraft that will have a power and propulsion system, a small habitat for the crew, a docking capability, an airlock and logistics modules. The Gateway is expected to serve as an intermediate way station between the Orion crew capsule and lunar landers as well as a platform for both crewed and un-crewed experiments. The Gateway is also intended to test technologies and operational procedures for suitability on long-duration space missions such as a mission to Mars.

The “Coordination and Control of Swarms of Space Vehicles” subtopic addresses technologies for control and coordination of planetary rovers, flyers, and in-space vehicles in dynamic environments. Coordinated swarms can provide a more robust and sensor-rich approach to space missions, allowing simultaneous recording of sensor data from dispersed vehicles and co-ordination especially in challenging environments such as cave exploration.

H6.22: Deep Neural Net and Neuromorphic Processors for In-Space Autonomy and Cognition (SBIR)

Lead Center: GRC

Participating Center(s): ARC

Technology Area: 11.0.0 Modeling, Simulation, Information Technology and Processing

Related Subtopic Pointer(s): S5.03 S3.08 H9.05 Z2.02 Z8.10 H9.07 T5.04

Scope Title

Neuromorphic Capabilities

Scope Description

The Neuromorphic Processors for In-Space Autonomy and Cognition subtopic specifically focuses on advances in signal and data processing. Neuromorphic processing will enable NASA to meet growing demands for applying artificial intelligence and machine learning algorithms on-board a spacecraft to optimize and automate operations. This includes enabling cognitive systems to improve mission communication and data processing capabilities, enhance computing performance, and reduce memory requirements. Neuromorphic processors can enable a spacecraft to sense, adapt, act and learn from its experiences and from the unknown environment without necessitating involvement from a mission operations team. Additionally, this processing architecture shows promise for addressing the power requirements that traditional computing architectures now struggle to meet in space applications.

The goal of this program is to develop neuromorphic processing software, hardware, algorithms, architectures, simulators and techniques as enabling capability for autonomous space operations. Emerging memristor and other radiation-tolerant devices, which shows potential for addressing the need for energy efficient neuromorphic processors and improved signal processing capability, is of particular interest due to its resistance to the effects of radiation.

Additional areas of interest for research and/or technology development include: a) spiking algorithms that learn from the environment and improve operations, b) neuromorphic processing approaches to enhance data processing, computing performance, and memory conservation, and c) new brain-inspired chips and breakthroughs in machine understanding/intelligence. Novel memristor approaches which show promise for space applications are also sought.

This subtopic seeks innovations focusing on low size, weight and power (SWaP) applications suitable lunar orbital or surface operations, enabling efficient on-board processing at lunar distances. Focusing on SWaP-constrained platforms opens up the potential for applying neuromorphic processors in spacecraft or robotic control situations traditionally reserved for power-hungry general purpose processors. This technology will allow for increased speed, energy efficiency and higher performance for computing in unknown and un-characterized space environments including the Moon and Mars.

Phase I will emphasize research aspects for technical feasibility and show a path toward a Phase II proposal. Phase I deliverables include concept of operations of the research topic, simulations and preliminary results. Early development and delivery of prototype hardware/software is encouraged.

Phase II will emphasize hardware and/or software development with delivery of specific hardware and/or software products for NASA, targeting demonstration operations on a low-SWaP platform. Phase II deliverables include a working prototype of the proposed product and/or software, along with documentation and tools necessary for NASA to use the product and/or modify and use the software. In order to enable mission deployment, proposed prototypes should include a path, preferably demonstrated, for fault tolerance and mission tolerance.

References

Several reference papers that have been published at the Cognitive Communications for Aerospace Applications (CCAA) workshop are available at: http://ieee-ccaa.com.

Expected TRL or TRL range at completion of the project 4 to 6

Desired Deliverables of Phase II

Prototype, Hardware, Software

Desired Deliverables Description

Phase 2 deliverables should include hardware/software necessary to show how the advances made in the development can be applied to a cubesat, small sat, and rover flight demonstration.

State of the Art and Critical Gaps

The current State-of-the-Art (SOA) for in-space processing is the High Performance Spaceflight Computing (HPSC) processor being developed by Boeing for NASA GSFC. The HPSC, called the Chiplet, contains 8 general purpose processing cores in a dual quad-core configuration. Delivery is expected by December 2022. In a submission to the STMD Game Changing Development (GCD) program, the highest computational capability required by a typical space mission is 35-70 GFLOPS (million fast logical operations per second).

The current SOA does not address the capabilities required for artificial intelligence and machine-learning applications in the space environment. These applications require significant amounts of multiply and accumulate operations, in addition to a substantial amount of memory to store data and retain intermediate states in a neural network computation. Terrestrially, these operations require General-Purpose Graphics Processing Units (GP-GPUs), which are capable of teraflops (TFLOPS) each -- approximately 3 orders of magnitude above the anticipated capabilities of the HPSC.

Neuromorphic processing offers the potential to bridge this gap through a novel hardware approach. Existing research in the area shows neuromorphic processors to be up to 1000 times more energy efficient than GP-GPUs in artificial intelligence applications. Obviously the true performance depends on the application, but nevertheless the architecture has demonstrated characteristics that make it well-adapted to the space environment.

Relevance / Science Traceability

The Cognitive Communications Project, through the Human Exploration and Operations Mission Directorate (HEOMD) Space Communications and Navigation (SCaN) Program, is one potential customer of work from this subtopic area. Neuromorphic processors are a key enabler to the cognitive radio and system architecture envisioned by this project. As communications become more complex, cognition and automation will play a larger role to mitigate complexity and reduce operations costs. Machine learning will choose radio configurations, adjust for impairments and failures. Neuromorphic processors will address the power requirements that traditional computing architectures now struggle to meet and are of relevance to lunar return and Mars for autonomous operations, as well as of interest to HEOMD and SMD for in-situ avionics capabilities.

S5.05: Fault Management Technologies (SBIR)

Lead Center: JPL

Participating Center(s): ARC, MSFC

Technology Area: 4.0.0 Robotics, Telerobotics and Autonomous Systems

Related Subtopic Pointer(s): H6.04 S5.04 H10.02 Z2.02 T4.04 T13.01 Z8.10 T11.03

Scope Title

Development, Design, and Implementation of Fault Management Technologies

Scope Description

NASA's science program has well over 100 spacecraft in operation, formulation, or development, generating science data accessible to researchers everywhere. As science missions have increasingly complex goals, often on compressed timetables, and have more pressure to reduce operations costs, system autonomy must increase in response.

Fault Management (FM) is a key component of system autonomy, serving to detect, interpret, and mitigate failures that threaten mission success. Robust FM must address the full range of hardware failures, but also must consider failure of sensors or the flow of sensor data, harmful or unexpected system interaction with the environment, and problems due to faults in software or incorrect control inputs -- including failure of autonomy components themselves.

Despite a wealth of lessons learned from past missions, spacecraft failures are still not uncommon and reuse of FM approaches is very limited, illustrating deficiencies our approach to handling faults in all phases of the flight project lifecycle. While this subtopic addresses particular interest in on-board Fault Management capabilities (viz. on-board sensing approaches, computing, algorithms, and models to assess and maintain spacecraft health), the goal is to provide a *system capability*, and thus off-board components such as modeling techniques and tools, development environments, testbeds, and verification and validation (V&V) technologies are also relevant. Specific algorithms and sensor technologies are in scope provided their impact is not limited to a particular subsystem, mission goal, or failure mechanism.

Innovations in Fault Management can be grouped into the categories below.

- Fault Management Design Tools: System modeling and analysis significantly contributes to the quality of FM design, and may prove decisive in trades of new vs. traditional FM approaches. However, the difficulty in translating system design information into system models often impacts modeling and analysis accuracy. Examples of enabling techniques and tools are automated modeling systems, spacecraft modeling libraries, algorithm prototyping and test environments, sensor placement analyses, and system modeling that supports multiple autonomy functions including FM. System design should enable multi-disciplinary assessment of FM approaches, addressing performance metrics, standardization of data products and models, and analyses to reduce design costs and design escapes.
- Fault Management Visualization Tools: FM systems have impacts on hardware, software, and operations. The ability to visualize the full FM system behavior and the contribution of each component to protecting mission functions and assets is critical to assessing completeness of the approach, and to evaluate appropriateness of the FM design against mission needs. Fault trees and state transition diagrams are simple visualization products. Other examples of visualization could focus on margin management, probabilistic risk assessment, or FM impacts on scenario timelines.
- Fault Management Operations Approaches: This category encompasses FM "in the loop," including algorithms, computing, state estimation / classification, machine learning, and model-based reasoning. Advanced FM approaches may reduce the need for spacecraft safing and reliance on mission operations through more accurate health assessment, early detection of problems, more effective discrimination and understanding of root causes, or automated recovery. Particularly desirable are technologies and approaches that enable new mission concepts with greater autonomy, minimizing or eliminating spacecraft safing in response to faults – for example, riding out failures gracefully, or autonomously recovering and restarting system behavior to complete science objectives that require timely execution. Future spacecraft must be able to make decisions about how to recover from failures or degraded capacity and continue the mission, and also to work cooperatively with mission operations to replan mission goals apace with changes in system capability.
- Fault Management Verification and Validation Tools: Along with difficulties in system engineering, the challenge of V&V'ing implementations of new FM technologies has been a significant barrier to infusion in flight projects. As complexity of spacecraft and systems increases, the testing required to verify and validate FM implementations can become prohibitively resource intensive without new approaches. Automated test case development, false positive/false negative test tools, model

verification and validation tools, and test coverage risk assessments are examples of contributing technologies.

- Fault Management Design Architectures: FM capabilities may be implemented through numerous system, hardware, and software architecture solutions. The FM architecture trade space includes options such as embedding within the flight control software or deployment as independent onboard software; on-board versus ground-based capabilities; centralized or distributed FM functions; sensor suite implications; integration of multiple FM techniques; innovative software FM architectures implemented on flight processors or on Field Programmable Gate Arrays (FPGAs); and execution in real-time or off-line analysis post-operations. Alternative architecture choices such as model-based approaches could help control FM system complexity and cost and could offer solutions to transparency, verifiability, and completeness challenges.

Expected outcomes and objectives of this subtopic are to mature the practice of Fault Management, leading to better estimation and control of FM complexity and development costs, more flexible and effective FM designs, and accelerated infusion into future missions through advanced tools and techniques. Specific objectives include the following:

- Improve predictability of FM system complexity and estimates of development and operations costs
- Enable cost-effective FM design architectures and operations
- Determine completeness and appropriateness of FM designs and implementations
- Decrease the labor and time required to develop and test FM models and algorithms
- Improve visualization of the full FM design across hardware, software, and operations procedures
- Determine extent of testing required, completeness of verification planned, and residual risk resulting from incomplete coverage
- Increase data integrity between multi-discipline tools
- Standardize metrics and calculations across FM, SE, S&MA and operations disciplines
- Increase reliability of FM systems
- *Overall, bound and improve costs and implementation risks of FM while improving capability, such that benefits demonstrably outweigh the risks, leading to mission infusion*

References

NASA's approach to Fault Management and the various needs are summarized in the NASA FM Handbook (https://www.nasa.gov/pdf/636372main_NASA-HDBK-1002_Draft.pdf). Additional information is included in the talks presented at the 2012 FM Workshop (https://www.nasa.gov/offices/oce/documents/2012_fm_workshop.html, particularly https://www.nasa.gov/pdf/637595main_day_1-brian_muirhead.pdf)

Another resource is the NASA Technical Memorandum "Introduction to System Health Engineering and Management for Aerospace (ISHEM)" (https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20060003929.pdf). This is greatly expanded on in the following publication: Johnson, S. (ed), System Health Management with Aerospace Applications, Wiley, 2011 (https://www.wiley.com/en-us/System+Health+Management%3A+with+Aerospace+Applications-p-9781119998730)

Fault Management Technologies are strongly associated with autonomous systems as a key component of situational awareness and system resilience. A useful overview was presented at the 2018 Science Mission

Directorate (SMD) Autonomy Workshop (https://science.nasa.gov/technology/2018-autonomy-workshop), archiving a number of talks on mission challenges and design concepts.

Expected TRL or TRL range at completion of the project: 3 to 4

Desired Deliverables of Phase II

Prototype, Analysis, Software

Desired Deliverables Description

The aim of the Phase I project should be to demonstrate the technical feasibility of the proposed innovation and thereby bring the innovation closer to commercialization. Note, however, the R&D undertaken in Phase I is intended to have high technical risk, and so it is expected that not all projects will achieve the desired technical outcomes.

The required deliverable at the end of an SBIR Phase I contract is a report that summarizes the project's technical accomplishments. As noted above, it is intended that proposed efforts conduct an initial proof of concept, after which successful efforts would be considered for follow-on funding by SMD missions as risk-reduction and infusion activities. Research should be conducted to demonstrate technical feasibility and NASA relevance during Phase I and show a path toward a Phase II prototype demonstration.

The Final Report should thoroughly document the innovation, its status at the end of the effort, and as much objective evaluation of its strengths and weaknesses as is practical. The report should include a description of the approach, foundational concepts and operating theory, mathematical basis, and requirements for application. Results should include strengths and weaknesses found, measured performance in tests where possible.

Additional deliverables may significantly clarify the value and feasibility of the innovation. These deliverables should be planned to demonstrate retirement of development risk, increasing maturity, and targeted applications of particular interest. While the wide range of innovations precludes a specific list, some possible deliverables are listed below:

- For innovations that are algorithmic in nature, this could include development code or prototype applications, demonstrations of capability, and results of algorithm stress-testing.
- For innovations that are procedural in nature, this may include sample artifacts such as workflows, model prototypes and schema, functional diagrams, examples, or tutorial applications.
- Where a suitable test problem can be found, documentation of the test problem and a report on test results, illustrating the nature of the innovation in a quantifiable and reproducible way. Test reports should discuss maturation of the technology, implementation difficulties encountered and overcome, and results and interpretation.

State of the Art and Critical Gaps

Many recent Science Mission Directorate (SMD) missions have encountered major cost overruns and schedule slips due to difficulty in implementing, testing, and verifying FM functions. These overruns are invariably caused by a lack of understanding of FM functions at early stages in mission development, and by FM architectures that are not sufficiently transparent, verifiable, or flexible enough to provide needed isolation capability or coverage. In addition, a substantial fraction of SMD missions continue to experience failures with significant mission impact, highlighting the need for better FM understanding early in the design cycle, more comprehensive and more accurate FM techniques, and more operational flexibility in response to failures provided by better visibility into failures and system performance. Furthermore, SMD increasingly selects missions with significant operations challenges, setting expectations for FM to evolve into more capable, faster-reacting, and more reliable on-board systems.

The SBIR program is an appropriate venue due to the following factors:

- Traditional FM design has plateaued, and new technology is needed to address emerging challenges. There is a clear need for collaboration and incorporation of research from outside the spaceflight community, as fielded FM technology is well behind the state of the art and failing to keep pace with desired performance and capability.
- The need for new FM approaches spans a wide range of missions, from improving operations for relatively simple orbiters to enabling entirely new concepts in challenging environments. Development of new FM technologies by SMD missions themselves is likely to produce point solutions with little opportunity for reuse and will be inefficient at best compared to a focused, disciplined research effort external to missions.
- SBIR level of effort is appropriately sized to perform intensive studies of new algorithms, new approaches, and new tools. The approach of this subtopic is to seek the right balance between sufficient reliability and cost appropriate to each mission type and associated risk posture. This is best achieved with small and targeted investigations, enabled by captured data and lessons learned from past or current missions, or through examination of knowledge capture and models of missions in formulation. Following this initial proof of concept, successful technology development efforts under this subtopic would be considered for follow-on funding by SMD missions as risk-reduction and infusion activities. Research should be conducted to demonstrate technical feasibility and NASA relevance during Phase I and show a path toward a Phase II prototype demonstration.

Relevance / Science Traceability

FM technologies are applicable to all SMD missions, albeit with different emphases. Medium to large missions have very low tolerance for risk of mission failure, leading to a need for sophisticated and comprehensive fault management. Small missions, on the other hand, have a higher tolerance for risks to mission success but must be highly efficient, and are increasingly adopting autonomy and FM as a risk mitigation strategy.

A few examples are provided below, although these may be generalized to a broad class of missions:

Lunar Flashlight: Enable very low-cost operations and high science return from a 6U cubesat through on-board error detection and mitigation, streamlining mission operations. Provide autonomous resilience to on-board errors and disturbances that interrupt or interfere with science observations.

Europa Clipper: Provide on-board capability to detect and correct radiation-induced execution errors. Provide reliable reasoning capability to restart observations after interruptions without requiring ground in-the-loop. Provide MBSE tools to model and analyze FM capabilities in support of design trades, V&V of FM capabilities, and coordinated development with flight software.

Rovers and Rotorcraft (Mars Sample Return, Dragonfly): Provide on-board capability for systems checkout, enabling lengthy drives/flights between Earth contacts and mobility after environmentally-induced anomalies (e.g., unexpected terrain interaction). Improve reliability of complex activities (e.g., navigation to features, drilling and sample capture, capsule pickup and remote launch).

Search for Extrasolar Planets (Observation): Provide sufficient system reliability through on-board detection, reasoning, and response to enable long-period, stable observations. Provide on-board or on-ground analysis capabilities to predict system response and optimize observation schedule. Enable reliable operations while out of direct contact (e.g., deliberately occluded from Earth to reduce photon, thermal, and radio frequency background).

T4.03: Coordination and Control of Swarms of Space Vehicles (STTR)

Lead Center: JPL

Participating Center(s): LaRC

Technology Area: 4.0.0 Robotics, Telerobotics and Autonomous Systems

Related Subtopic Pointer(s): Z8.02 S4.02

Scope Title

Enabling Technologies for Swarm of Space Vehicles

Scope Description

This subtopic is focused on developing and demonstrating technologies that enable cooperative operation of swarms of space vehicles in a dynamic environment. Primary interest is in technologies appropriate for low-cardinality (4-15 vehicle) swarms of small spacecraft, as well as planetary rovers and flyers (e.g., Mars helicopter). Large swarms and other platforms are of interest if well motivated in connection to NASA's strategic plan and needs identified in decadal surveys.

The proposed technology should be motivated by a well-defined design reference mission presented in the proposal.

Possible areas of interest include but are not limited to:

- High precision relative localization and time synchronization in orbit and on planet surface.
- Coordinated task planning, operation, and execution with realistic communication limitations.
- Fast, real-time, coordinated motion planning in areas densely crowded by other agents and obstacles.
- Operations concepts and tools that provide situational awareness and commanding capability for a team of spacecraft or swarm of robots on another planet.
- Communication-less coordination by observing and estimating the actions of other agents in the multi-agent system.
- Cooperative manipulation and in-space construction
- Cooperative information gathering and estimation for exploration and inspection of a target object (large space structure or small asteroid).

Phase I awards will be expected to develop theoretical frameworks, algorithms, software simulation and demonstrate feasibility (TRL 2-3). Phase II awards will be expected to demonstrate capability on a hardware testbed (TRL 4-6).

NASA has plans to purchase services for delivery of payloads to the Moon through the Commercial Lunar Payload Services (CLPS) contract. Under this subtopic, proposals may include efforts to develop payloads for flight demonstration of relevant technologies in the lunar environment. The CLPS payload accommodations will vary depending on the particular service provider and mission characteristics. Additional information on the CLPS program and providers can be found at this link: https://www.nasa.gov/content/commercial-lunar-payload-services. CLPS missions will typically carry multiple payloads for multiple customers. Smaller, simpler, and more self-sufficient payloads are more easily accommodated and would be more likely to be considered for a NASA-sponsored flight opportunity. Commercial payload delivery services may begin as early as 2020 and flight opportunities are expected to continue well into the future. In future years it is expected that larger and more complex payloads will be accommodated. Selection for award under this solicitation will not guarantee selection for a lunar flight opportunity.

References

[1] D. P. Scharf, F. Y. Hadaegh and S. R. Ploen, "A survey of spacecraft formation flying guidance and control (part 1): guidance," Proceedings of the 2003 American Control Conference, 2003. Denver, CO, USA, 2003, pp. 1733-1739.

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[3] Evan Ackerman, "PUFFER: JPL's Pop-Up Exploring Robot; This little robot can go where other robots fear to roll,“ https://spectrum.ieee.org/automaton/robotics/space-robots/puffer-jpl-popup-exploring-robot

[4] "Precision Formation Flying,” https://scienceandtechnology.jpl.nasa.gov/precision-formation-flying

[5] "Mars Helicopter to Fly on NASA’s Next Red Planet Rover Mission," https://www.nasa.gov/press-release/mars-helicopter-to-fly-on-nasa-s-next-red-planet-rover-mission/

[6] Miller, Duncan, Alvar Saenz-Otero, J. Wertz, Alan Chen, George Berkowski, Charles F. Brodel, S. Carlson, Dana Carpenter, S. Chen, Shiliang Cheng, David Feller, Spence Jackson, B. Pitts, Francisco Pérez, J. Szuminski and S. Sell. "SPHERES: A Testbed for Long Duration Satellite Formation Flying In MicroGravity Conditions." Proceedings of the AAS/AIAA Space Flight Mechanics Meeting, AAS 00-110, Clearwater, FL, Jan. 2000.

[7] S. Bandyopadhyay, R. Foust, G. P. Subramanian, S.-J. Chung, and F. Y. Hadaegh, "Review of Formation Flying and Constellation Missions Using Nanosatellites," Journal of Spacecraft and Rockets, vol. 53, no. 3, 2016, pp. 567-578.

[8] S. Kidder, J. Kankiewicz, and T. Vonder Haar. "The A-Train: How Formation Flying is Transforming Remote Sensing," https://atrain.nasa.gov/publications.php

[9] T. Huntsberger, A. Trebi-Ollennu, H. Aghazarian, P. Schenker, P. Pirjanian, and H. Nayar. "Distributed Control of Multi-Robot Systems Engaged in Tightly Coupled Tasks," Autonomous Robots 17, 79–92, 2004.

[10] Space Studies Board, "Achieving Science with CubeSats: Thinking Inside the Box," National Academies of Sciences, Engineering, and Medicine, 2016. http://sites.nationalacademies.org/SSB/CompletedProjects/SSB_160539

Expected TRL or TRL range at completion of the project: 3 to 6

Desired Deliverables of Phase II

Prototype, Software, Hardware, Research

Desired Deliverables Description

- Algorithms and research results clearly depicting metrics and performance of the developed technology in comparison to state of the art (SOA).
- Software implementation of the developed solution along with simulation platform.
- Prototype of the sensor or similar if proposal is to develop such subsystem.

State of the Art and Critical Gaps

Technologies developed under this subtopic enable and are critical for multi-robot missions (rovers and flying vehicles such as Mars helicopter) for collaborative planetary exploration, e.g., a team of small pop-up rovers (PUFFERS) that can collaboratively create a mesh network and explore high risk and hard to reach areas such as lava tubes, etc.

These technologies also enable successful formation flying spacecraft for multi-spacecraft synthetic aperture radar and interferometry (distributed space telescope) purposes, a team of smallsats forming a convoy which the lead triggers detailed measurements on the following spacecraft of a phenomena identified by the lead, or a team of smallsats collaboratively manipulating a defunct spacecraft or small asteroid.

Relevance / Science Traceability

Subtopic technology directly supports NASA Space Technology Roadmap TA4 (4.5.4 Multi-Agent Coordination, 4.2.7 Collaborative Mobility, 4.3.5 Collaborative Manipulation) and Strategic Space Technology Investment Plan (Robotic and Autonomous Systems: Relative GNC and Supervisory control of an S/C team), and is relevant to the following concepts:

- Multi-robot follow-on to the Mars 2020 and Mars Helicopter programs are likely to necessitate close collaboration among flying robots as advance scouts and rovers.
- Pop-Up Flat-Folding Explorer Robots (PUFFERs) are being developed at Jet Propulsion Laboratory (JPL) and promise a low-cost swarm of networked robots that can collaboratively explore lava-tubes and other hard to reach areas on planet surfaces.
- A convoy of spacecraft is being considered, in which the lead spacecraft triggers detailed measurement of a very dynamic event by the following spacecraft.
- Multiple concepts for distributed space telescopes and distributed synthetic apertures are proposed that rely heavily on coordination and control technologies developed under this subtopic.

T4.04: Autonomous Systems and Operations for the Lunar Orbital Platform-Gateway (STTR)

Lead Center: ARC

Participating Center(s): JSC, KSC, SSC

Technology Area: 11.0.0 Modeling, Simulation, Information Technology and Processing

Related Subtopic Pointer(s): S5.03 S5.05 T11.04 T4.01 Z5.04

Scope Title

Artificial Intelligence for the Lunar Orbital Platform-Gateway

Scope Description

The Gateway is a planned lunar-orbit spacecraft that will have a power and propulsion system, a small habitat for the crew, a docking capability, an airlock and logistics modules. The Gateway is expected to serve as an intermediate way station between the Orion crew capsule and lunar landers as well as a platform for both crewed and un-crewed experiments. The Gateway is also intended to test technologies and operational procedures for suitability on long-duration space missions such as a mission to Mars. As such, it will require new technologies such as autonomous systems to run scientific experiments onboard, including biological experiments; perform system health management, including caution and warning; autonomous data management and other functions. In contrast to the International Space Station, Gateway is much more representative of lunar and deep-space missions---for example, the radiation environment.

This subtopic solicits autonomy, artificial intelligence and machine learning technologies to manage and operate engineered systems to facilitate long-duration space missions, with the goal of testing proposed technologies on Gateway. The current concept of operations for Gateway anticipates un-crewed (dormant) periods of up to nine months. Technologies need to be capable of or enable long-term, mostly unsupervised, autonomous operation. While crew are present, technologies need to augment the crew's abilities and allow more autonomy from Earth-based Mission Control. Additionally, the technologies may need to allow for coordination with the Orion crew capsule, lunar landers, Earth and their various systems and subsystems.

Examples of needs include but are not limited to:

1. Autonomous operations and tending of science payloads including environmental monitoring and support for live biological samples, and in-situ automated analysis of science experiments.
2. Prioritizing data for transmission from the Gateway. Given communications limitations, it may be necessary to determine what data can be stored for transmission when greater bandwidth is available, and what data can be eliminated as it will turn out to be useless, based on criteria relevant to the conduct of science and/or maintenance of the physical assets. Alternatively, it may be useful to adaptively compress data for transmission from the Gateway, which could include scientific experiment data and status, voice communications, scientific experiment data and status, and/or systems health management data.
3. Autonomous operations and health management of the Gateway. When Gateway is unoccupied, unexpected events or faults may require immediate autonomous detection and response, demonstrating this capability in the absence of support from Mission Control (which is enabling for future Mars missions and time-critical responses in lunar environment as well). Efforts to develop smart habitats will allow long-term human presence on the moon and Mars, such as the Space Technology Research Institutes (https://www.nasa.gov/press-release/nasa-selects-two-new-space-tech-research-institutes-for-smart-habitats) are relevant.

References

Basic Moon to Mars Background: https://www.nasa.gov/topics/moon-to-mars/lunar-outpost

Basic Gateway Background: https://www.nasa.gov/topics/moon-to-mars/lunar-gateway

Crusan, J. C.; Smith, R. M.; Craig, D. A.; Caram, J. M.; Guidi, J.; Gates, M.; Krezel, J. M.; and Herrmann, N. 2018. Deep Space Gateway concept: Extending human presence into cislunar space. In *Proceedings of the IEEE Aerospace Conference*.

Autonomous Biological Systems (ABS) Experiments
https://www.jstage.jst.go.jp/article/bss/12/4/12_4_363/_pdf/-char/en

Deep Space Gateway Science Opportunities
https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20180001581.pdf

Conducting Autonomous Experiments in Space
https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20180004314.pdf

Expected TRL or TRL range at completion of the project: 2 to 6

Desired Deliverables of Phase II

Prototype, Analysis, Software, Hardware, Research

Desired Deliverables Description

The deliverables range from research results to prototypes demonstrating various ways that autonomy and artificial intelligence (e.g., automated reasoning, machine learning, and discrete control) can be applied to aspects of Gateway operations and health management individually and/or jointly. As one example, for autonomous biological science experiments, the prototype could include hardware to host live samples for a minimum of 30 days that provide monitoring and environmental maintenance, as well as software to autonomously remedy issues with live science experiments. As another example, software that monitors the gateway habitat while un-crewed, automatically notifies of any off-nominal conditions, and then, when crew arrive, transitions the gateway from quiescent status to a status capable of providing the crew with life support. As another example, machine learning from the data stream of Gateway sensors to determine anomalous vs. nominal conditions and prioritize and compress data communications to Earth.

Phase 1 deliverables minimally include a detailed concept for autonomy technology to support Gateway operations such as experiments. Prototypes of software and/or hardware are strongly encouraged. Phase 2 deliverables will be full technology prototypes that could be subsequently matured for deployment on Gateway. Coordination with related efforts, such as the Space Technology Research Institutes (https://www.nasa.gov/press-release/nasa-selects-two-new-space-tech-research-institutes-for-smart-habitats) is expected to eliminate redundancy of effort and allow appropriate interactions between Gateway and smart habitats.

State of the Art and Critical Gaps

The current state-of-the-art in human spaceflight allows for autonomous operations of systems of relatively limited scope, involving only a fixed level of autonomy (e.g., amount of human involvement needed), and learning at most one type of function (e.g., navigation). The Gateway will require all operations and health management to be autonomous at different levels (almost fully autonomous when no astronauts are on board vs. limited autonomy when astronauts are present), will require the autonomy to learn from human operations, and will require autonomy across all functions. The autonomy will also need to adapt to new missions and new technologies.

As NASA continues to expand with the eventual goal of Mars missions, the need for autonomous tending of science payloads will grow substantially. In order to address the primary health concerns for crew on these missions, it is necessary to conduct science in the most relevant environment. Acquisition of this type of data will be challenging while the gateway and Artemis missions are being performed due to limited crewed missions and limited crew time.

Relevance / Science Traceability

Gateway and other space station-like assets in the future will need: The ability to learn autonomous operations from human operations which will be critical as the assets are expected to operate increasingly autonomously due to increasing duration space missions such as missions to Mars.

Focus Area 4: Robotic Systems for Space Exploration

Lead MD: STMD

Participating MD(s): SMD, STTR

This focus area includes development of robotic systems technologies (hardware and software) that will enable and enhance future space exploration missions. In the coming decades, robotic systems will continue to change the way space is explored. Robots will be used in all mission phases: as independent explorers operating in environments too distant or hostile for humans, as precursor systems operating before crewed missions, as crew helpers working alongside and supporting humans, and as caretakers of assets left behind. As humans continue to work and live in space, they will increasingly rely on intelligent and versatile robots to perform mundane activities, freeing human and ground control teams to tend to more challenging tasks that call for human cognition and judgment. Technologies are needed for robotic systems to improve transport of crew, instruments, and payloads on planetary surfaces, on and around small bodies, and in-space. This includes hazard detection, sensing/perception, active suspension, grappling/anchoring, legged locomotion, robot navigation, end-effectors, propulsion, and user interfaces.

Innovative robot technologies provide a critical capability for space exploration. Multiple forms of mobility, manipulation and human-robot interaction offer great promise in exploring planetary bodies for science investigations and to support human missions. Enhancements and potentially new forms of robotic systems can be realized through advances in component technologies, such as actuation and structures (e.g. 3D printing). Mobility provides a critical capability for space exploration. Multiple forms of mobility offer great promise in exploring planetary bodies for science investigations and to support human missions. Manipulation provides a critical capability for positioning crew members and instruments in space and on planetary bodies. Robotic manipulation allows for the handling of tools, interfaces, and materials not specifically designed for robots, and it provides a capability for drilling, extracting, handling and processing samples of multiple forms and scales. This increases the range of beneficial tasks robots can perform and allows for improved efficiency of operations across mission scenarios. Furthermore, manipulation is important for human missions, human precursor missions, and unmanned science missions. Moreover, sampling, sample handling, transport, and distribution to instruments, or instrument placement directly on in-place rock or regolith, is important for robotic missions to locales too distant or dangerous for human exploration.

Future space missions may rely on co-located and distributed teams of humans and robots that have complementary capabilities. Tasks that are considered "dull, dirty, or dangerous" can be transferred to robots, thus relieving human crew members to perform more complex tasks or those requiring real-time modifications due to contingencies. Additionally, due to the limited number of astronauts anticipated to crew planetary exploration missions, as well as their constrained schedules, ground control will need to remotely supervise and assist robots using time-delayed and limited bandwidth communications. Advanced methods of human-robot interaction over time delay will enable more productive robotic exploration of the more distant reaches of the solar system. This includes improved visualization of alternative future states of the robot and the terrain, as well as intuitive means of communicating the intent of the human to the robotic system.

S4.02: Robotic Mobility, Manipulation and Sampling (SBIR)

Lead Center: JPL

Participating Center(s): ARC, GRC, GSFC, JSC

Technology Area: 4.0.0 Robotics, Telerobotics and Autonomous Systems

Related Subtopic Pointer(s): Z5.05 S4.05 S1.11 T4.03 S4.04

Scope Title

Robotic Mobility, Manipulation and Sampling

Scope Description

Technologies for robotic mobility, manipulation, and sampling are needed to enable access to sites of interest and acquisition and handling of samples for in-situ analysis or return to Earth from planets and small planetary bodies. The Moon and planetary moons with liquid oceans are of particular interest, as well as Mars, comets, and asteroids.

Mobility technologies are needed to enable access to steep and rough terrain for planetary bodies where gravity dominates, such as Earth’s moon and Mars. Wheeled, legged, and aerial solutions are of interest. Wheel concepts with good tractive performance in loose sand while being robust to harsh rocky terrain are of interest. Technologies to enable mobility on small bodies and access to liquid below the surface (e.g., in conduits or deep oceans) are desired, as well as the associated sampling technologies. Manipulation technologies are needed to deploy sampling tools to the surface, transfer samples to in-situ instruments and sample storage containers, and hermetically seal sample chambers. Sample acquisition tools are needed to acquire samples on planetary and small bodies through soft and hard materials, including ice. Minimization of mass and ability to work reliably in the harsh mission environment are important characteristics for the tools. Finally, design for planetary protection and contamination control is important for sample acquisition and handling systems.

Component technologies for low-mass and low-power systems tolerant to the in-situ environment, e.g. temperature, radiation, and dust, are of particular interest. Technical feasibility should be demonstrated during Phase I and a full capability unit of at least TRL 4 should be delivered in Phase II. Proposals should show an understanding of relevant science needs and engineering constraints and present a feasible plan to fully develop a technology and infuse it into a NASA program. Specific areas of interest include the following:

- Surface mobility and sampling systems for planets, small bodies, and moons
- Near subsurface sampling tools such as icy surface drills to 30 cm depth deployed from a manipulator
- Subsurface ocean access such as via a deep drill system
- Sample handling technologies that minimize cross contamination and preserve mechanical integrity of samples
- Pneumatic sample transfer systems and particle flow measurement sensors
- Low mass/power vision systems and processing capabilities that enable fast surface traverse
- Active lighting stereo systems for landers and rovers
- Electro-mechanical connectors enabling tool change-out in dirty environments
- Tethers and tether play-out and retrieval systems
- Miniaturized flight motor controllers
- Cryogenic operation actuators
- Robotic arms for low gravity environments

Proposers should also note a related subtopic exists that is focused solely on lunar robotic missions (see Z5.05, Lunar Rover Technologies for In-Situ Resource Utilization and Exploration), under the Space Technology Mission Directorate). With NASA's present emphasis on lunar exploration, Z5.05 is provided to help develop innovative lunar rover technologies to support in-situ resource utilization activities and for developing ideas, subsystem components, software tools, and prototypes that contribute to more capable and/or lower cost lunar robots. In particular, cryogenic or cryo-capable actuators that are specifically for lunar rover applications should be directed towards Z5.05.

References

Mars Exploration/Programs & Missions: https://mars.nasa.gov/programmissions/

Solar System Exploration: https://solarsystem.nasa.gov/

Ocean Worlds website: https://www.nasa.gov/specials/ocean-worlds/

Ocean Worlds article: https://science.nasa.gov/news-articles/ocean-worlds

Expected TRL or TRL range at completion of the project: 2 to 4

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Software, Research

Desired Deliverables Description

Hardware and software for component robotic systems.

State of the Art and Critical Gaps

Scoops, powder drills, and rock core drills and their corresponding handling systems have been developed for sample acquisition on Mars and asteroids. Non-flight systems have been developed for sampling on comets, Venus, and Earth's moon. However, these have not been incorporated in a robotic mission, and the lack of a sufficient solution or technology readiness level is in some cases the reason a mission has not yet been possible. Exploration of icy ocean worlds is in the concept phase and associated sampling and sample handling systems do not exist.

Relevance / Science Traceability

The subtopic supports multiple programs within Science Mission Directorate (SMD). The Mars program has had infusion of technologies such as a force-torque sensor in the Mars 2020 mission. Recent awards would support the Ocean Worlds program: surface and deep drills for Europa. Products from this subtopic have been proposed for New Frontiers program missions. With renewed interest in return to Earth's moon, the mobility and sampling technologies could support future robotic missions to the moon.

T4.01: Information Technologies for Intelligent and Adaptive Space Robotics (STTR)

Lead Center: ARC

Participating Center(s): JSC

Technology Area: 4.0.0 Robotics, Telerobotics and Autonomous Systems

Related Subtopic Pointer(s): A2.02 T4.04 Z5.04

Scope Title

Develop Information Technologies to Improve Space Robots.

Scope Description

Extensive and pervasive use of robots can significantly enhance space exploration and space science, particularly for missions that are progressively longer, complex, and distant. The performance of these robots is directly linked to the quality and capability of the information technologies used to build and operate them. With few exceptions, however, current information technology used for state-of-the-art robotics is designed only to meet the needs of terrestrial applications and environments.

The objective of this subtopic, therefore, is to encourage the adaptation, maturation, and retargeting of terrestrial information technologies for space robotics. Proposals should address at least one of the following research areas:

1. ***Perception systems for autonomous robot operations*** in man-made environments (inside spacecraft or habitats) and unstructured, natural environments (Earth, Moon, Mars). The primary objective is to significantly increase the performance and robustness of perception capabilities such as object/hazard identification, localization, mapping, etc. through new avionics (including Commercial Off-The-Shelf [COTS] processors for use in space), sensors and/or software. Proposals for small size, weight, and power (SWAP) systems or technology that can operate on existing rad-hard processors are particularly encouraged.
2. ***Robot user interfaces*** that facilitate distributed human-robot teams, geospatial data visualization, summarization and notification, performance monitoring, etc. The primary objective is to enable more effective and efficient interaction with robots remotely operated with discrete commands or supervisory control. User interface technology that helps optimize operator workload or improve human understanding of autonomous robot actions are particularly encouraged. Note: proposals to develop user interfaces for direct teleoperation (manual control), augmented/virtual reality, or telepresence are not solicited and will be considered non-responsive.
3. ***Robot Operating System v2 (ROS 2) for space robots***. The primary objective is reduce the risk of deploying, integrating, and verifying and validating the open-source ROS 2 for future space missions.

Proposals that develop software technology that can facilitate integration of ROS 2 with common flight software (Core Flight Software, Integrated Test and Operations System [ITOS], etc.) and standards (Consultative Committee for Space Data Systems [CCSDS], etc.), methods to improve the suitability of ROS 2 for use with current flight computing, or tools / process to make ROS 2 (or a subset) ready for near-term flight missions are particularly encouraged.

Proposals are particularly encouraged to develop technologies applicable to robots of similar archetypes and capabilities to current NASA robots, such as Astrobee, Curiosity, or Robonaut 2.

References

https://www.nasa.gov/astrobee

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M. Diftler, et al. 2011. "Robonaut 2 - The first humanoid robot in space". In Proceedings of IEEE International Conference on Robotics and Automation, Shanghai, China.

Expected TRL or TRL range at completion of the project: 4 to 6

Desired Deliverables (Phase I)

Proposers should develop technologies that can be demonstrated with, or integrated to existing NASA research robots or projects to maximize relevance and infusion potential.

1. Identify scenarios, use cases, and requirements.
2. Define specifications.
3. Develop preliminary design.

Desired Deliverables (Phase II)

1. Develop prototypes (hardware and/or software).
2. Demonstrate and evaluate prototypes in real-world settings.
3. Deliver prototypes to NASA.

State of the Art and Critical Gaps

Future exploration and science missions will require robots to operate in more difficult environments, carry out more complex tasks, and handle more dynamic and varying operational constraints than the current state of the art, which relies on low-performance, rad-hard computing and execution of pre-planned command sequences. To achieve these capabilities, numerous new information technologies need to be developed, including high performance space computing, autonomy algorithms, and advanced robot software systems (on-board and off-board).

For example, in contrast to the International Space Station, which is continuously manned, the Gateway is expected to only be intermittently occupied – perhaps as little as 8% of the time. Consequently, there is a significant need for the facility to be robotically tended, in order to maintain and repair systems in the absence of human crew. These robots will perform a wide range of caretaking work including inspection, monitoring, routine maintenance, and contingency handling. To do this, significant advances will need to be made in autonomous perception and robot user interfaces, particularly to handle mission-critical and safety-critical operations.

As another example, a mission to explore and map interior oceans beneath the ice on Europa will require a robot to penetrate an unknown thickness of ice, autonomously carry out a complex set of activities, and navigate back to the surface in order to transmit data back to Earth. The robot will need to perform these tasks with minimal human involvement and while operating in an extremely harsh and dynamic environment. To do this, significant advances will need to be made in autonomous perception and on-board software, particularly to compensate for poor (bandwidth-limited, high-latency, intermittent) communications and the need for high performance autonomy.

Relevance / Science Traceability

The development of information technology for intelligent and adaptive space robotics is well aligned with NASA goals for robotics. In particular, this development directly addresses multiple areas (TA4, TA7, TA11) of the 2015 NASA technology roadmap. Additionally, this development is directly aligned with multiple portions of the NASA Autonomous Systems SCLT (Systems Capability Leadership Team) technology taxonomy. Moreover, this development directly addresses a core technology area (robotics and autonomous systems) of the NASA Strategic Space Technology Investment Plan. Finally, the technology is directly aligned with the needs of numerous projects and programs in Aeronautics Research Mission Directorate (ARMD), Human Exploration and Operations Mission Directorate (HEOMD), Science Mission Directorate (SMD), and Space Technology Mission Directorate (STMD).

- ARMD: The technology can be applied to a broad range of unmanned aerial systems (UAS), including both small-scale drones and Predator / Global Hawk type systems. The technology can also be potentially infused into other flight systems that include autonomous capabilities, such as Urban Air Mobility vehicles.
- HEOMD: The technology is directly relevant to "caretaker" robots, which are needed to monitor and maintain human spacecraft (such as the Gateway) during dormant/uncrewed periods. The technology can also be used by precursor lunar robots to perform required exploration work prior to the arrival of humans on the Moon.
- SMD: The technology is required for future missions in Earth Science, Heliophysics, and Planetary Science (including the Moon, icy moons and ocean worlds) that require higher performance and autonomy than currently possible. In particular, missions that must operate in dynamic environments, or measure varying phenomena, will require the technology developed by this subtopic.
- STMD: The technology is directly applicable to numerous current mid-TRL (Game Changing Development program) and high-TRL (Technology Demonstration Mission program) Research and Development (R&D) activities, including Astrobee, In-space Robotic Manufacturing and Assembly, etc.

Z5.04: Technologies for Intra-Vehicular Activity Robotics (SBIR)

Lead Center: ARC

Participating Center(s): JSC

Technology Area: 4.0.0 Robotics, Telerobotics and Autonomous Systems

Related Subtopic Pointer(s): T4.04 T4.01 Z3.05

Scope Title

Improve the capability or performance of intravehicular activity robots

Scope Description

To support human exploration beyond Earth orbit, NASA is preparing to develop the "Gateway", which will be an orbiting facility near the Moon. This facility would serve as a starting point for missions to cis-lunar space and beyond. This facility could enable assembly and servicing of telescopes and deep-space exploration vehicles. This facility could also be used as a platform for astrophysics, Earth observation, heliophysics, and lunar science.

In contrast to the ISS (International Space Station), which is continuously manned, the Gateway is expected to only be intermittently occupied by humans – perhaps only 1 month per year. Consequently, there is a significant need for the Gateway to have autonomous capabilities for performing payload operations and spacecraft caretaking, particularly when astronauts are not present. Intra-Vehicular Activity (IVA) robots can potentially perform a wide variety of tasks including systems inspection, monitoring, diagnostics and repair, logistics and consumables stowage, exploration capability testing, aggregation of robotically returned destination surface samples, and science measurements and ops.

The objective of this subtopic, therefore, is to develop technologies that can improve the capability or performance of IVA robots to perform payload operations and spacecraft caretaking. Proposals are specifically sought to create technologies that can be integrated and tested with the NASA Astrobee or Robonaut 2 robots in the following areas: (1) Sensors and perception systems for interior environment monitoring, inspection, modeling and navigation; (2) Robotic tools for manipulating logistics and stowage or performing maintenance, housekeeping or emergency management operations (e.g. fire detection & suppression in multiple constrained locations or cleaning lunar dust out of HEPA (High-Efficiency Particulate Air) filters; and (3) Operational subsystems that enable extended robot operations (power systems, efficient propulsion, etc.), increase robot autonomy (planning, scheduling, and task execution), or improve human-robot teaming (software architecture, remote operations methods, etc.).

References

What is Astrobee? - https://www.nasa.gov/astrobee

What is a Robonaut? - https://www.nasa.gov/robonaut2

J. Crusan, et al. 2018. "Deep space gateway concept: Extending human presence into cislunar space", In Proceedings of IEEE Aerospace Conference, Big Sky, MT

M. Bualat, et al. 2018. "Astrobee: A new tool for ISS operations". In Proceedings of AIAA SpaceOps, Marseille, France.

T. Fong, et al. 2013. "Smart SPHERES: a telerobotic free-flyer for intravehicular activities in space". In Proceedings of AIAA Space 2013, San Diego, CA.

M. Diftler, et al. 2011. "Robonaut 2 - The first humanoid robot in space". In Proceedings of IEEE International Conference on Robotics and Automation, Shanghai, China.

M. Deans, et al. 2019. "Integrated System for Autonomous and Adaptive Caretaking (ISAAC)". Presentation, Gateway Intra-Vehicular Robotics Working Group Face to Face, Houston, TX; NASA Technical Reports Server [https://ntrs.nasa.gov/search.jsp?R=20190029054]

Expected TRL or TRL range at completion of the project: 4 to 5

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Software, Research

Desired Deliverables Description

Prototype components or subsystems. Proposals must describe how the technology will make a significant improvement over the current state of the art, rather than just an incremental enhancement, for a specific IVA robot application.

State of the Art and Critical Gaps

The technology developed by this subtopic would both enable and enhance the Astrobee free-flying robot and Robonaut 2 humanoid robot, which are the SOA for IVA robots. SBIR technology would improve the capability and performance of these robots to routinely and robustly perform IVA tasks, particularly internal spacecraft payload operations and logistics. New technology created by 2020 SBIR awards can be tested with these robots in ground testbeds at ARC and JSC during the SBIR period of performance. On-orbit testing on ISS may be possible during Phase 2 and beyond (Phase 2-E, 2-X, 3, etc.).

The technology developed by this subtopic would also fill technical gaps identified by the proposed GCD (Game Changing Development) "Integrated System for Autonomous and Adaptive Caretaking" (ISAAC) project, which will mature autonomy technology to support the caretaking of human exploration spacecraft. In particular, the SBIR technology would help provide autonomy and robotic capabilities that are required for in-flight maintenance (both preventive and corrective) of Gateway during extended periods when crew are not present.

Relevance / Science Traceability

This subtopic is directly relevant to the following STMD (Space Technology Mission Directorate) investments:

- Astrobee free-flying robot – GCD
- Integrated System for Autonomous and Adaptive Caretaking (ISAAC) – GCD
- Deep Space Smart Habitats – Space Technology Research Institutes (STRI)

This subtopic is directly relevant to the following HEOMD (Human Exploration and Operations Mission Directorate) investments:

- SPHERES/Astrobee facility – ISS
- Robonaut 2 humanoid robot – ISS
- Gateway program – Advanced Exploration Systems (AES)
- Logistics Reduction project – AES
- Autonomous Systems Operations project – AES

Z5.05: Lunar Rover Technologies for In-situ Resource Utilization and Exploration (SBIR)

Lead Center: JSC

Participating Center(s): ARC, GRC, KSC

Technology Area: 4.0.0 Robotics, Telerobotics and Autonomous Systems

Related Subtopic Pointer(s): S4.02 Z13.01 Z13.02 T2.05

Scope Title

Enabling Rover Technologies for Lunar Missions

Scope Description

The objective of this subtopic is to innovate lunar rover technologies that will enable In-Situ Resource Utilization (ISRU) and exploration missions. In particular, this subtopic will develop ideas, subsystems components, software tools, and prototypes that contribute to more capable and/or lower-cost lunar robots.

A potential lunar ISRU application is the prospecting, characterization, and collection of volatiles that could be processed to produce oxygen, fuel, etc. Recent remote sensing measurements, modeling, and data from LCROSS (Lunar Crater Observation and Sensing Satellite) indicates that there may be an abundance of volatiles (e.g., hydrogen) near the lunar poles. However, the distribution of the volatiles at and under the surface is unknown. The Lunar Rover Technologies for In-situ Resource Utilization and Exploration subtopic seeks new robotic technology that will enable rover technologies for lunar missions to support ISRU activities. This does not include new ISRU technology (which is solicited by subtopics T2.05 - Advanced Concepts for Lunar and Martian Propellant Production, Storage, Transfer, and Usage for the STTR solicitation and S4.02 - Robotic Mobility, Manipulation and Sampling for the SBIR solicitation).

The expected environment at the lunar poles involves all the challenges observed during the Apollo mission (thermal extremes, vacuum, radiation, abrasive dust, electrostatic dust) plus the addition of low sun angles, potentially less consolidated regolith, and permanently shadowed regions with temperatures as low as 40K. This subtopic seeks new technology to address these challenges.

Phase I success involves technical feasibility demonstration through analysis, prototyping, proof-of-concept, or testing. Phase II success will advance TRL to a level of 4-5. Of specific interest are:

- Mobility architectures, including novel mobility mechanisms and lunar dust tolerant mechanisms.
- Cryo-capable actuators capable of operating at extremely cold temperatures (in environments as cold as -230C). Preferably solutions will not include heaters as they significantly increase the power draw for normal operations during the lunar day. Novel materials capable of maintaining metallurgical properties at cryogenic temperatures will be considered. Also desired are cryo actuators featuring dust tolerances and the ability to operate at high temperatures as well (approaching 150C).
- Magnetic gearing applications for space. NASA and others are developing relatively low ratio (less than 25:1 per stage) concentric magnetic gearing for aeronautics applications. Space applications demand high speed-reduction ratio (often more than 1000:1) and high specific torque (>50 Nm/kg), operation in environmental temperatures down to -230C (40K), operation in low-atmosphere or hard vacuum, with high reliability and energy efficiency. Phase I work would include identifying the most suitable magnetic gear topologies to meet these space application needs, defining the technology development challenges including thermal and structural issues, advancing the most critical aspects of the technology, and producing a low-fidelity prototype to prove the feasibility of the concept(s).
- Perception systems and algorithms with a path toward flight for the lunar surface capable of operating in the harsh lighting conditions that might include high dynamic range, shadowed regions, low angle illumination, and opposition effects
- Lunar regolith terramechanical modeling tools and simulations, especially tools that integration with existing commercial and open source robotic analysis and simulation tools.
- Rover embedding and entrapment detection and escape approaches including slip monitoring, regolith sensing/modeling, low ground pressure wheels and soft soil tolerant mobility architectures.

For all the above, it is desired to have been demonstrated in, or have a clear path to operating in, the lunar environment. NASA has plans to purchase services for delivery of payloads to the Moon through the Commercial Lunar Payload Services (CLPS) contract. Under this subtopic, proposals may include efforts to develop payloads for flight demonstration of relevant technologies in the lunar environment. The CLPS payload accommodations will vary depending on the particular service provider and mission characteristics. Additional information on the CLPS program and providers can be found at this link:

https://www.nasa.gov/content/commercial-lunar-payload-services. CLPS missions will typically carry multiple payloads for multiple customers. Smaller, simpler, and more self-sufficient payloads are more easily accommodated and would be more likely to be considered for a NASA-sponsored flight opportunity. Commercial payload delivery services may begin as early as 2020 and flight opportunities are expected to continue well into the future. In future years it is expected that larger and more complex payloads will be accommodated. Selection for award under this solicitation will not guarantee selection for a lunar flight opportunity.

References

NASA is still formulating its approach to future lunar science and exploration. The current plan is to start with small commercial landers (<100kg) beginning as early as 2019, with relatively high launch cadence (2+ launches/year). In the future, NASA seeks to build mid-to-large landers, with an eye on human-rated landers with a first mid-sized lander planned for 2022.

Further information can be found at the following:

- How to survive a Lunar night: https://www.sciencedirect.com/science/article/pii/S0032063310003065
- Apollo Experience Report - Thermal Design of Apollo Lunar Surface Experiments Package: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19720013192.pdf
- The Lunar Environment: https://www.lpi.usra.edu/publications/books/lunar_sourcebook/pdf/Chapter03.pdf
- Commercial Lunar Payload Services - CLPS: https://www.fbo.gov/index?s=opportunity&mode=form&id=46b23a8f2c06da6ac08e1d1d2ae97d35&tab=core&_cview=0
- Survive and Operate Through the Lunar Night Workshop: https://www.hou.usra.edu/meetings/survivethenight2018/
- NASA's Exploration Campaign: Back to the Moon and on to Mars: https://www.nasa.gov/feature/nasas-exploration-campaign-back-to-the-moon-and-on-to-mars
- NASA Exploration Campaign: https://www.nasa.gov/sites/default/files/thumbnails/image/nasa-exploration-campaign.jpg

Additional information on NASA's interest in landers that might host the rovers can be found at the following:

- NASA Seeks Ideas to Advance toward Human-Class Lunar Landers (https://www.nasa.gov/feature/nasa-seeks-ideas-to-advance-toward-human-class-lunar-landers)
- Lunar Surface Transportation Capability Request for Information (RFI) (https://govtribe.com/project/lunar-surface-transportation-capability-request-for-information-rfi)

Magnetic gearing references:

- Tlali, P. M., Wang, R-J., and Gerber, S., “Magnetic gear technologies: A review,” 2014 Intl. Conference on Electrical Machines, p. 544-550, Berlin, Germany, Sept. 2 – 5, 2014.
- Justin J. Scheidler, Vivake M. Asnani, and Thomas F. Tallerico, “Overview of NASA’s Magnetic Gears Research,” presented at the AIAA / IEEE Electric Aircraft Technology Symposium, Cincinnati, Ohio, July 12 – 13, 2018.
- Vivake M. Asnani, Justin J. Scheidler, and Thomas F. Tallerico, “Magnetic Gearing Research at NASA,” presented at the 74th Annual Forum of the American Helicopter Society, Phoenix, AZ, May 14 – 17 2018.

- Aaron D. Anderson and Vivake M. Asnani, "Concentric Magnetic Gearing - State of the Art and Empirical Trends", NASA TM, in-press.

Expected TRL or TRL range at completion of the project: 3 to 5

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Software

Desired Deliverables Description

Example deliverables coming from a successful phase II within this subtopic, might including some of the following:

- Designs of cryo-capable or dust tolerant mechanisms motor controllers with test data and prototypes
- Prototype rovers or scale versions of prototype rovers showing novel mobility architecture for escaping entrapment in regolith
- Software algorithms including demonstrating slip detection or image processing in harsh lunar lighting conditions
- Software packages either standalone or integrated with commercially available or open-source robotic simulation packages (preferred).

NASA is also interested in technologies demonstrations that could serve as payloads on commercial landers at the end of phase II.

State of the Art and Critical Gaps

Current state of the art in robotic surface mobility is the MER/MSL (Mars Exploration Rover/Mars Science Laboratory) rovers for Mars and the Chinese Chang'e on the moon. Since the end of the NASA Constellation program in 2011, there has been only small pockets of technology development for the lunar surface within NASA and other space agencies, plus the small business/academic communities.

The specific areas noted above for targeted development (mechanisms, cryoactuators, magnetic gearing, perception systems, terramechanics simulations and novel mobility architectures) are all of specific interest as they are specific challenges unique to the lunar surface and lunar poles specifically.

Magnetic gearing has become practical in recent years due to the availability of high energy density magnets and design topologies that conserve volume. As a result, there has been an exponential growth in R&D for Earth applications like wind/wave energy generators and hybrid vehicle power-trains.

Relevance / Science Traceability

This SBIR resides within STMD as a vehicle for development of technology objectives. It is expected that successful projects would infuse technology into either the STMD Game Changing Development (GCD) or Technology Demonstration Missions (TDM) programs. Technology could also be infused into joint efforts involving STMD's partners (other mission directorates, other government agencies, and the commercial sector). Flights for these technology missions could be supported on small commercial lunar landers (SMD) or possibly mid-size NASA lunar landers (HEOMD).

Potential customers:

- Autonomy and robotics
- Robotic ISRU missions
- Payloads for Commercial Lunar Payload Services landers
- Commercial vendors

- Future prospecting/mining operations

Focus Area 5: Communications and Navigation

Lead MD: HEOMD

Participating MD(s): SMD, STTR

NASA seeks proposals to produce high impact developments in communications and navigation technologies to support space science and exploration missions, including the return of humans to the lunar surface. Missions are generating ever-increasing data volumes that require increased performance from communications systems while minimizing spacecraft impact. This requires higher peak throughput from the communications systems with lower flight communication system cost, mass, and power per bit transmitted. Long range, deep-space optical communications systems are needed to support data-intensive missions beyond Mars orbit. Effective communications on a non-interference basis are also required in complex RF environments such as inside a launch vehicle fairing or spacecraft cavity, where new analysis methods are needed for predicting the RF environment. Similarly, missions have a need for more precise timing, guidance, navigation, and control to meet their mission objectives while conserving resources. This requires new and more efficient trajectory planning methods, increased onboard autonomous navigation, and improved precision of onboard instrumentation while minimizing cost, mass, and power. This focus area supports development of innovative technologies for optical and quantum communications systems, cognitive communications, flight dynamics and navigation, transformational communications approaches, electric field prediction methods, and timing, guidance, navigation, and control that will provide a significant improvement over the current state of the art.

H9.01: Long Range Optical Telecommunications (SBIR)

Lead Center: JPL

Participating Center(s): GRC, GSFC

Technology Area: 5.0.0 Communication and Navigation

Related Subtopic Pointer(s): S2.04 Z8.02 H9.05 S2.02 S2.03 T5.04

Scope Title

Free-Space Optical Communications Technologies

Scope Description

This Free-space Long Range Optical Communications subtopic seeks innovative technologies for advancing free-space optical communications by pushing future data volume returns to and from space missions in multiple domains with return data-rates > 100 Gbit/s (cis-lunar, i.e. Earth or lunar orbit to ground), > 10 Gbit/s (Earth-sun L1 and L2), >1 Gbit/s per AU-squared (deep space), and >1 Gbit/s (planetary lander to orbiter) and forward data-rates > 25 Mb/s at ranges extending from the Moon to Mars. Innovative technologies should target improved efficiency, reliability, robustness, and longevity for existing or novel state-of-the-art flight laser communication systems. Photon-counting sensitivity, near infrared (NIR), space-flight worthy detectors/detector arrays for supporting laser ranging for potential navigation and science are of particular interest. Ground-based technologies targeting high power, NIR and intensity-modulated lasers with fast rise times and low timing jitter (sub-nanosecond) are needed to support high forward data-rates and laser ranging.

Proposals are sought in the following specific areas:

<u>Flight Laser Transceivers</u>

Low-mass, high-Effective Isotropic Radiated Power (EIRP) laser transceivers for links over planetary distances with:

- 30 to 50 cm clear aperture diameter telescopes for laser communications
- Targeted mass of opto-mechanical assembly per aperture area, less than 100 kg/square-meter
- Cumulative wave-front error and transmission loss not to exceed 2 dB.
- Advanced thermal-mechanical designs to withstand planetary launch loads and flight temperatures by the optics and structure, at least -20° C to 70° C operational range
- Design to mitigate stray light while pointing transceiver 3 degrees from edge of sun
- Survive direct sun pointing for extended duration

Transceivers fitting the above characteristics should support robust link acquisition tracking and pointing characteristics, including point-ahead implementation from space for beacon assisted and/or "beaconless" architectures. Innovative solutions for mechanically stiff, light-weighted thermally stable structural properties are sought.

- Pointing loss allocations not to exceed 1 dB (pointing errors associated loss of irradiance at target less than 20%)
- Receiver field-of-view of at least 1 milliradian angular radius for beacon assisted acquisition, tracking and pointing
- As a goal additional focal plane with field-of-view to support on-board astrometry is desired
- Beaconless pointing subsystems for operations beyond 3 AU
- Assume integrated spacecraft micro-vibration angular disturbance of 150 micro-radians (<0.1 Hz to ~500 Hz)

Low complexity small footprint agile laser transceivers for bi-directional optical links (> 1-10 Gbit/second at a nominal link range of 1000-20000 km) for planetary lander/rover to orbiter and/or space-to-space cross links.

- Disruptive low Size, Weight and Power (SWaP) technologies that can operate reliably in space over extended mission duration
- Vibration isolation/suppression systems that will integrate to the optical transceiver in order to reject high frequency base disturbance by at least 50 dB
- Desire integrated launch locks and latching mechanism
- Low burden (mass, power, volume)
- Robust for space flight
- Should afford limited +/- 5 mrad - +/-12 mrad actuated field-of-regard for the optical line of sight of the transceiver

<u>Flight Laser Transmitters</u>

High-gigabit/s laser transmitters

- 1550 nm wavelength
- Lasers, electronics and optical components ruggedized for extended space operations
- High rate 10-100 Gb/s for cis-lunar
- 1 Gb/s for deep-space

- Integrated hardware with embedded software/firmware for innovative coding/modulation/interleaving schemes that are being developed as a part of the Consultative Committee for Space Data Systems (CCSDS)

High peak-to-average power laser transmitters for regular or augmented M-ary PPM modulation with M=4, 8, 16, 32, 64, 128, 256 operating at NIR wavelengths, preferably 1550 nm with average powers from 5 - 50 W

- Sub-nanosecond pulse
- Low pulse jitter
- Long lifetime and reliability operating in space environment (> 5 and as long as 20 years)
- High modulation and polarization extinction ratio with 1-10 GHz line width

Space-qualifiable wavelength division multiplexing transmitters and amplifiers with 4 to 20 channels and average output power > 20W per channel; peak-to-average power ratios >200; >10 Gb/s channel modulation capability.

- >20% wall-plug efficiency (DC-to-optical, including support electronics) with description of approach for stated efficiency of space-qualifiable lasers. Multi-watt Erbium Doped Fiber Amplifier (EDFA), or alternatives, with high gain bandwidth (> 30nm, 0.5 dB flatness) concepts will be considered.
- Radiation tolerance better than 50 krad is required (including resilience to photo-darkening).

<u>Receivers/Sensors</u>

Space-qualifiable high-speed receivers and low light level sensitive acquisition, tracking, pointing, detectors, and detector arrays

- NIR wavelengths: 1064nm and/or 1550 nm
- Sensitive to low irradiance incident at flight transceiver aperture (~ fW/m2 to pW/m2) detection
- Low sub-nanosecond timing jitter and fast rise time
- Novel hybridization of optics and electronic readout schemes with in-built pre-processing capability
- Characteristics compatible with supporting time-of-flight or other means of processing laser communication signals for high precision range and range rate measurements
- Tolerant to space radiation effects, total dose > 50 krad, displacement damage and single event effects

<u>Novel technologies and accessories</u>

Narrow Bandpass Optical Filters

- Space-qualifiable, sub-nanometer to nanometer, noise equivalent bandwidth with ~90% throughput, large spectral range out-of-band blocking (~ 40 dB)
- NIR wavelengths from 1064 – 1550 nm region, with high transmission through Earth’s atmosphere
- Reliable tuning over limited range

Novel Photonics Integrated Circuit (PIC) devices targeting space applications with objective of reducing size, weight and power of modulators, without sacrificing performance. Proposed PIC solutions should allow improved integration and efficient coupling to discrete optics, when needed.

Concepts for offering redundancy to laser transmitters in space

- Optical fiber routing of high average powers (10’s of watts) and high peak powers (1-10 kW)

- Redundancy in actuators and optical components
- Reliable optical switching

Ground Assets for Optical Communication

Low cost large aperture receivers for faint optical communication signals from deep space subsystem technologies:

- Demonstrate innovative subsystem technologies for >10 m diameter deep-space ground collector
- Capable of operating to within 3 degrees of solar limb
- Better than 10 micro radian spot size (excluding atmospheric seeing contribution)
- Desire demonstration of low-cost primary mirror segment fabrication to meet a cost goal of less than $35 K per square meter
- Low-cost techniques for segment alignment and control, including daytime operations
- Partial adaptive correction techniques for reducing the field of view required to collect signal photons under daytime atmospheric "seeing" conditions
- Innovative adaptive techniques not requiring a wavefront sensor and deformable mirror of particular interest
- Mirror cleanliness monitor and control systems
- Active metrology systems for maintaining segment primary figure and its alignment with secondary optics
- Large core diameter multi-mode fibers with low temporal dispersion for coupling large optics to detectors remote (30-50 m) from the large optics

1550 nm sensitive photon counting detector arrays compatible with large aperture ground collectors with a means of coupling light from large aperture diameters to reasonably- sized detectors/detector arrays, including optical fibers with acceptable temporal dispersion

- Integrated time tagging readout electronics for >5 giga-photons/s incident rate
- Time resolution <50 ps at 1-sigma
- Highest possible single photon detection efficiency, at least 50% at highest incident rate
- Total detector active area > 0.3 - 1 mm2
- Integrated dark rate < 3 mega-count/s.

Cryogenic optical filters

- Operate at 40 K with sub-nanometer noise equivalent bandwidths
- 1550 nm spectral region, transmission losses < 0.5 dB, clear aperture
- >35 mm, and acceptance angle > 40 milliradians with out-of-band rejection of > 65 dB from 0.4 - 5 microns.

Multi-kilowatt laser transmitters for use as ground beacon and uplink laser transmitters

- Near infrared wavelengths in 1.0 or 1.55 micrometer spectral region
- Capable of modulating with narrow nanosecond and sub-nanosecond rise times
- Low-timing jitter and stable operation

- High speed real-time signal processing of serially concatenated pulse position modulation operating at a few bits per photon with user interface outputs
- 15-60 MHz repetition rates

For all technologies lowest cost for small volume production (5 to 20 units) is a driver. Research must convincingly prove technical feasibility (proof-of-concept) during Phase I, ideally with hardware deliverables that can be tested to validate performance claims, with a clear path to demonstrating and delivering functional hardware meeting all objectives and specifications in Phase II.

References

https://www.nasa.gov/mission_pages/tdm/lcrd/index.html

https://www.nasa.gov/directorates/heo/scan/opticalcommunications/illuma-t

https://www.nasa.gov/feature/goddard/2017/nasa-laser-communications-to-provide-orion-faster-connections

https://www.nasa.gov/mission_pages/tdm/dsoc/index.html

Expected TRL or TRL range at completion of the project: TRL 2-3 Phase I for maturation to TRL 3-5 in Phase II

Desired Deliverables of Phase II

Prototype, Hardware, Software

Desired Deliverables Description

Models of components or assemblies for flight laser transceivers or Ground receivers

State of the Art and Critical Gaps

The State Of the Art (SOA) for Free-Space Optical Communications (FSOC) can be subdivided into near-earth (extending to cis- and trans-lunar distances) and planetary ranges with the Lagrange points falling in between.

Near Earth FSOC technology has completed a number of technology demonstrations from space and is more mature. Nonetheless, low size-weight power novel high speed 10-100 Gb/s space-qualified laser transmitters and receivers are sought. These transmitters and receivers can possibly be infused for deep space proximity links, such as landed assets on planetary surfaces to orbiting assets with distances of 5000-100000 km or inter-satellite links. Innovative light-weight space-qualified modems for handling multiple optical modulation schemes.

A technology demonstration for deep space FSOC is anticipated in the next decade. Critical gaps following a successful technology demonstration will be light-weighted 30-50 cm optical with a wide operational temperature range -20C to 50C over which wave front error and focus is stable. High peak-to-average power space qualified lasers with average powers of 20-50 W. Single photon-sensitive radiation-hardened flight detectors with high detection efficiency, fast rise times low timing jitter. The detector size should be able to cover 1 milliradian Field-Of-View (FOV) with an instantaneous FOV comparable to the transmitted laser beam width. Laser pointing control systems that operate with dim laser beacons transmitted from earth or use celestial beacon sources.

For Deep Space Optical Communications (DSOC) ground laser transmitters with high average power (kW class) but narrow line-widths (< 0.3 nm) and high variable repetition rates are required. Innovative optical coatings for large aperture mirrors that are compatible with near-sun pointing applications for efficiently collecting the signal and lowering background and stray light.

Relevance / Science Traceability

A number of FSOC-related NASA projects are ongoing with launch expected in the 2019-2022 time frame. The Laser Communication Relay Demonstration (LCRD) is an earth-to-geostationary satellite relay demonstration to launch in late 2019. The Illuma -T Project will extend the relay demonstration to include a Low Earth Orbit (LEO) node on the ISS in 2021. In 2022 the EM-2 Optical to Orion (O2O) demonstration will transmit data from the Orion crewed capsule as it travels to the Moon and back. In 2022 the DSOC Project technology demonstration will be hosted by the Psyche Mission spacecraft extending FSOC links to astronomical unit distances.

These missions are being funded by NASA's Space Technology Mission Directorate (STMD) Technology Demonstration Mission (TDM) Program and Human Exploration Operations Mission Directorate (HEOMD) Space Communications and Navigation (SCaN) Program.

H9.03: Flight Dynamics and Navigation Technology (SBIR)

Lead Center: GSFC

Participating Center(s): JSC, MSFC

Technology Area: 5.0.0 Communication and Navigation

Related Subtopic Pointer(s): Z8.02 S5.03 Z3.05 A2.02 A3.03 S3.04

Scope Title

Advanced Techniques for Trajectory Optimization

Scope Description

Future NASA missions will require precision landing, rendezvous, formation flying, cooperative robotics, proximity operations (e.g., servicing) and coordinated platform operations. This drives the need for increased precision in absolute and relative navigation solutions and more advanced algorithms for both ground and onboard navigation, guidance and control. This sub-topic seeks advancements in flight dynamics and navigation technology for applications in Earth orbit, lunar, and deep space that enables future NASA missions. In particular, technology relating to autonomous onboard navigation, guidance, and control, and trajectory optimization are solicited. See Reference 1 below for NASA Technical Area (TA) roadmaps:

- Low-thrust trajectory optimization in a multi-body dynamical environment (TA 5.4.2.1)
- Advanced deep-space trajectory design techniques. (TA 5.4.2.7) and rapid trajectory design near small bodies (TA 5.4.5.1)
- Tools and techniques for orbit/trajectory design for distributed space missions including constellations and formations (TA 11.2.6)

Proposals that leverage state-of-the-art capabilities already developed by NASA, or that can optionally integrate with those packages, such as the General Mission Analysis Tool (GMAT), Copernicus, Evolutionary Mission Trajectory Generator (EMTG), Mission Analysis Low-Thrust Optimization (MALTO), Monte, and Optimal Trajectories by Implicit Simulation (OTIS), or other available software tools are encouraged. Proposers who contemplate licensing NASA technologies are highly encouraged to coordinate with the appropriate NASA technology transfer offices prior to submission of their proposals.

References

1. NASA Space Technology Roadmaps (2015): https://www.nasa.gov/offices/oct/home/roadmaps/index.html

2. General Mission Analysis Tool (GMAT): http://gmatcentral.org/display/GW/GMAT+Wiki+Home

3. Evolutionary Mission Trajectory Generator (EMTG): https://software.nasa.gov/software/GSC-16824-1

4. Copernicus: https://www.nasa.gov/centers/johnson/copernicus/index.html

5. Mission Analysis Low-Thrust Optimization (MALTO): https://software.nasa.gov/software/NPO-43625-1

6. Monte: https://montepy.jpl.nasa.gov/

Expected TRL or TRL range at completion of the project: 3 to 6

Desired Deliverables of Phase II

Prototype, Analysis, Software, Research

Desired Deliverables Description

Phase 1 research should be conducted to demonstrate technical feasibility, with preliminary software being delivered for NASA testing, as well as show a plan towards Phase 2 integration. Phase 2 new technology development efforts shall deliver components at the Technology Readiness Level (TRL) 5-6 level with mature algorithms and software components complete and preliminary integration and testing in an operational environment.

State of the Art and Critical Gaps

Algorithms and software for rapid and robust preliminary and high-fidelity design and optimization of low thrust trajectories in a multi-body dynamical environment (such as cislunar space) currently do not exist. Designing trajectories for these types of missions relies heavily on hands-on work by very experienced people. That works reasonably well for designing a single reference trajectory but not as well for exploring trade spaces or when designing thousands of trajectories for a Monte-Carlo or missed-thrust robustness analysis.

Relevance / Science Traceability

- Lunar Orbital Platform-Gateway
- WFIRST
- Europa Clipper
- Lucy
- Psyche

Trajectory design for these complex missions can take weeks or months to generate a single reference trajectory. Providing algorithms and software to speed up this process will enable missions to more fully explore trade spaces and more quickly respond to changes in the mission.

Scope Title

Autonomous Onboard Spacecraft Navigation, Guidance and Control

Scope Description

Future NASA missions require precision landing, rendezvous, formation flying, proximity operations (e.g., servicing and assembly), non-cooperative object capture and coordinated platform operations in Earth orbit, cislunar space, libration orbits and deep space. These missions require a high degree of autonomy. The subtopic seeks advancements in autonomous spacecraft navigation and maneuvering technologies for applications in Earth orbit, lunar, cislunar, libration and deep space to reduce dependence on ground-based tracking, orbit determination and maneuver planning. See Reference 1 for NASA Technical Area (TA) roadmaps:

- Advanced autonomous spacecraft navigation techniques including devices and systems that support significant advances in independence from Earth supervision while minimizing spacecraft burden by requiring low power and minimal mass and volume (TA 5.4.2.4, TA 5.4.2.6, TA 5.4.2.8).

- Onboard spacecraft trajectory planning and optimization algorithms for real-time mission re-sequencing, on-board computation of large divert maneuvers (TA 5.4.2.3, TA 5.4.2.5, TA 5.4.2.6, TA 9.2.6) primitive body/lunar proximity operations and pinpoint landing (TA 5.4.6.1), including the concept of robust onboard trajectory planning and optimization algorithms that account for system uncertainty (i.e., navigation errors, maneuver execution errors, etc.).
- Onboard relative and proximity navigation (TA 5.4.4) multi-platform relative navigation (relative position, velocity and attitude or pose) which support cooperative and collaborative space operations such as satellite servicing and in-space assembly.
- Rendezvous targeting (TA 4.6.2.1) Proximity Operations/Capture/ Docking Guidance (TA 4.6.2.2)
- Advanced filtering techniques (TA 5.4.2.4) that address rendezvous and proximity operations as a multi-sensor, multi-target tracking problem; handle non-Gaussian uncertainty; or incorporate multiple-model estimation.
- Advanced algorithms for safe precision landing on small bodies, planets and moons, including real-time three-dimensional (3D) terrain mapping (TA 9.2.81, 9.2.8.3), autonomous hazard detection and avoidance (TA 9.2.8.4), terrain relative navigation (TA 9.2.8.2), small body proximity operations (TA 9.2.8.8).
- Machine vision techniques to support optical/terrain relative navigation and/or spacecraft rendezvous/proximity operations.

Proposals that leverage state-of-the-art capabilities already developed by NASA, or that can optionally integrate with those packages, such as the Goddard Enhanced Onboard Navigation System (GEONS) (https://software.nasa.gov/software/GSC-14687-1), Navigator (http://itpo.gsfc.nasa.gov/wp-content/uploads/gsc_14793_1_navigator.pdf), NavCube (https://goo.gl/bdobb9) or other available NASA hardware and software tools are encouraged. Proposers who contemplate licensing NASA technologies are highly encouraged to coordinate with the appropriate NASA technology transfer offices prior to submission of their proposals.

References

1. NASA Space Technology Roadmaps (2015): https://www.nasa.gov/offices/oct/home/roadmaps/index.html

2. Goddard Enhanced Onboard Navigation System (GEONS), (https://software.nasa.gov/software/GSC-14687-1), (https://goo.gl/TbVZ7G)

3. Mission Analysis, Operations, and Navigation Toolkit Environment (MONTE), (https://montepy.jpl.nasa.gov/)

4. Navigator (http://itpo.gsfc.nasa.gov/wp-content/uploads/gsc_14793_1_navigator.pdf)

5. NavCube (https://goo.gl/bdobb9)

Expected TRL or TRL range at completion of the project: 3 to 6

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Software, Research

Desired Deliverables Description

Phase 1 research should be conducted to demonstrate technical feasibility, with preliminary software being delivered for NASA testing, as well as show a plan towards Phase 2 integration. For proposals that include hardware development, delivery of a prototype under the Phase 1 contract is preferred, but not necessary. Phase 2 new technology development efforts shall deliver components at the TRL 5-6 level with mature algorithms and software components complete and preliminary integration and testing in an operational environment.

State of the Art and Critical Gaps

Currently navigation, guidance and control functions rely heavily on the ground for tracking data, data processing and decision making. As NASA operates farther from Earth and performs more complex operations requiring coordination between vehicles, round trip communication time delays make it is necessary to reduce reliance on Earth for navigation solutions and maneuver planning. Spacecraft that arrive at a near-Earth asteroid (NEA) or a planetary surface, may have limited
ground inputs and no surface or orbiting navigational aids. NASA currently does not have the navigational, trajectory and attitude flight control technologies that permit fully autonomous approach, proximity operations and landing without navigation support from Earth.

Relevance / Science Traceability

- Lunar Orbital Platform-Gateway
- Orion Multi-Purpose Crew Vehicle
- Wide Field Infrared Survey Telescope (WFIRST)
- Europa Clipper
- Lucy
- Psyche

These complex, deep space missions require a high degree of autonomy. The technology produced in this subtopic enables these kinds of missions by reducing or eliminating reliance on the ground for navigation and maneuver planning. The subtopic aims to reduce the burden of routine navigational support and communications requirements on network services, increase operational agility, and enable near real-time re-planning and opportunistic science. It also aims to enable classes of missions that would otherwise not be possible due to round-trip light time constraints.

Scope Title

Conjunction Assessment Risk Analysis (CARA)

Scope Description

The U.S. Space Surveillance Network currently tracks more than 22,000 objects larger than 10 centimeters and the number of objects in orbit is steadily increasing which causes an increasing threat to human spaceflight and robotic missions in the near-Earth environment. The NASA Conjunction Assessment Risk Analysis (CARA) team receives screening data from the 18th Space Control Squadron concerning predicted close approaches between NASA satellites and other space objects. CARA determines the risk posed by those events and recommends risk mitigation strategies, including collision avoidance maneuvers, to protect NASA non-human-spaceflight assets in Earth orbit. The ability to perform CARA more accurately and rapidly will improve space safety for all near-Earth operations. This subtopic seeks innovative technologies to improve the CARA process including (see Reference 1 for NASA Technical Area (TA) roadmaps):

- Event evolution prediction methods, models and algorithms with improved ability to predict characteristics for single and ensemble risk assessment, especially using artificial intelligence/machine learning (TA 5.5.3).
- Methods for combining commercial data (observations or ephemerides) with 18 SPCS –derived solutions (available as Vector Covariance Messages, Conjunction Data Messages, or Astrodynamics Support Workstation output) to create a single improved orbit determination solution including more data sources.

References

1. NASA Space Technology Roadmaps (2015): https://www.nasa.gov/offices/oct/home/roadmaps/index.html
2. NASA Conjunction Assessment Risk Analysis (CARA) Office: https://satellitesafety.gsfc.nasa.gov/cara.html

   3. NASA Orbital Debris Program Office: https://www.orbitaldebris.jsc.nasa.gov/
3. Newman, Lauri, K., "The NASA robotic conjunction assessment process: Overview and operational experiences," Acta Astronautica, Vol. 66, Issues 7-8, Apr-May 2010, pp. 1253-1261, https://www.sciencedirect.com/science/article/pii/S0094576509004913.
4. Newman, Lauri K., et al. "Evolution and Implementation of the NASA Robotic Conjunction Assessment Risk Analysis Concept of Operations." (2014). https://ntrs.nasa.gov/search.jsp?R=20150000159
5. Newman, Lauri K., and Matthew D. Hejduk. "NASA Conjunction Assessment Organizational Approach and the Associated Determination of Screening Volume Sizes." (2015). https://ntrs.nasa.gov/search.jsp?R=20150011461

Expected TRL or TRL range at completion of the project: 2 to 5

Desired Deliverables of Phase II

Prototype, Analysis, Software, Research

Desired Deliverables Description

Phase 1 research should be conducted to demonstrate technical feasibility, with preliminary software being delivered for NASA testing, as well as show a plan toward Phase 2 integration. Phase 2 new technology development efforts shall deliver components at the TRL 5-6 level with mature algorithms and software components complete and preliminary integration and testing in a quasi-operational environment.

State of the Art and Critical Gaps

Current state of the art has been adequate in performing conjunction assessment and collision mitigation for space objects that fall under the high interest events (HIE). With the incorporation of the Space Fence, the number of objects tracked and assessed for conjunctions will increase by one or more orders of magnitude, this presents a critical gap in which current approaches may not suffice. Thus, smarter ways to perform conjunction analysis and assessments such as methods for bundling events and performing ensemble risk assessment, Middle-duration risk assessment (longer duration than possible for discrete events but shorter than decades-long analyses that use gas dynamics assumptions), Improved Conjunction Assessment (CA) event evolution prediction, Machine learning / Artificial Intelligence (AI) applied to CA risk assessment parameters and/or event evolution are needed. The decision space for collision avoidance relies on not only the quality of the data (state and covariance) but also the tools and techniques for conjunction assessment.

Collision avoidance maneuver decisions are based on predicted close approach distance and probability of collision. The accuracy of these numbers depend on underlying measurements and mathematics used in estimation. Current methods assume Gaussian distributions for errors and that all objects are shaped like cannon balls for non-gravitational force computations. These assumptions and others cause inaccurate estimates which can lead decision makers to perform unnecessary collision avoidance maneuvers, thus wasting propellant. Better techniques are needed for orbit prediction and covariance characterization and propagation. Better modeling of non-gravitational force effects is needed to improve orbit prediction. Modeling of non-gravitational forces relies on knowledge of individual object characteristics.

Relevance / Science Traceability

This technology is relevant and needed for all human spaceflight and robotic missions in the near-Earth environment. The ability to perform CARA more accurately will improve space safety for all near-Earth operations, improve operational support by providing more accurate and longer term predictions and reduce propellant usage for collision avoidance maneuvers.

H9.05: Transformational Communications Technology (SBIR)

Lead Center: GRC

Participating Center(s): GSFC

Technology Area: 5.0.0 Communication and Navigation

Related Subtopic Pointer(s): Z8.02 T5.04 H6.22 H9.07 H9.01

Scope Title

Revolutionary Concepts

Scope Description

NASA seeks revolutionary transformational communications technologies, for lunar exploration and beyond, that emphasize not only dramatic reduction in system size, mass and power but also dramatic implementation and operational cost savings while improving overall communications architecture performance. The proposer is expected to identify new ideas, create novel solutions and execute feasibility demonstrations. Emphasis for this subtopic is on the far-term (≈10yrs.) insofar as mission insertion and commercialization but it is expected that the proposer proves fundamental feasibility via prototyping within the normal scope of the SBIR program. The transformational communications technology development will focus research in the following areas:

- Systems optimized for energy efficiency (information bits per unit energy)
- Hybridization of communications and sensing systems to maximize performance and minimize Size, Weight and Power (SWaP), especially for harsh environments
- Advanced materials; smart materials; electronics embedded in structures; functional materials; graphene-based electronics/detectors
- Techniques to overcome traditional analog-to-digital converter speed and power consumption limitations
- Technologies that address flexible, scalable digital/optical core processing topologies to support both RF and optical communications in a single terminal
- Nanoelectronics and nanomagnetics; quantum logic gates; single electron computing; superconducting devices; technologies to leapfrog Moore’s law.
- Energy harvesting technologies to enhance space communication system efficiency
- Human/machine and brain-machine interfacing to enable new communications paradigms; the convergence of electronic engineering and bio-engineering; neural signal interfacing
- Quantum communications, methods for probing quantum phenomenon, methods for exploiting exotic aspects of quantum theory.

The research should be conducted to demonstrate theoretical and technical feasibility during the Phase I and Phase II development cycles and be able to demonstrate an evolutionary path to insertion within approximately 10 years. Delivery of a prototype of the most critically enabling element of the technology for NASA testing at the completion of the Phase II contract is expected.

Phase I deliverables shall include a final report describing theoretical analysis and prototyping concepts. The technology should have eventual commercialization potential. For Phase II consideration, the final report should include a detailed path towards Phase II prototype hardware.

References

https://sbir.nasa.gov/sites/default/files/Presentation15_CharlesNiederhaus.pdf

https://www.nasa.gov/pdf/675092main_SCaN_ADD_Executive_Summary.pdf

Expected TRL or TRL range at completion of the project: 2 to 4

Desired Deliverables of Phase II

Prototype, Analysis, Research

Desired Deliverables Description

The proposer is expected to identify new ideas, create novel solutions and execute feasibility demonstrations. Emphasis for this subtopic is on the far-term (≈10yrs.) insofar as mission insertion and commercialization but it is expected that the proposer proves fundamental feasibility via prototyping within the normal scope of the SBIR program.

State of the Art and Critical Gaps

While according to the Business R&D and Innovation Survey of the $323 billion of research and development performed by companies in the United States in 2013, Information and Computing Technology industries accounted for 41%. But it must be understood that the majority of these investments seek short term returns and that most of the investment is in computer technology, cloud computing and networking, semiconductor manufacturing, etc. - not new and futuristic "over-the-horizon" technologies with uncertain returns-on-investment. As a concrete example, deep-space mission modeling indicates a need for a 10X improvement in data rate per decade out to 2040. How will that be achieved? To some extent that goal will be achieved by moving to Ka-band and optical communications and perhaps antenna arraying on a massive scale. But given the ambitiousness of the goal, disruptive technologies like what is being sought here, will be required.

Relevance / Science Traceability

NASA seeks revolutionary, transformational communications technologies that emphasize not only dramatic reduction in system size, mass, and power but also dramatic implementation and operational cost savings while improving overall communications architecture performance. This is a broad sub-topic expected to identify new ideas, create novel solutions and execute feasibility demonstrations. Emphasis for this subtopic is on the far-term (≈10yrs.) insofar as mission insertion and commercialization but it is expected that the proposer proves fundamental feasibility via prototyping within the normal scope of the SBIR program.

H9.07: Cognitive Communication (SBIR)

Lead Center: GRC

Participating Center(s): GSFC, JPL

Technology Area: 5.0.0 Communication and Navigation

Related Subtopic Pointer(s): Z8.02 S3.08 H9.05 S5.03 Z2.02 H6.22 T5.04

Scope Title

Lunar Cognitive Capabilities

Scope Description

NASA's Space Communication and Navigation (SCaN) program seeks innovative approaches to increase mission science data return, improve resource efficiencies for NASA missions and communication networks and ensure resilience in the unpredictable space environment. The Cognitive Communication subtopic specifically focuses on advances in space communication driven by on-board data processing and modern space networking capabilities. A cognitive system is envisioned to sense, detect, adapt, and learn from its experiences and environment to optimize the communications capabilities for the user mission satellite or network infrastructure. The underlying need for these technologies is to reduce both the mission and network operations burden.

Examples of these cognitive capabilities include:

- Link technologies - reconfiguration and autonomy, maximizing use of bandwidth while avoiding interference
- Network technologies - robust inter-satellite links, data storage/forwarding, multi-node routing in unpredictable environments
- System technologies - optimal scheduling techniques for satellite and surface relays in distributed and real-time environments

Through Space Policy Directive-1, NASA is committed to landing American astronauts on the Moon by 2024. In support of this goal, cognitive communication techniques are needed for lunar communication satellite and surface relays. Cognitive agents operating on lunar elements will manage communication, provide diagnostics, automate resource scheduling, and dynamically update data flow in response to the types of data flowing over the lunar network. Goals of this capability are to improve communications efficiency, mitigate channel impairments, and reduce operations complexity and cost through intelligent and autonomous communications and data handling.

Examples of research and/or technology development include:

- On-board processing technology and techniques to enable data switching, routing, storage, and processing on a relay spacecraft
- Data-centric, decentralized network data routing and scheduling techniques that are responsive to quality of service metrics
- Simultaneous wideband sensing and communications for S-, X-, and Ka-bands, coupled with algorithms that learn from the environment
- Artificial intelligence and machine learning algorithms applied to optimize space communication links, networks, or systems
- Flexible communication platforms with novel signal processing technology to support cognitive approaches
- Other innovative, related areas of interest to the field of cognitive communications

Proposals to this subtopic should consider application to a lunar communications architecture consisting of surface assets (e.g., astronauts, science stations, surface relays), lunar communication relay satellites, Gateway, and ground stations on Earth. The lunar communication relay satellites require technology with low size, weight, and power attributes suitable for small satellite (e.g., 50kg) or cubesat operations. Proposed solutions should highlight advancements to provide the needed communications capability while minimizing use of on-board resources such as power and propellant. Proposals should consider how the technology can mature into a successful demonstration in the lunar architecture.

References

Several related reference papers and articles include:

- "NASA Explores Artificial Intelligence for Space Communications"
    - https://www.nasa.gov/feature/goddard/2017/nasa-explores-artificial-intelligence-for-space-communications

- "Implementation of a Space Communications Cognitive Engine"
    - https://ntrs.nasa.gov/search.jsp?R=20180002166
- "Reinforcement Learning for Satellite Communications: From LEO to Deep Space Operations"
    - https://ieeexplore.ieee.org/document/8713802
- "Cognitive Communications and Networking Technology Infusion Study Report"
    - https://ntrs.nasa.gov/search.jsp?R=20190011723
- "Multi-Objective Reinforcement Learning-based Deep Neural Networks for Cognitive Space Communications"
    - https://ntrs.nasa.gov/search.jsp?R=20170009153
- "Assessment of Cognitive Communications Interest Areas for NASA Needs and Benefits"
    - https://ntrs.nasa.gov/search.jsp?R=20170009386
- "Architecture for Cognitive Networking within NASAs Future Space Communications Infrastructure"
    - https://ntrs.nasa.gov/search.jsp?R=20170001295
- "Modulation Classification of Satellite Communication Signals Using Cumulants and Neural Networks"
    - https://ntrs.nasa.gov/search.jsp?R=20170006541

A related conference, co-sponsored by NASA and the Institute of Electrical and Electronics Engineers (IEEE), the Cognitive Communications for Aerospace Applications Workshop, has additional information available at: http://ieee-ccaa.com/

Expected TRL or TRL range at completion of the project: 4 to 6

Desired Deliverables of Phase II

Prototype, Hardware, Software

Desired Deliverables Description

Phase I will study technical feasibility, infusion potential for lunar operations, clear/achievable benefits and show a path towards a Phase II implementation. Phase I deliverables can include a feasibility assessment and concept of operations of the research topic, simulations and/or measurements, validation of the proposed approach to develop a given product (TRL 3-4) and a plan for further development of the specific capabilities or products to be performed in Phase II. Early development, integration, test, and delivery prototype hardware/software is encouraged but not necessary.

Phase II will emphasize hardware/software development with delivery of specific hardware or software product for NASA targeting demonstration operations on a small satellite or cubesat platform. Phase II deliverables include a working prototype (engineering model) of the proposed product/platform or software, along with documentation of development, capabilities, and measurements, and related documents and tools as necessary for NASA to modify and use the cognitive software capability or hardware component(s). Hardware prototypes shall show a path towards flight demonstration, such as a flight qualification approach and preliminary estimates of thermal, vibration, and radiation capabilities of the flight hardware. Software prototypes shall be implemented on platforms that have a clear path to a flight qualifiable platform. Opportunities and plans should be identified for technology commercialization. Software applications and platform/infrastructure deliverables for software defined radio platforms shall be compliant with the latest NASA standard for software defined radios, the Space Telecommunications Radio System (STRS), NASA-STD-4009 and NASA-HNBK-4009.

State of the Art and Critical Gaps

To summarize NASA Technology Roadmap TA5: "As human and science exploration missions move further from Earth and become increasingly more complex, they present unique challenges to onboard communications systems and networks...Intelligent radio systems will help manage the increased complexity and provide greater capability to the mission to return more science data...Reconfigurable radio systems...could autonomously optimize the RF links, network protocols, and modes used based on the needs of the various mission phases. A cognitive radio system would sense its RF environment and adapt and learn from its various configuration changes to optimize the communications links throughout the system in order to maximize science data transfer, enable substantial efficiencies, and reduce latency. The challenges in this area are in the efficient integration of different capabilities and components, unexpected radio or system decisions or behavior, and methods to verify decision-making algorithms as compared to known, planned performance."

The technology need for the lunar communication architecture includes:

- Data routing from surface assets to a lunar communication relay satellite, where data is unscheduled, a-periodic, and ad-hoc
- Data routing between lunar relay satellites as necessary to conserve power, route data to Earth, and meet quality of service requirements
- Efficient use of lunar communication spectrum while co-existing with future/current interference sources
- On-demand communication resource scheduling
- Multi-hop, delay tolerant routing

Critical gaps between the state of the art and the technology need include:

- Implementation of artificial intelligence and machine learning techniques on SWaP-constrained platforms
- Integrated wide-band sensing and narrow-band communication on the same radio terminal
- Inter-satellite networking and routing, especially in unpredictable and unscheduled environments
- On-demand scheduling technology for communication links
- Cross-layer optimization approaches for optimum communication efficiency at a system level

Relevance / Science Traceability

Cognitive technologies are critical for the lunar communications architecture. The majority of lunar operations will be run remotely from Earth, which could require substantial coordination and planning as NASA, foreign space agencies, and commercial interests all place assets on the Moon. As lunar communications and networks become more complex, cognition and automation are essential to mitigate complexity and reduce operations costs. Machine learning will configure networks, choose radio configurations, adjust for impairments and failures, and monitor short and long term performance for improvements.

S3.04: Guidance, Navigation, and Control (SBIR)

Lead Center: GSFC

Participating Center(s): JPL, MSFC

Technology Area: 5.0.0 Communication and Navigation

Related Subtopic Pointer(s): Z8.02 Z3.05 Z7.01 H9.03 Z8.09

Scope Title

Guidance, Navigation, and Control

Scope Description

NASA seeks innovative, groundbreaking, and high impact developments in spacecraft guidance, navigation, and control technologies in support of future science and exploration mission requirements. This subtopic covers mission enabling technologies that have significant Size, Weight and Power, Cost, and Performance (SWaP-CP) improvements over the state-of-the-art Commercial Off-The-Shelf (COTS) capabilities in the areas of Spacecraft Attitude Determination and Control Systems, Absolute and Relative Navigation Systems, and Pointing Control Systems, and Radiation-Hardened Guidance, Navigation, and Control (GNC) Hardware.

Component technology developments are sought for the range of flight sensors, actuators, and associated algorithms and software required to provide these improved capabilities. Technologies that apply to most spacecraft platform sizes will be considered.

Advances in the following areas are sought:

- Spacecraft Attitude Determination and Control Systems: Sensors and actuators that enable <0.1 arcsecond level pointing knowledge and arcsecond level control capabilities for large space telescopes, with improvements in size, weight, and power requirements.
- Absolute and Relative Navigation Systems: Autonomous onboard flight navigation sensors and algorithms incorporating both spaceborne and ground-based absolute and relative measurements. For relative navigation, machine vision technologies apply. Special considerations will be given to relative navigation sensors enabling precision formation flying, astrometric alignment of a formation of vehicles, robotic servicing and sample return capabilities, and other GNC techniques for enabling the collection of distributed science measurements. In addition, flight sensors and algorithms that support onboard terrain relative navigation are of interest.
- Pointing Control Systems: Mechanisms that enable milliarcsecond class pointing performance on any spaceborne pointing platforms. Active and passive vibration isolation systems, innovative actuation feedback, or any such technology that can be used to enable other areas within this subtopic applies.
- Radiation-Hardened Hardware: GNC sensors that could operate in a high radiation environment, such as the Jovian environment.
- Fast-light or Exceptional-Point Enhanced Gyroscopes and Accelerometers: In conventional ring laser gyros, precision increases with cavity size and measurement time. However, by using Fast-Light (FL) media or Exceptional Points (EPs) in coupled resonators, an increase in gyro sensitivity can be achieved without having to increase size or measurement time, thereby increasing the time for standalone spacecraft navigation. (The increased precision also opens up new science possibilities such as measurements of fundamental physical constants, improving the sensitivity-bandwidth product for gravity wave detection, and tests of general relativity.) Prototype FL- or EP-enhanced gyros are sought that can be implemented in a compact rugged design that is tolerant to variations in temperature and G-conditions, with the ultimate goal of demonstrating decreased angular random walk.

Phase I research should be conducted to demonstrate technical feasibility as well as show a plan towards Phase II integration and component/prototype testing in a relevant environment. Phase II technology development efforts shall deliver component/prototype at the TRL 5–6 level consistent with NASA SBIR/STTR Technology Readiness Level (TRL) Descriptions. Delivery of final documentation, test plans, and test results are required. Delivery of a hardware component/prototype under the Phase II contract is preferred.

Proposals should show an understanding of one or more relevant science or exploration needs and present a feasible plan to fully develop a technology and infuse it into a NASA program.

This subtopic is for all mission enabling Guidance, Navigation, and Control technology in support of SMD missions and future mission concepts. Proposals for the development of hardware, software, and/or algorithm are all welcome. The specific applications could range from CubeSats/SmallSats, to ISS payloads, to flagship missions.

References

- 2017 NASA Strategic Technology Investment Plan: https://go.usa.gov/xU7sE
- 2015 NASA Technology Roadmaps: https://go.usa.gov/xU7sy

Expected TRL or TRL range at completion of the project: 4 to 6

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Software

Desired Deliverables Description

Prototype hardware/software, documented evidence of delivered TRL (test report, data, etc.), summary analysis, supporting documentation.

State of the Art and Critical Gaps

Capability area gaps:

- Spacecraft GNC Sensors – Highly integrated, low power, low weight, rad-hard component sensor technologies, and multifunctional components.
- Spacecraft GNC Estimation and Control Algorithms – autonomous proximity operations algorithm, robust distributed vehicle formation sensing and control algorithms.

Relevance / Science Traceability

Science areas: Heliophysics, Earth Science, Astrophysics, and Planetary missions' capability requirement areas:

- Spacecraft GNC Sensors – optical, RF, inertial, and advanced concepts for onboard sensing of spacecraft attitude and orbit states
- Spacecraft GNC Estimation and Control Algorithms – Innovative concepts for onboard algorithms for attitude/orbit determination and control for single spacecraft, spacecraft rendezvous and docking, and spacecraft formations.

T5.03: Electric Field Mapping and Prediction Methods within Spacecraft Enclosures (STTR)

Lead Center: KSC

Participating Center(s): GSFC, JPL, JSC, MSFC

Technology Area: 5.0.0 Communication and Navigation

Related Subtopic Pointer(s): S5.06 Z13.01

Scope Title

Expected Electric Field Prediction Methods in Fairing/Aircraft and Spacecraft Enclosures

Scope Description

NASA Launch Services program is responsible for ensuring the safety of NASA payloads on commercial rockets. NASA has also undertaken Gateway. This includes prediction and mitigation of hazardous electric fields created within the payload enclosure and similar areas of the rocket. NASA and industry have commonly used approximation methods to determine the average fields in enclosures. In the last decade the Launch Services Program (LSP) has funded studies to support quantification of electromagnetic field characterization in fairing cavities due to internal and external sources. By accurately predicting these fields, acoustic and thermal blanketing can be optimized for Radio Frequency (RF) attenuation and design changes can be quickly evaluated reducing schedule impacts. Cost savings can also be realized by reducing stringent radiated susceptibility requirements, and reliability improved by accurately predicting signal transmission/reception environments within enclosures. This methodology can also improve human exposure safety limits evaluations for manned vehicle enclosures with transmitting systems.

Initially, studies focused on computational methods using the recent advances in computing power and the improved efficiency of matrix based solutions provided by Graphics Processing Unit (GPU) computing. Results indicate solution of an integrated fairing is deterministic, but sensitive to small variation in structures, materials. As of yet, only the empty or sparse cavity can be reliably solved with 3D computational tools, even with large computing systems and the use of non-linear basis functions. Results also indicate that computational approximation methods such as physical optics and multilevel fast multipole are not reliable prediction methods within enclosures of this scale because of the underlying assumption sets that are inconsistent with enclosure boundaries. More recently, LSP has concentrated on statistically formulating a compilation of test/computational results to produce a maximum expected environment. Preliminary results are promising in the area of statistical bounding of the desired solution. The researched methodology should offer the following advantages over 3D computational and standard volume based approximation methods:

- Predict both statistical mean and maximum expected E field and/or common mode current.
- Consider the over-moded (electrically large conductive cavities) and under-moded (electrically smaller damped enclosures).
- Consider complex materials with multiple joined enclosures.
- Applications of this prediction methodology are far reaching and include shielding effectiveness and prediction of fields within a cavity enclosure due to internal transmitters and operating avionics.

To enable bounded solutions in electromagnetic environment prediction, proposals are solicited to develop technology that does the following:

- Bounds the expected peak electric field environment inside enclosures such as rocket fairings, and spacecraft enclosures. The method should include the technology required, the technique, as well as the necessary verification efforts.
- Develops a numerical or statistically based methodology for characterizing shielding effectiveness of enclosures with associated applicable apertures.
- Develops methods field enhancement/reduction based on thermal/acoustic blanketing and metal/composite components such as avionics and Payload Attached Fitting (PAF) structures.
- Develops preliminary user friendly modeling software that can be easily customized to support NASA-specific applications.

References

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- [2] D. A. Hill, “Electromagnetic Fields in Cavities. Deterministic and Statistical Theories” John Wiley & Sons, Hoboken, New Jersey 2009
- [3] J. Ladbury, G. Koepke, and D. Camell, "Evaluation of the NASA Langley Research Center Mode-Stirred Chamber Facility," NIST, Technical Note 1508, 1999.
- [4] A. Schaffar and P. N. Gineste, "Application of the power balance methods to E- field calculation in the ARIANE 5 launcher payloads cavities," Presented at International Symposium on EMC, Long Beach, 2011, pp. 284-289.
- [5] D.H. Trout, "Electromagnetic Environment in Payload Fairing Cavities," Dissertation, University of Central Florida, 2012.
- [6] L. Kovalevsky, R.S. Langley, P. Besnier and J. Sol, “Experimental validation of the Statistical Energy Analysis for coupled reverberant rooms”, Proc. IEEE Intnl. Symp. EMC, Dresden, August 2015
- [7] Bremner, P.G, Vazquez, G., Trout, D.H and Cristiano, D.J., “Canonical Statistical Model for Maximum Expected Imission of Wire Conductor in an Aperture Enclosure”, Proc. IEEE Intnl. Symp. EMC, Ottawa, October 2016
- [8] G.B Tait, C. Hager, M.B. Slocum and M.O. Hatfiled, “On Measuring Shielding Effectiveness of Sparsely Moded Enclosures in a Reverberation Chamber”, IEEE Trans. on EMC, Volume: 55, Issue: 2, October 2012
- [9] P. Bremner, G.Vazquez, D. Trout, P. Edwards "Shielding Effectiveness: When to Stop Blocking and Start Absorbing", IEEE EMC International Symposium, New Orleans, July 2019

Expected TRL or TRL range at completion of the project: 3 to 6

Desired Deliverables of Phase II

Prototype, Analysis, Software, Research

Desired Deliverables Description

Phase I Deliverables: Research, identify and evaluate candidate algorithms or concepts for electromagnetic field mapping of typical spacecraft and rocket enclosures. Demonstrate the technical feasibility, and show a path towards a computer model development. It should identify improvements over the current state of the art for both time/resource savings and systems development and the feasibility of the approach in a varied-enclosure environment. Lab-level demonstrations are required. Deliverables must include a report documenting findings.

Phase II Deliverables: Emphasis should be placed on developing usable computer model and demonstrating the technology with under and over-moded conditions with testing. Deliverables shall include a report outlining the path showing how the technology could be matured and applied to mission-worthy systems, verification test results, computer model with user’s and other associated documentation. Deliverable of a functional computer model with associated software is expected at the completion of the Phase II contract.

State of the Art and Critical Gaps

Reliability of communications systems is critical for all spacecraft. Determining RF exposure limits in cavity environments is also critical. Given this criticality it is often desired to transmit and receive before separation from the launch vehicle where there is precise tracking information to improve the probability of signal capture. When the transmission or reception is in the launch vehicle fairing whether for pre-flight checks or during launch, the presence of the cavity surrounding the antennas causes significant uncertainties in the desired signal. In addition, there is a significant increase in the RF environment in which the spacecraft and launch vehicle hardware are exposed. Since hardware qualification testing is based on free space environments the higher fields in the cavity can lead to an increase mission risk of failure due to susceptible hardware. Prediction of fields within rectangular highly conductive over-moded chambers is well studied in the reverberation testing community; however, launch vehicle fairings are sometimes composite and always covered with acoustic damping materials that have unknown RF damping characteristics. There are also thermal materials surrounding launch vehicle and spacecraft avionics and instruments leading to further complications in defining the communication path losses and RF environment exposure and cavity mode underdamping characteristics where more research is needed especially in the layered wall covering case.

Determining the RF environment in the fairing cavity is a significant problem that affects every launched mission; even if transmission with the fairing is not planned, it has historically happened inadvertently and the effects of failed inhibits are required to be provided. Shielding effectiveness to external range and launch vehicle transmitters are also significantly affected by not only the material conductive properties, but also the characteristics of the penetrated cavity.

3D computational electromagnetic tools are limited by the size of the matrix required to solve the typical transmit frequency of at least 2GHz in a cavity with 5 meter diameters and over 10 meter length. The size of just modeling the fairing alone is daunting using method of moments (limited also by non-uniqueness for external radiators) and unachievable with finite difference frequency domain. When internal spacecraft and blanketing structures are added, the computational limits are quickly surpassed. Approximation techniques such as physical optics and multilevel fast multipole methods are limited by underlying assumptions that do not hold in cavity environments. Time domain techniques are not clearly fitted for frequency specific applications and have shown similar size/complexity limitations.

Substantially, new methods are needed to predict path loss, shielding effectiveness and RF environment in launch vehicle fairings and spacecraft cavities.

Relevance / Science Traceability

This subtopic is intended for STTR, but all NASA payloads, particularly those with hardware sensitive to electric fields, will benefit from launch and ascent risk reduction.

T5.04: Quantum Communications (STTR)

Lead Center: GRC

Participating Center(s): GSFC, JPL

Technology Area: 5.0.0 Communication and Navigation

Related Subtopic Pointer(s): H9.05 A2.02 T8.06 H6.22 H9.01 H9.07 Z8.02

Scope Description

NASA seeks to develop quantum networks to support the transmission of quantum information for aerospace applications. This distribution of quantum information could potentially be utilized in secure communication, sensor arrays and quantum computer networks. Quantum communication may provide new ways to improve communication link security and availability through techniques such as quantum cryptographic key distribution. Another area of benefit is the entanglement of distributed sensor networks to provide extreme sensitivity for applications such as astrophysics, planetary science and earth science. Also of interest are ideas or concepts to support the communication of quantum information between quantum computers over significant free space distances (greater than 10km up to GEO) for space applications. Technologies that are needed include quantum memory, quantum entanglement sources, quantum repeaters, high efficiency detectors, quantum processors, quantum sensors that make use of quantum communication for distributed arrays and integrated systems that bring several of these aspects together using Integrated Quantum

Photonics. A key need for all of these are technologies with low size, weight and power that can be utilized in aerospace applications. Some examples of requested innovation include:

- High brightness, efficient and tunable sources of entangled photon pairs.
- Photonic waveguide interferometric circuits for quantum information processing and manipulation of entangled quantum states; requires phase stability, low propagation loss, i.e. < 0.1 dB/cm, and efficient fiber coupling, i.e. coupling loss < 1.5 dB
- Waveguide-integrated single photon detectors for > 100 MHz incidence rate, 1-sigma time resolution of < 25 ps, dark count rate < 100 Hz, and single-photon detection efficiency > 50% at highest incidence rate
- Integrated sensors that support arrays of distributed sensors, such as an entangled interferometric imaging array
- Integrated photonic circuit quantum memory
- Integrated photonic circuits and detectors for balanced homodyne detection
- Quantum entanglement verifying system

Quantum sensor focused proposals that do not include an aspect of quantum communication should propose to the Quantum Sensing and Measurement subtopic as individual quantum sensors are not covered by this subtopic.

References

Katz, Evan, Benjamin Child, Ian Nemitz, Brian Vyhnalek, Tony Roberts, Andrew Hohne, Bertram Floyd, Jonathan Dietz, and John Lekki. “Studies on a Time-Energy Entangled Photon Pair Source and Superconducting Nanowire Single-Photon Detectors for Increased Quantum System Efficiency”, SPIE Photonics West, San Francisco, California, 02/06/2019.

Kitagawa, M. and Ueda, M., “Squeezed spin states," Phys. Rev. A 47, 5138{5143 (1993).

Daniel Gottesman, Thomas Jennewein, and Sarah Croke, “Longer-Baseline Telescopes Using Quantum Repeaters”, Phys. Rev. Lett. 109, 16 August 2012.

Nicolas Gisin & Rob Thew, “Quantum communication”, Nature Photonics volume 1, pages 165–171 (2007)

H. J. Kimble, “The quantum internet”, Nature volume 453, pages 1023–1030 (19 June 2008)

C. L. Degen, F. Reinhard, and P. Cappellaro, “Quantum sensing”, Rev. Mod. Phys. 89, 25 July 2017

Nemitz, Ian, Jonathan Dietz, Evan Katz, Brian Vyhnalek, and Benjamin Child. “Bell inequality experiment for a high brightness time-energy entangled source”, SPIE Photonics West, San Francisco, CA, 03/01/2019.

Expected TRL or TRL range at completion of the project: 3 to 5

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Research

Desired Deliverables Description

Phase I research should (highly encouraged) be conducted to demonstrate technical feasibility with preliminary hardware (i.e. beyond architecture approach/theory; a proof-of-concept) being delivered for NASA testing, as well as show a plan toward Phase II integration. Phase II new technology development efforts shall deliver components at the TRL 4-6 level with mature hardware and preliminary integration and testing in an operational environment. Deliverables are desired that substantiate the quantum communication technology utility for positively impacting the NASA mission. The quantum communication technology should impact one of three key areas: information security, sensor networks, and networks of quantum computers. Deliverables that substantiate technology efficacy include reports of key experimental demonstrations that show significant capabilities, but in general it is desired that the deliverable include some hardware that shows the demonstrated capability.

State of the Art and Critical Gaps

There is a critical gap between the United States and other countries, such as Japan, Singapore, Austria and China in quantum communications in space. Quantum communications is called for in the 2018 National Quantum Initiative (NQI) Act, which directs National Institute of Standards and Technology (NIST), National Science Foundation (NSF) and Department of Energy (DOE) to pursue research, development and education activities related to Quantum Information Science. Applications in quantum communication, networking and sensing, all proposed in this subtopic, are the contributions being pursued by NASA to integrate the advancements being made through the NQI.

Relevance / Science Traceability

This technology would benefit NASA communications infrastructure as well as enable new capabilities that support its core missions. For instance, advances in quantum communication would provide capabilities for added information security for spacecraft assets as well as provide a capability for linking quantum computers on the ground and in orbit. In terms of quantum sensing arrays, there are a number of sensing applications that could be supported through the use of quantum sensing arrays for dramatically improved sensitivity.

Focus Area 6: Life Support and Habitation Systems

Lead MD: HEOMD

Participating MD(s): STTR

The Life Support and Habitation Systems Focus Area seeks key capabilities and technology needs encompassing a diverse set of engineering and scientific disciplines, all of which provide technology solutions that enable extended human presence in deep space and on planetary surfaces, such as Moon and Mars. The focus is on those mission systems and elements that directly support astronaut crews, such as Environmental Control and Life Support Systems (ECLSS), Extravehicular Activity (EVA) systems, plant growth for bioregenerative food production, and radiation tolerant avionics and control systems. Because spacecraft and their systems may involve multiple partnerships, with institutional, corporate and governmental involvement, Model Based Systems Engineering approaches may enable and improve their distributed development.

For future crewed missions beyond low-Earth orbit (LEO) and into the solar system, regular resupply of consumables and emergency or quick-return options will not be feasible. New technologies must be compatible with attributes of the environments we encounter, including microgravity or partial gravity, varying atmospheric pressure and composition, space radiation, and the presence of planetary dust. Technologies of interest are those that enable long-duration, safe, economical and sustainable deep-space human exploration. Special emphasis is placed on developing technologies that will fill existing gaps as described in this solicitation, that reduce requirements for consumables and other resources, including mass, power, volume and crew time, and which will increase safety and reliability with respect to the state-of-the-art. Spacecraft may be untended by crew for long periods, therefore systems must be operable after these intervals of dormancy.

Environmental Control and Life Support Systems encompass process technologies and monitoring functions necessary to provide and maintain a livable environment within the pressurized cabin of crewed spacecraft, including environmental monitoring, water recycling, and atmosphere revitalization. These processes and functions include recovering resources from or repurposing gaseous, liquid and solid wastes. Unique needs exist for the Extra-vehicular Mobility Unit’s (EMU) pressure garment and Portable Life Support System (PLSS).

These include targeted improvements to the Liquid Cooling and Ventilation Garment (LCVG) along with new capabilities, including a regenerable trace contaminant control system, a thermal loop bypass relief valve capable of re-calibration, and a robust feed water supply assembly. Outside of the protection of the Earth's magnetosphere, radiation in deep space will be a challenge. However, within the shielded environment of human spacecraft and habitats, non-critical electronic systems may be able to use commercial off the shelf (COTS) rather than expensive radiation hardened parts.

The current collaborative environment between government, commercial and international sectors will result in the distributed development of human spacecraft elements and systems for human missions of the future such as Gateway and lunar surface missions including Artemis. Their integration may benefit from advances in model based systems engineering approaches.

Please refer to the description and references of each subtopic for further detail to guide development of proposals.

H3.01: Advancements in Carbon Dioxide Reduction: Critical Subsystems and Solid Carbon Repurposing (SBIR)

Lead Center: MSFC

Participating Center(s): ARC, GRC, JSC, KSC

Technology Area: 6.0.0 Human Health, Life Support and Habitation Systems

Related Subtopic Pointer(s):

Scope Title

Carbon Dioxide Reduction System Components and Unit Processes

Scope Description

NASA has invested in many carbon dioxide reduction technologies over the years to increase the percentage of oxygen recovery from carbon dioxide in human spacecraft for long duration missions. Examples of technologies include, but are not limited to, Series-Bosch, Continuous Bosch, Methane Pyrolysis and Microfluidic Carbon Dioxide Electrolysis. Significant technical challenges still face these process technologies and are impeding progress in technology maturation. Critical technical elements of these technologies have a high degree of technical difficulty. Examples where additional technology development is needed include (this is a partial list):

- High temperature gas purification and/or separation for CO, H_2, and hydrocarbon rich streams.
- Nuisance particulate carbon contamination.
- Solid carbon clogging of frits and filters in recycle gas streams.
- Safe collection, removal and disposal of solid carbon while reactors are in operation.
- Subsystems to recharge reactors with new catalyst and to efficiently use or recycle consumable catalysts.

This subtopic is open to consider novel ideas that address any of the numerous technical challenges that face development of carbon dioxide reduction hardware with particular attention to those listed above. Specifics on two of these challenges are provided below.

<u>Gas Purification and/or Separation for Carbon Monoxide, Hydrogen and Hydrocarbon Rich Streams</u>

Many process technologies currently under development have challenging multi-component streams which could benefit from improved gas separation technology. High purity, high yield and continuous supply of separated gases are all desirable features of a proposed technology. The targeted process streams that may benefit from improved gas separations are the following:

- Producing a high-purity hydrogen product from a hydrogen-rich gas stream containing acetylene (as high as 6.4 mole %), trace amounts of other hydrocarbons (ethylene, ethane, benzene), unreacted methane, carbon monoxide, carbon dioxide and water vapor. It is imperative that the proposed separation technologies do not hydrogenate hydrocarbons, such as acetylene. This separation is directed at methane pyrolysis technologies including the Plasma Pyrolysis Assembly (PPA).
- Hydrogen separation from an ethylene-rich stream. This separation is directed at the effluent stream from a Microfluidic Electrochemical Reactor which consists of ethylene, hydrogen, methane, carbon monoxide, carbon dioxide and water vapor.
- Recovery of unreacted carbon dioxide and hydrogen from a carbon monoxide-rich stream. This separation is needed for a Bosch/Reverse Water Gas Shift (RWGS) Reactor.

Technology solutions could include, but not be limited to, filtration, mechanical separation or novel sorbents. If novel sorbents are developed the proposed technology solution should also address issues with scale-up to kg quantities (difficult for some novel sorbents). Technology solutions proposed in this subtopic could potentially be leveraged for In-Situ Resource Utilization (ISRU) applications.

<u>Separation of Particulate Carbon and Hydrocarbons from Process Gas Streams</u>

Oxygen recovery technology options, including carbon formation reactors and methane pyrolysis reactors almost universally result in particulates in the form of solid carbon or solid hydrocarbons. Mitigation for these particulates will be essential to the success and maintainability of these systems during long duration missions. Techniques and methods leading to compact, regenerable devices for removing, managing and disposing of residual particulate matter within ECLSS process equipment are sought. Separation performance approaching HEPA rating is desired for ultrafine particulate matter with minimal pressure drop. The separator should be capable of operating for hours at high particle loading rates and then employ techniques and methods to restore its capacity back to nearly 100% of its original clean state through in-place and autonomous regeneration or self-cleaning operations using minimal or no consumables (including media-free hydrodynamic separators). The device must minimize crew exposure to accumulated particulate matter and enable easy particulate matter disposal or chemical repurposing.

State of the Art and Critical Gaps

Future long duration human exploration missions may benefit from further closure of the Atmosphere Revitalization System (ARS). The state-of-the-art Sabatier system, which has flown on the International Space Station as the Carbon Dioxide Reduction Assembly (CRA), only recovers about half of the oxygen from metabolic carbon dioxide. This is because there is insufficient hydrogen to react all available carbon dioxide. The Sabatier reacts hydrogen with carbon dioxide to produce methane and water. The methane is vented overboard as a waste product causing a net loss of hydrogen. Mars missions target >75% oxygen recovery from carbon dioxide, with a goal to approach 100% recovery. NASA is developing several alternate technologies that have the potential to increase the percentage of oxygen recovery from carbon dioxide, toward fully closing the ARS loop. Methane pyrolysis recovers hydrogen from methane, making additional hydrogen available to react with carbon dioxide. Other technologies under investigation process carbon dioxide, recovering a higher percentage of oxygen than the Sabatier. All of these alternative systems, however, need additional technology investment to reach a level of maturity necessary for consideration for use in a flight environmental control and life support system (ECLSS).

Scope Title

Solid Carbon Repurposing

Scope Description

Solid carbon is produced as a major by-product from many candidate oxygen recovery technologies under consideration for long-duration missions, including Bosch, Series Bosch, Methane Pyrolysis by Carbon Vapor Deposition, and technologies containing carbon formation reactors. Based on metabolic CO_2 production for a crew of 4, 1.135 kg of solid carbon, with a volume as high as 2.8 liters, may be produced each day by oxygen recovery technologies, which then must be disposed of or repurposed. Repurposing of this carbon reduces logistical challenges associated with its disposal and may ultimately result in materials or processes advantageous for long-duration missions. The produced solid carbon may include nanofibers, microfibers and amorphous material with varying particle size, with the smallest in the micrometer range (10-50 µm). It may contain quantities of metals including, but not limited to, iron, nickel and cobalt. The solid carbon may be in the form of a loose powder or a densified cake with densities ranging from 0.4 to 1.8 g/cc and will vary by technology. Venting or disposal of this carbon to space will present considerable logistical challenges and will result in large volumes of space debris. Disposal of this carbon on a planetary surface may result in concerns for planetary protection or planetary science. NASA is seeking technologies and/or processes that repurpose solid carbon and its contaminants resulting in useful products for transit, deep space or planetary surface missions. The technology and/or process must limit crew exposure to the raw carbon.

References for All Scopes

"Hydrogen Recovery by Methane Pyrolysis to Elemental Carbon" (49th International Conference on Environmental Systems, ICES-2019-103)

"Evolving Maturation of the Series-Bosch System" (47th International Conference on Environmental Systems, ICES-2017-219)

"State of NASA Oxygen Recovery" (48th International Conference on Environmental Systems, ICES-2018-48)

"Particulate Filtration from Emissions of a Plasma Pyrolysis Assembly Reactor Using Regenerable Porous Metal Filters" (47th International Conference on Environmental Systems, ICES-2017-174)

"Methane Post-Processing and Hydrogen Separation for Spacecraft Oxygen Loop Closure" (47th International Conference on Environmental Systems, ICES-2017-182)

“Trading Advanced Oxygen Recovery Architectures and Technologies” (48th International Conference on Environmental Systems, ICES-2018-321)

NASA-STD-3001, VOLUME 2, REVISION A, Section 6.4.4.1 “For missions longer than 14 days, the system shall limit the concentration in the cabin atmosphere of particulate matter ranging from 0.5 µm to 10 µm (respirable fraction) in aerodynamic diameter to <1 mg/m3 and 10 µm to 100 µm to <3 mg/m3.” https://www.nasa.gov/sites/default/files/atoms/files/nasa-std-3001-vol-2a.pdf.

Expected TRL or TRL range at completion of the project for Phase I: 3

Expected TRL or TRL range at completion of the project for Phase II for All Scopes: 4 to 5

Desired Deliverables of Phase II for All Scopes

Prototype, Analysis, Hardware, Research

Desired Deliverables Description for All Scopes

Phase I Deliverables - Reports demonstrating proof of concept, test data from proof of concept studies, concepts and designs for Phase II. Phase I tasks should answer critical questions focused on reducing development risk prior to entering Phase II. Conceptual solution in Phase I should look ahead to satisfying the requirement of limiting crew exposure to the raw carbon dust.

Phase II Deliverables - Delivery of technologically mature hardware, including components and subsystems that demonstrate performance over the range of expected spacecraft conditions. Hardware should be evaluated through parametric testing prior to shipment. Reports should include design drawings, safety evaluation, test data and analysis. Prototypes must be full scale unless physical verification in 1-g is not possible. Robustness must be demonstrated with long term operation and with periods of intermittent dormancy. System should incorporate safety margins and design features to provide safe operation upon delivery to a NASA facility.

State of the Art and Critical Gaps

No existing operational technology exists in this focused technical area. A crew of 6 during a 540 day Mars surface mission could potentially generate 920 kg of solid carbon - this will be a significant storage or disposal issue and may be a considerable raw product resource for potential utilization. Very limited research and development have been performed in this area. Some studies added carbon to plastic trash which subsequently was processed by a heat melt compactor to make "tiles", which encapsulated the carbon. Although these tiles are a safe way to get rid of trash waste, they were also studied for potential benefit for use as spacecraft radiation shielding. Other work included adding binders to make rudimentary bricks for structural use.

Relevance / Science Traceability

These technologies would be essential and enabling to long duration human exploration missions, in cases where closure of the atmosphere revitalization loop will trade over alternate ECLSS architectures. The atmosphere revitalization loop on the ISS is only about 50% closed when the Sabatier is operational. These technologies may be applicable to Gateway, Lunar surface, and Mars, including surface and transit. This technology could be proven on the ISS.

This subtopic is directed at needs identified by the Life Support Systems Capability Leadership Team (CLT) in areas of water recovery and environmental monitoring, functional areas of Environmental Control and Life Support Systems (ECLSS).

The Life Support Systems (LSS) Project, under the Advanced Exploration Systems (AES) Program, within the Human Exploration and Operations Mission Directorate (HEOMD), is the expected customer. The LSS Project would be in position to sponsor Phase III and technology infusion.

H3.02: Microbial Monitoring for Spacecraft Cabins (SBIR)

Lead Center: JPL

Participating Center(s): GRC, JSC, KSC, MSFC

Technology Area: 6.0.0 Human Health, Life Support and Habitation Systems

Related Subtopic Pointer(s): T6.06 T6.07

Scope Title

Spacecraft Microbial Monitoring for Long Duration Human Missions

Scope Description

With the advent of molecular methods, emphasis is now being placed on nucleic acids to rapidly detect microorganisms. However, the sensitivity of current gene-based microbial detection systems is low (~100 gene copies per reaction), requires elaborate sample processing steps, involves destructive analyses, and requires fluids to be transferred and detection systems are relatively large size. Recent advancements in the metabolomics field have potential to substitute (or augment) current gene-based microbial detection technologies that are multi-stepped, destructive and labor intensive (e.g. significant crew time). NASA is soliciting non-gene based microbial detection technologies and systems that target microbial metabolites and that quantify the microbial burden of surfaces, air and water inside future long-duration deep space habitats.

Potable Water:
A simple integrated, microbial sensor system that enables sample collection, processing and detection of microbes or microbial activity in the crew potable water supply is sought. A system that is fully-automated and can be in-line in an Environmental Control and Life Support Systems (ECLSS)-like water system is preferred.

Habitat Surfaces:
Future crewed habitats in cis-lunar space will be crew-tended and thus unoccupied for many months at a time. When crew reoccupies the habitat they will want to quickly, efficiently, and accurately assess the microbial status of the habitat surfaces. A microbial assessment / monitoring system or hand-held device that requires little to no consumables is sought.

Airborne Contamination:
Future human spacecraft, such as Gateway and Mars vehicles, may be required to be dormant while crew is absent from the vehicle, for periods that could last from 1 to 3 years. Before crews can return, these environments must be verified prior to crew return. These novel methods have the potential to enable remote autonomous microbial monitoring that does not require manual sample collection, preparation or processing.

References

A list of targeted contaminants for environmental monitoring can be found at "Spacecraft Water Exposure Guidelines for Selected Waterborne Contaminants" located at: https://www.nasa.gov/feature/exposure-guidelines-smacs-swegs

Advanced Exploration Systems Program, Life Support Systems Project: https://www.nasa.gov/content/life-support-systems

NASA Environmental Control and Life Support Technology Development and Maturation for Exploration: 2018 to 2019 Overview", 49th International Conference on Environmental Systems, ICES-2019-297

https://ttu-ir.tdl.org/bitstream/handle/2346/84496/ICES-2019-297.pdf

National Aeronautics and Space Administration, NASA Technology Roadmaps, TA 6: Human Health, Life Support, and Habitation Systems (National Aeronautics and Space Administration, Draft, May 2015, https://www.nasa.gov/sites/default/files/atoms/files/2015_nasa_technology_roadmaps_ta_6_human_health_life_support_habitation.pdf

NASA Standard 3001 - Requirements: https://www.nasa.gov/hhp/standards

Expected TRL or TRL range at completion of the project for Phase I: 3

Expected TRL or TRL range at completion of the project for Phase II: 4 to 5

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Research

Desired Deliverables Description

Phase I Deliverables - Reports demonstrating proof of concept, test data from proof of concept studies, concepts and designs for Phase II. Phase I tasks should answer critical questions focused on reducing development risk prior to entering Phase II.

Phase II Deliverables - Delivery of technologically mature hardware, including components and subsystems that demonstrate performance over the range of expected spacecraft conditions. Hardware should be evaluated through parametric testing prior to shipment. Reports should include design drawings, safety evaluation, test data and analysis. Prototypes must be full scale unless physical verification in 1-g is not possible. Robustness must be demonstrated with long term operation and with periods of intermittent dormancy. System should incorporate safety margins and design features to provide safe operation upon delivery to a NASA facility.

State of the Art and Critical Gaps

The State of the Art (SOA) on ISS for microbial monitoring is culturing and counting, as well as grab samples which are returned to earth. NASA has invested DNA-based (PCR) systems, partially robotic in some cases, to eliminate the need for on-orbit culturing. However, a fully automated system is still not ready and there is still a gap for a low- or no-crew time detection system.

Relevance / Science Traceability

The technologies requested could be proven on the ISS and would be useful to long duration human exploration missions away from earth, where sample return was not possible. The technologies are applicable to Gateway, Lunar surface, and Mars, including surface and transit. This subtopic is directed at needs identified by the Life Support Systems Capability Leadership Team (CLT) in areas of water recovery and environmental monitoring, functional areas of Environmental Control and Life Support Systems (ECLSS). The Life Support Systems (LSS) Project, under the Advanced Exploration Systems Program, Human Exploration and Operations Mission Directorate (HEOMD), is the expected customer. The LSS Project would be in position to sponsor Phase III and technology infusion. The ISS Program will have interest in successful awards for potential flight demonstrations.

H4.01: Exploration Portable Life Support System Component Challenges (SBIR)

Lead Center: JSC

Participating Center(s):

Technology Area: 6.0.0 Human Health, Life Support and Habitation Systems

Related Subtopic Pointer(s): None

As the design for the new Exploration Extra-vehicular Mobility Unit (xEMU) is developed, there are obvious gaps in technologies, which need to be fulfilled to meet the new exploration requirements. Various Exploration Portable Life Support System (xPLSS) Hatch components are at a stall in technology development and require new innovative ideas. These xPLSS Hatch Components (through three scopes) are the focus areas for this solicitation in an attempt to integrate new technologies into the xPLSS. NASA has plans to go to the moon and as the mission extends further out of Lower Earth Orbit, durability and extensibility will become some of the most important requirements.

This subtopic is relevant to the Exploration Extravehicular Mobility Unit (xEMU), ISS, as well as commercial space companies. As a new Space Suit Exploration Portable Life Support System (xPLSS) is being designed, built, integrated and tested at JSC and integrated into the xEMU, solutions will have a direct infusion path as the xPLSS is matured to meet the design and performance goals.

Scope Title

Feedwater Supply Assembly

Scope Description

<u>Sterile compliant bladder, capable of storing ultrapure feedwater with a relatively high cycle life</u>: In order for the thermal control loop to operate properly, a water source is needed. An effective, efficient, sterile and durable feedwater bladder is essential. The suit pressure acts on this bladder and as water evaporates, the bladder resupplies the loop. The bladder must be clean and not leak particulates or polymer chains over long periods of quiescence. The water in the control loop contains a biocide and the bladder must not react with these chemicals to form potential contaminants. The maximum design pressure (MDP) for the system at a

lunar environment will be 16 psid with a cycle life of 4 X 156 = 624 MDP. Having a bladder with these qualities not only buys down the safety risk of rupture, it promotes reliability at higher pressures and provides an avenue to extend Extravehicular Activity (EVA) length.

References

Feedwater Supply Assembly Requirements

Note to vendor: The following two drawings referenced in the above specification shall be provided if vendor is selected for award.

1. Feedwater Supply Assembly (FSA 431) Drawing SLN 13102397
   https://ntrs.nasa.gov/search.jsp?R=20190033446
2. Auxiliary Feedwater Supply Assembly (FSA 531) Drawing SLN 13102398
   https://ntrs.nasa.gov/search.jsp?R=20190033446

Scope Title

Bypass Relief Valve

Scope Description

Material dependent Relief Valve (RV) capable of re-calibration: The bypass relief valve cracks and flows from the pump outlet to the pump inlet, short-circuiting the pump when there is a blockage in the line. It is a safety feature designed to limit the head pressure that could be generated by the positive displacement pump, which is used in the primary and auxiliary thermal control loops. Materials, design pressures and re-calibration capabilities are a priority for this design. The desired housing material is titanium, which is a difficult metal to work with, but is a requirement as a preventative measure to avoid galvanic coupling between interfacing metals. To ensure the thermal loop pressure stays within a safe range, the crack and reseat pressures must be between 14-15 psid with a full flow of 220 lb/hr at <18 psid. The design should also include a method of setting or re-calibrating the cracking pressure in case there is drift over time. Replacement of the entire unit is not preferred due to accessibility and operational concerns.

References

Thermal Loop Bypass Relief Valve Requirements

Note to vendor: The following drawing referenced in the above specification shall be provided if vendor is selected for award.

- Bypass Relief Valve Assembly (RV-424/RV-524) SLN13102925
  https://ntrs.nasa.gov/search.jsp?R=20190033446

Scope Title

Trace Contaminant Control

Scope Description

Trace contaminant removal capability: Non-regenerable activated carbon is the current state of the art for trace contamination control. However, this provides a logistics impact to future missions. The primary trace contaminants that must be removed include ammonia (NH_3), carbon monoxide (CO), formaldehyde (CH_2O), and methanethiol (also known as methyl mercaptan) (CH_3SH). The minimum objective would be to remove all of the significant compounds that threaten to exceed the 7-day Spacecraft Maximum Allowable Concentrations (SMAC) values during an EVA. The ideal solution would be a vacuum-regenerable sorbent that could be integrated with the Exploration Portable Life Support System (xPLSS) CO_2/H_2O removal system. This system performs regeneration or desorption by exposing the sorbent to a pressure swing from 4.3 psia to <1 torr over approximately 2 minutes. Temperatures remain in the 60-80^{o}F range with a small amount of heat flux from the cross-coupled adsorbing bed. Additional heat input requirements from resistance heaters or other sources would negatively impact the system trade the more significant the value becomes.

References

Trace Contamination Control Cartridge Requirements

Note to vendor: The following drawing referenced in the above specification shall be provided if vendor is selected for award.

- Trace Contamination Control (TCC-360) Specification Control Drawing SLN13102266 https://ntrs.nasa.gov/search.jsp?R=20190033446

Expected TRL or TRL range at completion of the project for all scopes: 3 to 5

Desired Deliverables of Phase II for all scopes

Prototype

Desired Deliverables Description for all scopes

Phase I products: By the end of Phase I, it would be beneficial to have a concept design for infusion into the Exploration Portable Life Support System (xPLSS). Testing of the concept is desired at this Phase.

Phase II products: By the end of Phase II, a prototype ready for system-level testing in the xPLSS or in a representative loop of the PLSS is desired.

State of the Art and Critical Gaps

As the design for the new Exploration Extra-vehicular Mobility Unit (xEMU) is developed, there are obvious gaps in technologies, which need to be fulfilled to meet the new exploration requirements. Various Exploration Portable Life Support System (xPLSS) Hatch components are at a stall in technology development and require new innovative ideas. These xPLSS Hatch Components are the focus areas for this solicitation in an attempt to integrate new technologies into the xPLSS. NASA has plans to go to the moon and as the mission extends further out of Lower Earth Orbit, durability and extensibility will become some of the most important requirements.

Relevance / Science Traceability

It is relevant to the Exploration Extravehicular Mobility Unit (xEMU), ISS, as well as commercial space companies. As a new Space Suit Exploration Portable Life Support System (xPLSS) is being designed, built, integrated, and testing at JSC and integrated into the xEMU, solutions will have a direct infusion path as the xPLSS is matured in to meet the design and performance goals.

H4.05: Liquid Cooling and Ventilation Garment Connector Upgrade and Glove Humidity Reduction (SBIR)

Lead Center: JSC

Participating Center(s):

Technology Area: 6.0.0 Human Health, Life Support and Habitation Systems

Related Subtopic Pointer(s): None

Scope Title

Liquid Cooling and Ventilation Garment (LCVG) water loop connector upgrade and glove humidity reduction

Scope Description

LCVG water connector upgrade: The connector of the liquid cooling and ventilation garment (LCVG) for the space suit has been a source of failures in the current extra-vehicular mobility unit (EMU). Increased reliability and durability are needed for future space suits that will be used during long-duration missions, which include periods (up to 6 months) of quiescence. Two primary design problems can be addressed:

1) Cold flow of the ethyl-vinyl acetate tubing at the connection to the LCVG connector, which causes leaks to form
2) Sticking of the poppet seal, which allows the LCVG connector to leak. The poppet seal sticks after the seal lubricant is washed away.

A requirement that increases the challenge in designing a non-sticking poppet seal is, because the poppet seal is in the water loop of the space suit, the seal material used must maintain the high water quality requirements for the space suit water loop. Water leakage from the LCVG thermal loop connectors shall be less than 0.5 cc/hr when running at nominal operating pressure of 15 psid.

The connector should not generally leach material into the water flowing through it. Therefore, the connector needs to maintain water quality to the following levels in order to avoid affecting the performance of other equipment within the space suit water loop. In addition, galvanic corrosion in the water loop is of concern. Therefore the connector wetted surfaces, and in general the body should be constructed out of Titanium 6Al-4V wherever possible and stainless steel when necessary. Aluminum alloys should be avoided. Other wetted materials, such as seals or gaskets would preferably be constructed out of currently-used materials such as silicones.

The connector would also need to be compatible with the water solution of Iodine at concentrations of 0.5 – 5 ppm.

Additionally, the connector would need to be compatible with inlet water containing contaminants such as those listed below:

Contaminant	**Amount (mg/L)**
Barium	0.1
Calcium	1
Chlorine	5
Chromium	0.05
Copper	0.5
Iron	0.2
Lead	0.05
Magnesium	1
Manganese	0.05
Nickel	0.05
Nitrate	1
Potassium	5
Sulfate	5
Zinc	0.5
Organics	
Total Acids	0.5

Total Alcohols	0.5
Total Organic Carbon	0.3

Glove humidity reduction: Onycholysis due to humidity and water in space suit gloves during Neutral Buoyancy Laboratory (NBL) training and during extra-vehicular activity is a common observation. Ventilation in gloves is poor allowing moisture to accumulate, which contributes to onycholysis and results in nail bed damage, skin damage, and fungal infections. NASA seeks solutions to reducing moisture in space suit gloves. LCVG ventilation improvements that could ventilate the glove are difficult due to ducting required that would cross the elbow. This ducting is undesirable since it impedes mobility of the elbow joint. Alternative solutions are desired that will prevent onycholysis during suited operations.

The LCVG ventilation ducting consists of a ducting network with one duct running down each arm and each leg. See “Liquid Cooling and Ventilation Garment” description and images at “https://www.nasa.gov/audience/foreducators/spacesuits/home/clickable_suit_nf.html. The ventilation ducts end just above the elbows for the arms and at the feet for the legs. The ventilation gas enters the spacesuit at helmet and flows over the body because the ends of the ducts at the elbows and feet are open. The fan in the portable life support subsystem (PLSS) pulls the ventilation from these open ends and sends the gas to be processed before recycling it back to the helmet. Since the ventilation duct in the arms end at the elbows, the wrist and hand areas are not well ventilated.

References

“Liquid Cooling and Ventilation Garment” description and images located at the following link: https://www.nasa.gov/audience/foreducators/spacesuits/home/clickable_suit_nf.html.

A high-level schematic of the LCVG connector : https://www.nasa.gov/suitup/reference/catalog

Expected TRL or TRL range at completion of the project: 2 to 5

Desired Deliverables of Phase II

Hardware, Research

Desired Deliverables Description

The phase 1 needs to deliver a detailed design solution with information that provides confidence that hardware fabricated in the Phase II will resolve the current design challenges.

State of the Art and Critical Gaps

The 30+ history of the EMU has demonstrated these two design weaknesses as a potential for space suit failures for the exploration space suit. Without new design solutions, the exploration space suit will be limited by these weaknesses. In preparation for the exploration space suit, solving these problems are critical.

Relevance / Science Traceability

This subtopic is relevant across the Moon to Mars portfolio. Any mission in which an extra-vehicular activity suit is utilized will benefit from the increased reliability of a suit in which the current connector flaws are rectified.

H6.04: Model Based Systems Engineering for Distributed Development (SBIR)

Lead Center: ARC

Participating Center(s):

Technology Area: 11.0.0 Modeling, Simulation, Information Technology and Processing

Related Subtopic Pointer(s): S5.05 T11.03 T11.04

Scope Title

Model Based Systems Engineering for Distributed Development

Scope Description

Systems Engineering technology is both a critical capability and a bottleneck for NASA human exploration development. NASA looks to a sustainable return to the Moon to enable future exploration of Mars, components such as Lunar Gateway and Commercial Lunar Payload Services (CLPS) will require partnerships with a wide variety of communities. Building from the success of the international partnerships for International Space Station (ISS), space agencies from multiple governments are looking for roles on the Gateway. A particular focus has been made to include the rapidly growing commercial space industry to provide an important role in supporting a sustained presence on the Moon. All of these potential partners will have their own design capabilities, their own development processes and internal constituencies to support. Integrating and enabling disparate systems built in different locations by different owners to all work cohesively together will require a significant upgrade to the core systems engineering capabilities.

In the last decade Model-Based Systems Engineering (MBSE) technology has matured as evidenced by the development of Systems Modeling Language (SysML) tools and frameworks that support engineers in development efforts from requirements through hardware and software implementation. MBSE holds considerable promise for accelerating, reducing overhead labor, and improving the quality of systems development. However, a remaining bottleneck is the coordination and integration of system development across distributed organizations, such as the multiple partners developing lunar gateway and eventual Mars exploration. This subtopic seeks technology to fill this gap.

Areas of particular need include:

- Methodologies that support integration among tools and exchange of information between multidisciplinary artifacts using automated intelligent reasoning.
- The definition of open interface standards and tools to enable inspection of distributed models across engineering domains.
- Tools or systems that allow models to be shared across development environments and trace the resulting system model back to contributions from multiple partners.
- Modeling environments that facilitate user interaction from multiple stakeholders of varying expertise in MBSE.
- Continuous integration and verification of safety critical system requirements that depend on disparate development sources.

References:

- https://www.nasa.gov/consortium/ModelBasedSystems
- http://www.omgsysml.org
- Ensuring information exchange of digital artifacts are transferable and up to date among multiple stakeholders.
  - Digital Engineering Information Exchange Working Group (DEIX WG): http://www.omgwiki.org/MBSE/doku.php?id=mbse:deix
- Computational tools to augment human decision making and reasoning on complex systems with large amounts of data from disparate sources
  - Augmented Intelligence for Systems Engineering challenge team (AI-SECT): http://www.omgwiki.org/MBSE/doku.php?id=mbse:augmented

- Automated formal specification, formal verification, and test case generation of requirements with linked data and traceability to discipline specific (CAD, CAE, etc.) tools, particularly requirements with safety properties.
    - ReqIF: https://www.omg.org/reqif/
    - SysPhs: https://www.omg.org/spec/SysPhS/
    - FMI: https://fmi-standard.org
- Lightweight and intuitive cloud-based interfaces for CRUD (create, read, update, delete) operations on models particularly for users with limited MBSE experience.
- Open-MBEE: https://openmbee.org
- OSLC: https://open-services.net/

Expected TRL or TRL range at completion of the project: 4 to 6

Desired Deliverables of Phase II

Prototype, Software

Desired Deliverables Description

Methodologies and tools that support distributed development efforts

State of the Art and Critical Gaps

For distributed development, the state-of-the-art tends to be laboriously negotiated interface control documents and manual integration processes that are inherently slow and labor intensive. In an effort to overcome these challenges MBSE and SysML in particular has seen significant adoption at NASA (Gateway, Resource Prospector, Europa Clipper, Space Communications and Navigation [SCaN], Space Launch System [SLS]) especially after the MBSE Pathfinder ('16/'17) and MBSE Infusion And Modernization Initiative (MIAMI, '18/'19) studies. However, these pilot programs and a survey of NASA's use of MBSE conducted by NASA Independent Verification & Validation (IV&V) and Ames Research Center identified areas of critical need, including:

1. Sharing and version control of models.
2. Integration of SysML of domain specific tools
3. Steep learning curve for users with limited MBSE experience
4. Testing, Verification and Validation with SysML have limited use
5. No tools exist for formally specifying requirements and linking to model properties

With programs such as Gateway and Artemis that require coordination among multiple NASA centers, international space agencies, and commercial partnerships these needs will be amplified. Tool infrastructures that enable integrated support of requirements tracing, design reference points, intelligent reasoning of data and interface constructs are generally not available except within proprietary boundaries. We need tools that support integrated development and model sharing across development environments and that support use across multiple vendors.

Relevance / Science Traceability

This subtopic would be of relevance to all Human Exploration and Operations Mission Directorate (HEOMD) missions, but of particular interest will be Gateway and Artemis development. Those systems have already adopted the use of MBSE tools and tools sought help reduce potential system integration bottlenecks. Over the next 3 to 5 years, there will be considerable opportunity for small business contributions to be matured and integrated into the support infrastructure as Gateway evolves from concept to development program.

T6.05: Testing of COTS Systems in Space Radiation Environments (STTR)

Lead Center: LaRC

Participating Center(s): GRC, JSC

Technology Area: 6.0.0 Human Health, Life Support and Habitation Systems

Related Subtopic Pointer(s): S5.06 Z2.02 Z8.10 Z8.09

Scope Description

The use of commercial off-the-shelf (COTS) parts in space for electronics is a potential significant enabler for many capabilities during a mission. This subtopic is seeking a better understanding of the feasibility of COTS electronics in space environments. It seeks strategies based on a complete system analysis that include, but not limited only to, failure modes to mitigate radiation induced impacts to systems in the space radiation environment.

As background, spacecraft experience exposure to damaging radiation and that amount of exposure from various sources, (e.g., sun and galactic cosmic radiation sources) increases notably as the spacecraft ventures further away from the Earth's magnetic field, since the magnetic field offers some level of protection. As spacecraft, and their electronic systems, proceed again to the moon and further into deep space, considerable work has and continues to be done to evaluate and determine how to appropriately protect the astronauts and to shield or otherwise protect various spacecraft, habitats, and their electronic systems, depending upon the needs of the missions.

Many of the most protective physical shielding approaches known result in infrastructure which is too heavy for what is considered acceptable for many missions' intended launch and spaceflight conditions. Therefore, typically lighter infrastructure shielding is presently being used when and where possible. Spacecraft faring deeper into space for fly-by missions (e.g., New Horizons), orbiters (e.g., Mars Orbiter), or landers (e.g., Mars Rover) are examples of such relatively lightly shielded systems. The lighter shielding sacrifices some radiation protection and therefore results in some limitations in what their electronic systems could do. There are already ongoing projects to upgrade current radiation hardened parts, but these are not COTS items and are expensive to manufacture and to buy. For critical systems that must be operational continuously and which may also have more lightly shielded systems, there is no other option at this time. This subtopic does not seek work of that nature.

Unlike the lightly shielded space environments discussed above, space environments which are highly shielded from radiation, such as is inherently the case for the interiors of manned missions and for habitats where humans live and work, high level radiation hardened systems may not be as necessary even in deeper space beyond most of the present day low earth orbit (LEO) situations. Instead, a less expensive COTS solution may be acceptable for a number of non-critical tasks that are not harmed by power interruptions, hardware failures, radiation upsets, etc. in those environments over what may have been thought likely. In order to assess the feasibility of a COTS solution for those types of highly shielded space environments, this subtopic is seeking proposals.

Successful Small Business Concern/Research Institution teams would be able to do space radiation modeling and a complete analysis of the COTS (e.g., modelling for an appropriate space relevant environment; statistical modeling of the electronic parts themselves and their connections in a system; destructive testing and analysis; and testing in an appropriate space relevant environment [e.g., in particle beams]). Further, since all parts in these systems cannot be individually tested, an understanding of what parts are susceptible to radiation damage is crucial so as to create the list of potential test candidates.

Phase I proposers are expected to develop a plan or strategy that explains and details how they would approach solving the problem that helps NASA mitigate radiation induced failures in the system/components, identify COTS equipment that are likely candidates based on environmentally relevant testing, as well as modeling of interior environment and data analysis of similarly known/used approaches like the Orion vehicle testing (EM-1 when released). They should highlight the innovation in the suggested approach and explain why it would be a better solution over what may presently be used. Additionally, they should also indicate how the proposed strategies could be used commercially if developed. Phase I concept studies are expected raise the TRL to at least a 3/4 when completed. Phase II proposals would use that innovative approach to refine and conduct further relevant interior environmental modeling and conduct the space radiation relevant testing and analysis on the selected COTS parts/systems which could lead toward creating prototypes of the potential commercial items that come from the analysis. The deliverables from a successful Phase II is expected to raise the TRL to 5/6.

References

There are many references on each individual aspect of the work involved, but very few references on the entire process wanted. For a tool that can model the radiation environment inside a spacecraft:

OLTARIS: On-line Tool for the Assessment of Radiation in Space, NASA/TP-2010-216722, July 2010. R.C.Singleterry, S.R.Blattnig, M.S.Clowdsley, G.D.Qualls, C.A.Sandridge, L.C.Simonsen, J.W.Norbury, T.C.Slaba, S.A.Walker, F.F.Badavi, J.L.Spangler, A.R.Aumann, E.N.Zapp, R.D.Rutledge, K.T.Lee, R.B.Norman.

A reference to help understand the radiation testing of powered COTS parts, see:

Correlation of Neutron Dosimetry Using a Silicon Equivalent Proportional Counter Microdosimeter and SRAM SEU Cross Sections for Eight Energy Spectra, IEEE Transaction on Nuclear Science, Vol.~50, No.~6, pp.~2363-2366, December 2003. B.Gersey, R.Wilkins, H.Huff, R.C.Dwivedi, B.Takala, J.O'Donnell, S.A.Wender, R.C.Singleterry

Expected TRL or TRL range at completion of the project: 3 to 6

Desired Deliverables of Phase II

Prototype, Analysis, Software, Hardware, Research

Desired Deliverables Description

Either a prototype or flyable hardware to perform the proposed task. Either software or software reports that show theoretically, the hardware will withstand the space environment with any predictions of failure rates or potential upset rates and mitigation.

State of the Art and Critical Gaps

Many systems have never been subjected to replacement with COTS part based systems, either off the shelf systems or specialty designed systems with COTS parts. The list is long and not appropriate for NASA to designate a list. It is up to the proposer to identify what has been done in the past to mitigate COTS parts in a system, if anything.

Relevance / Science Traceability

This work would benefit all entities flying specialty systems in space. If reduced cost, more reliable and capable systems are needed, then COTS is a pathway to this. It just needs to be confirmed that the system can survive in the space environment.

T6.06: Spacecraft Water Sustainability through Nanotechnology (STTR)

Lead Center: JSC

Participating Center(s): ARC, GRC, JPL, KSC, MSFC

Technology Area: 6.0.0 Human Health, Life Support and Habitation Systems

Related Subtopic Pointer(s): H3.02 T6.07

Scope Title

Nanotechnology Innovations for Spacecraft Water Management Applications

Scope Description

Water recovery from wastewater sources is key to long duration human exploration missions. Without substantial water recovery, life support system launch weights are prohibitively large. Regenerative systems are utilized on the International Space Station (ISS) to recycle water from humidity condensate and urine. The Water Processor Assembly (WPA) accepts distillate from the Urine Processor Assembly (UPA) and humidity condensate from condensing heat exchanges. The WPA contains multi-filtration beds to remove inorganic and non-volatile organic contaminants, followed by a catalytic oxidation reactor where low molecular weight organics not removed by the adsorption process are oxidized in the presence of oxygen, elevated temperature, and a catalyst. To stabilize urine and protect components from biofouling and precipitation, a toxic pretreatment formula is added to collected urine. Simple measurements of water composition are made during flight, including conductivity, total organic carbon and iodine concentration. For determination of ionic or organic species in water and wastewater, samples must be returned to earth.

This subtopic solicits for technologies to fill specific gaps in NASA's water management systems for human spaceflight. Proposals must address needs in one of the three target areas specified. These areas of scope are aligned with the three specific thrusts described within the white paper of the Nanotechnology Signature Initiative (NSI) "Water Sustainability through Nanotechnology". Please see references for additional information, including water quality requirements and guidelines.

<u>Increasing Water Availability Using Nanotechnology: Removal of Problematic Contaminants from Processed Wastewater</u>

Two problematic organic compounds are recalcitrant to WPA processing on the ISS. Dimethylsilanediol (DMSD) is a silicon-containing degradation byproduct from siloxane based compounds. DMSD can violate ISS potable water quality standards over time, requiring premature multifiltration (MF) bed replacement. Dimethyl sulfone (DMSO2) is a sulfur-containing metabolic byproduct that has historically been consistently present in ISS potable water delivered to the Oxygen Generation Assembly (OGA) for electrolysis to O_2 and H_2. DMSO2 accumulates in the OGA water recirculation loop and is thus present in the OGA hydrogen product stream. When fed to the Sabatier reactor this contaminated H_2 has been shown to poison the Sabatier catalyst over time from sulfur exposure. The presence of DMSO2 is negatively impacting exploration design requirements and Concepts of Operation (CONOPS) for the Advanced-OGA and the Sabatier subsystems, including periodic automated flushing and trace contaminant getter devices. The development of a technology or method for physicochemical removal of these contaminants, compatible with the ISS WRS/WPA, will benefit both current manned and future exploration missions. Although technical solutions are sought that involve novel utilization of nanotechnology, proposals using more conventional or alternative approaches will also be considered.

<u>Improving the Efficiency of Water Delivery and Use with Nanotechnology: Management and Monitoring of Silver Biocide in Potable Water</u>

NASA is considering using silver as the active biocide in potable water systems for use in future spacecraft. NASA is seeking technologies for delivery, maintenance and monitoring silver in potable water.

- NASA seeks technologies to deliver and replenish silver ions in potable water, to maintain a concentration at a chosen set point within a range of 200 to 400 ug/L. The system should be capable of operating in-line, to deliver silver at a flow rate of 0.1 to 0.15 L/min potable water. Furthermore, the device should be able to operate at ambient temperature, pH ranges between 4.5 - 9.0, and system pressures up to 30 psig (200 kPa). Moreover, the device should also be small, robust, lightweight, and have minimal power and consumable mass requirements. Additionally, candidate technologies should be microgravity compatible and have no adverse effects on the potability of the drinking water system. The technology should also be capable of providing continuous, stable and autonomous operation, and be fully functional following periods of long-term system dormancy – up to 1 year.

- Silver ions may drop out of solution, depositing on fluid lines and tank surfaces, resulting in loss of silver concentration, impacting its efficacy as a residual disinfectant in potable water. Alternative methods are sought to minimize loss of silver ions in spacecraft potable water plumbing systems.
- NASA is interested in sensing technologies for the in-line measurement of ionic silver in spacecraft potable water systems. Overall, the sensing technology should offer small, robust, lightweight, low-power, compatible design solutions capable of stable, continuous, and autonomous measurements of silver for extended periods of time. Sensors of particular interest would provide: continuous in-line measurement of ionic silver at concentrations between 0 and, at least, 1000 parts per billion (ppb); a minimum detection limit of 10 ppb or less; measurement accuracy of at least 2.5% full scale (1000 ppb); stable measurements in flows up to 0.5 L/min and pipe diameters up to ¾ inch; high sampling frequency, e.g., up to 1 measurement per minute; stable calibration, greater than 3 years preferred; minimal and/or no maintenance requirements; operation at ambient temperature, system pressures up to 30 psig (200 kPa), and a solution pH between 4.5 - 9.0; and finally, a volumetric footprint less than 2000 cubic centimeters. The sensing technology should have little to no impact on the overall volume and concentration of silver being maintained within the spacecraft water system.

Enabling Next-Generation Water Monitoring Systems with Nanotechnology

NASA is seeking miniature analytical systems to measure mineral and organic constituents in potable water and wastewater. NASA is interested in sensor suites capable of simultaneous measurement of inorganic and organic species. Spacecraft applications exist for monitoring species within wastewater (potential waste streams: urine, humidity condensate, Sabatier product water, waste hygiene, and waste laundry water), regenerated potable water and in support of on-board science. Multi-species analyte measurement capability is of interest that would be competitive to standard water monitoring instruments such as ion-chromatography, inductively coupled plasma spectroscopy, and high performance liquid chromatography. Components that enable the miniaturization of these monitoring systems, such as microfluidics and small scale detectors, will be considered. Technologies should be targeted to have >3 year service life and >50% size reduction compared to current state of the art. Ideally, monitoring systems should require no hazardous reagents, have long-term calibration stability, and require very little crew time to operate and maintain.

References

NASA is a collaborating agency with the NTSC Committee on Technology Subcommittee on Nanoscale Science, Engineering and Technology's Nanotechnology Signature Initiative (NSI): "Water Sustainability through Nanotechnology" (Water NSI). For a white paper on the NSI, see https://www.nano.gov/node/1580

A high-level overview of NASA's spacecraft water management was presented at a webinar sponsored by the Water NSI: "Water Sustainability through Nanotechnology: A Federal Perspective, Oct. 19, 2016" https://www.nano.gov/publicwebinars

A general overview of the state of the art of spacecraft water monitoring and technology needs was presented at a webinar sponsored by the Water NSI: "Water Sustainability through Nanotechnology: Enabling Next-Generation Water Monitoring Systems, Jan. 18, 2017" located at https://www.nano.gov/publicwebinars

For a list of targeted contaminants and constituents for water monitoring, see "Spacecraft Water Exposure Guidelines for Selected Waterborne Contaminants" located at https://www.nasa.gov/feature/exposure-guidelines-smacs-swegs

Advanced Exploration Systems Program, Life Support Systems Project https://www.nasa.gov/content/life-support-systems

National Aeronautics and Space Administration, NASA Technology Roadmaps, TA 6: Human Health, Life Support, and Habitation Systems (National Aeronautics and Space Administration, Draft, May 2015, www.nasa.gov/sites/default/files/atoms/files/2015_nasa_technology_roadmaps_ta_6_human_health_life_support_habitation.pdf).

Layne Carter, Jill Williamson, Daniel Gazda, Chris Brown, Ryan Schaezler, Frank Thomas, Jesse Bazley, Sunday Molina "Status of ISS Water Management and Recovery" 49th International Conference on Environmental Systems, ICES-2019-36 https://ttu-ir.tdl.org/bitstream/handle/2346/84720/ICES-2019-36.pdf

Dean L. Muirhead, Layne Carter "Dimethylsilanediol (DMSD) Source Assessment and Mitigation on ISS: Estimated Contributions from Personal Hygiene Products Containing Volatile Methyl Siloxanes (VMS)" 48th International Conference on Environmental Systems, ICES-2018-123. https://ttu-ir.tdl.org/bitstream/handle/2346/74112/ICES_2018_123.pdf

Chad Morrison, Christopher McPhail, Mike Callahan, Stuart Pensinger "Concepts for a Total Organic Carbon Analyzer for Exploration Missions" 49th International Conference on Environmental Systems, ICES-2018-254 https://ttu-ir.tdl.org/bitstream/handle/2346/84465/ICES-2019-254.pdf

Molly S. Anderson, Ariel V. Macatangay, Melissa K. McKinley, Miriam J. Sargusingh, Laura A. Shaw, Jay L. Perry, Walter F. Schneider, Nikzad Toomarian, Robyn L. Gatens " NASA Environmental Control and Life Support Technology Development and Maturation for Exploration: 2018 to 2019 Overview", 49th International Conference on Environmental Systems, ICES-2019-297 https://ttu-ir.tdl.org/bitstream/handle/2346/84496/ICES-2019-297.pdf

Donald Layne Carter, David Tabb, Molly Anderson "Water Recovery System Architecture and Operational Concepts to Accommodate Dormancy", 47th International Conference on Environmental Systems, Paper ICES-2017-43 https://ttu-ir.tdl.org/ttu-ir/bitstream/handle/2346/72884/ICES_2017_43.pdf

Li, Wenyan, Calle, Luz, Hanford, Anthony, Stambaugh, Imelda and Callahan, Michael "Investigation of Silver Biocide as a Disinfection Technology for Spacecraft – An Early Literature Review", 48th International Conference on Environmental Systems, Paper ICES-2018-82

Expected TRL or TRL range at completion of the project for Phase I: 3

Expected TRL or TRL range at completion of the project for Phase II: 4 to 5

Desired Deliverables of Phase II:

Research, Analysis, Prototype, Hardware

Desired Deliverables Description

Phase I Deliverables - Reports demonstrating proof of concept, including test data from proof of concept studies, and concepts and designs for Phase II. Phase I tasks should answer critical questions focused on reducing development risk prior to entering Phase II.

Phase II Deliverables - Delivery of technologically mature hardware, including components and subsystems that demonstrate performance over the range of expected spacecraft conditions. Hardware should be evaluated through parametric testing prior to shipment. Reports should include design drawings, safety evaluation, test data and analysis. Prototypes must be full scale unless physical verification in 1-g is not possible. Robustness must be demonstrated with long term operation and with periods of intermittent dormancy. System should incorporate safety margins and design features to provide safe operation upon delivery to a NASA facility.

State of the Art and Critical Gaps

NASA has unique water needs in space that have analogous applications on Earth. NASA's wastewater collection differs from systems used on Earth in that it is highly concentrated with respect to urine, uses minimal flush water, is separated from solid wastes, and contains highly acidic and toxic pretreatment chemicals. NASA is interested in recovery of potable water from waste water, low toxicity residual disinfection, antifouling treatments for plumbing lines and tanks, "microbial check valves" that prevent microbial cross-contamination where water treatment and potable water systems share connections, and miniaturized sensors and monitoring systems for contaminants in potable water and waste water. NASA's goal is zero-discharge water treatment, targeting 100% water recycling and reuse. Spacecraft traveling away from Earth require the capability of a fully functional water analysis laboratory, including identification and quantification of known and unknown inorganic ions, organics, and microbes, as well as pH, conductivity, total organic carbon and other typical measurements. Spacecraft Water Exposure Guidelines (SWEGs) have been published for selected contaminants. Nanotechnology may offer solutions in all of these application areas.

Relevance / Science Traceability

This technology could be proven on the ISS and would be useful to long duration human exploration missions, including Gateway, Lunar surface, and Mars, including surface and transit. It is essential and enabling for water to be recycled to reduce launch costs associated with life support consumables. This subtopic is directed at needs identified by the Life Support Systems Capability Leadership Team (CLT) in areas of water recovery and environmental monitoring, functional areas of Environmental Control and Life Support Systems (ECLSS).

This subtopic is directed at meeting NASA's commitments as a collaborating agency in the National Nanotechnology Signature Initiative: "Water Sustainability through Nanotechnology". This initiative was established under the NTSC Committee on Technology, Subcommittee on Nanoscale Science, Engineering and Technology.

T6.07: Space Exploration Plant Growth (STTR)

Lead Center: KSC

Participating Center(s): JSC

Technology Area: 7.0.0 Human Exploration Destination Systems

Related Subtopic Pointer(s): H3.02 S1.11 S1.08 T6.06

Scope Title

Nutrient Recovery from Urine and Wastewater

Scope Description

Estimates for growing enough plants to support one human's food (dietary calories) suggest that 90-100 kg of fertilizer would be required per person per year. Even if plants were used only for partial life support (1/4 or 1/2 of the oxygen or food), this fertilizer mass would be substantial. NASA seeks methods and approaches for using *in situ* waste streams, such as urine and waste water to provide important nutrients and fertilizer for plants. Concepts should consider alternate approaches for how urine might be pre-treated to make it more amenable for fertilizer, and how the high levels of sodium typically found in urine might be separated or managed, since most plants are not tolerant to high levels of sodium.

References

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Expected TRL or TRL range at completion of the project: 3 to 5

Desired Deliverables of Phase II

Prototype, Hardware, Research

Desired Deliverables Description

Phase I proposals should at a minimum deliver proof of concept for retrieving useful plant nutrients and removal / partitioning sodium from urine or ersatz urine wastewater. By the completion of Phase II, we hope to have prototypic or engineering development unit hardware delivered to NASA for the technology. The potential for Phase III funding for spaceflight validation would then be explored.

State of the Art and Critical Gaps

Current approaches for fertilizing plants for space depend largely on time-release fertilizer pellets that are mixed in with a solid rooting media (used both in Veggie and APH). This approach is not sustainable for multiple crop cycles and requires that all the fertilizer be delivered from Earth. Hydroponic approaches have been suggested for space (e.g., AES NextSTEP AstroGarden) and will hopefully be tested soon on the International Space Station (ISS), and eventually on surface settings. In this case, fertilizer salts would be mixed with water to provide a nutrient solution for the plants. Growing plants in space would be more sustainable if the cost and amount of fertilizer salts could be reduced by using recycled wastes, including processed urine.

Relevance / Science Traceability

This technology would be relevant and science traceable to:

- Human Exploration and Operations Mission Directorate (HEOMD): Space Life and Physical Science (SLPSRA)
- HEOMD: Advanced Exploration Systems (AES)
- HEOMD: Human Research Program (HRP)

- Space Technology Mission Directorate (STMD): Game Changing Development (GCD)
- STMD: Space Technology Research Institute (STRI)

Scope Title

Ethylene Gas Sensor

Scope Description

Ethylene is a 2-carbon alkene gas that has growth regulating effects on plants. Plants can produce ethylene through natural metabolic processes, and this ethylene can accumulate in closed environments (such as closed plant growth chambers) and have undesirable effects on the plants. These effects can include reduced growth, impaired pollen development and/or fertilization, leaf epinasty, flower abortion, accelerated fruit ripening, and more (Abeles et al., 1992). Being hormonal in nature, ethylene can affect plants at very low concentrations, with levels as low as 25 ppb being reported to have subtle effects on some plants. More sophisticated plant growth chambers for space have included ethylene removal systems, such as $KMnO_4$ coated pellets, but this is a consumable material and adds resistance to air circulation in the chamber. Real time ethylene monitoring would allow more judicious use of ethylene removal for controlling plant growth, and save on consumables. NASA seeks a miniature, sensitive (25 ppb), real time or near-real time sensor to monitor ethylene in plant growth environments for space.

References

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Expected TRL or TRL range at completion of the project: 4 to 7

Desired Deliverables of Phase II

Prototype, Hardware, Research

Desired Deliverables Description

Phase I proposals should at a minimum deliver proof of concept for a principle to detect ethylene real-time to a target level of 25 ppb. By the completion of Phase II, we hope to have prototypic or engineering development unit hardware delivered to NASA for the technology. The potential for Phase III funding for spaceflight validation with hardware like the Veggie or Advanced Plant Habitat chambers would then be explored.

State of the Art and Critical Gaps

Ethylene monitoring has traditionally been conducted using gas chromatography with either flame ionization or photo-ionization detection. However, gas chromatographs can be large instruments and require collection of gas samples, which are then analyzed. This limits their use in small spaces/volumes and their ability to analyze gases real-time.

Relevance / Science Traceability

This technology would be relevant and science traceable to:

- Human Exploration and Operations Mission Directorate (HEOMD): Space Life and Physical Science (SLPSRA)
- HEOMD: Advanced Exploration Systems (AES)
- HEOMD: Human Research Program (HRP)
- Space Technology Mission Directorate (STMD): Game Changing Development (GCD)
- STMD: Space Technology Research Institute (STRI)

Focus Area 7: Human Research and Health Maintenance

Lead MD: HEOMD

Participating MD(s): None

NASA's Human Research Program (HRP) investigates and mitigates the highest risks to astronaut health and performance for exploration missions. HRP achieves this through a focused program of basic, applied and operational research leading to the development and delivery of:

- Human health, performance, and habitability standards.
- Countermeasures and other risk mitigation solutions.
- Advanced habitability and medical support technologies.

HRP has developed an Integrated Research Plan (IRP) to describe the requirements and notional approach to understanding and reducing the human health and performance risks. The IRP describes the Program's research activities that are intended to address the needs of human space exploration and serve HRP customers. The Human Research Roadmap (http://humanresearchroadmap.nasa.gov) is a web-based version of the IRP that allows users to search HRP risks, gaps, and tasks.

The HRP is organized into several research Elements:

- Human Health Countermeasures.
- Human Factors and Behavioral Performance.
- Exploration Medical Capability.
- Space Radiation.

Each of the HRP Elements address a subset of the risks. A fifth Element, Research Operations and Integration (ROI), is responsible for the implementation of the research on various space and ground analog platforms. HRP subtopics are aligned with the Elements and solicit technologies identified in their respective research plans.

H12.01: Radioprotectors and Mitigators of Space Radiation-induced Health Risks (SBIR)

Lead Center: JSC

Participating Center(s): None

Technology Area: 6.0.0 Human Health, Life Support and Habitation Systems

Related Subtopic Pointer(s): None

Scope Title

Radioprotectors and Mitigators of Space Radiation-Induced Health Risks

Scope Description

Space radiation is a significant obstacle when sending humans on long-duration missions beyond low earth orbit. Although various forms for radiation exist in space, astronauts during Lunar or Mars missions will be exposed constantly to galactic cosmic radiation (GCR), which consists of high energy particles ranging from protons to extremely heavy ions. Astronaut health risks from space radiation exposure are categorized into cancer, late and early central nervous systems (CNS) effects, and degenerative risks, which include cardiovascular diseases and premature aging. With the current exposure limits for cancer risks, few female astronauts will be able to fly long duration missions without countermeasures.

This subtopic solicits proposals to develop biological countermeasures that mitigate one or several of the radiation risks associated with space travel. Compounds that target common pathways (e.g., inflammation) across aging, cancer, cardiovascular disease and neurodegeneration would be preferred. Most of the countermeasure developments in the medical arena have focused on mitigating the effects of X- or gamma rays. The proposed project should focus on re-purposing of technology and compounds for high-energy charged-particle applications. Compounds that are under current development or have been proven effective for other applications are both suitable for this subtopic.

In Phase I of the project, the company should test radioprotectors or mitigators using protons or other charged particles at doses simulating exposure to space radiation. This testing can be done with cell models at the location of choice. Deliverables for the Phase I will be data generated from this exposure with the radioprotector selected. After contract award, due to the nature of this research, the contractor should immediately coordinate with their technical monitor for any special considerations for testing. In Phase II of the project, we would expect the company to expand testing radioprotectors or mitigators with combinations of different particles and energies that simulate the space radiation environment. Appropriate animal models, which may include chimeric humanized mouse models, should be used for the Phase II project.

This subtopic seeks technology development that benefits the Space Radiation Element of the NASA Human Research Program (HRP). Biomedical countermeasures are needed for all of the space radiation risks.

References

The following references discuss the different health effects NASA has identified in regard to space radiation exposure:

- Evidence report on central nervous systems effects - https://humanresearchroadmap.nasa.gov/evidence/reports/CNS.pdf.
- Evidence report on degenerative tissue effects - https://humanresearchroadmap.nasa.gov/evidence/reports/Degen.pdf.
- Evidence report on carcinogenesis - https://humanresearchroadmap.nasa.gov/evidence/reports/Cancer.pdf.

Expected TRL or TRL range at completion of the project 5 to 8

Desired Deliverables Description

Phase I will test radioprotectors or mitigators using protons or other charged particles at space relevant doses. This testing can be done with cell models at the location of choice. After contract award, due to the nature of this research, the contractor should immediately coordinate with their technical monitor for any special considerations for testing.

Phase II will test effective radioprotectors or mitigators in space radiation simulated environments (HZE) to determine if they are able to minimize or prevent space radiation risks. Companies should provide a test plan for in vivo evaluation that describes the expected effect from the compound. Testing in NASA-owned space radiation simulation facilities will be an option for Phase II.

State of the Art and Critical Gaps

Exposure of crew members to space radiation during Lunar and Mars missions can potentially impact the success of the missions and cause long-term diseases. Space radiation risks include cancer, late and early CNS effects, cardiovascular diseases, and accelerated aging. Abiding by the current exposure limits for cancer risks, few female astronauts will be able to fly long-duration missions. Mitigation of space radiation risks can be achieved with physical (shielding) and biomedical means. This subtopic addresses development of drugs that mitigate one or several of the identified space radiation risks. Countermeasures for adverse health effects from radiation exposure are of interest to Department of Defense (DoD), Department of Homeland Security (DHS) and the radiation therapy community as well.

Relevance / Science Traceability

This subtopic seeks technology development that benefits the Space Radiation Element of the NASA Human Research Program (HRP). Biomedical countermeasures are needed for all of the space radiation risks.

H12.05: Autonomous Medical Operations (SBIR)

Lead Center: JSC

Participating Center(s): ARC, GRC

Technology Area: 6.0.0 Human Health, Life Support and Habitation Systems

Related Subtopic Pointer(s): None

Scope Title
Autonomous Medical Operations

Scope Description

Current medical operations on the International Space Station (ISS) rely significantly on the Mission Control Center (MCC) and telemedicine to enable Crew Health and Performance (CHP). Near real-time communications allow MCC staff (Flight Surgeons, Flight Controllers, etc.) to guide the crew when a medical scenario exceeds the crew’s knowledge, skills or abilities. Prior to launch, crew are trained in the basic operation of the medical assets on the ISS and use detailed procedures to respond to a variety of planned and unplanned events. The training and procedures, however, are limited and do not adequately address the breadth of medical situations that may arise in flight. MCC expertise extends these capabilities allowing the crew to respond to an even larger set of events. Despite this, it is possible that some events will exceed the crew's and MCC’s ability to respond and will require the crew to rapidly return to earth and seek definitive medical care in a hospital.

Mars missions, however, will not have real-time communications with MCC nor will they have a rapid return capability. Round trip communications between the surface of Mars and Earth is approximately 40 minutes and the return trip will be months, which significantly complicates NASA’s current medical operations.

Communication bandwidth considerations may also limit data transmission between the crew and MCC even in the event of high acuity medical situations. More specifically, a variety of existing ISS medical operations require the crew to 'Contact MCC' or 'Notify Surgeon' for additional instructions, a capability that will be significantly reduced on Mars. Examples of existing ISS medical operations can be found within the links found in the references section.

NASA requires new technologies that will enable a greater degree of autonomy and self-reliance for the crew and allow them to operate in a progressively Earth independent manner. These technologies should also be dual-purposed to enable MCC to better monitor and predict adverse conditions. Ideally, these solutions should require minimal mass, volume, power and/or crew time. Examples of technology developments can include, but are not limited to, advanced just-in-time training modalities, enhanced procedure execution technologies (augmented reality), autonomous physiologic monitoring and trend prediction, automated and in-situ diagnostic and image interpretation, multipurpose medical supplies and devices, etc. The best technology solutions will 1) maximize crew autonomy and self-reliance across a wide range of medical operations, 2) demonstrate how technology could be leveraged to prevent adverse medical conditions, and 3) extend the amount of time needed before MCC intervention is required.

References

http://spaceref.com/iss/medical.ops.html

https://www.nasa.gov/hrp/elements/exmc

Expected TRL or TRL range at completion of the project 2 to 4

Desired Deliverables of Phase II

Prototype, Hardware, Software

Desired Deliverables Description

Phase I Deliverable - Conceptual prototype of a monitoring device/algorithm and final report detailing the conceptual prototype and hardware/software development plans.

Phase II Deliverable - Completed monitoring device/algorithm, and final report on the development, testing, and validation of the tool.

State of the Art and Critical Gaps

There are a variety of innovative technologies that are being developed, but the bulk of this technology is either not yet in clinical practice or has not been translated to a clinical domain.

Relevance / Science Traceability

A significant portion of ISS Medical Operations procedures require MCC to properly execute a medical procedure. Contacting MCC on Mars will be significantly limited and technologies need to be developed that allow the crew to operate for longer periods of time without direct MCC interaction.

Focus Area 8: In-Situ Resource Utilization

Lead MD: STMD

Participating MD(s): STTR

In-Situ Resource Utilization (ISRU) involves any hardware or operation that harnesses and utilizes 'in-situ' resources (natural and discarded) to create products and services for robotic and human exploration. ISRU encompasses a broad range of systems, and is typically divided into six focus areas: Resource Assessment, Resource Acquisition, Resource Processing/Consumable Production, In Situ Manufacturing, In Situ

Construction, and In-Situ Energy. ISRU products and services can be used to reduce Earth launch mass or lander mass by not bringing everything from Earth, reduce risks to the crew and/or mission by reducing logistics, increasing shielding, and providing increased self-sufficiency, or reduce costs by needing less launch vehicles to complete the mission and/or through the reuse of hardware and lander/space transportation vehicles. Since ISRU can be performed wherever resources may exist, ISRU technologies and systems may need to operate in a variety of environments and gravities, and may need to consider a wide variety of potential resource physical and mineral characteristics. This year’s solicitation will focus on critical technologies needed in the areas of Resource Acquisition and Consumable Production for the Moon and Mars. The ISRU focus area is seeking innovative technology for:

- Solar Concentrators
- Oxygen Extraction from Lunar Regolith
- Lunar Ice Mining
- Propellant Recovery
- Relaxed Propellant Grade Specification
- Chemical Flow Cells

As appropriate, the specific needs and metrics of each of these specific technologies are described in the subtopic descriptions.

T2.05: Advanced Concepts for Lunar and Martian Propellant Production, Storage, Transfer, and Usage (STTR)

Lead Center: GRC

Participating Center(s): JSC

Technology Area: 2.0.0 In-Space Propulsion Technologies

Related Subtopic Pointer(s): Z12.01 Z10.01 Z5.05

Scope Description

This subtopic seeks technologies related to cryogenic propellant (e.g. hydrogen, oxygen, methane) production, storage, transfer, and usage to support NASA's in-situ resource utilization (ISRU) goals. This includes a wide range of applications, scales, and environments consistent with future NASA missions to the Moon and Mars. Anticipated outcome of Phase I proposals are expected to deliver proof of the proposed concept with some sort of basic testing or physical demonstration. Proposals shall include plans for a prototype and demonstration in a defined relevant environment (with relevant fluids) at the conclusion of Phase II. Solicited topics are as follows:

- Subgrid Computational Fluid Dynamics (CFD) model that would model spray transport heat transfer and wall interactions during spray heat transfer during cryogenic propellant tank chilldown and fill in microgravity. Three submodels should be developed, including a (1) droplet transport and heat and mass transfer model, (2) fluid-to-wall boiling model covering all pertinent regimes (flash evaporation, film boiling, transition boiling, nucleate boiling, condensation), and (3) model that is used to capture bulk phases (e.g., volume of fluid). There should be seamless coupling between all three submodels. Emphasis should be on cryogenic fluids such as liquid hydrogen, oxygen, methane, and nitrogen. Phase I should have an emphasis on 1-g while Phase II should include microgravity applications. Models must be anchored to experimental cryogenic data.
- Develop and demonstrate methodologies for recovering propellant from lunar and Martian descent stages that have low fill levels (< 5%) of liquid oxygen, hydrogen, and/or methane mixed with helium. Methodologies can assume liquid extraction (for a short amount of time) or vapor extraction. Possible

uses of the fluids could include fuel cells, life support/breathing air, or other applications. Methodologies should focus on the amount of propellant that might be extractable at different purities (prop/helium). Phase I should focus on defining and refining the methodologies for scavenging, as well as defining what should be done to the landers to enable or facilitate later access for scavenging. Phase II should include some sort of a demonstration, perhaps using simulant or similar fluids.

- Develop and defend a proposed relaxed propellant grade specification for liquid oxygen, liquid methane, and/or liquid hydrogen, allowing higher amounts of water contaminants in the oxygen and hydrogen, and higher amounts of water, hydrogen, and carbon monoxide/dioxide in the methane. Starting with assessment of potential impurities coming out of the ISRU production plant, analysis should evaluate the effects on the liquefaction system, pump and pressure-fed propellant feed system, and engine performance, especially potential stability effects. Phase I should conclude with a proposed relaxed propellant specification for at least one propellant (oxygen or methane priority over hydrogen), with identification of the propulsion component (liquefaction, feed system, injectors, etc.) that has the most sensitivity to the impurities and will therefore drive the limits on the specification. Phase II should include a hardware demonstration of the critical element at a minimum to validate the accuracy of the analytical predictions.
- Advance non-liquid electrolyte technologies for chemical flow cells (e.g., fuel cells, electrolyzers, flow batteries, etc.) that generate electrical power from a chemical reaction or reconstitute a reaction byproduct into fuels and oxidizer for such a chemical flow cell. These electrolytes are required to be cycled through very low temperatures (< 150 K) during storage to survive a lunar night or cis-lunar travel and recover completely (>98%) mechanical, electrical, and chemical performance. Ideally, these electrolytes would be able to process propellants (hydrogen, oxygen, methane, kerosene, etc.) and either tolerate or recover from exposure to standard propellant contaminants with minimal/no performance loss. Due to the potential for high fluid pressures and vibration loads, any proposal will illustrate how the electrolyte could be mechanically supported to operate hermetically under these conditions. To demonstrate that the electrolyte exceeds the State of Art, the deliverable test article will support an electrical current density of at least 300 mA/cm2 for at least 500 hours, support transient currents > 750 mA/cm2 for at least 30 seconds, and support slew rates > 50 A/cm2/s. Providing test data for the electrolyte performance degradation rate when operated as intended is required with test times >5,000 hours significantly strengthening the proposal. It would be beneficial if the electrolyte operated reversibly with equal efficiently. Liquid electrolytes, loose or contained within a support structure, are excluded from this Scope due to the complications that liquid electrolytes pose for an eventual system during launch.

NASA has plans to purchase services for delivery of payloads to the Moon through the Commercial Lunar Payload Services (CLPS) contract. Under this subtopic, proposals may include efforts to develop payloads for flight demonstration of relevant technologies in the lunar environment. The CLPS payload accommodations will vary depending on the particular service provider and mission characteristics. Additional information on the CLPS program and providers can be found at this link: https://www.nasa.gov/content/commercial-lunar-payload-services. CLPS missions will typically carry multiple payloads for multiple customers. Smaller, simpler, and more self-sufficient payloads are more easily accommodated and would be more likely to be considered for a NASA-sponsored flight opportunity. Commercial payload delivery services may begin as early as 2020 and flight opportunities are expected to continue well into the future. In future years it is expected that larger and more complex payloads will be accommodated. Selection for award under this solicitation will not guarantee selection for a lunar flight opportunity.

References

1. Kartuzova, O., and Kassemi, M., "Modeling K-Site LH2 Tank Chilldown and no Vent Fill in Normal Gravity" AIAA-2017-4662

2. Chato, D. "LOX Tank Helium Removal for Propellant Scavenging Test" presentation at 2008 AIAA Aerospace Sciences Meeting, Orlando, FL, 2008.

3. Regenerative Fuel Cell Power Systems for Lunar and Martian Surface Exploration (https://arc.aiaa.org/doi/abs/10.2514/6.2017-5368)

4. NASA Technology roadmap (https://gameon.nasa.gov/about/space-technology-roadmap/), §TA03.2.2.1.2. Chemical Power Generation and §TA03.2.2.2.3. Regenerative Fuel Cell Energy Storage (NOTE: This may be a dated link as this Roadmap still references ETDP/ETDD)

5. Commercial Lunar Propellant Architecture: A Collaborative Study of Lunar Propellant Production (https://doi.org/10.1016/j.reach.2019.100026)

6. Linne, et.al. "Feasibility of Scavenging Propellants from Lander Descent Stage to Supply Fuel Cells and Life Support," AIAA-2009-6511, September, 2009.

Expected TRL or TRL range at completion of the project: 2 to 4

Desired Deliverables of Phase II

Prototype, Hardware, Software

Desired Deliverables Description

Phase I proposals should at minimum deliver proof of the concept, including some sort of testing or physical demonstration, not just a paper study. Phase II proposals should provide component validation in a laboratory environment preferably with hardware (or model subroutines) deliverable to NASA.

Electrolyte technologies for chemical cell product deliverables would be an operational electrochemical test article demonstrating the capability of the electrolyte to support the listed current density by processing the intended propellants when packaged as a flow cell. This test article will have an active area of at least 50 cm2 and would ideally contain multiple cells to demonstrate extensibility to existing stack designs. It would be favorable to include empirical electrochemical performance data of the electrolyte over as much of the pressure range from 5 psia to 3015 psia as possible to illustrate the potential viability range for Lunar applications.

State of the Art and Critical Gaps

Cryogenic Fluid Management is a cross-cutting technology suite that supports multiple forms of propulsion systems (nuclear and chemical), including storage, transfer, and gauging, as well as liquefaction of ISRU produced propellants. Space Technology Mission Directorate (STMD) has identified that Cryogenic Fluid Management (CFM) technologies are vital to NASA's exploration plans for multiple architectures, whether it is hydrogen/oxygen or methane/oxygen systems including chemical propulsion and nuclear thermal propulsion. For spray transport and film condensation, there are significant gaps in modeling. For scavenging, only small scale tests have been conducted to remove residual helium from a liquid oxygen tank.

There is currently no standard on propellant grade specification for an ISRU plant.

Existing electrolytes for space applications are limited to a polymeric membrane based on perfluorinated teflon and ceramic electrolyte. While it has the necessary electrochemical and mechanical properties, the polymeric membrane has very tight thermal constraints due to a high moisture content which complicates thermal system designs for lunar systems during transit. It is also very sensitive to chemical contamination. The ceramic electrolyte has significant mechanical and slew rate limitations, but is more resilient to chemical contamination and has a much larger thermal range which allows storage in very cold environments. Once operational and at temperature, either existing electrolyte technology operates in cold lunar regions. Should an off-nominal event occur during the lunar night that results in a cold-soak, neither existing electrolyte technology has a meaningful chance of recovering from the exposure to the low temperatures.

Relevance / Science Traceability

STMD strives to provide the technologies that are needed to enable exploration of the solar system, both manned and unmanned systems; cryogenic fluid management is a key technology to enable exploration. Whether liquid oxygen/liquid hydrogen or liquid oxygen/liquid methane is chosen by Human Exploration and Operations Mission Directorate (HEOMD) as the main in-space propulsion element to transport humans, CFM will be required to store propellant for up to 5 years in various orbital environments. Transfer will also be required, whether to engines or other tanks (e.g., depot/aggregation), to enable the use of cryogenic propellants that have been stored. In conjunction with ISRU, cryogens will have to be produced, liquefied, and stored, the latter two of which are CFM functions for the surface of the Moon or Mars. ISRU and CFM liquefaction drastically reduces the amount of mass that has to be landed on the Moon or Mars.

NASA already has proton exchange-membrane (PEM) based electrochemical hardware in the International Space Station (ISS) Oxygen Generator Assembly and is developing electrochemical systems for space applications through the Evolved Regenerative Fuel Cell. These system designs could be readily adapted to a solid electrolyte with capabilities beyond the existing State of Art for specific applications such as In Situ Resource Utilization, lunar fuel cell power systems, or regenerative fuel cell energy storage systems. As Commercial Lunar Payload Services (CLPS) companies have identified primary fuel cell power systems as a required technology, it would be helpful to ensure that there are options available that could survive the lunar night when off-line without active thermal control. This would enable a longer period between missions to re-fuel and recover the electrochemical system.

Z12.01: Extraction of Oxygen from Lunar Regolith (SBIR)

Lead Center: JSC

Participating Center(s): GRC, JPL, KSC, MSFC

Technology Area: 7.0.0 Human Exploration Destination Systems

Related Subtopic Pointer(s): T2.05 Z13.01 Z4.03

Scope Title
Solar Concentrator Technologies for Oxygen Extraction and In-Situ Construction

Scope Description

Solar concentrators have been used to successfully demonstrate multiple In-Situ Resource Utilization (ISRU) technologies including hydrogen and carbothermal reduction, sintering of surfaces pads, and production of blocks for construction. Terrestrial state of the art solar concentrators are heavy, not designed for easy packaging/shipping and assembly/installation, and can be maintained and cleaned on a periodic basis to maintain performance. For ISRU space applications, NASA is interested in solar concentrators that are able to be packaged into small volumes, are light weight, easily deployed and set up, can autonomously track the sun, and can perform self-cleaning operations to remove accumulated dust. Materials, components, and systems that would be necessary for the proposed technology must be able to operate on the lunar surface: up to 110^{o}C (230^{o}F) during sunlit periods and survive temperatures down to -170oC (-274^{o}F) during periods of darkness. Systems must also be able to operate for at least one year with a goal of 5 years without substantial maintenance in the dusty regolith environment. Proposers should assume that regolith mining operations will be tens of meters away from the solar concentrators, but that regolith processing systems and solar concentrators will be co-located on a single lander. Phase 1 efforts can be demonstrated at any scale, Phase 2 efforts must be scalable up to 11.1 kW of delivered solar energy assuming an incoming solar flux of ~1350 W/m2 while also considering volumetric constraints for launch and landing. Each of the following specific areas of technology interest may be developed as a standalone technology, but proposals that address multiple areas are encouraged.

Lightweight Mirrors/Lenses: Proposals must clearly state the estimated W/kg for the proposed technology. Phase 2 deliverables must be deployed and supported in Earth 1-g (without wind loads) but should include design recommendations for mass reductions for lunar gravity (1/6-g) deployment. Proposals should address the following attributes: high reflectivity, low coefficient of thermal expansion, strength, mass, reliability and cost.

(See Z13.01 - Active and Passive Dust Mitigation Surfaces to propose dust repellent mirror/lens related technologies. This will help to solve issues where dust particles cling to the surface of a mirror or lens and degrade the performance of a solar concentrator.)

Efficient transmission of energy for oxygen/metal extraction: While the solar concentrator will need to move to track the sun, reactors requiring direct thermal energy for oxygen extraction will be in a fixed position and orientation. Concentrated sunlight must be able to be directed to a single or multiple spots to effectively heat or melt the regolith. Proposals must define the expected transition losses from collection to delivery and should capture any assumptions made regarding the distance from collection to delivery.

Sintering end effector: Solar concentrators have been used to demonstrate the fabrication of 3D printed components using regolith as the only feedstock. However, an end effector designed to melt regolith at 1600^{o}C will not be optimized for selective sintering. Proposals responding to this specific technology area must produce a focal point temperature between 1000^{o}C to 1100^{o}C for the purpose of sintering lunar regolith.

References

Gordon, P. E., Colozza, A. J., Hepp, A. F., Heller, R. S., Gustafson, R., Stern, T., & Nakamura, T. (2011). Thermal energy for lunar in situ resource utilization: technical challenges and technology opportunities.

Nakamura, T., & Smith, B. (2011, January). Solar thermal system for lunar ISRU applications: development and field operation at Mauna Kea, HI. In 49th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition (p. 433).

Gustafson, R., White, B., Fidler, M., & Muscatello, A. (2010). Demonstrating the solar carbothermal reduction of lunar regolith to produce oxygen. In 48th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition (p. 1163).

Expected TRL or TRL range at completion of the project: 3 to 4

Desired Deliverables of Phase II

Prototype

Desired Deliverables Description

TRL4 hardware that can be deployed during a field demonstration

State of the Art and Critical Gaps

The 2011 paper *Thermal Energy for Lunar in Situ Resource Utilization: Technical Challenges and Technology Opportunities* summarized the work performed in this area and recommends future efforts focus on lightweight mirrors (possibly using composite materials) and dust mitigation techniques.

The last solar concentrator system developed for ISRU had an overall efficiency of ~33%. The performance of the system is captured in the 2011 Paper *Solar thermal system for lunar ISRU applications: development and field operation at Mauna Kea, HI*

Relevance / Science Traceability

The last time NASA was focused on a lunar destination, solar concentrators were used for multiple ISRU applications.

Scope Title

Novel Oxygen Extraction Concepts

Scope Description

Lunar regolith is approximately 45% oxygen by mass. The majority of the oxygen is bound in silicate minerals. Previous efforts have shown that it is possible to extract oxygen from silicates using various techniques such as carbothermal reduction and molten regolith electrolysis. NASA is interested in developing novel oxygen extraction systems that can be proven to handle large amounts of lunar regolith throughput, while minimizing consumables, mass and energy.

- Phase 1 demonstrations can be at any scale, but eventually the technology must be able to demonstrate an average rate of 1.85 kg O_2/hr (10 metric tons of Oxygen in 225 days).
- Phase 2 demonstrations can be subscale, but must define the number of subscale units necessary to achieve an average extraction rate of 1.85 kg O_2/hr.
- Demonstrations do not need to produce actual oxygen gas, but can end at a reaction product that has successfully removed oxygen atoms from the silicate mineral.
- Proposers need to define any Earth supplied reagents or hardware that might be consumed or need to be recycled and should estimate replenishment or loss rates expected.
- Proposals should state expected energy requirements (both electrical and thermal) as well as temperatures at which the proposed process will operate.
- Proposers should estimate Wh/kg 0_2 for concepts and/or provide a plan to determine that value as part of the effort.
- Proposers should address how concepts can be shutdown and restarted.
- Proposers should address the ability of a concept to be able to operate for at least one year with a goal of 5 years without substantial maintenance.

References

1. Gustafson, R., White, B., & Fidler, M. (2011, January). 2010 field demonstration of the solar carbothermal regolith reduction process to produce oxygen. In *49th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition* (p. 434).
2. Sirk, A. H., Sadoway, D. R., & Sibille, L. (2010). Direct electrolysis of molten lunar regolith for the production of oxygen and metals on the moon. *ECS Transactions*, *28*(6), 367-373.

Expected TRL or TRL range at completion of the project: 4 to 6

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Research

Desired Deliverables Description

TRL 4-6 hardware that can demonstrate a scalable oxygen extraction process in a manner that accommodates the movement of material through the extraction zone.

State of the Art and Critical Gaps

The carbothermal reduction process was demonstrated at a relevant scale using an automated reactor in 2010. The approach was successful but used many moving parts and was never life tested for the types of durations that will be required on the lunar surface. Molten Regolith Electrolysis has been demonstrated at the bench scale, but current designs lack a means to move regolith in and out of the oxygen extraction zone. Both processes are used terrestrially, but industrial designs do not provide a means to keep gases from escaping to the vacuum of space.

Relevance / Science Traceability

STMD (Space Technology Mission Directorate) has identified the need for oxygen extraction from regolith. The alternative path, oxygen from lunar water, currently has much more visibility. However, we currently do not know enough about the concentration and accessibility of lunar water to know if it would offer a better return on energy investment than oxygen extracted from the regolith. A lunar water prospecting mission is required to properly assess the utilization potential of water on the lunar surface. Until water prospecting data becomes available, NASA recognizes the need to make progress on the technology needed to extract oxygen from dry lunar regolith.

Scope Title
Lunar Ice Mining

Scope Description

We now know that water ice exists on the poles of the Moon from data obtained from missions like the Lunar Prospector, Chandrayaan-1, Lunar Reconnaissance Orbiter (LRO) and the Lunar Crater Observation and Sensing Satellite (LCROSS). We know that water is present in Permanently Shadowed Regions (PSR), where temperatures are low enough to keep water in a solid form despite the lack of atmospheric pressure. One challenge with extracting the water is that desorption and sublimation can occur at temperatures as low as 150 Kelvin. The inverse challenge exists with water collection. Unless the water vapor is under pressure, extremely cold temperatures will be necessary to capture it. NASA is seeking methods to acquire lunar water ice from permanently shadowed regions. Proposals must describe a method for extracting and/or collecting lunar water ice that exists at temperatures between 40 to 100 Kelvin and 10-9 torr vacuum.

- Phase 1 demonstrations can be at any scale, but eventually the technology must be able to demonstrate an average rate of 2.78 kg H_2O/hr (15 metric tons of water in 225 days).
- Phase 2 demonstrations can be subscale, but must define the number of subscale units necessary to achieve an average extraction rate of 2.78 kg H_2O/hr.
- Proposals should state expected energy requirements (both electrical and thermal).
- Proposers should assume a mobile platform is considered to be available, but should not be necessary for technology demonstration.
- Proposers should state their assumptions about water ice concentration.
- Proposals should describe a tolerance for a trace amount of organics or volatiles that may accumulate on collection surfaces.
- Proposers should estimate Wh/kg H_20 for concepts and/or provide a plan to determine that value as part of the effort.
- Proposers should address the ability of a concept to be able to operate for at least one year with a goal of 5 years without substantial maintenance.

Estimates for mass and volume of the final expected hardware should be specified.

References

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Hibbitts, C. A., Grieves, G. A., Poston, M. J., Dyar, M. D., Alexandrov, A. B., Johnson, M. A., & Orlando, T. M. (2011). Thermal stability of water and hydroxyl on the surface of the Moon from temperature-programmed desorption measurements of lunar analog materials. *Icarus*, *213*(1), 64-72.

Poston, M. J., Grieves, G. A., Aleksandrov, A. B., Hibbitts, C. A., Darby Dyar, M., & Orlando, T. M. (2013). Water interactions with micronized lunar surrogates JSC-1A and albite under ultra-high vacuum with application to lunar observations. *Journal of Geophysical Research: Planets*, *118*(1), 105-115.

Andreas, E. L. (2007). New estimates for the sublimation rate for ice on the Moon. *Icarus*, *186*(1), 24-30.

Expected TRL or TRL range at completion of the project 4 to 6

Desired Deliverables of Phase II

Prototype, Analysis, Hardware

Desired Deliverables Description

TRL 4-5 hardware that can demonstrate scalable water ice extraction technology in a relevant environment

State of the Art and Critical Gaps

Scoops and bucket-wheel excavators have been demonstrated for the collection of unconsolidated material but may not be effective at excavating consolidated regolith-ice composites. The Planetary Volatiles Extractor (PVEx) developed by Honeybee Robotics is the state of the art for heated core drills, but life testing is required to determine the rate of wear due to repeated excavation. Multiple groups have investigated the use of thermal mining methods to separate water from regolith, but the depth of water removed is relatively shallow. Very little work has been performed on the ability to capture water in a lunar environment after it has been released from the surface.

Relevance / Science Traceability

The current NASA Administrator has referenced water ice as one of the reasons we have chosen the lunar poles as the location to establish a sustained human presence. STMD has identified the need for water extraction from permanently shadowed regions. Multiple mission directorates over the past several years have provided funding for a water prospecting mission so that we can gain the information required to establish an ice mining architecture.

Focus Area 9: Sensors, Detectors and Instruments

Lead MD: SMD

Participating MD(s): STTR

NASA's Science Mission Directorate (SMD) (https://science.nasa.gov/) encompasses research in the areas of Astrophysics, Earth Science, Heliophysics and Planetary Science. The National Academy of Science has provided NASA with recently updated Decadal surveys that are useful to identify technologies that are of interest to the above science divisions. Those documents are available at https://sites.nationalacademies.org/SSB/SSB_052297.

A major objective of SMD instrument development programs is to implement science measurement capabilities with smaller or more affordable spacecraft so development programs can meet multiple mission needs and therefore make the best use of limited resources. The rapid development of small, low-cost remote sensing and in-situ instruments is essential to achieving this objective. For Earth Science needs, in particular, the subtopics reflect a focus on instrument development for airborne and uninhabited aerial vehicle (UAV) platforms. Astrophysics has a critical need for sensitive detector arrays with imaging, spectroscopy, and polarimetric capabilities, which can be demonstrated on ground, airborne, balloon, or suborbital rocket instruments. Heliophysics, which focuses on measurements of the sun and its interaction with the Earth and the other planets in the solar system, needs a significant reduction in the size, mass, power, and cost for instruments to fly on smaller spacecraft. Planetary Science has a critical need for miniaturized instruments with in-situ sensors that can be deployed on surface landers, rovers, and airborne platforms. For the 2020 program year, we are continuing to update the Sensors, Detectors and Instruments Topic, adding new, rotating out, and retiring some of the subtopics. Please read each subtopic of interest carefully. We continue to emphasize Ocean Worlds and solicit development of in-situ instrument technologies and components to advance the maturity of science instruments focused on the detection of evidence of life, especially extant of life, in the Ocean Worlds. The microwave technologies continue as two subtopics, one focused on active microwave remote sensing and the second on passive systems such as radiometers and microwave spectrometers. A key objective of this SBIR topic is to develop and demonstrate instrument component and subsystem technologies that reduce the risk, cost, size, and development time of SMD observing instruments and to enable new measurements. Proposals are sought for development of components, subsystems and systems that can be used in planned missions or a current technology program. Research should be conducted to demonstrate feasibility during Phase I and show a path towards a Phase II prototype demonstration. The following subtopics are concomitant with these objectives and are organized by technology.

S1.01: Lidar Remote Sensing Technologies (SBIR)

Lead Center: LaRC

Participating Center(s): GSFC

Technology Area: 8.0.0 Science Instruments, Observatories & Sensor Systems

Related Subtopic Pointer(s): S1.04 Z7.01

Scope Description

NASA recognizes the potential of lidar technology to meet many of its science objectives by providing new capabilities or offering enhancements over current measurements of atmospheric and topographic parameters from ground, airborne, and space-based platforms. To meet NASA's requirements for remote sensing from space, advances are needed in state-of-the-art lidar technology with an emphasis on compactness, efficiency, reliability, lifetime, and high performance. Innovative lidar subsystem and component technologies that directly address the measurement of atmospheric constituents and surface topography of the Earth, Mars, the Moon, and other planetary bodies will be considered under this subtopic. Compact, high-efficiency lidar instruments for deployment on unconventional platforms, such as balloons, SmallSats, and CubeSats are also considered and encouraged.

Proposals must show relevance to the development of lidar instruments that can be used for NASA science-focused measurements or to support current technology programs. Meeting science needs leads to four primary instrument types:

- Backscatter - Measures beam reflection from aerosols to retrieve the opacity of a gas.
- Ranging - Measures the return beam's time-of-flight to retrieve distance.
- Doppler - Measures wavelength changes in the return beam to retrieve relative velocity.
- Differential absorption - Measures attenuation of two different return beams (one centered on a spectral line of interest) to retrieve concentration of a trace gas.

References

NASA missions are aligned with the National Research Council's decadal surveys, with the latest survey published in 2018 under the title "Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space" (http://sites.nationalacademies.org/DEPS/esas2017/index.htm).

NASA lidar applications and technology needs for Earth Science are also summarized in the report "NASA ESTO Lidar Technologies Investment Strategy: 2016 Decadal Update." (https://ntrs.nasa.gov/search.jsp?R=20180002566)

Conference proceedings on NASA lidar interests in earth science, exploration, and aeronautics can be found at the Technical Interchange Meeting on Active Optical Systems (https://www.nasa.gov/nesc/tim-active-optical-systems)

Expected TRL or TRL range at completion of the project 3 to 6

Desired Deliverables of Phase II

Prototype, Hardware, Software

Desired Deliverables Description

Phase I research should demonstrate technical feasibility and show a path toward a Phase II prototype unit. Phase II prototypes should be capable of laboratory demonstration and preferably suitable for operation in the field from a ground-based station, an aircraft platform, or any science platform amply defended by the proposer.

State of the Art and Critical Gaps

- Compact and rugged single-frequency continuous-wave and pulsed lasers operating between 290-nm and 2050-nm wavelengths suitable for lidar. Specific wavelengths are of interest to match absorption lines or atmospheric transmission: 290 to 320-nm (ozone absorption), 450 to 490-nm (ocean sensing), 532-nm, 817-nm (water line), 935-nm (water line), 1064-nm, 1570-nm (CO_2 line), 1650-nm (methane line), and 2050-nm (Doppler wind). Architectures involving new developments in diode laser, quantum cascade laser, and fiber laser technology are especially encouraged. For pulsed lasers two different regimes of repetition rate and pulse energies are desired: from 1-kHz to 10-kHz with pulse energy greater than 1-mJ and from 20-Hz to 100-Hz with pulse energy greater than 100-mJ. Laser sources of wavelength at or around 780-nm are not sought this year.

- Novel approaches and components for lidar receivers such as: integrated optical/photonic circuitry, compact and lightweight Cassegrain telescopes compatible with existing differential absorption lidar (DIAL) and HSRL lidar systems, frequency agile solar blocking filters at 817-nm and/or 935-nm, and scanners for large apertures of telescope of at least 10-cm diameter and scalable to 50-cm diameter.

- New space lidar technologies that use small and high-efficiency diode or fiber lasers to measure range and surface reflectance of planets or asteroids from >100-km altitude during mapping to < 1-m during landing or sample collection, within size, weight, and power fit into a 4U CubeSat or smaller. New lidar technologies that allow system reconfiguration in orbit, single photon sensitivities and single beam for long distance measurement, and variable dynamic range and multiple beams for near-range measurements.

- Transformative technologies and architectures are sought to vastly reduce the cost, size, and complexity of lidar instruments. Advances are needed in generation of high pulse energy (>> 1-mJ) from compact (CubeSat size) packages, avoiding the long cavity lengths associated with current solid-state laser transmitter designs. Mass-producible laser designs, perhaps by a hybrid diode/fiber/crystal architecture, are desirable for affordable sensor solutions and reducing parts count. Heat removal from lasers is a persistent problem, requiring new technologies for thermal management of laser transmitters. New materials concepts could be of interest for the reduction of weight for optical benches and telescopes. Distributed transmitter/receiver apertures may offer another option for weight reduction.

Relevance / Science Traceability

The proposed subtopic address many missions, programs, and projects identified by the Science Mission Directorate including:

Aerosols--ongoing and planned missions include ACE (Aerosols/Clouds/Ecosystems), PACE (Plankton, Aerosol, Cloud, ocean Ecosystems), and MESCAL (Monitoring the Evolving State of Clouds and Aerosols).

Greenhouse Gases--planned missions include sensing of carbon dioxide and methane. The ASCENDS (Active Sensing of CO2 Emissions over Nights, Days, and Seasons) mission was recommended by the Decadal Survey.

Ice Elevation--ongoing and planned missions include ICESat (Ice, Cloud, and land Elevation Satellite), as well as aircraft-based projects such as IceBridge.

Atmospheric Winds--planned missions include 3D-Winds, as recommended by the Decadal Survey. Lidar wind measurements in the Mars atmosphere are also under study in the MARLI (Mars Lidar for Global Climate Measurements from Orbit) program.

Planetary Topography--altimetry similar to Earth applications is being planned for planetary bodies such as Titan and Europa.

Gases related to Air Quality--planned missions include sensing of tropospheric ozone, nitrogen dioxide, or formaldehyde to support NASA projects such as TOLNet (Tropospheric Ozone Lidar Network) and the Pandora Global Network.

Automated Landing, Hazard Avoidance, and Docking--technology development is called for under programs and missions such as ALHAT (Autonomous Landing and Hazard Avoidance Technology), SPLICE (Safe and Precise Landing Integrated Capabilities Evolution), and NPLP (NASA Provided Lunar Payloads).

S1.02: Technologies for Active Microwave Remote Sensing (SBIR)

Lead Center: JPL

Participating Center(s): GSFC

Technology Area: 8.0.0 Science Instruments, Observatories & Sensor Systems

Related Subtopic Pointer(s): None

This subtopic supports technologies to aid NASA in its active microwave sensing missions. Specifically, we are seeking:

1 Watt G-band (167-175 GHz) Solid State Power Amplifier for Remote Sensing Radars - Future cloud, water, and precipitation missions require higher frequency electronics, with small form factors and high Power Added Efficiencies (PAE) in order to measure smaller particles and enable compact instruments. Solid state amplifiers that meet high efficiency (> 20% PAE) requirements and have small form factors would be suitable for SmallSats, support single satellite missions (such as RainCube), and enable future swarm techniques. No such devices at these high frequencies, high powers, and efficiencies are currently available. We expect a power amplifier with TRL 2-4 at the completion of the project.

GPS (Global Positioning System) Denied Timing Synchronization - This would enable multi-platform instruments to share timing, which is enabling for GPS-denied environments (e.g., planetary exploration or GPS-hostile locations on Earth such as the subsurface). Multi-static radar has many applications for planetary science, but is impractical due to the lack of universal timing systems, such as what GPS provides on Earth. A low SWaP (size, weight, and power) system would be enabling for small, multi-static radars to perform in non-terrestrial environments. We desire to wirelessly distribute a synchronized PPS and/or 10 MHz clock in a GPS-denied environment between multiple radar units with <0.5 ns accuracy. The system should perform at distances of up to 5 km; synchronization hardware should be low mass (<1 kg), low power (<1 W), and small size (<5x5x10 cm). Ideally, the system should have a path to flight qualification to be used for lunar and planetary science. Deliverables include design and analysis of potential solutions, for which realizable hardware exists or is plausibly able to be developed with current technology. We expect a system with TRL 2-4 at the completion of the project.

V Band SSPA (65-71 GHz) – We seek highly efficient solid-state power amplifier (SSPA) for pressure sensing. No commercial solutions exist that satisfy high power added efficiency and bandwidth in a form factor suitable for CubeSat/SmallSat platforms. The desired capability is for smallsats doing surface pressure sensing absorption radar using V-band. The total SSPA bandwidth desired is 65-71 GHz with a maximum power of 10+ Watts at 65 GHz and 1+ Watt at 70 GHz. The package should be suitable for CubeSat/SmallSat platforms with high power added efficiency. SSPA should be pulsed with a minimum duty cycle of 25% and be suitable for a spaceflight environment. Desired deliverables are V-band SSPA prototype. We expect TRL 4-5 at the completion of the project.

Extreme environments Digital-to-Analog Converter (DAC) – We seek a single chip (or single package) DAC, capable of surviving and maintaining performance in high radiation environments (~100's krad), including ELDRS (enhanced low dose rate sensitivity) in the range of approximately 0.5-10 mrad (Si)/s. This capability is relevant to planetary remote sensing. The DAC should support a sampling rate of 500Ms/s or higher, with an effective number of bits >6. The desired deliverable is a DAC prototype.

NASA has plans to purchase services for delivery of payloads to the Moon through the Commercial Lunar Payload Services (CLPS) contract. Under this subtopic, proposals may include efforts to develop payloads for flight demonstration of relevant technologies in the lunar environment. The CLPS payload accommodations will vary depending on the particular service provider and mission characteristics. Additional information on the CLPS program and providers can be found at this link: https://www.nasa.gov/content/commercial-lunar-payload-services. CLPS missions will typically carry multiple payloads for multiple customers. Smaller, simpler, and more self-sufficient payloads are more easily accommodated and would be more likely to be considered for a NASA-sponsored flight opportunity. Commercial payload delivery services may begin as early as 2020 and flight opportunities are expected to continue well into the future. In future years it is expected that larger and more complex payloads will be accommodated. Selection for award under this solicitation will not guarantee selection for a lunar flight opportunity.

References

Radar in a CubeSat (RainCube): https://www.jpl.nasa.gov/cubesat/missions/raincube.php

Global Atmospheric Composition Mission: https://www.nap.edu/read/11952/chapter/9

Global Precipitation Measurement Mission: https://www.nasa.gov/mission_pages/GPM/overview/index.html

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Research

S1.03: Technologies for Passive Microwave Remote Sensing (SBIR)

Lead Center: GSFC

Participating Center(s): JPL

Technology Area: 8.0.0 Science Instruments, Observatories & Sensor Systems

Related Subtopic Pointer(s): None

Scope Title

Components for addressing gain instability in Low Noise Amplifier (LNA) based radiometers from 100 and 600 GHz

Scope Description

NASA requires low insertion loss solutions to the challenges of developing stable radiometers and spectrometers operating above 100 GHz that employ LNA based receiver front ends. This includes noise diodes with Excess Noise Ratio (ENR) > 10dBm with better than ≤ 0.01 dB/°C thermal stability, Dicke switches with better than 30 dB isolation, phase modulators, and low loss isolators along with fully integrated state-of-art receiver systems operating at room and cryogenic temperatures.

Expected TRL or TRL range at completion of the project: 4 to 5

Desired Deliverables of Phase II

Prototype, Hardware

Desired Deliverables Description

Hardware to enable low-loss radiometer gain calibration above 100 GHz.

State of the Art and Critical Gaps

Traditional internal microwave radiometer gain instability calibration electronics become prohibitively lossy as the frequency increases above 100 GHz. As such, radiometers at this frequency are most commonly calibrated with external references. These are larger and more massive than internal calibration electronics.

Relevance / Science Traceability

Critical need: Immediate for future earth observing, planetary, and astrophysics missions. The wide range of frequencies in this scope are used for numerous science measurements such as earth science temperature profiling, ice cloud remote sensing, and planetary molecular species detection.

Scope Title
Ultra Compact Radiometer

Scope Description

An ultra-compact radiometer of either a switching or pseudo-correlation architecture with internal calibration sources is needed. Designs with operating frequencies at the conventional passive microwave bands of 36.6 GHz (priority), 18.65 GHz, and 23.8 GHz enabling dual-polarization inputs. Interfaces include waveguide input, control, and digital data output. Ideal design features enable subsystems of multiple (10's of) integrated units to be efficiently realized.

Expected TRL or TRL range at completion of the project: 4 to 5

Desired Deliverables of Phase II

Prototype, Hardware

Desired Deliverables Description

Ultra-compact radiometer prototype.

State of the Art and Critical Gaps

Current microwave radiometers at this frequency are bulky with significant waveguide and coaxial interconnects. Dramatically smaller systems are desired for small SmallSat and CubeSat payloads, or for arrays of radiometer receivers.

Relevance / Science Traceability

This technology, in conjunction with deployable antenna technology, would enable traditional Earth land and ocean radiometry with significantly reduced instrument size, making it suitable for CubeSat or SmallSat platforms.

Scope Title
Correlating radiometer front-ends and low 1/f-noise detectors for 100-700 GHz

Scope Description

Low DC power correlating radiometer front-ends and low 1/f-noise detectors are required for 100-700 GHz. Deliverables should provide improved calibration stability, sensitivity, or 1/f noise performance compared to conventional total-power or Dicke / noise-injection radiometers at these frequencies.

Expected TRL or TRL range at completion of the project: 4 to 5

Desired Deliverables of Phase II

Prototype, Hardware

Desired Deliverables Description

Low DC power correlating radiometer front-ends and low 1/f-noise detectors for 100-700 GHz.

State of the Art and Critical Gaps

The low DC power consumption is critical for small missions, such as CubeSats. Low 1/f-noise of the detectors and correlating radiometers needed for radiometer stability across the scan for measurements at above 100 GHz for atmospheric humidity and cloud measurements as well as atmospheric chemistry.

Relevance / Science Traceability

The wide range of frequencies in this scope are used for numerous science measurements such as earth science temperature profiling, ice cloud remote sensing, and planetary molecular species detection.

Scope Title
Photonic Integrated Circuits for Microwave Remote Sensing

Scope Description

Photonic Integrated Circuits are an emerging technology for passive microwave remote sensing. NASA is looking for photonic integrated circuits for processing microwave signals in spectrometers, beam forming arrays, correlation arrays and other active or passive microwave instruments.

Expected TRL or TRL range at completion of the project: 3 to 5

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Research

Desired Deliverables Description

PIC designs to enable increased capability in passive microwave remote sensing instruments. This is a low-TRL emerging technology, so vendors are encouraged to identify and propose designs where PIC technology would be most beneficial.

State of the Art and Critical Gaps

Photonic Integrated Circuits (PIC) are an emerging technology not used in current NASA microwave missions, but may enable significant increases in bandwidth.

Relevance / Science Traceability

PICs may enable significantly increased bandwidth of Earth viewing, astrophysics, and planetary science missions. In particular, this may allow for increased bandwidth or resolution receivers, with applications such as hyperspectral radiometry.

Scope Title

Spectrometer back ends for microwave radiometers

Scope Description

Technology for low-power, rad-tolerant broad band spectrometer back ends for microwave radiometers.

Possible Implementations Include:

- Digitizers starting at 20 Gsps, 20 GHz bandwidth, 4 or more bit and simple interface to FPGA;
- ASIC implementations of polyphase spectrometer digital signal processing with ~1 Watt/GHz.
- 5-GHz bandwidth polarimetric-spectrometer with 512 channels. Two simultaneously sampled ADC inputs. Spectrometer filter banks and either polarization combiners or cross correlators for computing all four Stokes parameters (any Stokes vector basis is acceptable: e.g., IQUV, vhUV, vhpmlr). Kurtosis detectors on at least the two principal channels. Rad-hard and minimized power dissipation.
- Combined radar/radiometer receiver with radiometer spectral processing (polyphase filter bank or FFT) synchronized with radar matched filtering and moment processing.

Expected TRL or TRL range at completion of the project: 4 to 5

Desired Deliverables of Phase II

Prototype, Analysis, Hardware

Desired Deliverables Description

The desired deliverable of this Subtopic Scope is a low-power Spectrometer ASIC or other component that can be incorporated into multiple NASA radiometers.

State of the Art and Critical Gaps

Current FPGA based spectrometers require ~10 W/GHz and are not flight qualifiable. High speed digitizers exist but have poorly designed output interfaces. Specifically designed ASICs could reduce this power by a factor of 10.

Relevance / Science Traceability

Broadband spectrometers are required for Earth observing, planetary, and astrophysics missions. Improved digital spectrometer capability is directly applicable to planetary science, and enables Radio Frequency Interference (RFI) mitigation for Earth science.

S1.04: Sensor and Detector Technologies for Visible, IR, Far-IR, and Submillimeter (SBIR)

Lead Center: JPL

Participating Center(s): ARC, GSFC, LaRC

Technology Area: 8.0.0 Science Instruments, Observatories & Sensor Systems

Related Subtopic Pointer(s): S2.04 S1.01 S2.01 S2.05

Scope Description

NASA is seeking new technologies or improvements to existing technologies to meet the detector needs of future missions, as described in the most recent decadal surveys:

- Earth Science and Applications from Space: http://www.nap.edu/catalog/11820.html
- New Frontiers in the Solar System: http://www.nap.edu/catalog/10432.html
- Astronomy and Astrophysics in the New Millennium: http://www.nap.edu/books/0309070317/html/

Technologies for visible detectors are ***not*** *being solicited this year*.

LOW-POWER & LOW-COST READOUT INTEGRATED ELECTRONICS

Photodiode Arrays: In-pixel Digital Readout Integrated Circuit (DROIC) for high dynamic range infrared imaging and spectral imaging (10-60 Hz operation) focal plane arrays to circumvent the limitations in charge well capacity, by using in-pixel digital counters that can provide orders of magnitude larger effective well depth, thereby affording longer integration times.

MKID/TES Detectors: A radiation tolerant, digital readout system is needed for the readout of low temperature detectors such as Microwave Kinetic Inductance Detector (MKIDs) or other detector types that use microwave frequency domain multiplexing techniques. Each readout channel of the system should be capable of generating a set of at least 1500 carrier tones in a bandwidth of at least 1 GHz with 14 bit precision and 1 kHz frequency placement resolution. The returning frequency multiplexed signals from the detector array will be digitized with at least 12 bit resolution. A channelizer will then perform a down-conversion at each carrier frequency with a configurable decimation factor and maximum individual subchannel bandwidth of at least 50 Hz. The power consumption of a system consisting of multiple readout channels should be at most 20 mW per subchannel or 30 W per 1 GHz readout channel. That requirement would most likely indicate the use of an RF System on a Chip or ASIC with combined digitizer and channelizer functionality.

Bolometric Arrays: Low power, low noise, cryogenic multiplexed readout for large format two-dimensional bolometer arrays with 1000 or more pixels, operating at 65-350 mK. We require a superconducting readout capable of reading two Transition Edge Sensors (TESs) per pixel within a 1 mm-square spacing. The wafer-scale readout of interest will be capable of being indium-bump bonded directly to two-dimensional arrays of membrane bolometers. We require row and column readout with very low crosstalk, low read noise \, and low detector Noise Equivalent Power degradation.

Thermopile Detector Arrays: Mars Climate Sounder (MCS), the Diviner Lunar Radiometer Experiment (DLRE), and the Polar Radiant Energy in the Far Infrared Experiment (PREFIRE) are NASA space-borne radiometers that utilize custom thermopile detector arrays. Next-generation radiometers will use larger format thermopile detector arrays, indium bump bonding to hybridize the detector arrays to the Readout Integrated Circuits (ROICs), low input-referred noise, and low power consumption. ROICs compatible with 128x64 element Bi-Sb-Te thermopile arrays with low 1/f noise, an operating temperature between 200-300 K, radiation hardness to 300 krad and on-ROIC analog-to-digital converter (ADC) will be desirable.

LIDAR DETECTORS

Development of single-mode fiber-coupled extended-wavelength integrated InGaAs detectors/preamplifiers for heterodyne detection lidar at 2-2.1 um wavelengths with near shot-noise-limited performance for less than 3 mW local oscillator power, quantum efficiency > 90% over 2-2.1 um wavelengths, and bandwidth > 5 GHz. Specifications should be demonstrated in heterodyne detection experiments.

IR & Far-IR/SUBMILLIMETER-WAVE DETECTORS

Novel Materials and Devices**:** New or improved technologies leading to measurement of trace atmospheric species (e.g., CO, CH4, N2O) or broadband energy balance in the IR and far-IR from geostationary and low-Earth orbital platforms. Of particular interest are new direct detector or heterodyne detector technologies made using high temperature superconducting films (YBCO, MgB2) or engineered semiconductor materials, especially 2-Dimensional Electron Gas (2DEG) and Quantum Wells (QW).

Array Receivers**:** Development of a robust wafer level packaging/integration technology that will allow high-frequency capable interconnects and allow two dissimilar substrates (i.e., Silicon and GaAs) to be aligned and mechanically 'welded' together. Specially develop ball grid and/or Through Silicon Via (TSV) technology that can support submillimeter-wave (frequency above 300 GHz) arrays.

Receiver Components**:** Local Oscillators capable of spectral coverage 2-5 THz; Output power up to > 2 mW; Frequency agility with > 1 GHz near chosen THz frequency; Continuous phase-locking ability over the THz tunable range with < 100 kHz line width. Both solid-state (low parasitic Schottky diodes) as well as Quantum Cascade Lasers (for f > 2 THz) will be needed. Components and devices such as mixers, isolators, and orthomode transducers, working in the THz range, that enable future heterodyne array receivers are also desired. GaN based power amplifiers at frequencies above 100 GHz and with PAE > 25% are also needed. ASIC based SoC (System on Chip) solutions are needed for heterodyne receiver backends. ASICs capable of binning > 6 GHz intermediate frequency bandwidth into 0.1-0.5 MHz channels with low power dissipation < 0.5 W would be needed for array receivers

References

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Schleeh, J. et al, "Ultralow-Power Cryogenic InP HEMT with Minimum Noise Temperature of 1 K at 6 GHz", IEEE ELECTRON DEVICE LETTERS, VOL. 33, NO. 5, MAY 2012.

Desired Deliverables of Phase II

Prototypes and analysis

Desired Deliverables Description

- All of the detectors and associated readout and other technologies can be built as prototypes to advance TRL. Detailed analysis of the operation and tradeoff space would also be very helpful.

State of the Art and Critical Gaps

Efficient multi-pixel readout electronics are needed both for room temperature operation as well as cryogenic temperatures. We can produce millions-of-pixel detector arrays at infrared wavelengths up to about 14 microns, only because there are readout circuits (ROIC) available on the market. Without these, high-density, large-format infrared arrays such as Quantum Well Infrared Photodiode, HgCdTe, and Strained Layer Superlattice would not exist. The Moore's Law corollary for pixel count describes the number of pixels for the digital camera industry as growing in an exponential manner over the past several decades, and the trend is continuing. The future of long-wave detectors is moving toward tens of thousands of pixels and beyond. Readout circuits capable of addressing their needs do not exist, and without them the astronomical community will not be able to keep up with the needs of the future. These technology needs must be addressed now, or we are at risk of being unable to meet the science requirements of the future.

- Commercially available readout integrated circuits (ROICs) typically have well depths of less than 10 million electrons.
- 6-9bit, ROACH-2 board solutions with 2000 bands, <10kHz bandwidth in each are SOA.
- IR detector systems are needed for Earth imaging based on the recently release Earth Decadal Survey.
- Direct detectors with D~10^9 cm-rtHz/W achieved in this range. Technologies with new materials that take advantage of cooling to the 30-100K range are capable of D~10^12 cm-rtHz/W. Broadband (>15%) heterodyne detectors that can provide sensitivities of 5 to 10 times the quantum limit in the submillimeter-wave range while operating at 30-77 K are an improvement in the state or art due to higher operating temperature.

- Detector array detection efficiency < 20% at 532nm (including fill factor and probability of detection) for low after pulsing, low dead time designs is SOA.
- Far-IR bolometric heterodyne detectors are limited to 3dB gain bandwidth of around 3 GHz. Novel superconducting material such a MgB2 can provide significant enhancement of up to 9 GHz IF bandwidth.
- Cryogenic Low Noise Amplifiers (LNAs) in the 4-8 GHz bandwidth with thermal stability are needed for Focal Plane Arrays, Origins Space Telescope (OST) instruments, Origins Survey Spectrometers (OSS), microwave kinetic inductance detectors (MKIDs), Far-infrared Imager and Polarimeters (FIP), Heterodyne Instrument on OST (HERO), and the Lynx Telescope. DC power dissipation should be only a few mW.
- Another frequency range of interest for LNAs is 0.5-8.5 GHz. This is useful for Heterodyne Receiver for OST (HERO). Other NASA systems in the Space Geodesy Project (SGP) would be interested in bandwidths up to 2-14 GHz.
- 15-20 dB Gain and <5 Kelvin Noise over the 4-8 GHz bandwidth has been demonstrated.
- -Currently, all space borne heterodyne receivers are single pixel. Novel architectures are needed for ~100 pixel arrays at 1.9 THz
- The current State of the Art readout circuit is capable of reading one TES per pixel in a 1 mm square area. 2D arrays developed by NIST have been a boon for current NASA programs. However, NIST has declined to continue to produce two-dimensional circuits, or to develop one capable of two TES-per-pixel readout. This work is extremely important to NASA’s filled, kilopixel bolometer array program.
- Two dimensional cryogenic readout circuits are analogous to semiconductor Readout Integrated Circuits operating at much higher temperatures. We can produce millions-of-pixel detector arrays at infrared wavelengths up to about 14 microns, only because there are readout circuits (ROIC) available on the market. Without these, high-density, large-format infrared arrays such as Quantum Well Infrared Photodiode, HgCdTe, and Strained Layer Superlattice would not exist.
- For Lidar detectors, extended wavelength InGaAs detector/preamplifier packages operating at 2-2.1 micron wavelengths with high quantum efficiency (> 90%) operating up to about 1 GHz bandwidth are available as are packages operating up to about 10 GHz with lower quantum efficiency. Detectors that have > 90% quantum efficiency over the full bandwidth from near DC to > 5 GHz and capable of achieving near-shot-noise limited operation are not currently available.

Relevance / Science Traceability

- Future short-wave, mid-wave, and long-wave infrared Earth science and planetary science missions all require detectors that are sensitive and broadband with low power requirements.
- Future Astrophysics instruments require cryogenic detectors that are super-sensitive and broadband and provide imaging capability (multi-pixel).
- Aerosol spaceborne lidar as identified by 2017 decadal survey to reduce uncertainty about climate forcing in aerosol-cloud interactions and ocean ecosystem carbon dioxide uptake. Additional applications in planetary surface mapping, vegetation, and trace gas lidar.
- Earth Radiation Budget measurement per 2007 decadal survey Clouds and Earth’s Radiant Energy System (CERES) Tier-1 designation to maintain the continuous radiation budget measurement for climate modeling and better understand radiative forcings.
- Astrophysical missions such as Origins Space Telescope (OST) will need IR and Far-IR detector and related technologies.

- LANDSAT Thermal InfraRed Sensor (TIRS), Climate Absolute Radiance and Refractivity Observatory (CLARREO), BOReal Ecosystem Atmosphere Study (BOREAS), Methane Trace Gas Sounder or other infrared earth observing missions.
- Current Science missions utilizing two-dimensional, large-format cryogenic readout circuits: (1) HAWC + (High Resolution Airborne Wideband Camera Upgrade) for SOFIA (Stratospheric Observatory for Infrared Astronomy)Future missions:
    1) PIPER (Primordial Inflation Polarization Experiment), Balloon-borne
    2) PICO (Probe of Inflation and Cosmic Origins, a Probe-class Cosmic Microwave Background mission concept
- Lidar detectors are needed for 3D wind measurements from space.

S1.05: Detector Technologies for UV, X-Ray, Gamma-Ray Instruments (SBIR)

Lead Center: JPL

Participating Center(s): GSFC, MSFC

Technology Area: 8.0.0 Science Instruments, Observatories & Sensor Systems

Related Subtopic Pointer(s): S1.12 S2.02 S1.07 S1.11

Scope Title
Detectors

Scope Description

This subtopic covers detector requirements for a broad range of wavelengths from ultraviolet (UV) through to gamma ray for applications in Astrophysics, Earth Science, Heliophysics, and Planetary Science. Requirements across the board are for greater numbers of readout pixels, lower power, faster readout rates, greater quantum efficiency, single photon counting, and enhanced energy resolution.

The proposed efforts must be directly linked to a requirement for a NASA mission. These include Explorers, Discovery, Cosmic Origins, Physics of the Cosmos, Solar-Terrestrial Probes, Vision Missions, and Earth Science Decadal Survey missions. Proposals should reference current NASA missions and mission concepts where relevant. Specific technology areas are:

- Large-format, solid-state single photon counting radiation tolerant detectors in charge-coupled device (CCD) or Complementary metal-oxide-semiconductor (CMOS) architecture, including 3D stacked architecture, for astrophysics, planetary, and UV heliophysics missions
- Solid-state detectors with polarization sensitivity relevant to astrophysics as well as planetary and Earth science applications for example in spectropolarimetry
- Significant improvement in wide band gap semiconductor materials (such as AlGaN, ZnMgO and SiC), individual detectors and detector arrays for astrophysics missions and planetary science composition measurements. For example, SiC Avalanche Photodiodes (APDs) must show: EUV photon counting, a linear mode gain > 10E6 at a breakdown reverse voltage between 80 and 100 V; detection capability of better than 6 photons/pixel/s down to 135 nm wavelength. See needs of National Research Council's Earth Science Decadal Survey (NRC, 2007): Tropospheric ozone.
- Solar-blind (visible-blind) UV, far-UV (80-200 nm), EUV sensor technology with high pixel resolution, large format, high sensitivity and high dynamic range, low voltage and power requirements; with or without photon counting.
- UV detectors suitable for upcoming Ultrahigh-Energy Cosmic Ray (UHECR) mission concepts

- Solar X-ray detectors with small independent pixels (<250 µm) and fast read-out (>10,000 count/s/pixel) over an energy range from <5 keV to 300 keV.
- Supporting technologies that would help enable X-ray Surveyor mission that requires the development of X-ray microcalorimeter arrays with much larger field of view, ~10^5-10^6 pixels, of pitch ~25-100 µm, and ways to read out the signals. For example, modular superconducting magnetic shielding is sought that can be extended to enclose a full-scale focal plane array. All joints between segments of the shielding enclosure must also be superconducting.
- Improved long-wavelength blocking filters are needed for large-area, X-ray microcalorimeters. Filters with supporting grids are sought that, in addition to increasing filter strength, also enhance EMI shielding (1 - 10 GHz) and thermal uniformity for decontamination heating. X-ray transmission of greater than 80% at 600 eV per filter is sought, with infrared transmissions less than 0.01% and ultraviolet transmission of less than 5% per filter. Means of producing filter diameters as large as 10 cm should be considered.
- Detectors with fast readout that can support high count rates and large incident flux from the extreme UV (EUV) and X-Rays for heliophysics applications, especially solar-flare measurements.

References

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- Planetary Missions Program Office: https://planetarymissions.nasa.gov/
- Explorers and Heliophysics Projects Division (EHPD): https://ehpd.gsfc.nasa.gov/
- NASA Astrophysics Roadmap: https://smd-prod.s3.amazonaws.com/science-red/s3fs-public/atoms/files/secure-Astrophysics_Roadmap_2013_0.pdf
- NASA Heliophysics Roadmap: https://smd-prod.s3.amazonaws.com/science-red/s3fs-public/atoms/files/2014_HelioRoadmap_Final_Reduced_0.pdf
- "Vision and Voyages for Planetary Science in the Decade 2013-2022": http://solarsystem.nasa.gov/2013decadal/

Expected TRL or TRL range at completion of the project: 3 to 5

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Research

Desired Deliverables Description

Results of tests and analysis of designs and/or prototype hardware. Hardware for further testing and evaluation.

State of the Art and Critical Gaps

This subtopic aims to develop and advance detector technologies focused on ultraviolet, x-ray, gamma ray spectral range. The science needs in this range spans a number of fields with main focus on astrophysics, planetary science, and UV heliophysics. A number of solid-state detector technologies promise to surpass the traditional image-tube based detectors. Silicon-based detectors leverage enormous investments and promise high performance detectors while more complex material such as gallium nitride and silicon carbide offer intrinsic solar blind response. This subtopic supports efforts to advance technologies that significantly improve the efficiency, dynamic range, noise, radiation tolerance, spectral selectivity, reliability, and manufacturability in detectors.

Relevance / Science Traceability

Flagship missions under study: Large Ultraviolet Optical Infrared Surveyor (LUVOIR), Habitable Exoplanet Observatory (HabEx), Lynx, New Frontier-IO,

- Luvoir - Large UV/Optical/IR Surveyor: https://asd.gsfc.nasa.gov/luvoir/
- Habitable Exoplanet Observatory (HabEx): https://www.jpl.nasa.gov/habex/
- The LYNX Mission Concept: https://wwwastro.msfc.nasa.gov/lynx/
- NASA Astrophysics: https://science.nasa.gov/astrophysics/
- The Explorers Program: https://explorers.gsfc.nasa.gov/

S1.06: Particles and Fields Sensors & Instrument Enabling Technologies (SBIR)

Lead Center: GSFC

Participating Center(s): JPL, MSFC

Technology Area: 8.0.0 Science Instruments, Observatories & Sensor Systems

Related Subtopic Pointer(s): Z4.05 S5.06 S1.12

Scope Description:

The 2013 National Research Council's, Solar and Space Physics: A Science for a Technological Society (http://nap.edu/13060) motivates this subtopic: "Deliberate investment in new instrument concepts is necessary to acquire the data needed to further solar and space physics science goals, reduce mission risk, and maintain an active and innovative hardware development community." This subtopic solicits development of advanced in-situ instrument technologies and components suitable for deployment on heliophysics missions. Advanced sensors for the detection of elementary particles (atoms, molecules and their ions) and electric and magnetic fields in space and associated instrument technologies are often critical for enabling transformational science from the study of the sun's outer corona, to the solar wind, to the trapped radiation in Earth's and other planetary magnetic fields, and to the atmospheric composition of the planets and their moons. These technologies must be capable of withstanding operation in space environments, including the expected pressures, radiation levels, launch and impact stresses, and range of survival and operational temperatures. Technology developments that result in a reduction of mass, power, volume, and data rates for instruments and instrument components without loss of scientific capability are of particular importance. In addition, technologies that can increase instrument resolution and sensitivity or achieve new and innovative scientific measurements are solicited. Improvements in particles and fields sensors and associated instrument technologies enable further scientific advancement for upcoming NASA missions such as CubeSats, Explorers, Solar Terrestrial Probe (STP), Living With a Star (LWS), and planetary exploration missions.

Specifically, this subtopic solicits instrument development that provides significant advances in the following areas:

- Mini scalar-only temperature insensitive absolute magnetometer for CubeSats
- Magnetically clean >2 meter compact deployable booms for CubeSats
- Complementary metal-oxide-semiconductor (CMOS) active pixel type or charge-coupled device (CCD) type electron detectors in the energy range ~0.1-20KeV
- Fast visible light CMOS or CCD imaging detectors for high sensitivity (10 photons per pixel) read out of scintillator crystal light tracks caused by incident neutrons or protons

- Wide energy fast particle detectors resistant to very high radiation of >100Mrads, for instance diamond detectors.
- Grids, collimators and other components that enable the rejection of stray UV or visible light
- Innovative high efficiency neutral particle ionizers based on thermionic, cold electron emission or UV ionization
- Direct neutral particle detectors to energies <1eV
- High-resolution and high-efficiency UV-blind ENA detectors
- High voltage space qualified optocoupler components for >20KV power supplies
- Innovative miniature nested electrostatic analyzers for scan-less energy analysis
- Detectors/sensors for interplanetary/interstellar dust detection
  - Electronics technologies (e.g., field programmable gate array (FPGA) and application-specific integrated circuit (ASIC) implementations, advanced array readouts, miniature high voltage power supplies)

NASA has plans to purchase services for delivery of payloads to the Moon through the Commercial Lunar Payload Services (CLPS) contract. Under this subtopic, proposals may include efforts to develop payloads for flight demonstration of relevant technologies in the lunar environment. The CLPS payload accommodations will vary depending on the particular service provider and mission characteristics. Additional information on the CLPS program and providers can be found at this link: https://www.nasa.gov/content/commercial-lunar-payload-services. CLPS missions will typically carry multiple payloads for multiple customers. Smaller, simpler, and more self-sufficient payloads are more easily accommodated and would be more likely to be considered for a NASA-sponsored flight opportunity. Commercial payload delivery services may begin as early as 2020 and flight opportunities are expected to continue well into the future. In future years it is expected that larger and more complex payloads will be accommodated. Selection for award under this solicitation will not guarantee selection for a lunar flight opportunity.

References:

For example missions, see http://science.nasa.gov/missions. (E.g. NASA Magnetospheric Multiscale (MMS) mission, Fast Plasma Instrument)
For details of the specific requirements see the National Research Council's, Solar and Space Physics: A Science for a Technological Society (http://nap.edu/13060).

Expected TRL or TRL range at completion of the project: 3-6

Desired Deliverables of Phase II (Check all that apply):

Prototype, Hardware

Desired Deliverables Description:

A prototype component that can be tested in engineering model instruments.

State of the Art and Critical Gaps:

In situ particles and fields instruments and technologies are essential bases to achieve the Science Mission Directorate's (SMD) Heliophysics goals summarized in the National Research Council's, Solar and Space Physics: A Science for a Technological Society. These technologies play indispensable roles for NASA's LWS and STP mission programs, as well as a host of smaller spacecraft in the Explorers Program. In addition, there is growing demand for particles and fields instrumentation amenable to CubeSats and SmallSats. To narrow the critical gaps between the current state of art and the technology needed for the ever-increasing science/exploration requirements, in-situ technologies are being sought to achieve much higher resolution and sensitivity with significant improvements over existing capabilities, and at the same time with lower mass, power and volume.

Relevance / Science Traceability:

Particles and fields instruments and technologies are essential bases to achieve SMD's Heliophysics goals summarized in the National Research Council's, Solar and Space Physics: A Science for a Technological Society. In situ instruments and technologies play indispensable roles for NASA's LWS and STP mission programs, as well as a host of smaller spacecraft in the Explorers Program. In addition, there is growing demand for particles and fields technologies amenable to CubeSats and SmallSats. NASA SMD has two excellent programs to bring this subtopic technologies to higher level: Heliophysics Instrument Development for Science (H-TIDeS) and Heliophysics Flight Opportunities for Research and Technology (H-FORT). H-TIDeS seeks to advance the development of technologies and their application to enable investigation of key heliophysics science questions. This is done through incubating innovative concepts and development of prototype technologies. It is intended that technologies developed through H-TIDeS would then be proposed to H-FORT to mature by demonstration in a relevant environment. The H-TIDES and H-FORT programs are in addition to Phase III opportunities. Further opportunities through SMD include Explorer Missions, New Frontiers Missions, and the upcoming Geospace Dynamic Constellation.

S1.07: In Situ Instruments/Technologies for Lunar and Planetary Science (SBIR)

Lead Center: JPL

Participating Center(s): ARC, GRC, GSFC, MSFC

Technology Area: 8.0.0 Science Instruments, Observatories & Sensor Systems

Related Subtopic Pointer(s): S3.05 S1.05

Scope Description

This subtopic solicits development of advanced instrument technologies and components suitable for deployment on *in situ* planetary and lunar missions. These technologies must be capable of withstanding operation in space and planetary environments, including the expected pressures, radiation levels, launch and impact stresses, and range of survival and operational temperatures. Technologies that reduce mass, power, volume, and data rates for instruments and instrument components without loss of scientific capability are of particular importance, for both conventional missions as well as for small satellite missions. In addition, technologies that can increase instrument resolution and sensitivity or achieve new & innovative scientific measurements are solicited. For examples of NASA science missions, see https://science.nasa.gov/missions-page. For details of the specific requirements see the National Research Council report "Vision and Voyages for Planetary Science in the Decade 2013-2022" (http://solarsystem.nasa.gov/2013decadal/), hereafter referred to as the Planetary Decadal Survey). Of particular interest are technologies to support future missions under the New Frontiers and Discovery programs.

Specifically, this subtopic solicits instrument development that provides significant advances in the following areas, broken out by planetary body:

- Mars - Sub-systems relevant to current *in situ* instrument needs (e.g., lasers and other light sources from UV to microwave, X-ray and ion sources, detectors, mixers, mass analyzers, etc.) or electronics technologies (e.g., field programmable gate array (FPGA) and application-specfic integrated circuit (ASIC) implementations, advanced array readouts, miniature high voltage power supplies). Technologies that support high precision *in situ* measurements of elemental, mineralogical, and organic composition of planetary materials are sought. Conceptually simple, low risk technologies for *in situ* sample extraction and/or manipulation including fluid and gas storage, pumping, and chemical labeling to support analytical instrumentation. Seismometers, mass analyzers, technologies for heat flow probes, and atmospheric trace gas detectors are sought. Improved robustness and g-force survivability for instrument components, especially for geophysical network sensors, seismometers, and advanced detectors (intensified charge-coupled devices (iCCDs), photomultiplier tube (PMT) arrays, etc.). Instruments geared towards rock/sample interrogation prior to sample return.

- Venus - Sensors, mechanisms, and environmental chamber technologies for operation in Venus's high temperature, high-pressure environment with its unique atmospheric composition. Approaches that can enable precision measurements of surface mineralogy and elemental composition and precision measurements of trace species, noble gases and isotopes in the atmosphere.
- Small Bodies - Technologies that can enable sampling from asteroids and from depth in a comet nucleus, improved *in situ* analysis of comets. Imagers and spectrometers that provide high performance in low light environments. Dust environment measurements and particle analysis, small body resource identification, and/or quantification of potential small body resources (e.g., oxygen, water and other volatiles, hydrated minerals, carbon compounds, fuels, metals, etc.). Advancements geared towards instruments that enable elemental or mineralogy analysis (such as high-sensitivity X-ray and UV-fluorescence spectrometers, UV/fluorescence systems, scanning electron microscopy with chemical analysis capability, mass spectrometry, gas chromatography and tunable diode laser sensors, calorimetry, imaging spectroscopy, and laser-induced breakdown spectroscopy (LIBS).
- Saturn, Uranus, and Neptune - Components, sample acquisition, and instrument systems that can enhance mission science return and withstand the low-temperatures/high-pressures of the atmospheric probes during entry.
- The Moon - This topic seeks advancement of concepts and components to develop a Lunar Geophysical Network as envisioned in the Planetary Decadal Survey. Understanding the distribution and origin of both shallow and deep moonquakes will provide insights into the current dynamics of the lunar interior and its interplay with external phenomena (e.g., tidal interactions with Earth). The network is envisioned to be comprised of multiple free-standing seismic stations which would operate over many years in even the most extreme lunar temperature environments. Technologies to advance all aspects of the network including sensor emplacement, power, and communications in addition to seismic, heat flow, magnetic field and electromagnetic sounding sensors are desired.

Novel instrument concepts are encouraged particularly if they enable a new class of scientific discovery. Technology developments relevant to multiple environments and platforms are also desired. Proposers should show an understanding of relevant space science needs and present a feasible plan to fully develop a technology and infuse it into a NASA mission.

NASA has plans to purchase services for delivery of payloads to the Moon through the Commercial Lunar Payload Services (CLPS) contract. Under this subtopic, proposals may include efforts to develop payloads for flight demonstration of relevant technologies in the lunar environment. The CLPS payload accommodations will vary depending on the particular service provider and mission characteristics. Additional information on the CLPS program and providers can be found at this link: https://www.nasa.gov/content/commercial-lunar-payload-services. CLPS missions will typically carry multiple payloads for multiple customers. Smaller, simpler, and more self-sufficient payloads are more easily accommodated and would be more likely to be considered for a NASA-sponsored flight opportunity. Commercial payload delivery services may begin as early as 2020 and flight opportunities are expected to continue well into the future. In future years it is expected that larger and more complex payloads will be accommodated. Selection for award under this solicitation will not guarantee selection for a lunar flight opportunity.

Expected TRL or TRL range at completion of the project: 3 to 5

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Software

Desired Deliverables Description

In-situ instruments in TRL 3 - 5 for planetary science purpose

State of the Art and Critical Gaps

In situ instruments and technologies are essential bases to achieve Science Mission Directorate's (SMD's) planetary science goals summarized in the Planetary Decadal Survey. *In situ* instruments and technologies play indispensable role for NASA's New Frontiers and Discovery missions to various planetary bodies (Mars, Venus, Small Bodies, Saturn, Uranus, Neptune, Moon, etc.).

There are currently various *in situ* instruments for diverse planetary bodies. However, there are ever increasing science and exploration requirement and challenges for diverse planetary bodies. For example, there is urgent need for exploring RSL (recurring slope lineae) on Mars, plumes from planetary bodies, as well as a growing demand for *in situ* technologies amenable to small spacecraft.

To narrow the critical gaps between the current state of art and the technology needed for the ever increasing science/exploration requirements, *in situ* technologies are being sought to achieve much higher resolution and sensitivity with significant improvements over existing capabilities with lower mass, power and volume.

Relevance / Science Traceability

In situ instruments and technologies are essential bases to achieve SMD's planetary science goals summarized in the Planetary Decadal Survey. *In situ* instruments and technologies play an indispensable role for NASA's New Frontiers and Discovery missions to various planetary bodies.

In additional to Phase III opportunities, SMD offers several instrument development programs as paths to further development and maturity. These include the Planetary Instrument Concepts for the Advancement of Solar System Observations (PICASSO) Program, which invests in low-TRL technologies and funds instrument feasibility studies, concept formation, proof-of-concept instruments, and advanced component technology, and the Maturation of Instruments for Solar System Exploration (MatISSE) Program, which invests in mid-TRL technologies and enables timely and efficient infusion of technology into planetary science missions.

S1.08: Suborbital Instruments and Sensor Systems for Earth Science Measurements (SBIR)

Lead Center: LaRC

Participating Center(s): ARC, GSFC, JPL

Technology Area: 8.0.0 Science Instruments, Observatories & Sensor Systems

Related Subtopic Pointer(s): T6.07 A2.02

Scope Description

NASA seeks measurement capabilities that support current satellite and model validation, advancement of surface-based remote sensing networks, and targeted Airborne Science Program and ship-based field campaign activities as discussed in the Research Opportunities in Space and Earth Science (ROSES) solicitation. Data from such sensors also inform process studies to improve our scientific understanding of the Earth System. In-situ sensor systems (airborne, land, and water-based) can comprise stand-alone instrument and data packages; instrument systems configured for integration on ship-based (or alternate surface-based platform) and in-water deployments, NASA's Airborne Science aircraft fleet or commercial providers, Unmanned Aircraft Systems (UAS), or balloons, ground networks; or end-to-end solutions providing needed data products from mated sensor and airborne/surface/subsurface platforms. An important goal is to create sustainable measurement capabilities to support NASA's Earth science objectives, with infusion of new technologies and systems into current/future NASA research programs. Instrument prototypes as a deliverable in Phase II proposals and/or field demonstrations are highly encouraged.

Complete instrument systems are generally desired, including features such as remote/unattended operation and data acquisition, and minimum size, weight, and power consumption. All proposals must summarize the current state of the art and demonstrate how the proposed sensor or sensor system represents a significant improvement over the current state of the art.

Specific desired sensors or mated platform/sensors include:

- A hyperspectral radiometry system with polarization capability covering the UV-Vis-NIR wavelength range (350-865 with a minimum resolution of 5 nm; 2.5-nm desired). The instrument shall measure hyperspectral above water upwelling radiance, sky radiance, downwelling irradiance and polarization state of the atmosphere and ocean, and be capable of autonomously positioning itself with respect to the sun for optimized measurement geometry.
- An in situ hyperspectral ocean water absorption instrument (ocean submersible to 300 m) covering the UV-Vis wavelength range (resolution of ≤2nm for 350-750 nm and ≤5nm for 300-350nm) with an accuracy better than 0.005 m^{-1} or 5% of the signal and precision better than 0.001 m^{-1}. Instrument design must mitigate/correct for the confounding effects of scattering and fluorescence.
- In-situ measurements of ocean particulate backscatter, depolarization, beam attenuation, and diffuse attenuation coefficients relevant for combined ocean-atmosphere lidar remote sensing (355, 473, 486, 532, 1064 nm wavelengths and 170-180° scattering angle with ≤1 degree angular resolution).
- In situ polarized hyperspectral UV-Vis volume scattering function (VSF) instrument (ocean submersible to 300 m) covering the angular range close to 0 degrees and, more importantly so, as far as 180 degrees (with ≤2 degree angular resolution). Instrument should have ability to measure (at least) horizontal and vertical aspects of linear polarization. Degree of resolution in angles and wavelength can be decreased for instrument portability and robustness (such as for autonomous underwater vehicle (AUV) deployments).
- Portable hyperspectral UV-Vis-NIR radiometric calibration system with a stabilized optical light source for verification of field radiometer stability by traceable NIST standards with variable flux levels. System must include thermal stabilization for the instrument to be independent of ambient temperature for evaluation of radiometric stability as function of time.
- Innovative, high-value sensors directly targeting a stated NASA need (including aerosols and trace gases) may also be considered. Proposals must identify a specific, relevant NASA subject matter expert.

Expected TRL or TRL range at completion of the project is: 4 to 7

Desired Deliverables of Phase II: Prototype, Hardware, and/or Software

Desired Deliverables Description: The ideal Phase II effort would build, characterize, and deliver a prototype instrument to NASA including necessary hardware and operating software. The prototype would be fully-functional, but the packaging may be more utilitarian (i.e., less polished) than a commercial model.

State of the Art and Critical Gaps

The S1.08 subtopic is and remains highly relevant to NASA Science Mission Directorate (SMD) and Earth Science research programs, in particular the Earth Science Atmospheric Composition, Climate Variability & Change, and Carbon Cycle and Ecosystems focus areas. In situ and ground-based sensors inform NASA ship and airborne science campaigns led by these programs and provide important validation of the current and next-generation of satellite-based sensors (e.g., PACE, OCO-2, TEMPO, SGB, and A-CCP – see links in references). The solicited measurements will be highly relevant to current and future NASA campaigns with objectives and observing strategies similar to past campaigns, e.g., NAAMES, EXPORTS, CAMP2EX, FIREX-AQ, KORUS-AQ, DISCOVER-AQ (see links in references).

References:

Relevant current and past satellite missions and field campaigns include:

PACE Satellite Mission, scheduled to launch in 2022 that focuses on observations of ocean biology, aerosols, and clouds (https://pace.gsfc.nasa.gov/)

Decadal Survey Recommended ACCP Mission focusing on aerosols, clouds, convection, and precipitation/Aerosols and Clouds, Convection and Precipitation (ACCP) (combined) (https://science.nasa.gov/earth-science/decadal-surveys)

Decadal Survey Recommended SGB Mission focusing on surface biology and geology/ Surface Biology and Geology (https://science.nasa.gov/earth-science/decadal-surveys)

OCO-2 Satellite Mission that targets spaceborne observations of carbon dioxide and the Earth's carbon cycle (https://www.nasa.gov/mission_pages/oco2/index.html)

TEMPO Satellite Mission focusing on geostationary observations of air quality over North America (http://tempo.si.edu/overview.html)

NAAMES Earth Venture Suborbital field campaign targeting the North Atlantic phytoplankton bloom cycle and impacts on atmospheric aerosols, trace gases, and clouds (https://naames.larc.nasa.gov)

EXPORTS field campaign targeting the export and fate of upper ocean net primary production using satellite observations and surface-based measurements (https://oceanexports.org)

CAMP2Ex airborne field campaign focusing on tropical meteorology and aerosol science (https://espo.nasa.gov/camp2ex)

FIREX-AQ airborne and ground-based field campaign targeting wildfire and agricultural burning emissions in the United States (https://www.esrl.noaa.gov/csd/projects/firex-aq/)

AToM airborne field campaign mapping the global distribution of aerosols and trace gases from pole-to-pole (https://espo.nasa.gov/atom/content/ATom)

KORUS-AQ airborne and ground-based field campaign focusing on pollution and air quality in the vicinity of the Korean Peninsula (https://espo.nasa.gov/korus-aq/content/KORUS-AQ)

DISCOVER-AQ airborne and ground-based campaign targeting pollution and air quality in four areas of the United States (https://discover-aq.larc.nasa.gov/)

S1.09: Cryogenic Systems for Sensors and Detectors (SBIR)

Lead Center: GSFC

Participating Center(s): JPL

Technology Area: 8.0.0 Science Instruments, Observatories & Sensor Systems

Related Subtopic Pointer(s): Z4.05 T13.01

Scope Title

Low temperature/high efficiency cryocoolers

Scope Description

NASA seeks improvements to multistage low temperature spaceflight cryocoolers. Coolers are sought with the lowest temperature stage typically in the range of 4 to 10 K, with cooling power at the coldest stage larger than currently available, and high efficiency. The desired cooling power is application specific, but two examples are 0.3 Watts at 10 K and 0.2 Watts at 4 K. Devices that produce extremely low vibration, particularly at frequencies below a few hundred Hz, are of special interest. System or component level improvements that improve efficiency and reduce complexity and cost are desirable.

Expected TRL or TRL range at completion of the project: 2 to 5

Desired Deliverables of Phase II:

Prototype Hardware

Desired Deliverables Description

Functioning hardware ready for functional and possibly environmental testing.

State of the Art and Critical Gaps

Current spaceflight cryocoolers for this temperature range include linear piston driven Stirling cycle or pulse tube cryocoolers with Joule-Thompson low temperature stages. One such state-of-the-art cryocooler provides 0.09 W of cooling at 6 K. For large future space observatories, large cooling power and much greater efficiency will be needed. For cryogenic instruments or detectors on instruments with tight point requirements, orders of magnitude improvement in the levels of exported vibration will be required.

Some of these requirements are laid out in the "Advanced cryocoolers" Technology gap in the latest (2017) Cosmic Origins Program Annual Technology Report.

Relevance / Science Traceability

Science traceability: Goal 1 and Objective 1.6 of NASA's Strategic Plan:

- Goal 1: Expand the frontiers of knowledge, capability, and opportunity in space
    - Objective 1.6: Discover how the universe works, explore how it began and evolved, and search for life on planets around other stars.

Low temperature cryocoolers are listed as a "Technology Gap" in the latest (2017) Cosmic Origins Program Annual Technology Report.

Future missions that would benefit from this technology include two of the large missions under study for the 2020 Astrophysics Decadal Survey:

- Origins Space Telescope
- Lynx microcalorimeter instrument

References

For more information on the Origins Space Telescope, see:
https://asd.gsfc.nasa.gov/firs/

Scope Title
Actuators and other cryogenic devices

Scope Description

NASA seeks devices for cryogenic instruments, including:

- Small, precise motors and actuators, preferably with superconducting windings, that operate with extremely low power dissipation. Devices using standard NbTi conductors, as well as devices using higher temperature superconductors that can operate above 5 K, are of interest.

- Cryogenic heat pipes for heat transport within instruments. Heat pipes using hydrogen, neon, oxygen, argon, and methane are of interest. Length should be at least 0.3 m.

Expected TRL or TRL range at completion of the project: 3 to 4

Desired Deliverables of Phase II:

Prototype Hardware

Desired Deliverables Description

Working prototypes ready for testing in the relevant environments are desired.

State of the Art and Critical Gaps

Motors and actuators: Instruments often have motors and actuators, typically for optical elements. In current cryogenic instruments, these devices often dissipate relatively large powers and are a significant design drivers.

Cryogenic heat pipes: Currently, heat transport in cryogenic instruments are handled with solid thermal straps. These do not scale well for larger heat loads.

Relevance / Science Traceability

Science traceability:
NASA Strategic plan 2018, Objective 1.1: Understand The Sun, Earth, Solar System,
And Universe

Almost all instruments have motors and actuators for changing filters, adjusting focus, scanning, and other functions. On low temperature instruments, for example on mid- to far-IR observatories, dissipation in actuators can be a significant design problem.

References

For more information on earlier low temperature heat pipes, see

- Brennen, et al. AIAA paper 93-2735, https://doi.org/10.2514/6.1993-2735
- Prager, R.C., AIAA paper 80-1484, https://doi.org/10.2514/6.1980-1484
- Alario, J. and Kosson, R. AIAA paper 80-0212, https://doi.org/10.2514/6.1980-212

Scope Title
Ultra-Lightweight Dewars

Scope Description

NASA seeks extremely lightweight thermal isolation systems for scientific instruments. An important example is a large cylindrical, open top dewar to enable large, cold balloon telescopes. In one scenario, such a dewar would be launched warm, and so would not need to function at ambient pressure, but at altitude, under ~4 millibar external pressure, it would need to contain cold helium vapor. The ability to rapidly pump and hold a vacuum at altitude is necessary. An alternative concept is that the dewar would be launched at operating temperature, with some or all of the needed liquid helium. In both cases, heat flux through the walls should be less than 0.5 Watts per square meter, and the internal surfaces must be leak tight against superfluid helium. Initial demonstration units of greater than 1 meter diameter and height are desired, but the technology must be scalable to an inner diameter of 3 – 4 meters with a mass that is a small fraction of the net lift capability of a scientific balloon (~2000 kg).

Expected TRL or TRL range at completion of the project: 3 to 4

Desired Deliverables of Phase II:

Prototype Hardware

Desired Deliverables Description

A working prototype of the scale described is desired.

State of the Art and Critical Gaps

Currently available liquid helium dewars have heavy vacuum shells that allow them to be operated in ambient pressure. Such dewars have been used for balloon-based astronomy, as in the Absolute Radiometer for Cosmology, Astrophsyics, and Diffuse Emission (ARCADE) experiment. However, the current dewars are already near the limit of balloon lift capacity, and cannot be scaled up to the required size for future astrophysics measurements.

Relevance / Science Traceability

Science traceability: NASA Strategic plan 2018, Objective 1.1: Understand the Sun, Earth, Solar System, and Universe.

The potential for ground-based infrared astronomy is extremely limited. Even in airborne observatories, such as SOFIA, observations are limited by the brightness of the atmosphere and the warm telescope itself. However, high altitude scientific balloons are above enough of the atmosphere that, with a telescope large enough and cold enough, background-limited observations are possible. The ARCADE project demonstrated that at high altitudes, it is possible to cool instruments in helium vapor. Development of ultra-lightweight dewars that could be scaled up to large size, yet still be liftable by a balloon would enable ground-breaking observational capability.

References

For a description of a state-of-the art balloon cryostat, see
Singal, et al. "The ARCADE 2 instrument," The Astrophysical Journal, 730:138 (12pp), 2011 April 1

Scope Title
Miniaturized/Efficient Cryocooler Systems

Scope Description

NASA seeks miniature, highly efficient cryocoolers for instruments on earth and planetary missions. A range of cooling capabilities sought. Two examples include 0.2 Watt at 30 K with heat rejection at 300 K, and 0.3 W at 35K with heat reject of 150 K. For both examples, an input power of ≤ 5 Watt and a total mass of ≤ 400 grams is desired. The ability to fit within the volume and power limitations of a SMALLSAT platform would be highly advantageous. Components, such as low-cost cryocooler electronics that are sufficiently rad hard for lunar or planetary missions, are also sought.

Expected TRL or TRL range at completion of the project: 2 to 4

Desired Deliverables of Phase II:

Prototype Hardware

Desired Deliverables Description

Desired deliverables include miniature coolers and components, such as electronics, that are ready for functional and environmental testing.

State of the Art and Critical Gaps

Present state of the art capabilities provide 0.1 W of cooling capacity with heat rejection at 300 K at approximately 5 W input power with a system mass of 400 grams.

Cryocoolers enable the use of highly sensitive detectors, but current coolers cannot operate within the tight power constraints of outer planetary missions. Cryocooler power could be greatly reduced by lowering the heat rejection temperature, but presently there are no spaceflight systems that can operate with a heat rejection temperature significantly below ambient.

Relevance / Science Traceability

Science traceability: NASA Strategic plan 2018, Objective 1.1: Understand the Sun, Earth, Solar System, and Universe.

NASA is moving toward the use of small, low cost satellites to achieve many of its Earth science, and some of its planetary science goals. The development of cryocoolers that fit within the size and power constraints of these platforms will greatly expand their capability, for example, by enabling the use of infrared detectors.

In planetary science, progress on cryogenic coolers will enable the use of far- to mid-infrared sensors with orders of magnitude improvement in sensitivity for outer planetary missions. These will allow thermal mapping of outer planets and their moons.

References

An example of cubesat mission using cryocoolers is given at:
https://www.jpl.nasa.gov/cubesat/missions/ciras.php

Scope Title
Sub-Kelvin Cooling Systems

Scope Description

Future NASA missions will require requiring sub-Kelvin coolers for extremely low temperature detectors. Systems are sought that will provide continuous cooling with high cooling power (> 5 microWatts at 50 mK), low operating temperature (<35 mK), and higher heat rejection temperature (preferably > 10K), while maintaining high thermodynamic efficiency and low system mass.

Improvements in components for adiabatic demagnetization refrigerators are also sought. Specific components include:

1) Compact, lightweight, low current superconducting magnets capable of producing a field of at least 4 Tesla while operating at a temperature of at least 10 K, and preferably above 15 K. Desirable properties include:
   - A high engineering current density (including insulation and coil packing density), preferably > 300 Amp/mm^2.
   - A field/current ratio of >0.33 Tesla/Amp, and preferably >0.66 Tesla/Amp.
   - Low hysteresis heating.
2) Lightweight Active/Passive magnetic shielding (for use with 4 Tesla magnets) with low hysteresis and eddy current losses, and low remanence. Also needed are lightweight, highly effective outer shields that reduce the field outside an entire multi-stage device to < 5 microTesla. Outer shields must operate at 4 - 10 K, and must have penetrations for low temperature, non-contacting heat straps.
3) Heat switches with on/off conductance ratio > 30,000 and actuation time of <10 s. Materials are also sought for gas gap heat switch shells: these are tubes with extremely low thermal conductance below

1 K; they must be impermeable to helium gas, have high strength, including stability against buckling, and have an inner diameter > 20 mm.

4) High cooling power density magnetocaloric materials, especially single crystals with volume > 20 cc. Examples of desired single crystals include GdF_3, $GdLiF_4$, and Gd elpasolite.
5) 10 mK- 300 mK high resolution thermometry.
6) Suspensions with the strength and stiffness of Kevlar, but lower thermal conductance from 4 K to 0.050 K.

References

For a description of the state-of-the-art subKelvin cooler in the Hitomi mission, see:
Shirron, et al. "Thermodynamic performance of the 3-stage ADR for the Astro-H Soft-X-ray Spectrometer instrument," Cryogenics 74 (2016) 24–30, and references therein.

For articles describing magnetic subKelvin coolers and their components, see the July 2014 special issue of Cryogenics: Cryogenics 62 (2014) 129–220.

NASA has plans to purchase services for delivery of payloads to the Moon through the Commercial Lunar Payload Services (CLPS) contract. Under this subtopic, proposals may include efforts to develop payloads for flight demonstration of relevant technologies in the lunar environment. The CLPS payload accommodations will vary depending on the particular service provider and mission characteristics. Additional information on the CLPS program and providers can be found at this link: https://www.nasa.gov/content/commercial-lunar-payload-services. CLPS missions will typically carry multiple payloads for multiple customers. Smaller, simpler, and more self-sufficient payloads are more easily accommodated and would be more likely to be considered for a NASA-sponsored flight opportunity. Commercial payload delivery services may begin as early as 2020 and flight opportunities are expected to continue well into the future. In future years it is expected that larger and more complex payloads will be accommodated. Selection for award under this solicitation will not guarantee selection for a lunar flight opportunity.

Expected TRL or TRL range at completion of the project: 2 to 4

Desired Deliverables of Phase II:

Prototype Hardware

Desired Deliverables Description

For components, functioning hardware that is directly usable in NASA systems is desired.

State of the Art and Critical Gaps

The adiabatic demagnetization refrigerator in the Soft X-ray Spectrometer instrument on the Hitomi mission represents the state of the art in spaceflight sub-Kelvin cooling systems. The system is a 3 stage, dual-mode device. In the more challenging mode, it provides 650 µW of cooling at 1.625 K, while simultaneously absorbing 0.35 µW from a small detector array at 0.050 K. It rejects heat at 4.5 K. In this mode, the detector is held at temperature for 15.1 hour periods, with a 95% duty cycle. Future missions with much larger pixel count will require much higher cooling power at 0.050 K or lower, higher cooling power at intermediate stages, and 100% duty cycle. Heat rejection at a higher temperature is also needed to enable the use of a wider range of more efficient cryocoolers.

Relevance / Science Traceability

Science traceability: Science traceability:
NASA Strategic plan 2018, Objective 1.1: Understand The Sun, Earth, Solar System,
And Universe.

SubKelvin coolers are listed as a "Technology Gap" in the latest (2017) Cosmic Origins Program Annual Technology Report.

Future missions that would benefit from this technology include two of the large missions under study for the 2020 Astrophysics Decadal Survey:

- Origins Space Telescope
- Lynx (microcalorimeter instrument)

Also: Probe of Inflation and Cosmic Origins

S1.10: Atomic Interferometry (SBIR)

Lead Center: GSFC

Participating Center(s): JPL

Technology Area: 8.0.0 Science Instruments, Observatories & Sensor Systems

Related Subtopic Pointer(s):

Scope Description

Recent developments of laser control and manipulation of atoms have led to new types of precision inertial force and gravity sensors based on atom interferometry. Atom interferometers exploit the quantum mechanical wave nature of atomic particles and quantum gases for sensitive interferometric measurements. Ground-based laboratory experiments and instruments have already demonstrated beyond the state-of-the-art performances of accelerometer, gyroscope, and gravity measurements. The microgravity environment in space provides opportunities for further drastic improvements in sensitivity and precision. Such inertial sensors will have great potential to provide new capabilities for NASA Earth and planetary gravity measurements, for spacecraft inertial navigation and guidance, and for gravitational wave detection and test of properties of gravity in space.

Currently the most mature development of atom interferometers as measurement instruments are those based on light pulsed atom interferometers with freefall cold atoms. There remain a number of technical challenges to infuse this technology in space applications. Some of the identified key challenges are (but not limited to):

- Compact high flux ultra-cold atom sources for free space atom interferometers (Example: >1e+06 total useful free-space atoms, <1 nK, Rb, K, Cs, Yb, Sr, and Hg. Performance and species can be defined by offeror. Other related innovative methods and components for cold atom sources are of great interest, such as a highly compact and regulatable atomic vapor cell.
- Ultra-high vacuum technologies that allow completely sealed, non-magnetic enclosures with high quality optical access and the base pressure maintained
- <1e-09 Torr. Consideration should be given to the inclusion of cold atom sources of interest.
- Beyond the state-of-the-art photonic components at wavelengths for atomic species of interest, particularly at Near Infrared (NIR) and visible: efficient acousto-optic modulators (low RF power ~200 mW, low thermal distortion, ~80% or greater diffraction efficiency); efficient electro-optic modulators (low bias drift, residual AM, and return loss, fiber- coupled preferred), miniature optical isolators (~30 dB isolation or greater, ~ -2 dB loss or less), robust high-speed high-extinction shutters (switching time < 1 ms, extinction > 60 dB are highly desired).

- Flight qualifiable lasers or laser systems of narrow linewidth, high tunability, and/or higher power for clock and cooling transitions of atomic species of interest. Cooling and trapping lasers: 10 kHz linewidth and ~ 1 W or greater total optical power.
- Compact clock lasers: 5e-15 Hz/tau^{½} near 1 s (wavelengths for Yb+, Yb, Sr clock transitions are of special interest).

All proposed system performances can be defined by offeror with sufficient justification. Subsystem technology development proposals should clearly state the relevance, define requirements, relevant atomic species and working laser wavelengths, and indicate its path to a space-borne instrument.

References

- 2017 NASA Strategic Technology Investment Plan: https://go.usa.gov/xU7sE
- 2015 NASA Technology Roadmaps: https://go.usa.gov/xU7sy
- *NOTE: The 2015 NASA Technology Roadmaps will be replaced beginning early fall of 2019 with the 2020 NASA Technology Taxonomy and the NASA Strategic Technology Integration Framework. The 2015 NASA Technology Roadmaps will be archived and remain accessible via their current Internet address as well as via the new 2020 NASA Technology Taxonomy Internet page.*

Expected TRL or TRL range at completion of the project: 3 to 5

Desired Deliverables of Phase II

Prototype, Hardware

Desired Deliverables Description

Prototype hardware, documented evidence of delivered TRL (test report, data, etc.), summary performance analysis, supporting documentation.

State of the Art and Critical Gaps

This technology reduces gravitational sensors from two satellites to a single, table-top instrument and enhances the sensitivity of the state-of-the-art, including time measurement accuracy by factor of 100+.

Relevance / Science Traceability

Currently, no technology exists that can compete with the (potential) sensitivity, (potential) compactness, and robustness of Atom Optical-based gravity and time measurement devices. Earth science, planetary science, and astrophysics all benefit from unprecedented improvements in gravity and time measurement. Specific roadmap items supporting science instrumentation include, but are not limited to:

- TA-7.1.1: Destination Reconnaissance, Prospecting, and Mapping (gravimetry)
- TA-8.1.2: Electronics (reliable control electronics for laser systems)
- TA-8.1.3: Optical Components (reliable laser systems)
- TA-8.1.4: Microwave, Millimeter, and Submillimeter-Waves (ultra-low noise microwave output when coupled w/ optical frequency comb)
- TA-8.1.5: Lasers (reliable laser system w/ long lifetime)

See note in References section regarding the status of the 2015 NASA Technology Roadmaps.

S1.11: In Situ Instruments/Technologies and Plume Sampling Systems for Ocean Worlds Life Detection (SBIR)

Lead Center: JPL

Participating Center(s): ARC, GRC, GSFC

Technology Area: 8.0.0 Science Instruments, Observatories & Sensor Systems

Related Subtopic Pointer(s): S4.02 T6.07 S4.04 S1.05

Scope Description

This subtopic solicits development of in-situ instrument technologies and components to advance the maturity of science instruments and plume sample collection systems focused on the detection of evidence of life, especially extant life, in the Ocean Worlds (e.g., Europa, Enceladus, Titan, Ganymede, Callisto, Ceres, etc.). Technologies that can increase instrument resolution and sensitivity or achieve new and innovative scientific measurements are of particular interest. Technologies that allow collection during high speed (>1 km/sec) velocity passes through a plume are solicited as are technologies that can maximize total sample mass collected while passing through tenuous plumes. This fly-through sampling focus is distinct from S4.02, which solicits sample collection technologies from surface platforms.

These technologies must be capable of withstanding operation in space and planetary environments, including the expected pressures, radiation levels, launch and impact stresses, and range of survival and operational temperatures. Technologies that reduce mass, power, volume, and data rates for instruments and instrument components without loss of scientific capability are of particular importance.

Specifically, this subtopic solicits instrument technologies and components that provide significant advances in the following areas, broken out by planetary body:

- General to Europa, Enceladus, Titan and other Ocean Worlds - Technologies and components relevant to life detection instruments (e.g., microfluidic analyzer, microelectromechanical systems (MEMS) chromatography/mass spectrometers, laser-ablation mass spectrometer, fluorescence microscopic imager, Raman spectrometer, tunable laser system, liquid chromatography/mass spectrometer, X-ray fluorescence, digital holographic microscope-fluorescence microscope, antibody microarray biosensor, nanocantilever biodetector, etc.) Technologies for high radiation environments, e.g., radiation mitigation strategies, radiation tolerant detectors, and readout electronic components, which enable orbiting instruments to be both radiation-hard and undergo the planetary protection requirements of sterilization (or equivalent).
    - Collecting samples for a variety of science purposes is also sought. These include samples that allow for determination of the chemical and physical properties of the source ocean, samples for detailed characterization of the organics present in the gas and particle phases, and samples for analysis for biomarkers indicative of life. Front-end system technologies include sample collection systems and subsystems capable of capture, containment, and/or transfer of gas, liquid, ice, and/or mineral phases from plumes to sample processing and/or instrument interfaces.
    - Technologies for characterization of collected sample parameters including mass, volume, total dissolved solids in liquid samples, and insoluble solids. Sample collection and sample capture for in-situ imaging. Systems capable of high-velocity sample collection with minimal sample alteration to allow for habitability and life detection analyses. Microfluidic sample collection systems that enable sample concentration and other manipulations. Plume material collection technologies that minimize risk of terrestrial contamination, including organic chemical and microbial contaminates. These technologies would enable high-priority sampling and potential sample return from the plumes of Enceladus with a fly-by mission. This would be a substantial cost savings over a landed mission.

- Europa - Life detection approaches optimized for evaluating and analyzing the composition of ice matrices with unknown pH and salt content. Instruments capable of detecting and identifying organic molecules (in particular biomolecules), salts and/or minerals important to understanding the present conditions of Europa's ocean are sought (such as high resolution gas chromatograph or laser desorption mass spectrometers, dust detectors, organic analysis instruments with chiral discrimination, etc.). These developments should be geared towards analyzing and handling very small sample sizes (microg to mg) and/or low column densities/abundances. Also of interest are imagers and spectrometers that provide high performance in low-light environments (visible and NIR imaging spectrometers, thermal imagers, etc.), as well as instruments capable of improving our understanding of Europa's habitability by characterizing the ice, ocean, and deeper interior and monitoring ongoing geological activity such as plumes, ice fractures, and fluid motion (e.g., seismometers, magnetometers). Improvements to instruments capable of gravity (or other) measurements that might constrain properties such as ocean and ice shell thickness will also be considered.
- Enceladus (including plume material and E-ring particles) - Life detection approaches optimized for analyzing plume particles, as well as for determining the chemical state of Enceladus icy surface materials (particularly near plume sites). Instruments capable of detecting and identifying organic molecules (in particular biomolecules), salts and/or minerals important to understand the present conditions of the Enceladus ocean are sought (such as high resolution gas chromatograph or laser desorption mass spectrometers, dust detectors, organic analysis instruments with chiral discrimination, etc.). These developments should be geared towards analyzing and handling very small sample sizes (microg to mg) and/or low column densities/abundances. Also of interest are imagers and spectrometers that provide high performance in low-light environments (visible and NIR imaging spectrometers, thermal imagers, etc.), as well as instruments capable of monitoring the bulk chemical composition and physical characteristics of the plume (density, velocity, variation with time, etc.). Improvements to instruments capable of gravity (or other) measurements that might constrain properties such as ocean and ice shell thickness will also be considered.
- Titan - Life detection approaches optimized for searching for biosignatures and biologically relevant compounds in Titan's lakes, including the presence of diagnostic trace organic species, and also for analyzing Titan's complex aerosols and surface materials. Mechanical and electrical components and subsystems that work in cryogenic (95 K) environments; sample extraction from liquid methane/ethane, sampling from organic 'dunes' at 95 K and robust sample preparation and handling mechanisms that feed into mass analyzers are sought. Balloon instruments, such as IR spectrometers, imagers, meteorological instruments, radar sounders, solid, liquid, air sampling mechanisms for mass analyzers, and aerosol detectors are also solicited. Low mass and power sensors, mechanisms and concepts for converting terrestrial instruments such as turbidimeters and echo sounders for lake measurements, weather stations, surface (lake and solid) properties packages, etc. to cryogenic environments (95 K).
- Other Ocean Worlds targets may include Ganymede, Callisto, Ceres, etc.

Proposers are strongly encouraged to relate their proposed development to:

- NASA's future Ocean Worlds exploration goals (see references)
- Existing flight instrument capability, to provide a comparison metric for assessing proposed improvements.

Proposed instrument architectures should be as simple, reliable, and low risk as possible while enabling compelling science. Novel instrument concepts are encouraged particularly if they enable a new class of scientific discovery. Technology developments relevant to multiple environments and platforms are also desired.

Proposers should show an understanding of relevant space science needs, and present a feasible plan to fully develop a technology and infuse it into a NASA program.

References

For the NASA Roadmap for Ocean World Exploration see: http://www.lpi.usra.edu/opag/ROW

In situ instruments and technologies for NASA's Ocean Worlds exploration goals see: https://www.nasa.gov/specials/ocean-worlds/

NASA technology solicitation, see ROSES 2016/C.20 Concepts for Ocean worlds Life Detection Technology (COLDTECH) call: https://nspires.nasaprs.com/external/solicitations/summary.do?method=init&solId={5C43865B-0C93-6ECA-BCD2-A3783CB1AAC8}&path=init

Instrument Concepts for Europa Exploration 2 (final text released May 17, 2018;.PDF): https://nspires.nasaprs.com/external/viewrepositorydocument/cmdocumentid=628697/solicitationId=%7B17B73E96-6B65-FE78-5B63-84C804831035%7D/viewSolicitationDocument=1/C.23%20ICEE2%20Schulte%20POC.pdf

Expected TRL or TRL range at completion of the project: 3 to 5

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Software

Desired Deliverables Description

In-situ instruments in TRL 3 - 5 for Ocean Worlds exploration

State of the Art and Critical Gaps

In situ instruments and technologies are essential bases to achieve NASA's Ocean Worlds exploration goals. There are currently some in situ instruments for diverse Ocean Worlds bodies. However, there are ever increasing science and exploration requirements and challenges for diverse Ocean Worlds bodies. For example, there are urgent needs for the exploration of icy or liquid surface on Europa, Enceladus, Titan, Ganymede, Callisto, etc. and, plumes from planetary bodies such as Enceladus.

To narrow the critical gaps between the current state of art and the technology needed for the ever increasing science/exploration requirements, in-situ technologies are being sought to achieve much higher resolution and sensitivity with significant improvements over existing capabilities, and at the same time with lower resource (mass, power and volume) requirements.

Relevance / Science Traceability

In situ instruments and technologies are essential bases to achieve Science Mission Directorate's (SMD) planetary science goals summarized in Decadal Study (National Research Council's Vision and Voyages for Planetary Science in the Decade 2013-2022.) In situ instruments and technologies play indispensable role for NASA's New Frontiers and Discovery missions to various planetary bodies.

NASA SMD has two programs to bring this subtopic technologies to higher level: PICASSO and MatISSE. The Planetary Instrument Concepts for the Advancement of Solar System Observations (PICASSO) Program invests in low-TRL technologies and funds instrument feasibility studies, concept formation, proof-of-concept instruments, and advanced component technology. The Maturation of Instruments for Solar System Exploration (MatISSE) Program invests in mid-TRL technologies and enables timely and efficient infusion of technology into planetary science missions. The PICASSO and MatISSE are in addition to Phase III opportunities.

S1.12: Remote Sensing Instrument Technologies for Heliophysics (SBIR)

Lead Center: GSFC

Participating Center(s): HQ, MSFC

Technology Area: 8.0.0 Science Instruments, Observatories & Sensor Systems

Related Subtopic Pointer(s): S1.05 S2.04 S1.06

Scope Description

The 2013 National Research Council's, Solar and Space Physics: A Science for a Technological Society (http://nap.edu/13060) motivates this subtopic: "Deliberate investment in new instrument concepts is necessary to acquire the data needed to further solar and space physics science goals, reduce mission risk, and maintain an active and innovative hardware development community." This subtopic solicits development of advanced remote sensing instrument technologies and components suitable for deployment on heliophysics missions. These technologies must be capable of withstanding operation in space environments, including the expected pressures, radiation levels, launch and impact stresses, and range of survival and operational temperatures. Technologies that reduce mass, power, volume, and data rates for instruments and instrument components without loss of scientific capability are of particular importance. In addition, technologies that can increase instrument resolution and sensitivity or achieve new and innovative scientific measurements are solicited. For example missions, see https://science.nasa.gov/missions-page?field_division_tid=5&field_phase_tid=All. For details of the specific requirements see the Heliophysics Decadal Survey. Technologies that support science aspects of missions in NASA's Living With a Star and Solar-Terrestrial Probe programs are of top priority, including long-term missions like Interstellar Probe mission (as called out in the Decadal Survey).

Remote sensing technologies are being sought to achieve much higher resolution and sensitivity with significant improvements over existing capabilities. Remote sensing technologies amenable to CubeSats and SmallSats are also encouraged. Specifically, this subtopic solicits instrument development that provides significant advances in the following areas:

- Light Detection and Ranging (LIDAR) systems for high-power, high frequency geospace remote sensing, such as sodium and helium lasers
- Technologies or components enabling auroral, airglow, geospace, and solar imaging in the visible, far-ultraviolet and soft x-ray (e.g., mirrors and gratings with high-reflectance coatings, multi-layer coatings, narrow-band filters, and blazed gratings with high ruling densities)
- Technologies that enable the development of dedicated solar flare sensors with intrinsic ion suppression and sufficient angular resolution in the extreme UV (EUV) to soft x-ray wavelength range such as fast cadence charge-coupled devices, complementary metal-oxide semiconductor devices
- Technologies that enable x-ray detectors to observe bright solar flares in x-ray from 1 to hundreds of keV without saturation
- Technologies that attenuate solar x-ray fluences by flattening the observed spectrum by a factor of 100 to 1000 across the energy range encompassing both low and high energy x-rays – preferably flight programmable
- X-ray optics technologies to reduce the size, complexity, or mass or to improve the point spread function of solar telescopes used for imaging solar x-rays in the ~1 to 300 keV range
- Technologies that allow polarization and wavelength filtering without mechanical moving parts

Proposers are strongly encouraged to relate their proposed development to NASA's future heliophysics goals as set out in the Heliophysics Decadal Survey (2013-2022) and the NASA Heliophysics Roadmap (2014-2033). Proposed instrument components and/or architectures should be as simple, reliable, and low risk as possible while enabling compelling science. Novel instrument concepts are encouraged particularly if they enable a new class of scientific discovery. Technology developments relevant to multiple environments and platforms are also desired. Proposers should show an understanding of relevant space science needs, and present a feasible plan to fully develop a technology and infuse it into a NASA program. Detector technology proposals should be referred to the S116 subtopic.

References

For example missions, see https://science.nasa.gov/missions

For details of the specific requirements see the National Research Council's, Solar and Space Physics: A Science for a Technological Society (http://nap.edu/13060).

For details of NASA's Heliophysics roadmap, see the NASA Heliophysics Roadmap: https://smd-prod.s3.amazonaws.com/science-red/s3fs-public/atoms/files/2014_HelioRoadmap_Final_Reduced_0.pdf

Expected TRL or TRL range at completion of the project: 3 to 5

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Software

Desired Deliverables Description

Remote sensing instruments in TRL 3 - 5 for heliophysics science purpose

State of the Art and Critical Gaps

Remote sensing instruments and technologies are essential bases to achieve Science Mission Directorate's (SMD) Heliophysics goals summarized in National Research Council's, Solar and Space Physics: A Science for a Technological Society. These instruments and technologies play indispensable roles for NASA's LWS and STP mission programs, as well as a host of smaller spacecraft in the Explorers Program. In addition, there is growing demand for remote sensing technologies amenable to CubeSats and SmallSats. To narrow the critical gaps between the current state of art and the technology needed for the ever increasing science/exploration requirements, remote sensing technologies are being sought to achieve much higher resolution and sensitivity with significant improvements over existing capabilities, and at the same time with lower mass, power and volume.

Relevance / Science Traceability

Remote sensing instruments and technologies are essential bases to achieve SMD's Heliophysics goals summarized in National Research Council's, Solar and Space Physics: A Science for a Technological Society. These instruments and technologies play indispensable roles for NASA's Living with a Star (LWS) and Solar Terrestrial Probe (STP) mission programs, as well as a host of smaller spacecraft in the Explorers Program. In addition, there is growing demand for remote sensing technologies amenable to Cubesats and Smallsats. NASA SMD has two excellent programs to bring this subtopic technologies to higher level: Heliophysics Instrument Development for Science (H-TIDeS) and Heliophysics Flight Opportunities for Research and Technology (H-FORT). H-TIDeS seeks to advance the development of technologies and their application to enable investigation of key heliophysics science questions. This is done through incubating innovative concepts and development of prototype technologies. It is intended that technologies developed through H-TIDeS would then be proposed to H-FORT to mature by demonstration in a relevant environment. The H-TIDeS and H-FORT programs are in addition to Phase III opportunities.

T8.04: Metamaterials and Metasurfaces Technology for Remote Sensing Applications (STTR)

Lead Center: GSFC

Participating Center(s): JPL

Technology Area: 8.0.0 Science Instruments, Observatories & Sensor Systems

Related Subtopic Pointer(s): T12.01

Scope Title
Research and Development Opportunities for Metamaterials

Scope Description

Metamaterials are man-made (synthesized) composite materials whose electromagnetic, acoustic, optical, etc. properties are determined by their constitutive structural materials and their configurations. Metamaterials can be precisely tailored to manipulate electromagnetic waves, including visible light, microwaves, and other parts of the spectrum, in ways that no natural materials can. The development of metamaterials continues to redefine the boundaries of materials science. In the field of electromagnetic research and beyond, these materials offer excellent design flexibility with their customized properties and their tunability under external stimuli. These properties enable Metamaterials to be a game changer for many technologies needing reduced size, weight, and power (SWaP), enhanced tunability and reconfigurability. Topics of interest for NASA's applications are listed below.

1. Beam shaping with metamaterials (at optical as well as microwave wavelengths).
2. Control of emission and absorption with metamaterials (for applications such as tunable lenses).
3. Engineering mid-infrared and optical nonlinearities with metamaterials.
4. Development of microwave and millimeter-wave metamaterials: radar scanning systems, flat panel antennas, mobile communication antennas, novel magnetic materials and high-performance absorbing and shielding materials for electromagnetic compatibility (EMC) and reduction of radio frequency interference (RFI).
5. Thin-film technology incorporated with metamaterial nanocomposites to collect light from wide angles and absorption over wide spectrum.
6. Tunable, reconfigurable metamaterials using liquid crystal medium (Applications: IR and Optical spectrometers).
7. Development of artificial ferrites and artificial dielectrics using metamaterial concepts to design electrically small, lightweight, and efficient RF components.
8. Transformation electromagnetic techniques with advances in fabricating metamaterials (Applications: microwaves and infrared wavelength sensors).

Expected TRL or TRL range at completion of the project: 1 to 3

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Research

Desired Deliverables Description

It is expected at the end of year one for selected teams to provide a comprehensive feasibility study to address an applicable area of interest within the field of metamaterial technology. Deliverables in subsequent years could involve prototypes and demonstration of performance.

State of the Art and Critical Gaps

Metamaterial research is interdisciplinary and involves such fields as electrical engineering, electromagnetics, classical optics, solid state physics, microwave and antenna engineering, optoelectronics, material sciences, as well as nanoscience and semiconductor engineering.

Potential applications of metamaterials are diverse and include: optical filters, remote aerospace applications, sensor detection, radomes, and lenses for high-gain antennas. Metamaterials also offer the potential to create superlenses, which could allow imaging below the diffraction limit that is the minimum resolution that can be achieved by conventional glass lenses. Transformation optics is a technique that simplifies the modeling of optical devices by altering the coordinate system to control the trajectories of light rays. At microwave frequencies, the first, imperfect invisibility cloak was realized in 2006.

Relevance / Science Traceability

Metamaterial technology has the biggest potential to impact the future of space borne instrumentation by reducing size, weight, and power (SWaP) as well as the overall cost of future space missions. There is especially a need for these improved capabilities in the development of instruments for Planetary and the Earth Science missions to reduce their cost. Due to the nature of metamaterials, there are a multitude of possible applications for this technology. For example, applications of metamaterials for remote sensing include tunability, complex filtering, light channeling/trapping, superbeaming, and determination of optical angular momentum modes via metamaterials. For additional information regarding Science Mission Directorate (SMD) technology needs, please review https://science.nasa.gov/about-us/science-strategy/decadal-surveys.

References

www.centerformetamaterials.org/

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Rainsford, Tamath J.; D. Abbott; Abbott, Derek (9 March 2005). Al-Sarawi, Said F, ed. "T-ray sensing applications: review of global developments". Proc. SPIE. Smart Structures, Devices, and Systems II.

Conference Location: Sydney, Australia 2004-12-13: The International Society for Optical Engineering. 5649 Smart Structures, Devices, and Systems II (Poster session): 826–38. Bibcode:2005SPIE.5649..826R. doi:10.1117/12.607746.

Zouhdi, Saïd; Ari Sihvola; Alexey P. Vinogradov (December 2008). Metamaterials and Plasmonics: Fundamentals, Modelling, Applications. New York: Springer-Verlag. pp. 3–10, Chap. 3, 106. ISBN 978-1-4020-9406-4.

Werner, Douglas H. (editor) and Do-Hoon Kwon (editor) 2014. Transformation Electromagnetics and Metamaterials: Fundamental Principles and Applications.

T8.06: Quantum Sensing and Measurement (STTR)

Lead Center: GSFC

Participating Center(s): GRC, JPL

Technology Area: 8.0.0 Science Instruments, Observatories & Sensor Systems

Related Subtopic Pointer(s): S2.04 A2.02 T5.04

Scope Title
Quantum Sensing and Measurement

Scope Description

This Quantum Sensing subtopic calls for proposals using quantum systems to achieve unprecedented measurement sensitivity and performance, including quantum-enhanced methodologies that outperform their classical counterparts. Shepherded by advancements in our ability to detect and manipulate single quantum objects, the so called "Second Quantum Revolution" is upon us. The emerging quantum sensing technologies promise unrivaled sensitivities and are potentially game changing in precision measurement fields. Significant gains include technology important for a range of NASA missions such as: efficient photon detection, optical clocks, gravitational wave sensing, ranging, and interferometry. Atom Interferometry and Quantum Communication focused proposals should apply to those specific subtopics and are not covered in this Quantum Sensing and Measurement subtopic.

Specifically identified applications of interested include quantum sensing methodologies achieving the optimal collection light for photon-starved astronomical observations, quantum-enhanced ground penetrating radar, and quantum-enhanced telescope interferometry.

- Superconducting Quantum Interference Device (SQUIDs) systems for enhanced multiplexing factor reading out of arrays of cryogenic energy-resolving single-photon detectors, including the supporting resonator circuits, amplifiers, and room temperature readout electronics.
- Quantum light sources capable of efficiently and reliably producing prescribed quantum states including entangled photons, squeezed states, photon number states, and broadband correlated light pulses. Such entangled sources are sought for the vis-IR and in the microwave entangled photons sources for quantum ranging and ground penetrating radar.
- On-demand single photon sources with narrow spectral linewidth are needed for system calibration of single photon counting detectors and energy-resolving single-photon detector arrays in the MIR, NIR, and visible. Such sources are sought for operation at cryogenic temperatures for calibration on the ground and aboard space instruments.

References

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- National Quantum Initiative Act:
  - https://www.congress.gov/congressional-report/115th-congress/house-report/950/1
  - https://www.congress.gov/congressional-report/115th-congress/senate-report/389
  - https://www.lightourfuture.org/getattachment/7ad9e04f-4d21-4d98-bd28-e1239977e262/NPI-Recommendations-to-HSC-for-National-Quantum-Initiative-062217.pdf
- European Union Quantum Flagship Program: https://qt.eu
- UK National Quantum Technologies Programme http://uknqt.epsrc.ac.uk
- DLR Institute of Quantum Technologies https://www.dlr.de/qt/en/desktopdefault.aspx/tabid-13498/23503_read-54020/
- C. L. Degen, F. Reinhard, and P. Cappellaro, Quantum Sensing, Rev. Mod. Phys. **89**, 035002 (2017).

Expected TRL or TRL range at completion of the project: 2 to 4

Desired Deliverables of Phase II

Prototype, Analysis, Research

Desired Deliverables Description

NASA is seeking innovative ideas and creative concepts for science sensor technologies using quantum sensing techniques. The proposals should include results from designs and models, proof-of-concept demonstrations and prototypes showing the performance of the novel quantum sensor.

State of the Art and Critical Gaps

Sources for entangled photons.

Quantum dot source produced entangled photons with a fidelity of 0.90, a pair generation rate of 0.59, a pair extraction efficiency of 0.62, and a photon indistinguishability of 0.90 simultaneously. (881 nm light) at 10 MHz. Wang Phys. Rev. Lett. 122, 113602 2019.

Spectral brightness of 0.41 MHz/mW/nm for multi-mode and 0.025 MHz/mW/nm for single mode coupling. Jabir *Scientific Reports* **volume 7**, Article number: 12613 (2017).

Higher brightness and multiple entanglement and heralded multiphoton entanglement and boson sampling sources. Sources that produce photon number states or Fock states are also sought for various applications including energy-resolving single photon detector applications.

For energy resolving single photon detectors current state of the art multiplexing can achieve kilopixel detector arrays which with advances in microwave SQUID mux can be increased to megapixel arrays. (Morgan Physics Today 71, 8, 28 (2018)).

Relevance / Science Traceability

Quantum technologies enable a new generation in sensitivities and performance. Including atomic clocks and ultra-precise sensors with applications ranging from natural resource exploration and biomedical diagnostic to navigation.

HEOMD - Astronaut Health Monitoring.

SMD - Earth, Planetary and Astrophysics including imaging spectrometers on a chip across the electromagnetic spectrum from X-ray through the IR.

STMD - Game changing technology for small spacecraft communication and navigation (optical communication, laser ranging, gyroscopes).

STTR- Rapid increased interest.

Space Technology Roadmap - 6.2.2, 13.1.3, 13.3.7, all sensors 6.4.1, 7.1.3, 10.4.1, 13.1.3, 13.4.3, and 14.3.3.

Focus Area 10: Advanced Telescope Technologies

Lead MD: SMD

Participating MD(s): None

The NASA Science Mission Directorate (SMD) seeks technology for cost-effective high-performance advanced space telescopes for astrophysics and Earth science. Astrophysics applications require large aperture light-weight highly reflecting mirrors, deployable large structures and innovative metrology, control of unwanted radiation for high-contrast optics, precision formation flying for synthetic aperture telescopes, and cryogenic optics to enable far infrared telescopes. A few of the new astrophysics telescopes and their subsystems will require operation at cryogenic temperatures as cold a 4 K. This topic will consider technologies necessary to enable future telescopes and observatories collecting electromagnetic bands, ranging from UV to millimeter waves, and also include gravity waves. The subtopics will consider all technologies associated with the collection and combination of observable signals. Earth science requires modest apertures in the 2 to 4 meter size category that are cost effective. New technologies in innovative mirror materials, such as silicon, silicon carbide and nanolaminates, innovative structures, including nanotechnology, and wavefront sensing and control are needed to build telescopes for Earth science.

S2.01: Proximity Glare Suppression for Astronomical Direct Detection of Exoplanets (SBIR)

Lead Center: JPL

Participating Center(s): GSFC

Technology Area: 8.0.0 Science Instruments, Observatories & Sensor Systems

Related Subtopic Pointer(s): S2.04 S2.02 S1.04

Scope Title
Control of Scattered Starlight with Coronagraphs and Starshades

Scope Description

This subtopic addresses the unique problem of imaging and spectroscopic characterization of faint astrophysical objects that are located within the obscuring glare of much brighter stellar sources. Examples include planetary systems beyond our own, the detailed inner structure of galaxies with very bright nuclei, binary star formation, and stellar evolution. Contrast ratios of one million to ten billion over an angular spatial scale of 0.05 - 1.5 arcsec are typical of these objects. Achieving a very low background requires control of both scattered and diffracted light. The failure to control either amplitude or phase fluctuations in the optical train severely reduces the effectiveness of starlight cancellation schemes.

This innovative research focuses on advances in coronagraphic instruments, starlight cancellation instruments, and potential occulting technologies that operate at visible and near infrared wavelengths. The ultimate application of these instruments is to operate in space as part of a future observatory mission concepts such as the Habitable Exoplanet Observatory (HabEx) and Large Ultraviolet Optical Infrared Surveyor (LUVOIR). Measurement techniques include imaging, photometry, spectroscopy, and polarimetry. There is interest in component development and innovative instrument design, as well as in the fabrication of subsystem devices to include, but not limited to, the following areas:

Starlight Suppression Technologies:

- Hybrid metal/dielectric and polarization apodization masks for diffraction control of phase and amplitude for coronagraph scaled starshade experiments.
- Low-scatter, low-reflectivity, sharp, flexible edges for control of solar scatter in starshades.
- Low-reflectivity coatings for flexible starshade optical shields.
- Systems to measure spatial optical density, phase inhomogeneity, scattering, spectral dispersion, thermal variations, and to otherwise estimate the accuracy of high-dynamic range apodizing masks.
- Methods to distinguish the coherent and incoherent scatter in a broadband speckle field.

Wavefront Measurement and Control Technologies:

- Small stroke, high precision, deformable mirrors and associated driving electronics scalable to 10,000 or more actuators (both to further the state-of-the-art towards flight-like hardware and to explore novel concepts). Multiple deformable mirror technologies in various phases of development and processes are encouraged to ultimately improve the state-of-the-art in deformable mirror technology. Process improvements are needed to improve repeatability, yield, and performance precision of current devices.
- Multiplexers with ultra-low power dissipation for electrical connection to deformable mirrors
- Low-order wavefront sensors for measuring wavefront instabilities to enable real-time control and post-processing of aberrations.
- Thermally and mechanically insensitive optical benches and systems.

Optical Coating and Measurement Technologies:

- Instruments capable of measuring polarization cross-talk and birefringence to parts per million.
- Polarization-insensitive coatings for large optics.
- Methods to measure the spectral reflectivity and polarization uniformity across large optics.
- Methods to apply carbon nanotube coatings on the surfaces of the coronagraphs for broadband suppression from visible to near infrared (NIR).

References

See SPIE conference papers and articles published in the Journal of Astronomical Telescopes and Instrumentation on high contrast coronagraphy, segmented coronagraph design and analysis, and starshades.

Websites:

- Exoplanet Exploration - Planets Beyond Our Solar System: https://exoplanets.jpl.nasa.gov
- Exoplanet Exploration Program: https://exoplanets.nasa.gov/exep/

- Goddard Space Flight Center: https://www.nasa.gov/goddard

Expected TRL or TRL range at completion of the project: 3 to 5

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Research

Desired Deliverables Description

This subtopic solicits proposals to develop components that improve the footprint, robustness, power consumption, reliability, and wavefront quality of high-contrast, low-temporal bandwidth, adaptive optics systems. These include ASIC drivers that easily integrate with the deformable mirrors, improved connectivity technologies, as well as high-actuator count deformable mirrors with high-quality, ultrastable wavefronts.

It also seeks coronagraph masks that can be tested in ground-based high-contrast testbeds in place at a number of institutions, as well as devices to measure the masks to inform optical models. The masks include transmissive scalar, polarization-dependent, and spatial apodizing masks including those with extremely low reflectivity regions that allow them to be used in reflection.

The subtopic seeks samples of optical coatings that reduce polarization and can be applied to large optics, and methods and instruments to characterize them over large optical surfaces.

Finally, for starshades, the subtopic seeks low reflectivity and potentially diffraction-controlling edges that minimize scattered sunlight while also remaining robust to handling and cleaning. Low-reflectivity optical coatings that can be applied to the surfaces for the large (hundreds of square meters) optical shield are also desired.

State of the Art and Critical Gaps

Coronagraphs have been demonstrated to achieve high contrast in moderate bandwidth in laboratory environments. Starshades will enable even deeper contrast over broader bands but to date have demonstrated deep contrast in narrow band light. The extent to which the telescope optics will limit coronagraph performance is a function of the quality of the optical coating and the ability to control polarization over the full wavefront. Neither of these technologies is well characterized at levels required for 1e10 contrast. Wavefront control using deformable mirrors is critical. Controllability and stability to picometer levels is required. To date, deformable mirrors have been up to the task of providing contrast approaching 1e10, but they require thousands of wires, and overall wavefront quality and stroke remain concerns.

Relevance / Science Traceability

These technologies are directly applicable to the Wide Field Infrared Survey Telescope (WFIRST), coronagraph instrument (CGI), and the HabEx and LUVOIR concept studies.

S2.02: Precision Deployable Optical Structures and Metrology (SBIR)

Lead Center: JPL

Participating Center(s): GSFC

Technology Area: 8.0.0 Science Instruments, Observatories & Sensor Systems

Related Subtopic Pointer(s): Z8.08 S2.03 Z3.03 S2.01 S1.05 H9.01

Scope Title

Precision Deployable Optical Structures and Metrology

Scope Description

Future space astronomy missions from ultraviolet to millimeter wavelengths will push the state of the art in current optomechanical technologies. Size, dimensional stability, temperature, risk, manufacturability, and cost are important factors, separately and in combination. The Large Ultraviolet Optical Infrared Surveyor (LUVOIR) calls for deployed apertures as large as 15 m in diameter, the Origins Space Telescope (OST) for operational temperatures as low as 4 K, LUVOIR and the Habitable Exoplanet Observatory (HabEx) for exquisite optical quality. Methods to construct large telescopes in space are also under development. Additionally, sunshields for thermal control and starshades for exoplanet imaging require deployment schemes to achieve 30-70 m class space structures.

This subtopic addresses the need to mature technologies that can be used to fabricate 10-20 m class, lightweight, ambient or cryogenic flight qualified observatory systems and subsystems (telescopes, sunshields, starshades). Proposals to fabricate demonstration components and subsystems with direct scalability to flight systems through validated models will be given preference. The target launch volume and expected disturbances, along with the estimate of system performance, should be included in the discussion. Novel metrology solutions to establish and maintain optical alignment will also be accepted.

Technologies including, but not limited to, the following areas are of particular interest:

Precision structures/materials:

- Low Coefficient Thermal Expansion (CTE)/Coefficient of Moisture Expansion (CME) materials/structures to enable highly dimensionally stable optics, optical benches, metering structures
- Materials/structures to enable deep cryogenic (down to 4 K) operation
- Novel athermalization methods to join materials/structures with differing mechanical/thermal properties
- Lightweight materials/structures to enable high mass-efficiency structures
- Precision joints/latches to enable sub-micron level repeatability
- Mechanical connections providing micro-dynamic stability suitable for robotic assembly

Deployable Technologies:

- Precision deployable modules for assembly of optical telescopes (e.g., innovative active or passive deployable primary or secondary support structures)
- Hybrid deployable/assembled architectures, packaging, and deployment designs for large sunshields and external occulters (20-50 m class)
- Packaging techniques to enable more efficient deployable structures

Metrology:

- Techniques to verify dimensional stability requirements at sub-nanometer level precisions (10 – 100 picometers)
- Techniques to monitor and maintain telescope optical alignment for on-ground and in-orbit operation

A successful proposal shows a path toward a Phase II delivery of demonstration hardware scalable to 5-meter diameter for ground test characterization. Proposals should show an understanding of one or more relevant science needs, and present a feasible plan to fully develop the relevant subsystem technologies and to transition into future NASA program(s).

References

Large UV/Optical/IR Surveyor (LUVOIR): https://asd.gsfc.nasa.gov/luvoir/

Habitable Exoplanet Observatory (HabEx): https://www.jpl.nasa.gov/habex/

Origins Space Telescope: https://asd.gsfc.nasa.gov/firs/

What is an Exoplanet? https://exoplanets.nasa.gov/what-is-an-exoplanet/technology/

NASA in-Space Assembled Telescope (iSAT) Study: https://exoplanets.nasa.gov/exep/technology/in-space-assembly/iSAT_study/

Expected TRL or TRL range at completion of the project: 3 to 5

Desired Deliverables of Phase II

Prototype, Analysis, Research

Desired Deliverables Description

A successful deliverable would include a demonstration of the functionality and/or performance of a system/subsystem with model predictions to explain observed behavior as well as make predictions on future designs. This should be demonstrated on units that can be scaled to future flight sizes.

State of the Art and Critical Gaps

The James Webb Space Telescope, currently set to launch in 2021, represents the state of the art in large deployable telescopes. The Wide Field Infrared Survey Telescope's (WFIRST) coronagraph instrument (CGI) will drive telescope/instrument stability requirements to new levels. The mission concepts in the upcoming Astro2020 decadal survey will push technological requirements even further in the areas of deployment, size, stability, lightweighting, and operational temperature. Each of these mission studies have identified technology gaps related to their respective mission requirements.

Relevance / Science Traceability

These technologies are directly applicable to the WFIRST CGI and the HabEx, LUVOIR, and OST mission concepts.

S2.03: Advanced Optical Systems and Fabrication/Testing/Control Technologies for EUV/Optical and IR Telescope (SBIR)

Lead Center: MSFC

Participating Center(s): GRC, GSFC, JPL, LaRC

Technology Area: 8.0.0 Science Instruments, Observatories & Sensor Systems

Related Subtopic Pointer(s): S2.02 H9.01

Scope Title

Optical Components and Systems for Large Telescope Missions

Scope Description

To accomplish NASA's high-priority science at all levels (flagship, probe, Medium-Class Explorers (MIDEX), Small Explorers (SMEX), rocket and balloon) requires low-cost, ultra-stable, normal incidence mirror systems with low mass-to-collecting area ratios. Where a mirror system is defined as the mirror substrate, supporting structure, and associated actuation and thermal management systems. After performance, the most important metric for an advanced optical system is affordability or areal cost (cost per square meter of collecting aperture). Current normal incidence space mirrors cost $4 million to $6 million per square meter of optical surface area. This research effort seeks to improve the performance of advanced precision optical components while reducing their cost by 5 to 50 times, to between $100K/m2 to $1M/m2.

Specific metrics are defined for each wavelength application region:

Aperture Diameter for all wavelengths, except Far-IR

- Monolithic: 1 to 8 meters
- Segmented: 3 to 20 meters

For UV/Optical

- Areal Cost < $500K/m2
- Wavefront Figure < 5 nm RMS (via passive design or active deformation control)
- Wavefront Stability < 10 pm/10 min
- First Mode Frequency 60 to 500 Hz
- Actuator Resolution < 1 nm RMS
- Optical Path-length Stability < 1 pm/10,000 seconds for precision metrology
- Areal density < 15 kg/m2 (< 35 kg/m2 with backplane)
- Operating Temperature Range of 250 to 300K

For Far-IR

- Aperture diameter 1 to 4 m (monolithic), or 5 to 10 m (segmented)
- Telescope diffraction-limited at <30 microns at operating temperature 4 K
- Cryo-Deformation < 100 nm RMS
- Areal cost < $500K/m2
- Production rate > 2 m2 per month
- Areal density < 15 kg/m2 (< 40 kg/m2 with backplane)
- Thermal conductivity at 4 K > 2 W/m*K
- Survivability at temperatures ranging from 315 K to 4 K

For EUV

- Surface Slope < 0.1 micro-radian

Also needed is ability to fully characterize surface errors and predict optical performance.

Proposals must show an understanding of one or more relevant science needs, and present a feasible plan to develop the proposed technology for infusion into a NASA program: sub-orbital rocket or balloon; competed SMEX or MIDEX; or, Decadal class mission. Successful proposals will demonstrate an ability to manufacture, test and control ultra-low-cost optical systems that can meet science performance requirements and mission requirements (including processing and infrastructure issues). Material behavior, process control, active and/or passive optical performance, and mounting/deploying issues should be resolved and demonstrated.

References

The Habitable Exoplanet Imager (HabEx) and Large UVOIR (LUVOIR) space telescope studies are developing concepts for UVOIR space telescopes for exoEarth discovery and characterization, exoplanet science, general astrophysics and solar system astronomy. The HabEx Interim Report is available at: https://www.jpl.nasa.gov/habex/documents/. The LUVOIR Interim Report is available at: https://asd.gsfc.nasa.gov/luvoir/.

The Origins Space Telescope (OST) is a single-aperture telescope concept for the Far-Infrared Surveyor mission described in the NASA Astrophysics Roadmap, "Enduring Quests, Daring Visions: NASA Astrophysics in the Next Three Decades": https://smd-prod.s3.amazonaws.com/science-pink/s3fs-public/atoms/files/secure-Astrophysics_Roadmap_2013_0.pdf.

The OST mission is described on the website: https://origins.ipac.caltech.edu.

The Space Infrared Interferometric Telescope (SPIRIT) and its optical system requirements are described on the website: https://asd.gsfc.nasa.gov/cosmology/spirit/.

LISA (Laser Interferometer Space Antenna) mission description: https://lisa.nasa.gov/.

Expected TRL or TRL range at completion of the project: 3 to 5

Desired Deliverables of Phase II

Prototype, Hardware, Research

Desired Deliverables Description

An ideal Phase 1 deliverable would be a precision optical system of at least 0.25 meters; or a relevant sub-component of a system; or a prototype demonstration of a fabrication, test or control technology leading to a successful Phase 2 delivery; or a reviewed preliminary design and manufacturing plan which demonstrates feasibility. While detailed analysis will be conducted in Phase 2, the preliminary design should address how optical, mechanical (static and dynamic) and thermal designs and performance analysis will be done to show compliance with all requirements. Past experience or technology demonstrations which support the design and manufacturing plans will be given appropriate weight in the evaluation.

An ideal Phase 2 project would further advance the technology to produce a flight-qualifiable optical system greater than 0.5 meters or relevant sub-component (with a TRL in the 4 to 5 range); or a working fabrication, test or control system. Phase 1 and Phase 2 mirror system or component deliverables would be accompanied by all necessary documentation, including the optical performance assessment and all data on processing and properties of its substrate materials. A successful mission oriented Phase 2 would have a credible plan to deliver for the allocated budget a fully assembled and tested telescope assembly which can be integrated into the potential mission; and, demonstrate an understanding of how the engineering specifications of their system meets the performance requirements and operational constraints of the mission (including mechanical and thermal stability analysis).

State of the Art and Critical Gaps

Current normal incidence space mirrors cost $4 million to $6 million per square meter of optical surface area. This research effort seeks a cost reduction for precision optical components by 5 to 50 times, to between $100K/m2 to $1M/m2.

Relevance / Science Traceability

S2.03 primary supports potential Astrophysics Division missions. S2.03 has made optical systems in the past for potential balloon experiments. Future potential Decadal missions include LISA, Habitable Exoplanet Observatory (HabEx), Large UV/Optical/Near-IR Surveyor (LUVOIR) and the Origins Space Telescope (OST).

Scope Title
Balloon Planetary Telescope

Scope Description

Astronomy from a stratospheric balloon platform offers numerous advantages for planetary science. At typical balloon cruise altitudes (100,000 to 130,000 ft.), 99%+ of the atmospheric is below the balloon and the attenuation due to the remaining atmosphere is small, especially in the near ultraviolet band and in the infrared bands near 2.7 and 4.25 µm. The lack of atmosphere nearly eliminates scintillation and allows the resolution potential of relatively large optics to be realized, and the small amount of atmosphere reduces scattered light and allows observations of brighter objects even during daylight hours.

For additional discussion of the advantages of observations from stratosphere platforms, refer to “Planetary Balloon-Based Science Platform Evaluation and Program Implementation - Final Report,” Dankanich et.al. (Available from https://ntrs.nasa.gov/, search for "NASA/TM-2016-218870")

To perform Planetary Science requires a 1-meter class telescope 500 nm diffraction limited performance or Primary Mirror System that can maintain < 10 nm rms surface figure error for elevation angles ranging from 0 to 60 degrees over a temperature range from 220K to 280K.

Phase I will produce a preliminary design and report including initial design requirements such as wave-front error budget, mass allocation budget, structural stiffness requirements, etc., trade studies performed and analysis that compares the design to the expected performance over the specified operating range. Development challenges shall be identified during phase I including trade studies and challenges to be addressed during Phase II with subsystem proof of concept demonstration hardware. If Phase II can only produce a sub-scale component, then it should also produce a detailed final design, including final requirements (wave-front error budget, mass allocation, etc) and performance assessment over the specified operating range.

Additional information about Scientific Balloons can be found at https://www.csbf.nasa.gov/docs.html.

Telescope Specifications:

- Diameter > 1 meter
- System Focal Length 14 meter (nominal)
- Diffraction Limit < 500 nm
- Mass < 300 kg
- Shock 10G without damage
- Elevation 0 to 60 degrees
- Temperature 220 to 280 K

Primary Mirror Assembly Specifications:

- Diameter > 1 meter
- Radius of Curvature 3 meters (nominal)
- Surface Figure Error < 10 nm rms
- Mass < 150 kg
- Shock 10G without damage
- Elevation 0 to 60 degrees
- Temperature 220 to 280 K

References

For additional discussion of the advantages of observations from stratosphere platforms, refer to “Planetary Balloon-Based Science Platform Evaluation and Program Implementation - Final Report,” Dankanich et.al. (Available from https://ntrs.nasa.gov/, search for "NASA/TM-2016-218870")

Expected TRL or TRL range at completion of the project: 3 to 5

Desired Deliverables of Phase II

Prototype, Analysis, Hardware

Desired Deliverables Description

If Phase II can only produce a sub-scale component, then it should also produce a detailed final design, including final requirements (wave-front error budget, mass allocation, etc.) and performance assessment over the specified operating range.

State of the Art and Critical Gaps

To perform Planetary Science requires a 1-meter class telescope 500 nm diffraction limited performance or Primary Mirror System that can maintain < 10 nm rms surface figure error for elevation angles ranging from 0 to 60 degrees over a temperature range from 220K to 280K.
Significant science returns may be realized through observations in the 300 nm to 5 µm range.
Current SOA (State of the Art) mirrors made from Zerodur or ULE for example require light weighting to meet balloon mass limitations, and cannot meet diffraction limited performance over the wide temperature range due to the coefficient of thermal expansion limitations.

Relevance / Science Traceability

From "Vision and Voyages for Planetary Science in the Decade 2013-2022":

- Page 22, Last Paragraph of NASA Telescope Facilities within the Summary Section:
  Balloon- and rocket-borne telescopes offer a cost-effective means of studying planetary bodies at wavelengths inaccessible from the ground.6 Because of their modest costs and development times, they also provide training opportunities for would-be developers of future spacecraft instruments. Although NASA's Science Mission Directorate regularly flies balloon missions into the stratosphere, there are few funding opportunities to take advantage of this resource for planetary science, because typical planetary grants are too small to support these missions. A funding line to promote further use of these suborbital observing platforms for planetary observations would complement and reduce the load on the already oversubscribed planetary astronomy program.
- Page 203, 5th paragraph, Section titled Earth and Space-Based Telescopes:
  Significant planetary work can be done from balloon-based missions flying higher than 45,000 ft. This altitude provides access to electromagnetic radiation that would otherwise be absorbed by Earth's atmosphere and permits high-spatial-resolution imaging unaffected by atmospheric turbulence. These facilities offer a combination of cost, flexibility, risk tolerance, and support for innovative solutions that is ideal for the pursuit of certain scientific opportunities, the development of new instrumentation, and infrastructure support. Given the rarity of giant-planet missions, these types of observing platforms (high-altitude telescopes on balloons and sounding rockets) can be used to fill an important data gap.154, 155,156.

Potential Advocates include Planetary Scientists at GSFC, APL, and Southwest Research Institute, etc. The NASA Balloon Workshop.

Potential Projects Gondola for High Altitude Planetary Science (GHAPS).

Scope Title
Large UV/Optical (LUVOIR) and Habitable Exoplanet (HabEx) Missions

Scope Description

Potential UV/Optical missions require 4 to 16 meter monolithic or segmented primary mirrors with < 5 nm RMS surface figures. Active or passive alignment and control is required to achieve system level diffraction limited performance at wavelengths less than 500 nm (< 40 nm RMS wavefront error, WFE). Additionally, potential Exoplanet mission, using an internal coronagraph, requires total telescope wavefront stability on order of 10 pico-meters RMS per 10 minutes. This stability specification places severe constraints on the dynamic mechanical and thermal performance of 4 meter and larger telescope. Potential enabling technologies include: active thermal control systems, ultra-stable mirror support structures, athermal telescope structures, athermal mirror struts, ultra-stable low CTE/high-stability joints, and vibration compensation.

Mirror areal density depends upon available launch vehicle capacities to Sun-Earth L2 (i.e. 15 kg/m2 for a 5 m fairing EELV vs. 150 kg/m2 for a 10 m fairing SLS). Regarding areal cost, a good goal is to keep the total cost of the primary mirror at or below $100M. Thus, an 8-m class mirror (with 50 m2 of collecting area) should have an areal cost of less than $2M/m2. And, a 16-m class mirror (with 200 m2 of collecting area) should have an areal cost of less than $0.5M/m2.

Key technologies to enable such a mirror include new and improved:

- Mirror substrate materials and/or architectural designs
- Processes to rapidly fabricate and test UVO quality mirrors
- Mirror support structures, joints and mechanisms that are athermal or zero CTE at the desired scale
- Mirror support structures, joints and mechanisms that are ultra-stable at the desired scale
- Mirror support structures with low-mass that can survive launch at the desired scale
- Mechanisms and sensors to align segmented mirrors to < 1 nm RMS precisions
- Thermal control (< 1 mK) to reduce wavefront stability to < 10 pm RMS per 10 min
- Dynamic isolation (> 140 dB) to reduce wavefront stability to < 10 pm RMS per 10 min

Also needed is ability to fully characterize surface errors and predict optical performance via integrated opto-mechanical modeling.

Potential solutions for substrate material/architecture include, but are not limited to: ultra-uniform low CTE glasses, silicon carbide, nanolaminates or carbon-fiber reinforced polymer. Potential solutions for mirror support structure material/architecture include, but are not limited to: additive manufacturing, nature inspired architectures, nanoparticle composites, carbon fiber, graphite composite, ceramic or SiC materials, etc. Potential solutions for new fabrication processes include, but are not limited to: additive manufacture, direct precision machining, rapid optical fabrication, roller embossing at optical tolerances, slumping or replication technologies to manufacture 1 to 2 meter (or larger) precision quality components. Potential solutions for achieving the 10 pico-meter wavefront stability include, but are not limited to: metrology, passive, and active control for optical alignment and mirror phasing; active vibration isolation; metrology, passive, and active thermal control.

References

The Habitable Exoplanet Imager (HabEx) and Large UVOIR (LUVOIR) space telescope studies are developing concepts for UVOIR space telescopes for exoEarth discovery and characterization, exoplanet science, general astrophysics and solar system astronomy. The HabEx Interim Report is available at: https://www.jpl.nasa.gov/habex/documents/. The LUVOIR Interim Report is available at: https://asd.gsfc.nasa.gov/luvoir/.

The Origins Space Telescope (OST) is a single-aperture telescope concept for the Far-Infrared Surveyor mission described in the NASA Astrophysics Roadmap, "Enduring Quests, Daring Visions: NASA Astrophysics in the Next

Three Decades" (https://smd-prod.s3.amazonaws.com/science-pink/s3fs-public/atoms/files/secure-Astrophysics_Roadmap_2013_0.pdf).

The OST mission is described on the website https://origins.ipac.caltech.edu.

The Space Infrared Interferometric Telescope (SPIRIT) and its optical system requirements are described on the website https://asd.gsfc.nasa.gov/cosmology/spirit/.

Expected TRL or TRL range at completion of the project: 2 to 4

Desired Deliverables of Phase II

Analysis, Hardware, Software, Research

Desired Deliverables Description

An ideal Phase 1 deliverable would be a precision optical system of at least 0.25 meters; or a relevant sub-component of a system; or a prototype demonstration of a fabrication, test or control technology leading to a successful Phase 2 delivery; or a reviewed preliminary design and manufacturing plan which demonstrates feasibility. While detailed analysis will be conducted in Phase 2, the preliminary design should address how optical, mechanical (static and dynamic) and thermal designs and performance analysis will be done to show compliance with all requirements. Past experience or technology demonstrations which support the design and manufacturing plans will be given appropriate weight in the evaluation.

An ideal Phase 2 project would further advance the technology to produce a flight-qualifiable optical system greater than 0.5 meters or relevant sub-component (with a TRL in the 4 to 5 range); or a working fabrication, test or control system. Phase 1 and Phase 2 mirror system or component deliverables would be accompanied by all necessary documentation, including the optical performance assessment and all data on processing and properties of its substrate materials. A successful mission oriented Phase 2 would have a credible plan to deliver for the allocated budget a fully assembled and tested telescope assembly which can be integrated into the potential mission; and, demonstrate an understanding of how the engineering specifications of their system meets the performance requirements and operational constraints of the mission (including mechanical and thermal stability analysis).

State of the Art and Critical Gaps

Hubble at 2.4m is the SOA.

Relevance / Science Traceability

S2.03 primary supports potential Astrophysics Division missions. S2.03 has made optical systems in the past for potential balloon experiments. Future potential Decadal missions include LISA, Habitable Exoplanet Observatory (HabEx), Large UV/Optical/Near-IR Surveyor (LUVOIR) and the Origins Space Telescope (OST).

Scope Title

NIR LIDAR Beam Expander Telescope

Scope Description

Potential airborne coherent LIDAR missions need compact 15-cm diameter 20X magnification beam expander telescopes. Potential space based coherent LIDAR missions need at least 50-cm 65X magnification beam expander telescopes. Candidate coherent LIDAR systems (operating with a pulsed 2-micrometer laser) have a narrow, almost diffraction limited field of view, close to 0.8 lambda/D half angle. Aberrations, especially spherical aberration, in the optical telescope can decrease the signal. Additionally, the telescope beam expander should maintain the laser beam's circular polarization. The incumbent telescope technology is a Dahl-Kirkham beam expander. Technology advance is needed to make the beam expander more compact with less mass while retaining optical performance, and to demonstrate the larger diameter. Additionally, technology for non-moving scanning of the beam expander output is needed.

References

NRC Decadal Surveys at: http://sites.nationalacademies.org/DEPS/ESAS2017/index.htm.

https://smd-prod.s3.amazonaws.com/science-pink/s3fs-public/atoms/files/Weather_Focus_Area_Workshop_Report_2015_0.pdf.

A. K. DuVivier, J. J. Cassano, S. Greco and G. D. Emmitt, 2017, "A Case Study of Observed and Modeled Barrier Flow in the Denmark Strait in May 2015" Monthly Weather Review 145, 2385 – 2404 (2017): (https://doi.org/10.1175/MWR-D-16-0386.1). See also Supplemental Material: http://dx.doi.org/10.1175/MWR-D-16-0386.s1

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Expected TRL or TRL range at completion of the project: 3 to 4

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Research

Desired Deliverables Description

A detailed design or a small prototype or a full-sized beam expander.

State of the Art and Critical Gaps

The current SOA is a COTS beam expander with a 15-cm diameter primary mirror, a heavy aluminum structure, an Invar rod providing thermally insensitive primary-to-secondary mirror separation, and a manually adjustable and lockable variable focus setting by changing the mirror separation. Critical gaps include 1) a 50-70 cm diameter primary mirror beam expander that features near-diffraction limited performance, low mass design, minimal aberrations with an emphasis on spherical, characterization of the polarization changes vs. beam cross section assuming input circular polarization, a lockable electronic focus adjustment, both built-in and removable fiducial aids for aligning the input laser beam to the optical axis, and a path to space qualification; and 2) a 15-cm diameter primary mirror beam expander with the same features for airborne coherent lidar systems.

Relevance / Science Traceability

Science Mission Directorate (SMD) desires both an airborne coherent-detection wind-profiling lidar systems and a space-based wind measurement. The space mission has been recommended to SMD by both the 2007 and 2017 earth science Decadal Surveys. SMD has incorporated the wind lidar mission in its planning and has named it "3-D Winds". SMD recently held the Earth Venture Suborbital competition for 5-years of airborne science campaigns. The existing coherent wind lidar at Langley, DAWN, was included in three proposals which are under review. Furthermore, SMD is baselining DAWN for a second CPEX-type airborne science campaign, and for providing cal/val assistance to the ESA AEOLUS space mission. DAWN flies on the DC-8 and it is highly desired to fit DAWN on other NASA and NOAA aircraft. DAWN needs to lower its mass for several of the aircraft, and a low-mass telescope retaining the required performance is needed. Additionally, an electronic remote control of telescope focus is needed to adapt to aircraft cruise altitude and weather conditions during science flights.

Scope Title

Fabrication, Test and Control of Advanced Optical Systems

Scope Description

Future UV/Optical/NIR telescopes require mirror systems that are very precise and ultra-stable.

Regarding precision, this subtopic encourages proposals to develop technology which makes a significant advance the ability to fabricate and test an optical system.

One area of current emphasis is the ability to non-destructively characterize CTE homogeneity in 4-m class Zerodur and 2-m class ULE mirror substrates to an uncertainty of 1 ppb/K and a spatial sampling of 100 x 100. This characterization capability is needed to select mirror substrates before they undergo the expense of turning them into a light-weight space mirror.

Regarding stability, to achieve high-contrast imaging for exoplanet science using a coronagraph instrument, systems must maintain wavefront stability to < 10 pm RMS over intervals of ~10 minutes during critical observations. The ~10-minute time period of this stability is driven by current wavefront sensing and control techniques that rely on stellar photons from the target object to generate estimates of the system wavefront. This subtopic aims to develop new technologies and techniques for wavefront sensing, metrology, and verification and validation of optical system wavefront stability.

Current methods of wavefront sensing include image-based techniques such as phase retrieval, focal-plane contrast techniques such as electric field conjugation and speckle nulling, and low-order and out-of-band wavefront sensing that use non-science light rejected by the coronagraph to estimate drifts in the system wavefront during observations. These techniques are limited by the low stellar photon rates of the dim objects being observed (~5 - 11 Vmag), leading to 10s of minutes between wavefront control updates.

New methods may include: new techniques of using out-of-band light to improve sensing speed and spatial frequency content, new control laws incorporating feedback and feedforward for more optimal control, new algorithms for estimating absolute and relative wavefront changes, and the use of artificial guide stars for improved sensing signal to noise ratio and speed.

Current methods of metrology include edge sensors (capacitive, inductive, or optical) for maintaining segment cophasing, and laser distance interferometers for absolute measurement of system rigid body alignment. Development of these techniques to improve sensitivity, speed, and component reliability is desired. Low power, high-reliability electronics are also needed.

Finally, metrology techniques for system verification and validation at the picometer level during integration and test (I&T) are needed. High speed spatial and speckle interferometers are currently capable of measuring single-digit picometer displacements and deformations on small components in controlled environments. Extension of these techniques to large-scale optics and structures in typical I&T environments is needed.

References

The HabEx Interim Report is available at: https://www.jpl.nasa.gov/habex/pdf/interim_report.pdf. The LUVOIR Interim Report is available at:
https://asd.gsfc.nasa.gov/luvoir/resources/docs/LUVOIR_Interim_Report_Final.pdf.

Expected TRL or TRL range at completion of the project: 2 to 4

Desired Deliverables of Phase II

Analysis, Hardware, Software, Research

Desired Deliverables Description

An ideal Phase 1 deliverable would be a prototype demonstration of a fabrication, test or control technology leading to a successful Phase 2 delivery; or a reviewed preliminary design and manufacturing plan which demonstrates feasibility. While detailed analysis will be conducted in Phase 2, the preliminary design should address how optical, mechanical (static and dynamic) and thermal designs and performance analysis will be done to show compliance with all requirements. Past experience or technology demonstrations which support the design and manufacturing plans will be given appropriate weight in the evaluation.

An ideal Phase 2 project would further advance the technology to produce a flight-qualifiable relevant sub-component (with a TRL in the 4 to 5 range); or a working fabrication, test or control system. Phase 1 and Phase 2 mirror system or component deliverables would be accompanied by all necessary documentation, including the optical performance assessment and all data on processing and properties of its substrate materials. A successful mission oriented Phase 2 would have a credible plan to deliver for the allocated budget a fully assembled and tested telescope assembly which can be integrated into the potential mission; and, demonstrate an understanding of how the engineering specifications of their system meets the performance requirements and operational constraints of the mission (including mechanical and thermal stability analysis).

State of the Art and Critical Gaps

Wavefront sensing using star images, including dispersed-fringe and phase retrieval methods, is at TRL 6, qualified for space by JWST. Wavefront sensing and control for coronagraphs, including electric field conjugation and Low-Order WF Sensing (LOWFS) is at TRL4, and is being developed and demonstrated by WFIRST/CGI.

Laser distance interferometers for point-to-point measurements with accuracies from nanometers to picometers have been demonstrated on the ground by the Space Interferometry Mission and other projects, and on orbit by the Lisa Pathfinder and Grace Follow-On mission. Application to telescope alignment metrology has been demonstrated on testbeds, to TRL4 for nanometer accuracy. Picometer accuracy for telescopes awaits demonstration.

Edge sensors are in use on segmented ground telescopes, but not yet on space telescopes. New designs are needed to provide picometer sensitivity and millimeter range in a space qualified package.

Higher-order WFS for coronagraphs using out-of-band light is beginning development, with data limited to computer simulations. Such techniques are best used

Relevance / Science Traceability

These technologies are enabling for coronagraph-equipped space telescopes, segmented space telescopes, and others that utilize actively controlled optics. The LUVOIR and HabEx mission concepts currently under study provide good examples.

Scope Title
Optical Components and Systems for potential Infrared/Far-IR missions

Scope Description

The Far-IR Surveyor Mission described in NASA's Astrophysics Roadmap, "Enduring Quests, Daring Visions":

In the context of subtopic S2.03, the challenge is to take advantage of relaxed tolerances stemming from a requirement for long wavelength (30 micron) diffraction-limited performance in the fully-integrated optical telescope assembly to minimize the total mission cost through innovative design and material choices and novel approaches to fabrication, integration, and performance verification.

The Far-IR Surveyor is a cryogenic far-infrared mission, which could be either a large single-aperture telescope or an interferometer. There are many common and a few divergent optical system requirements between the two architectures.

Common requirements:

- Telescope operating temperature ~4 K
- Telescope diffraction-limited at 30 microns at the operating temperature
- Mirror survivability at temperatures ranging from 315 K to 4 K
- Mirror substrate thermal conductivity at 4 K > 2 W/m*K
- Zero or low CTE mismatch between mirror substrate and backplane

Divergent requirements:

- Large single-aperture telescope:
    - Segmented primary mirror, circular or hexagonal
    - Primary mirror diameter 5 to 10 m
    - Possible 3 dof (tip, tilt and piston) control of mirror segments on orbit
- Interferometer:
    - Monolithic primary mirrors
    - Afocal, off-axis telescope design
    - Primary mirror diameter 1 to 4 m

Success metrics:

- Areal cost < $500K/m2
- Areal density < 15 kg/m2 (< 40 kg/m2 with backplane)
- Production rate > 2 m2 per month
- Short time span for optical system integration and test

References

The Far-Infrared Surveyor is described in NASA's Astrophysics Roadmap, "Enduring Quests, Daring Visions," which can be downloaded from https://smd-prod.s3.amazonaws.com/science-pink/s3fs-public/atoms/files/secure-Astrophysics_Roadmap_2013_0.pdf.

Program Annual Technology Reports (PATR) can be downloaded from the NASA PCOS/COR Technology Development website at https://apd440.gsfc.nasa.gov/technology/.

Expected TRL or TRL range at completion of the project: 3 to 5

Desired Deliverables of Phase II

Prototype, Hardware, Research

Desired Deliverables Description

Mirrors or optical systems that demonstrably advance TRL to address the overall challenge described under Scope Description while meeting requirements for a single-aperture or interferometric version of the notional Far-IR Surveyor mission.

State of the Art and Critical Gaps

Current SOA is represented by the Herschel Space Observatory (3.5 m monolith; SiC) and James Webb Space Telescope (6.5 m segmented primary mirror; beryllium).

Relevance / Science Traceability

The technology is relevant to the Far-IR Surveyor mission described in NASA's Astrophysics Roadmap and prioritized in NASA's Program Annual Technology Reports for Cosmic Origins and Physics of the Cosmos. A future NASA far-infrared astrophysics mission will answer compelling questions, such as: How common are life-bearing planets?; How do the conditions for habitability develop during the process of planet formation?; and How did the universe evolve in response to its changing ingredients (build-up of heavy elements and dust over time)? To answer these questions, NASA will need telescopes and interferometers that reach fundamental sensitivity limits imposed by astrophysical background photon noise. Only telescopes cooled to a cryogenic temperature can provide such sensitivity.

Novel approaches to fabrication and test developed for a far-infrared astrophysics mission may be applicable to far-infrared optical systems employed in other divisions of the NASA Science Mission Directorate, or to optical systems designed to operate at wavelengths shorter than the far-infrared.

Scope Title
Low-Cost Compact Reflective Telescope for NIR/SWIR Optical Communication

Scope Description

The need exists for a low cost methodology to produce compact (for ex., cubesat-class), scalable, diffraction limited, athermalized, off-axis reflective-type, optics for NIR/SWIR-band communication applications. Typically, specialty optical aperture systems are designed and built as “one-offs” which are inherently high in cost and often out of scope for smaller projects. A Phase I would investigate current compact off-axis reflective designs and develop a trade space to identify the most effective path forward. The work would include a strategy for aperture diameter scalability, athermalization, and low cost fabrication. Detailed optical designs would be developed along with detailed structural, thermal, optical performances (STOP) analyses confirming diffraction limited operation across a wide range of operational disturbances, both structural dynamic and thermal. Commercial of the shelf (COTS) NIR/SWIR optical communication support hardware should be assumed towards an integrated approach, including fiber optics, fast steering mirrors, and applicable detectors. Phase II may follow up with development of prototypes, built at multiple aperture diameters and fidelities.

References

An example of an on-axis design has been utilized in LLCD: https://www.spiedigitallibrary.org/conference-proceedings-of-spie/10563/105630X/NASAs-current-activities-in-free-space-optical-communications/10.1117/12.2304175.full?SSO=1

An example of an off-axis design is being developed by JPL for deep space optical comm (DSOC): https://www.spiedigitallibrary.org/conference-proceedings-of-spie/10096/100960V/Discovery-deep-space-optical-communications-DSOC-transceiver/10.1117/12.2256001.full

Expected TRL or TRL range at completion of the project: 2 to 4

Desired Deliverables of Phase II

Prototype, Analysis, Hardware

Desired Deliverables Description

Prototype unobscured telescope with the required scale size

State of the Art and Critical Gaps

Currently, the state of the art for reflective optical system for communications applications are:

1) On-axis or axisymmetric designs are typically used for (space) optical comm and imaging, which inherently are problematic due to the central obscuration.
2) Off-axis designs provide superior optical performance due to the clear aperture, however, are rarely considered due to complex design, manufacturing, and metrology procedures needed.

Relevance / Science Traceability

Optical Communication enable high data-rate downlink of science data. The initial motivation for this scalable off-axis optical design approach is for bringing high-performance reflective optics within reach of laser communication projects with limited resources. However, this exact optical hardware is applicable for any diffraction limited, athermalized science imaging applications. Any science mission could potentially be able to select from a “catalog” of optical aperture systems that would already have (flight) heritage and reduced risks.

S2.04: X-Ray Mirror Systems Technology, Coating Technology for X-Ray-UV-OIR, and Free-Form Optics (SBIR)

Lead Center: GSFC

Participating Center(s): JPL, MSFC

Technology Area: 8.0.0 Science Instruments, Observatories & Sensor Systems

Related Subtopic Pointer(s): S1.04 S2.01 H9.01 Z8.08 S1.12 T8.06

Scope Title
X-Ray Mirror Systems Technology, Coating Technology for X-Ray-UV-OIR, and Free-Form Optics

Scope Description

The National Academy Astro2010 Decadal Report identifies studies of optical components and ability to manufacture, coat, and perform metrology needed to enable future X-Ray observatory missions such as Next Generation of X-Ray Observatories (NGXO).

The Astrophysics Decadal specifically calls for optical coating technology investment for future UV, Optical, Exoplanet, and IR missions while Heliophysics 2009 Roadmap identifies the coating technology for space missions to enhance rejection of undesirable spectral lines, improve space/solar-flux durability of Extreme Ultraviolet (EUV) optical coatings, and coating deposition to increase the maximum spatial resolution.

Future optical systems for NASAs low-cost missions, CubeSat and other small-scale payloads, are moving away from traditional spherical optics to non-rotationally symmetric surfaces with anticipated benefits of freeform optics such as fast wide-field and distortion-free cameras.

This subtopic solicits proposals in the following three focus areas:

- X-Ray manufacturing, coating, testing, and assembling complete mirror systems in addition to maturing the current technology.
- Coating technology including Carbon Nanotubes (CNT) for wide range of wavelengths from X-Ray to IR (X-Ray, EUV, LUV, VUV, Visible, and IR).

- Free-form Optics design, fabrication, and metrology for CubeSat, SmallSat and various coronagraphic instruments.

References

The Habitable Exoplanet Observatory (HabEx) is a concept for a mission to directly image planetary systems around Sun-like stars. HabEx will be sensitive to all types of planets; however its main goal is, for the first time, to directly image Earth-like exoplanets, and characterize their atmospheric content. By measuring the spectra of these planets, HabEx will search for signatures of habitability such as water, and be sensitive to gases in the atmosphere possibility indicative of biological activity, such as oxygen or ozone.

The study pages are available at:

Habitable Exoplanet Observatory (HabEx): https://www.jpl.nasa.gov/habex/

LUVOIR: https://asd.gsfc.nasa.gov/luvoir/

Origins Space Telescope: https://asd.gsfc.nasa.gov/firs/

The LYNX Mission Concept: https://wwwastro.msfc.nasa.gov/lynx/

The Large UV/Optical/IR Surveyor (LUVOIR) is a concept for a highly capable, multi-wavelength space observatory with ambitious science goals. This mission would enable great leaps forward in a broad range of science, from the epoch of re-ionization, through galaxy formation and evolution, star and planet formation, to solar system remote sensing. LUVOIR also has the major goal of characterizing a wide range of exoplanets, including those that might be habitable - or even inhabited. The LUVOIR Interim Report is available at: https://asd.gsfc.nasa.gov/luvoir/.

The Origins Space Telescope (OST) is the mission concept for the Far-IR Surveyor study. NASA's Astrophysics Roadmap, Enduring Quests, Daring Visions, recognized the need for an Origins Space Telescope mission with enhanced measurement capabilities relative to those of the Herschel Space Observatory, such as a three order of magnitude gain in sensitivity, angular resolution sufficient to overcome spatial confusion in deep cosmic surveys or to resolve protoplanetary disks, and new spectroscopic capability. The community report is available at: https://science.nasa.gov/science-committee/subcommittees/nac-astrophysics-subcommittee/astrophysics-roadmap

Expected TRL or TRL range at completion of the project: 3 to 6

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Software, Research

Desired Deliverables Description

Typical deliverables based on sub-elements of this subtopic:

- X-ray optical mirror system: Analysis, reports, and prototype
- Coating: Analysis, reports, software, demonstration of the concept and prototype
- Freeform Optics: Analysis, design, software and hardware prototype of optical components

State of the Art and Critical Gaps

This subtopic focuses on three areas of technology development:

- X-Ray manufacturing, coating, testing, and assembling complete mirror systems in addition to maturing the current technology. This work is a very costly and time consuming. Most of SOA (State of the Art) requiring improvement is ~10 arc-seconds angular resolution. SOA straylight suppression is bulky and ineffective for wide-field of view telescopes. We seek significant reduction in both expense and time. Reduce the areal cost of telescope by 2x such that the larger collecting area can be produced for the same cost or half the cost.

- Coating technology for wide range of wavelengths from X-Ray to IR (X-Ray, EUV, LUV, VUV, Visible, and IR). The current X-ray coating is defined by NuSTAR. Current EV is defined by Heliophysics (80% reflectivity from 60-200 nm). Current UVOIR is defined by Hubble. MgFI2 over coated aluminum on 2.4 m mirror. This coating has birefringence concerns and marginally acceptable reflectivity between 100-200 nm.
- Free-form Optics design, fabrication, and metrology for package constrained imaging systems. This field is in early stages of development. Improving the optical surfaces with large field of view and fast F/#s is highly desirable.

Relevance / Science Traceability

S2.04 supports variety of Astrophysics Division missions. The technologies in this subtopic encompasses fields of X-Ray, coating technologies ranging from UV to IR, and Freeform optics in preparation for Decadal missions such as HabEx, LUVOIR and OST.

Optical components, systems, and stray light suppression for X-ray missions: The 2010 National Academy Decadal Report specifically identifies optical components and the ability to manufacture and perform precise metrology on them needed to enable several different future missions (NGXO). The NRC NASA Technology Roadmap Assessment ranked advanced mirror technology for new x-ray telescopes as the #1 Object C technology requiring NASA investment.

Freeform Optics: NASA missions with alternative low-cost science and small size payload are increasing. However, the traditional interferometric testing as a means of metrology are unsuited to freeform optical surfaces due to changing curvature and lack of symmetry. Metrology techniques for large fields of view and fast F/#s in small size instruments is highly desirable specifically if they could enable cost-effective manufacturing of these surfaces. (CubeSat, SmallSat, NanoSat, various coronagraphic instruments)

Coating for X-ray, EUV, LUV, UV, Visible, and IR telescopes: Astrophysics Decadal specifically calls for optical coating technology investment for: Future UV/Optical and Exoplanet missions (Habitable Exoplanet Observatory (HabEx) or Large Ultraviolet Optical Infrared Surveyor (LUVOIR)). Heliophysics 2009 Roadmap identifies optical coating technology investments for: Origins of Near-Earth Plasma (ONEP); Ion-Neutral Coupling in the Atmosphere (INCA); Dynamic Geospace Coupling (DGC); Fine-scale Advanced Coronal Transition-Region Spectrograph (FACTS); Reconnection and Micro-scale (RAM); & Solar-C Nulling polarimetry/coronagraph for exoplanet imaging and characterization, dust and debris disks, extra-galactic studies and relativistic and non-relativistic jet studies (VNC).

Scope Title
X-Ray Mirror Systems Technology

Scope Description

NASA large X-Ray observatory requires low-cost, ultra-stable, light-weight mirrors with high-reflectance optical coatings and effective stray light suppression. The current state-of-art of mirror fabrication technology for X-Ray missions is very expensive and time consuming. Additionally, a number of improvements such as 10 arc-second angular resolutions and 1 to 5 m2 collecting area are needed for this technology. Likewise, the stray-light suppression system is bulky and ineffective for wide-field of view telescopes.

In this area, we are looking to address the multiple technologies including: improvements to manufacturing (machining, rapid optical fabrication, slumping or replication technologies), improved metrology, performance prediction and testing techniques, active control of mirror shapes, new structures for holding and actively aligning of mirrors in a telescope assembly to enable X-Ray observatories while lowering the cost per square meter of collecting aperture and effective design of stray-light suppression in preparation for the Decadal Survey of 2020. Additionally, we need epoxies to bond mirrors that are made of silicon. The epoxies should absorb IR radiation with wavelengths between 1.5 um and 6 um that traverses silicon with little or no absorption, and therefore can be cured quickly with a beam of IR radiation. Currently, X-Ray space mirrors cost $4 million to $6 million per square meter of optical surface area. This research effort seeks a cost reduction for precision optical components by 5 to 50 times, to less than $1M to $100 K/m2.

Additionally, proposals are solicited to develop new advanced-technology Computer-Numerical-Control (CNC) machines to polish inside and/or outside surfaces of full-shell (between 100-1000mm in height, 100-2800mm in diameter, varying radial prescription along azimuth, and approximately 2mm in thickness), grazing-incidence optics to x-ray quality surface tolerances (with surface figure error < 1 arcsecond Half-Power Diameter (HPD), radial slope error < 1 microradian, and out of round < 2 microns). Current state-of-the-art technology in CNC polishing of full-shell, grazing-incidence optics yields 2.5 arcseconds HPD on the outside of a mandrel used for replicating shells. Technology advances beyond current state of the art include application of CNC and deterministic polishing techniques that (1) allow for direct force closed-loop control, (2) reduce alignment precision requirements, and (3) optimize the machine for polishing cylindrical optics through simplifying the axis arrangement and the layout of the cavity of the CNC polishing machine.

References

NASA High Energy Astrophysics (HEA) mission concepts including X-Ray missions and studies are available at https://heasarc.gsfc.nasa.gov/docs/heasarc/missions/concepts.html.

Expected TRL or TRL range at completion of the project: 3 to 6

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Software, Research

Desired Deliverables Description

Typical deliverable based on sub-elements of this subtopic:
X-ray optical mirror system: Demonstration, analysis, reports, software and hardware prototype

State of the Art and Critical Gaps

X-ray optics manufacturing, metrology, coating, testing, and assembling complete mirror systems in addition to maturing the current technology. This work is very costly and time-consuming. Most of SOA (State of the Art) requiring improvement is ~10 arc-seconds angular resolution. SOA straylight suppression is bulky and ineffective for wide-field of view telescopes. We seek a significant reduction in both expense and time. Reduce the areal cost of a telescope by 2x such that the larger collecting area can be produced for the same cost or half the cost.

The gaps to be covered in this track are:

- Light-weight, low-cost, ultra-stable mirrors for large X-ray observatory
- Stray light suppression systems (baffles) for large advanced X-Ray observatories
- Ultra-stable inexpensive light-weight X-Ray telescope using grazing-incidence optics for high altitude balloon-borne and rocket-borne mission

Relevance / Science Traceability

The 2010 National Academy Decadal Report specifically identifies optical components and the ability to manufacture and perform precise metrology on them needed to enable several different future missions (Lynx and Advanced X-ray Imaging Satellite (AXIS)).

The NRC NASA Technology Roadmap Assessment ranked advanced mirror technology for new x-ray telescopes as the #1 Object C technology requiring NASA investment.

Scope Title

Coating Technology for X-Ray-UV-OIR

Scope Description

The optical coating technology is a mission-enabling feature that enhances the optical performance and science return of a mission. Lowering the areal cost of coating determines if a proposed mission could be funded in the current cost environment. The most common forms of coating used on precision optics are anti-reflective (AR) coating and high reflective coating.

The current coating technology of optical components needed to support the 2020 Astrophysics Decadal process. Historically, it takes 10 years to mature mirror technology from TRL-3 to 6.
To achieve these objectives requires sustained systematic investment.

The telescope optical coating needs to meet low temperature operation requirement. It’s desirable to achieve 35 degrees Kelvin in future.

A number of future NASA missions require suppression of scattered light. For instance, the precision optical cube utilized in a beam-splitter application forms a knife-edge that is positioned within the optical system to split a single beam into two halves. The scattered light from the knife-edge could be suppressed by CNT coating. Similarly, the scattered light for gravitational-wave application and lasercom system where the simultaneous transmit/receive operation is required, could be achieved by highly absorbing coating such as CNT. Ideally, the application of CNT coating needs to achieve:

- Broadband (visible plus Near IR), reflectivity of 0.1% or less
- Resist bleaching of significant albedo changes over a mission life of at least 10 years
- Withstand launch conditions such vibe, acoustics, etc.
- Tolerate both high continuous wave (CW) and pulsed power and power densities without damage. ~10 W for CE and ~ 0.1 GW/cm2 density, and 1 kW/nanosecond pulses
- Adhere to the multi-layer dielectric or protected metal coating including Ion Beam Sputtering (IBS) coating

NASA's Laser Interferometer Space Antenna (LISA) mission on-axis design telescope operates both in transmission and reception simultaneously where the secondary mirror sends the transmitted beam directly back at the receiver. The apodized petal-shaped mask inherently suppress the diffraction once patterned at the center of the secondary mirror. The emerging cryogenic etching of black-silicon has demonstrated BRDF ultralow specular reflectance of 1e-7 in the range of 500-1064 nm. The advancement of this technology is desired to obtain ultralow reflectivity.

- Improve the specular reflectance to 1e-10 and hemispherical reflectance better than 0.1%
- Improve the cryogenic etching process to provide a variation of the reflectance (apodization effect) by increasing or decreasing the height of the grass
- Explore etching process and duration

References

Laser Interferometer Space Antenna (LISA) is a space-based gravitational wave observatory building on the success of LISA Pathfinder and LIGO. Led by ESA, the new LISA mission (based on the 2017 L3 competition) is a collaboration of ESA and NASA.

More information could be found at https://lisa.nasa.gov

Expected TRL or TRL range at completion of the project: 3 to 6

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Software, Research

Desired Deliverables Description

Coating: Analysis, reports, software, demonstration of the concept and prototype

State of the Art and Critical Gaps

Coating technology for wide range of wavelengths from X-Ray to IR (X-Ray, EUV, LUV, VUV, Visible, and IR).

- The current X-ray coating is defined by NuSTAR.
- Current EUV is defined by Heliophysics (80% reflectivity from 60-200 nm).
- Current UVOIR is defined by Hubble. MgFl2 over coated aluminum on 2.4 m mirror. This coating has birefringence concerns and marginally acceptable reflectivity between 100-200 nm.

Metrics for X-Ray:

- Multilayer high-reflectance coatings for hard X-Ray mirrors
- Multilayer Depth Gradient Coatings for 5 to 80 keV with high broadband reflectivity.
- Zero-net-stress coating of iridium or other high reflectance elements on thin substrates (< 0.5 mm)

Metrics for EUV:

- Reflectivity > 90% from 6 nm to 90 nm onto a < 2 meter mirror substrate.

Metrics for LUVOIR:

- Broadband Reflectivity > 70% from 90nm-120nm (LUV) and > 90% from 120nm-2.5um (VUV/Visible/IR).Reflectivity Non-uniformity < 1% 90nm-2.5um
- Induced polarization aberration < 1% 400nm-2.5um spectral range from mirror coating applicable to a 1-8m substrate

Metrics for LISA:

- HR: Reflectivity > 99% at 1064 +/- 2 nm with very low scattered light and polarization-independent performance over apertures of ~ 0.5 m.
- AR: Reflectivity < 0.005% at 1064 +/- 2 nm
    - Low-absorption, low-scatter, laser-line optical coatings at 1064nm
    - High reflectivity, R>0.9995
    - Performance in a space environment without significant degradation over time, due for example to radiation exposure or outgassing
    - High polarization purity, low optical birefringence over a range of incident angles from ~5 degrees to ~20 degrees
    - Low coating noise (thermal, photothermal, etc.) for high precision interferometric measurements
    - Ability to endure applied temperature gradients (without destructive effects, such as de-lamination from the substrate)

- Ability to clean and protect the coatings and optical surfaces during mission integration and testing. Cleaning should not degrade the coating performance.

Non-stationary Optical Coatings:

- Used in reflection & transmission that vary with location on the optical surface.

Carbon Nanotube (CNT) Coatings

- Broadband Visible to NIR, Total Hemispherical Reflectivity of 0.01% or less, adhere to the multi-layer dielectric or protected metal coating

Black-Silicon Cryogenic Etching (New)

- Broadband UV+Visible+NIR+IR, Reflectivity of 0.01% or less, adhere to the multi-layer dielectric (silicon) or protected metal

Software tools to simulate, and assist the anisotropic etching by employing variety of modeling techniques such as Rigorous Coupled Wave Analysis (RCWA), Method of Moments (MOM), Finite-Difference Time Domain (FDTD), Finite Element Method (FEM), Transfer Matrix Method (TMM), and Effective Medium Theory (ETM).

Relevance / Science Traceability

Coating for X-ray, EUV, LUV, UV, Visible, and IR telescopes: Astrophysics Decadal specifically calls for optical coating technology investment for: Future UV/Optical and Exoplanet missions. Heliophysics 2009 Roadmap identifies optical coating technology investments for: Origins of Near-Earth Plasma (ONEP); Ion-Neutral Coupling in the Atmosphere (INCA); Dynamic Geospace Coupling (DGC); Fine-scale Advanced Coronal Transition-Region Spectrograph (FACTS); Reconnection and Micro-scale (RAM); & Solar-C.

LISA requires low scatter HR coatings and low reflectivity coatings for scatter suppression near 1064 nm. Polarization-independent performance is important.

Nulling polarimetry/coronagraph for Exoplanets imaging and characterization, dust and debris disks, extra-galactic studies and relativistic and non-relativistic jet studies (VNC).

Scope Title
Free-Form Optics

Scope Description

Future NASA science missions demand wider fields of view in a smaller package. These missions could benefit greatly by freeform optics as they provide non-rotationally symmetric optics which allow for better packaging while maintaining desired image quality. Currently, the design and fabrication of freeform surfaces is costly. Even though various techniques are being investigated to create complex optical surfaces, small-size missions highly desire efficient small packages with lower cost that increase the field of view and expand operational temperature range of un-obscured systems. In addition to the freeform fabrication, the metrology of freeform optical components is difficult and challenging due to the large departure from planar or spherical shapes accommodated by conventional interferometric testing. New methods such as multibeam low-coherence optical probe and slope sensitive optical probe are highly desirable.

Specific metrics are:

- Design: Innovative reflective optical designs with large fields of view (> 5 degrees) and fast F/#s
- Fabrication: 10 cm diameter optical surfaces (mirrors) with free form optical prescriptions with surface figure tolerances are 1-2 nm rms, and roughness < 5 Angstroms. Larger mirrors are also desired for flagship missions for UV and coronagraphy applications, with 10cm-1m diameter surfaces having figure tolerances <5nm RMS, and roughness <1 Angstroms RMS

- Metrology: Accurate metrology of 'freeform' optical components with large spherical departures (>1 mm), independent of requiring prescription specific null lenses or holograms.

References

A presentation on application of Freeform Optics at NASA is available at: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170010419.pdf

Expected TRL or TRL range at completion of the project: 3 to 6

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Software, Research

Desired Deliverables Description

Demonstration, analysis, design, software and hardware prototype of optical components

State of the Art and Critical Gaps

Free-form Optics design, fabrication, and metrology for package constrained imaging systems. This field is in early stages of development. Improving the optical surfaces with large field of view and fast F/#s is highly desirable.

Relevance / Science Traceability

NASA missions with alternative low-cost science and small size payload are increasing. However, the traditional interferometric testing as a means of metrology is unsuited to freeform optical surfaces due to changing curvature and lack of symmetry. Metrology techniques for large fields of view and fast F/#s in small size instruments are highly desirable specifically if they could enable cost-effective manufacturing of these surfaces. (CubeSat, SmallSat, and NanoSat). Additionally, design studies for large observatories such as OST and LUVOIR (currently being proposed for the 2020 Astrophysics Decadal Survey) have demonstrated improved optical performance over a larger field of view afforded by freeform optics. Such programs will require advances in freeform metrology to be successful."

S2.05: Technology for the Precision Radial Velocity Measurement Technique (SBIR)

Lead Center: JPL

Participating Center(s): GSFC

Technology Area: 8.0.0 Science Instruments, Observatories & Sensor Systems

Related Subtopic Pointer(s): S1.04

Scope Title

Components, assemblies, and subsystems for Extreme Precision Radial Velocity Measurements and Detection of Extrasolar Planets

Scope Description

Astronomical spectrographs have proven to be powerful tools for exoplanet searches. When a star experiences periodic motion due to the gravitational pull of an orbiting planet, its spectrum is Doppler-modulated in time. This is the basis for the Precision Radial Velocity (PRV) method, one of the first and most efficient techniques for detecting and characterizing exoplanets. Since spectrographs have their own drifts which must be separated from the periodic Doppler shift, a stable reference is always needed for calibration. Optical Frequency Combs (OFCs) and line-referenced etalons are capable of providing the instrument precision needed for detecting and characterizing Earth-like planets in the Habitable Zone of their Sun-like host stars. While "stellar jitter" (a star's photospheric velocity contribution to the RV signal) is unavoidable, the contribution to the error budget from Earth's atmosphere would be eliminated in future space missions. Thus, there is a need to develop robust spectral references with Size, Weight and Power (SWaP) suitable for space qualified operation to calibrate the next generation of high-resolution spectrographs with precision corresponding to < ~1 cm/s over multiple years of observations.

This subtopic solicits proposals to develop cost effective component and subsystem technology for low SWaP, long-lived, robust implementation of radial velocity measurement instruments both on the ground and in space. Research areas of interest include but are not limited to:

- Integrated photonic spectrographs
- PRV spectrograph calibration sources
- High efficiency photonic lanterns
- Advanced fiber scrambling techniques for modal noise reduction
- Software for advanced statistical techniques to mitigate effects of telluric absorption and stellar jitter on RV precision and accuracy

References

Precision Radial Velocity:

- Fischer et al. (2016) State of the Field: Extreme Precision Radial Velocities http://adsabs.harvard.edu/abs/2016PASP..128f6001
- Plavchan et al. (2015) Radial Velocity Prospects Current and Future: A White Paper Report prepared by the Study Analysis Group 8 for the Exoplanet Program Analysis Group (ExoPAG) http://adsabs.harvard.edu/abs/2015arXiv150301770P
- Plavchan et al. (2019) EarthFinder Probe Mission Concept Study (Final Report): https://smd-prod.s3.amazonaws.com/science-red/s3fs-public/atoms/files/Earth_Finder_Study_Rpt.pdf

Photonic Lanterns:

- Gris-Sanchez et al. (2018) Multicore fibre photonic lanterns for precision radial velocity Science: https://academic.oup.com/mnras/article/475/3/3065/4769655
- Jvanovic, N. et al. (2012). Integrated photonic building blocks for next-generation astronomical instrumentation I: the multimode waveguide. *Optics Express*, 20:17029.

Astrocombs:

- Yi, X., et al. (2016) Demonstration of a near-IR line-referenced electro-optical laser frequency comb for precision radial velocity measurements in astronomy. *Nature Communications*, 7:10436.
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Nonlinear Waveguides:

- Chang, L., et al. (2018) Heterogeneously integrated GaAs waveguides on insulator for efficient frequency conversion, Laser Photonics Reviews, 12, 1800149: https://doi.org/10.1002/lpor.201800149

- Halir, R., et al. (2012) Ultrabroadband supercontinuum generation in a CMOS-compatible platform, Optics letters, 37, 1685: https://di.org/10.1364/OL.37.001685

Spectral Flattening:

- Probst, R.A., et al. (2015) Spectrally Flattened, Broadband Astronomical Frequency Combs https://di.org/10.1364/CLEO_SI.2015.SW4G.7

Expected TRL or TRL range at completion of the project: 3 to 5

Desired Deliverables of Phase II

Hardware/software

Desired Deliverables Description

This subtopic solicits proposals to develop cost effective component and subsystem technology for low SWaP, long-lived, robust implementation of radial velocity measurement instruments both on the ground and in space. Research areas of interest include but are not limited to:

- Integrated photonic spectrographs that meet PRV specifications (e.g. wavelength coverage, resolution, throughput, and polarization). These devices should be able to accept multiple fibers - at least two for the science light and simultaneous calibration light source. Ideally, they should be able to include on-chip cross-dispersion to eliminate bulk optics.
- PRV spectrograph calibration sources, particularly optical frequency combs (a.k.a. "astrocombs") from the UV through the NIR (~350 nm – ~2400 nm) with ~10-30 GHz mode spacing, potentially self-referenced, or line stabilized for Allan Deviation <1E-11 over 100 seconds to years
    - Spectral flattening to provide uniform power across the spectral band covered by the instrument
    - Spectral broadening to obtain wide spectral coverage, preferably octave-spanning to enable self-referencing
    - Integrated photonic solutions including nonlinear waveguides, microresonators or other comb generators, pump lasers, and f-2f beat-note generation
    - Low phase-noise solutions
    - Tunability of comb lines to scan spectrograph detectors for pixel characterization
- Optical etalons with similar requirements for stability as the frequency combs
- High efficiency photonic lanterns
- Advanced fiber scrambling techniques for modal noise reduction
- Software for advanced statistical techniques to mitigate effects of telluric absorption and stellar jitter on RV precision and accuracy.

Proposals should show an understanding of the science needs, as well as present a feasible plan to fully develop the relevant subsystem technologies and to transition into future NASA program(s).

Phase I will emphasize research aspects for technical feasibility, infusion potential into ground or space operations, clear and achievable benefits (e.g., reduction in SWaP and/or cost, improved RV precision), and show a path towards a Phase II proposal. Phase I Deliverables include feasibility and concept of operations of the research topic, simulations and measurements, validation of the proposed approach to develop a given product (TRL 3-4), and a plan for further development of the specific capabilities or products to be performed in Phase II. Early development and delivery of prototype hardware/software is encouraged.

Phase II will emphasize hardware/software development with delivery of specific hardware or software products for NASA targeting demonstration operations at a ground-based telescope in coordination with the lead NASA center. Phase II deliverables include a working prototype or engineering model of the proposed product/platform or software, along with documentation of development, capabilities, and measurements (showing specific improvement metrics), documents and tools as necessary. Proposed prototypes shall demonstrate a path towards a flight-capable platform. Opportunities and plans should also be identified and summarized for potential commercialization or NASA infusion.

State of the Art and Critical Gaps

The classical bulk optic spectrographs that are traditionally used for PRV science impose architectural constraints due to their large mass and limited optical flexibility. The spectrograph is the single element that if replaced with a photonic alternative could dramatically alter the course of astronomical instrumentation. Integrated Photonic Spectrographs (IPS) are wafer thin devices that could reduce instrument volume by up to three orders of magnitude. Furthermore, high resolving power spectrographs (R~150,000) with simultaneous UV, visible, and NIR coverage and exquisite long-term stability are required for PRV studies. Spectrometers that are fiber-fed with high illumination stability, excellent wavelength calibration, and precise temperature and pressure control represent the immediate future of precision RV measurements.

As spectrograph stability imposes limits on how precisely the Radial Velocity (RV) can be measured, spectral references play a critical role in characterizing and ensuring this precision. Only Laser Frequency Combs (LFCs) and line-referenced Fabry-Pérot etalons are capable of providing the broad spectral coverage and long term (years) stability needed for extreme PRV detection of exoplanets. While both frequency combs and etalons can deliver high precision spectrograph calibration, the former requires relatively complex and sophisticated hardware in the visible portion of the spectrum. Visible band frequency combs for astronomy (a.k.a. astrocombs) were initially based on mode-locked laser comb technology. However, the intrinsic free spectral range of these instruments, 100s of MHz to 1 GHz, is too fine to be resolved by astronomical spectrographs of R~150,000 or less. Thus, mode filtering of comb lines to create a more spectrally sparse calibration grid is necessary. The filtering step introduces complexity and additional sources of instability to the calibration process, as well as instrument assemblies too large in mass and volume for flight.

Commercial fiber laser astrocombs covering 450 - 1400 nm at 25 GHz line spacing and <3 dB intensity variations over the entire bandwidth are available for ground-based astronomical spectrographs and have been developed for HARPS-S and ESPRESSO RV instruments. However, the cost for these systems is often so prohibitive that recent RV spectrograph projects such as CARMENES and Keck Planet Finder either do not use a frequency comb or include it only as a future upgrade, owing to the cost impact on the project.

Alternatively, frequency combs produced by Electro-Optic Modulation (EOM) of a laser source have been demonstrated at observatories for PRV studies in the near-IR. EOM combs produce modes spaced at a RF modulation frequency, typically 10-30 GHz, and are inherently suitable as ground-based astrocombs. Significantly, EOM combs avoid the line filtering step of commercial mode-locked fiber laser combs. Comb frequency stabilization can be accomplished in a variety of ways, including referencing the laser pump source to a molecular absorption feature or another frequency comb. Where octave spanning EOM combs are available, f-2f self-referencing provides the greatest stability.

EOM combs must be spectrally broadened to provide the octave bandwidth necessary for f-2f stabilization for stability traceable to the Standard International (SI) second. This is accomplished through pulse amplification followed by injection into Highly Non-Linear Fiber (HNLF) or nonlinear optical waveguides, but the broadening process is accompanied by multiplication of the optical phase noise from the EOM comb modulation signal and must be optically filtered. Also, at these challenging microwave pulse repetition rates, the pulse duty-cycle requires pulse amplification to 4-5 Watts of average optical power in order to generate the high enough peak intensity needed for nonlinear broadening. This necessitates use of high power, non-telecom amplifiers that are more prone to lifetime issues, making EOM combs not optimal for flight either. It is important to note that very little comb light is actually required on the spectrograph detectors for calibration. In fact, most of the generated comb light must be deliberately attenuated to avoid detector saturation.

Power consumption of the frequency comb calibration system will be a significant driver of mission cost for space-based PRV systems, and motivates the development of a comb system that operates with less than 20 Watts of spacecraft power. Thus, for flight applications, it is highly desirable to develop frequency comb technology with low power consumption, ~10 GHz mode spacing, compact size, broad (octave spanning) spectral grasp across both the visible and NIR, phase noise insensitivity, stability traceable to the definition of the SI second, and very importantly, long life.

Relevance / Science Traceability

The NASA Strategic Plan (2018) and Space Mission Directorate Science Plan (2014) both call for discovery and characterization of habitable Earth analogs and the search for biosignatures on those worlds. These goals were endorsed and amplified upon in the recent National Academy of Science (NAS) Exoplanet Report which emphasized that a knowledge of the orbits and masses is essential to the complete and correct characterization of potentially habitable worlds. PRV measurements are needed to follow up on the transiting worlds discovered by Kepler, K2, and Transiting Exoplanet Survey Satellite (TESS). The interpretation of the transit spectra which James Webb Space Telescope (JWST) will obtain will depend on knowledge of a planet's surface gravity which comes from its radius (from the transit data) and its mass (from PRV measurements or in some cases Transit Timing Variations). Without knowledge of a planet's mass, the interpretation of its spectrum is subject to many ambiguities.

These ambiguities will only be exacerbated for the direct imaging missions such as the proposed Habitable Exoplanet Observatory (HabEx) and Large Ultraviolet Optical Infrared Surveyor (LUVOIR) flagships which will obtain spectra of Earth analogs around a few tens to hundreds of stars. Even if a radius can be inferred from the planet's brightness and an estimate of its albedo, the lack of a dynamical mass precludes any knowledge of the planet's density, bulk composition, and surface gravity which are needed to determine, for example, absolute gas column densities. Moreover, a fully characterized orbit is challenging to determine from just a few direct images and may even be confused in the presence of multiple planets. Is a planet in a highly eccentric orbit habitable or not? Only dynamical (PRV) measurements can provide such information. Thus, highly precise and highly stable PRV measurements are absolutely critical to the complete characterization of habitable worlds.

The NAS report also noted that measurements from space might be a final option if the problem of telluric contamination cannot be solved. The Earth's atmosphere will limit precise radial velocity measurements to ~10 cm/s at wavelengths longer than ~700 nm and greater than 30 cm/s at >900 nm, making it challenging to mitigate the effects of stellar activity without a measurement of the color dependence due to stellar activity in the PRV time series. A space-based PRV mission, such as has been suggested in the NASA EarthFinder mission concept study, may be necessary. If so, the low SWaP technologies developed under this SBIR program could help enable space-based implementations of the PRV method.

Focus Area 11: Spacecraft and Platform Subsystems

Lead MD: SMD

Participating MD(s): STMD

The Science Mission Directorate (SMD) will carry out the scientific exploration of our Earth, the planets, moons, comets, and asteroids of our solar system, and the universe beyond. SMD's future direction will be moving away from exploratory missions (orbiters and flybys) into more detailed/specific exploration missions that are at or near the surface (landers, rovers, and sample returns) or at more optimal observation points in space. These future destinations will require new vantage points or would need to integrate or distribute capabilities across multiple assets. Future destinations will also be more challenging to get to, have more extreme environmental conditions and challenges once the spacecraft gets there, and may be a challenge to get a spacecraft or data back from. A major objective of the NASA science spacecraft and platform subsystems development efforts are to enable science measurement capabilities using smaller and lower cost spacecraft to meet multiple mission requirements thus making the best use of our limited resources. To accomplish this objective, NASA is seeking innovations to significantly improve spacecraft and platform subsystem capabilities while reducing the mass and cost that would in turn enable increased scientific return for future NASA missions. A spacecraft bus is made up of many subsystems such as: propulsion; thermal control; power and power distribution; attitude control; telemetry command and control; transmitters/antenna; computers/on-board processing/software; and structural elements. High performance space computing technologies are also included in this focus area. Science platforms of interest could include unmanned aerial vehicles, sounding rockets, or balloons that carry scientific instruments/payloads, to planetary ascent vehicles or Earth return vehicles that bring samples back to Earth for analysis. This topic area addresses the future needs in many of these sub-system areas, as well as their application to specific spacecraft and platform needs. For planetary missions, planetary protection requirements vary by planetary destination, and additional backward contamination requirements apply to hardware with the potential to return to Earth (e.g., as part of a sample return mission). Technologies intended for use at/around Mars, Europa (Jupiter), and Enceladus (Saturn) must be developed so as to ensure compliance with relevant planetary protection requirements. Constraints could include surface cleaning with alcohol or water, and/or sterilization treatments such as dry heat (approved specification in NPR 8020.12; exposure of hours at 115° C or higher, non-functioning); penetrating radiation (requirements not yet established); or vapor-phase hydrogen peroxide (specification pending). The National Academies' Decadal Surveys for Astrophysics, Earth Science, Heliophysics, and Planetary Science discuss some of NASA's science mission and technology needs and are available at https://sites.nationalacademies.org/SSB/SSB_052297. In addition, the Heliophysics roadmap "The Solar and Space Physics of a New Era: Recommended Roadmap for Science and Technology 2009-2030" is available at http://hpde.gsfc.nasa.gov/2009_Roadmap.pdf.

S3.05: Terrestrial Balloons and Planetary Aerial Vehicles (SBIR)

Lead Center: GSFC

Participating Center(s): AFRC, JPL

Technology Area: 4.0.0 Robotics, Telerobotics and Autonomous Systems

Related Subtopic Pointer(s): S1.07 S4.04

Planetary Aerial Vehicles for Venus, Satellite Communications for Balloons, and Helium Replenishment System

Scope Title
Planetary Aerial Vehicles for Venus

Scope Description

NASA is interested in scientific investigation of the Venus atmosphere and planetary surface using aerial vehicles. Aerial vehicles are expected to carry scientific payloads at Venus that will perform in-situ investigations of its atmosphere, surface and interior structure. The 2018 Venus Aerial Platforms Study report identified several key science investigations that are ideally suited to aerial platforms. The areas of scientific interest include: Atmospheric Gas Composition, Cloud and Haze Particle Characterization, Atmospheric Structure, Surface Imaging and Geophysical Investigations. Venus features a challenging atmospheric environment that significantly impacts the design of aerial vehicles. Proposals are sought in the following areas:

Aerial Vehicle Platforms for Venus - Concepts for Lighter-than-Air (e.g., balloons, airships) and Heavier-than-Air (e.g., fixed wing, rotary wing) vehicles are encouraged. The current state of the art in Venus aerial vehicles has been designed to operate within the altitude range of 50 to 60 km above the surface where the atmosphere is similar to the lower Earth atmosphere. The science objectives described in the Venus Aerial Platform study indicate that a wider range of altitudes is strongly desirable.

There are 3 areas of interest in this call:

1. Aerial systems that can maneuver throughout the range 40 to 70 km altitude for a long duration. The aerial platform should be able to operate on the sunlit side of Venus and be able to transit the night side and survive several circumnavigations around the planet. The proposal should describe how the vehicle concept would be deployed into the atmosphere and operated for its mission. The proposal does not have to address thermal design of the payload (if it is suspended under a balloon), but should include concepts for addressing the thermal requirements for the aerial platform. The atmospheric temperature ranges from 145C at 40 km to -10C at 60 km altitude. The aerial platform is not expected to operate extensively at the lower altitudes but should be capable of operating for short durations at high temperatures. Concepts for any of the following capabilities of aerial vehicle are encouraged:
    - Technology demonstration with science payload less than 5 kg.
    - Pathfinder mission with science payload less than 30 kg.
    - Flagship mission with science payload up to 60 kg.

Other areas of interest include low cost approaches to:

2. Solar heated balloon systems to carry small science payloads (i.e. less than 10 kg payload) from 60 to 70 km altitude which would operate only on the sunlit side. These should be relatively simple systems that could operate collectively as a swarm system.
3. Deep atmospheric probes, deployed from aerial vehicles, to measure diurnal variations in the deep atmosphere of Venus. These could be deployed at different locations around Venus to capture atmospheric differences between day and night. Concepts for vehicles or neutrally buoyant probes that perform vertical descents, or guided/gliding descents to the surface are desired.

References

The Venus Aerial Platforms Study report can be found here: https://solarsystem.nasa.gov/resources/2197/aerial-platforms-for-the-scientific-exploration-of-venus/

Information about Venus can be found here: https://solarsystem.nasa.gov/planets/venus/in-depth/

Hall, J., Kerzhanovich, V., Fredrikson, T., Sandy, C., Pauken, M., Kulczycki, E....Day, S. (2017). Technology development for a Long Duration Mid-Cloud level Venus Balloon. Advances in Space Research Vol. 48 No. 7, 1238-1247.

Khatuntsev, I. V. (2017). Winds in the Middle Cloud Deck from the Near-IR. Journal of Geophysical Research: Planets. https://doi.org/10.1002/2017JE005355

Expected TRL or TRL range at completion of the project: 2 to 3

Desired Deliverables of Phase II

Prototype, Analysis, Research

Desired Deliverables Description

It is expected that a Phase I effort will consist of a system-level design and a proof-of-concept experiment on one or more key components.

Deliverables shall be a final report describing the results of the concept analysis, demonstration of any key technology developed and photos of any prototypes that were built and tested.

State of the Art and Critical Gaps

Terrestrial based aerial vehicles, including lighter-than-air and heavier-than-air are mature technologies and continue making advancements in capability, reliability and autonomy. But these need adaptation for operation in the Venus environment.

A gap exists in aerial vehicle technology that allows for variable altitude investigation in the Venus atmospheric environment. Floating at a fixed altitude means the vehicle is basically collecting samples of the same atmosphere each time it performs a collection since it floats with the wind. Having variable altitude capability allows significantly better investigation into the atmospheric structure. Variable altitude balloon concepts have been developed to operate over the altitude range of 50 to 60 km. New science goals defined in the Venus Aerial Platforms Study have indicated that stretching this operating range over 40 to 60 km is needed. This is a significant challenge because of the high atmospheric temperature at the 40 km altitude.

Relevance / Science Traceability

Relevance: Applied Physics Laboratory’s (APL) Dragonfly mission selection by New Frontiers shows there is significant interest in aerial vehicles for science investigations. It is in NASA's interests through the SBIR program to continue fostering innovative ideas to develop mission concepts to explore Venus using aerial vehicles.

JPL's Solar System Mission Formulation Office and the NASA Science Mission Directorate's Planetary Science Division advocate Venus aerial vehicle platform development. Furthermore, there are many enthusiastic supporters of exploring other worlds with aerial platforms throughout NASA.

Science Traceability: The 2018 Venus Aerial Platforms Study report identified several key science investigations that are ideally suited to aerial platforms. The areas of scientific interest include: Atmospheric Gas Composition, Cloud and Haze Particle Characterization, Atmospheric Structure, Surface Imaging and Geophysical Investigations. The variable altitude aerial vehicle platform is ideal for investigating these science goals and objectives.

Scope Title
Satellite Communications for Balloons

Scope Description

Improved downlink bitrates and innovative solutions using satellite relay communications from balloon payloads are needed. Long duration balloon flights currently utilize satellite communication systems to relay science and operations data from the balloon to ground based control centers. The current maximum downlink bit rate is 150 kilobits per second operating continuously during the balloon flight. Future requirements are for bit rates of 1 megabits per second or more. Improvements in bit rate performance, reduction in size and mass of existing systems, or reductions in cost of high bit rate systems are needed. Tracking and Data Relay Satellite (TDRSS) and Iridium satellite communications are currently used for balloon payload applications. A commercial S-band TDRSS transceiver and a mechanically steered 18 dBi gain antenna provide 150 kbps continuous downlink. TDRSS K-band transceivers are available but are currently cost prohibitive. Open port Iridium service is also in use, but the operational cost is high per byte transferred.

References

NASA's SuperTIGER Balloon Flies Again to Study Heavy Cosmic Particles: https://sites.wff.nasa.gov/code820/

Expected TRL or TRL range at completion of the project: 1 to 3

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Software, Research

Desired Deliverables Description

Desired deliverables include results of analysis or simulation, or test results of actual prototype hardware and/or software. Phase II deliverables could include a prototype that could be test flown on a balloon mission.

State of the Art and Critical Gaps

Current commercially available satellite relays systems that could be used for balloon flight are either too costly, or do not provide the needed downlink data rates.

Relevance / Science Traceability

Science Mission Directorate (SMD) - NASA HQ (Astrophysics Division). Enables multiple Research Opportunities in Space and Earth Science (ROSES) opportunities, Small Explorer (SMEX) Announcement of Opportunity (AO) (Astrophysics), Astrophysics Mission of Opportunity, Hands-On Project Experience (HOPE) (annually). Improvements to satellite communications for research balloons would enable greater and better data collection, possibly extended flight duration, and other such potential benefits.

Scope Title
Helium Replenishment System

Scope Description

NASA long duration Super Pressure Balloons (SPB) are large and complex structures that contain seams and fittings. Since these balloons are hand constructed, there is potential for gas loss due to leaks through the seams or fittings, or permeation through the balloon envelope that is made of linear low-density polyethylene. In the event of a gas loss, a helium replenishment system is needed to augment the lifting gas in order to increase the likelihood of payload recovery overland, and to extend the flight duration. The desired system shall not significantly affect the overall mass of the payload and shall require limited power for efficient operation.

References

NASA's SuperTIGER Balloon Flies Again to Study Heavy Cosmic Particles: https://sites.wff.nasa.gov/code820/

Expected TRL or TRL range at completion of the project: 1 to 3

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Software, Research

Desired Deliverables Description

Desired deliverables include results of analysis or simulation, or test results of actual prototype hardware and/or software. Phase II deliverables could include a prototype that could be test flown on a balloon mission.

State of the Art and Critical Gaps

No such system currently exists.

Relevance / Science Traceability

SMD - NASA HQ (Astrophysics Division). Enables multiple ROSES opportunities, Small Explorer (SMEX) Announcement of Opportunity (AO) (Astrophysics), Astrophysics Mission of Opportunity, Hands-On Project Experience (HOPE) (annually). A replenishment system can potentially prove very beneficial for avoiding payload termination over water by extending flight duration and enabling payload recovery overland in case of limited gas loss. This in turn can result in salvaging high value science data and payload recovery. Such a system can also possibly extend flight duration enabling more science data collection as well as other such potential benefits.

S3.08: Command, Data Handling, and Electronics (SBIR)

Lead Center: GSFC

Participating Center(s): JPL, LaRC, MSFC

Technology Area: 11.0.0 Modeling, Simulation, Information Technology and Processing

Related Subtopic Pointer(s): Z8.10 Z8.02 H9.07 Z2.02 S5.06 H6.22 Z8.09

Scope Description

NASA's space based observatories, fly-by spacecraft, orbiters, landers, and robotic and sample return missions, require robust command and control capabilities. Advances in technologies relevant to command and data handling and instrument electronics are sought to support NASA's goals and several missions and projects under development.

The 2020 subtopic goals are to develop platforms for the implementation of miniaturized highly integrated avionics and instrument electronics that:

- Are consistent with the performance requirements for NASA missions.
- Minimize required mass/volume/power as well as development cost/schedule resources.
- Can operate reliably in the expected thermal and radiation environments.

Successful proposal concepts should significantly advance the state-of-the-art. Furthermore, proposals developing hardware should indicate an understanding of the intended operating environment, including temperature and radiation. Note that environmental requirements vary significantly from mission to mission. For example, some low earth orbit missions have a total ionizing dose (TID) radiation requirement of less than 10 krad(Si), while planetary missions can have requirements well in excess of 1 Mrad(Si).

Specific technologies sought by this subtopic include:

Fault-tolerant computing: Processor and eco-system (ASIC & Design IP) designed to mitigate single event upsets (SEUs) – Technologies are sought that implement fault tolerant computers leveraging industry standard processor instruction set architectures (ISPIAs) and interfaces. Although not limited to, there is particular interest in leveraging the reduced instruction set computer (RISC) principles of RISC-V architecture. Offerors should identify coding language of IP cores, use of architecture specific modules which would limit the ability to swap hardware chipsets, options for scaling fault tolerance, code/gate size and features versus power and speed. Offerors working application-specific integrated circuit (ASIC) efforts should identify possible foundries and their radiation tolerance processes. Offerors offering processing units should identify operating system / toolchain support. Offerors proposing design intellectual property (IP) should identify mitigation technique(s) including burdens on code development time / hardware performance and size.

Multiple output point of load power regulator: This module, preferably implemented utilizing one or more controller ASICs, will source a minimum of 3 settable output voltages when provided with standard spacecraft power bus input. Output voltages shall be independently settable to any voltage between 3.3V and .9 V with efficiency of at least 95%. Regulation, noise filtering and other operational specifications should be commensurate with industry standards for space-based systems. Output current in the 10A range to handle field-programmable gate array (FPGA) core requirements. The module should provide standard spacecraft power supply features, including over voltage protection, fault tolerance, load monitoring, sequencing, synchronization, soft start and should allow control and status monitoring by a remote power system controller. Using fewer external components is also highly desirable. There is also interest in a capability to provide data over power line communication to the converter for control and monitoring functions. The offeror should determine radiation tolerance levels achievable utilizing commercially available processes and indicate, in the proposal, the radiation tolerance goals.

High density high-reliability interconnections: A high reliability connector or interconnect mechanism that can operate in space environments (vacuum, vibration) and deliver hundreds of signal/power connections while using as little physical board area as possible is desired. The design should handle everything from carrying power to high speed (10+ Gbps) impedance controlled connections. The design should be scalable in different sizes to accommodate fewer connections and save board space. Low insertion force is desirable. Right angle and stacking design options should be considered.

References

For descriptions of radiation effects in electronics, the proposer may visit (http://radhome.gsfc.nasa.gov/radhome/overview.htm).

Expected TRL or TRL range at completion of the project: 3 to 5

Desired Deliverables of Phase II

Prototype, Hardware, Software

Desired Deliverables Description

Desired Phase 2 deliverables for fault tolerant computing architectures are IP cores / ASIC designs implemented using an appropriate hardware design language (VHDL or Verilog) that have been demonstrated as an integrated system. Any required system software should be available, preferably as open source, to provide compilers, debuggers, and operating systems to the architecture. The fault tolerance of the architecture should be demonstrated.

Desired Phase 2 deliverable for the multiple output point of load switcher is a prototype multi-output point of load regulator. The regulator should be integrated onto a test board and be performance tested under varying resistive, capacitive, and transient load conditions.

Desired Phase 2 deliverables for the high density high-reliability interconnect are prototypes of the connection system (different size, orientations, etc.). The connector should be integrated onto a test board where its performance (speed, cross talk, etc.) can be verified.

State of the Art and Critical Gaps

There is a need for a broader range of offerings for fault tolerant computing architectures. This includes the need for viable options between performance, size (gate count) and power tradeoffs. There are currently a few sources of fault tolerant computing, and additional variety would help reduce costs for future NASA missions. Fault tolerant computing enables robust autonomous systems to be designed and implemented. Furthermore, recent commercial processor architecture developments offer improved performance and a broader array of performance options, and fault tolerant variants of these could significantly benefit NASA missions.

There are multiple output point of load converters available from commercial companies. The existing commercial parts require many external components eliminating their space savings. Commercial parts are not built on radiation tolerant processes.

Current connectors are too large, especially for small satellites and CubeSats. As the size of the printed circuit boards has shrunk, the percent of board space being used by the I/O connectors has become unacceptable. The connectors are taking away from circuitry and sensors that could be providing additional functionality and science products. High density commercial connectors also tend to be lacking in their general ruggedness, outgassing, and ability to prevent intermittent connections in high vibration environments like orbital launches.

Relevance / Science Traceability

Fault tolerant / autonomous computing architectures are relevant to increasing science return and lowering costs for missions across all Science Mission Directorate (SMD) divisions. However, the benefits are most significant for miniaturized instruments and subsystems that must operate in harsh environments. These missions include interplanetary CubeSats and smallsats, outer planets instruments, and heliophysics missions to harsh radiation environments. For these missions, the inherent fault tolerance would provide an additional level of protection on top of the radiation tolerance of the FPGA or ASIC on which the computing system is implemented. Additionally, for missions with large communication delays, the inherent fault tolerance can limit the need for ground intervention.

Multi-output point of load converters and high-density high-reliability interconnects are relevant to miniaturizing electronics. Miniaturized flight electronics allows one to fit more functionality into less volume, allowing smaller spacecraft to perform science that was previously done by larger satellites. These missions include interplanetary CubeSats and smallsats, outer planets instruments, and heliophysics missions.

S4.04; Extreme Environments Technology (SBIR)

Lead Center: JPL

Participating Center(s): GRC, GSFC, LaRC

Technology Area: 4.0.0 Robotics, Telerobotics and Autonomous Systems

Related Subtopic Pointer(s): Z8.02 Z1.06 S4.02 S1.11 Z7.06 H5.02 Z1.05 S5.06 S3.05

Scope Description

This subtopic addresses NASA's need to develop technologies for producing space systems that can operate without environmental protection housing in the extreme environments of NASA missions. Key performance parameters of interest are survivability and operation under the following conditions:

1) Very low temperature environments (e.g., temperatures at the surface of Titan and of other Ocean Worlds as low as -180 deg C; and in permanently shadowed craters on the Moon), or
2) Combination of low temperature and radiation environments (e.g., surface conditions at Europa of -180 deg C with very high radiation), or
3) Very high temperature, high pressure and chemically corrosive environments (e.g., Venus surface conditions having very high pressure and temperature of 486 deg C).

NASA is interested in expanding its ability to explore the deep atmospheres and surfaces of planets, asteroids, and comets through the use of long-lived (days or weeks) balloons and landers. Survivability in extreme high temperatures and high pressures is also required for deep atmospheric probes to the giant planets. Proposals are sought for technologies that are suitable for remote sensing applications at cryogenic temperatures, and in-situ atmospheric and surface explorations in the high temperature, high pressure environment at the Venusian surface (485°C, 93 atmospheres), or in low-temperature environments such as those of Titan (-180°C), Europa (-220°C), Ganymede (-200°C), Mars, the Moon, asteroids, comets and other small bodies. Also, Europa-Jupiter missions may have a mission life of 10 years and the radiation environment is estimated at 2.9 Mega-rad total ionizing dose (TID) behind 0.1 inch thick aluminum. Proposals are sought for technologies that enable NASA's long duration missions to extreme wide-temperature and cosmic radiation environments. High reliability, ease of maintenance, low volume, low mass, and low out-gassing characteristics are highly desirable. Special interest lies in development of the following technologies that are suitable for the environments discussed above:

- Wide temperature range precision mechanisms, e.g., beam steering, scanner, linear and tilting multi-axis mechanisms
- Radiation-tolerant/radiation-hardened low-power, low-noise, mixed-signal mechanism control electronics for precision actuators and sensors
- Wide temperature range feedback sensors with sub-arcsecond/nanometer precision
- Long life, long stroke, low power, and high torque force actuators with sub-arc-second/nanometer precision
- Long life bearings/tribological surfaces/lubricants
- High temperature energy storage systems
- High-temperature actuators and gear boxes for robotic arms and other mechanisms
- Low-power and wide-operating-temperature radiation-tolerant/ radiation hardened RF electronics
- Radiation-tolerant/radiation-hardened low-power/ultra-low power, wide-operating-temperature, low-noise mixed-signal electronics for space-borne systems such as guidance and navigation avionics and instruments
- Radiation-tolerant/radiation-hardened power electronics
- Radiation-tolerant/radiation-hardened electronic packaging (including shielding, passives, connectors, wiring harness and materials used in advanced electronics assembly)

Research should be conducted to demonstrate technical feasibility during Phase I and show a path toward a Phase II hardware demonstration, and when possible, deliver a demonstration unit for functional and environmental testing at the completion of the Phase II contract.

NASA has plans to purchase services for delivery of payloads to the Moon through the Commercial Lunar Payload Services (CLPS) contract. Under this subtopic, proposals may include efforts to develop payloads for flight demonstration of relevant technologies in the lunar environment. The CLPS payload accommodations will vary depending on the particular service provider and mission characteristics. Additional information on the CLPS program and providers can be found at this link: https://www.nasa.gov/content/commercial-lunar-payload-services. CLPS missions will typically carry multiple payloads for multiple customers. Smaller, simpler, and more self-sufficient payloads are more easily accommodated and would be more likely to be considered for a NASA-sponsored flight opportunity. Commercial payload delivery services may begin as early as 2020 and flight opportunities are expected to continue well into the future. In future years it is expected that larger and more complex payloads will be accommodated. Selection for award under this solicitation will not guarantee selection for a lunar flight opportunity.

References

1. Proceedings of the Extreme Environment Sessions of the IEEE Aerospace Conference. https://www.aeroconf.org/ or via IEEE *Xplore* Digital Library
2. Proceedings of the meetings of the Venus Exploration Analysis Group (VEXAG). https://www.lpi.usra.edu/vexag/
3. Proceedings of the meetings of the Outer Planet Assessment Group (OPAG). https://www.lpi.usra.edu/opag/

Expected TRL or TRL range at completion of the project: 3 to 5

Desired Deliverables of Phase II

Prototype, Hardware

Desired Deliverables Description

Deliverables include proof of concept working prototypes that demonstrate the innovations defined in the proposal and enable direct operation in extreme environments.

State of the Art and Critical Gaps

Future NASA missions to high priority targets in our solar system will require systems that have to operate at extreme environmental conditions. NASA missions to the surfaces of Europa and other Ocean Worlds bodies will be exposed to temperatures as low as -180 deg C and radiation levels that are at megarad levels. Operation in permanently shadowed craters on the Moon is also a region of particular interest. In addition, NASA missions to the Venus surface and deep atmospheric probes to Jupiter or Saturn will be exposed to high temperatures, high pressures, and chemically corrosive environments.

Current state-of-practice for development of space systems for the above missions is to place hardware developed with conventional technologies into bulky and power-inefficient environmentally protected housings. The use of environmental protection housing will severely increase the mass of the space system, limit the life of the mission and the corresponding science return. This solicitation seeks to change the state of the practice by support technologies that will enable development of lightweight, highly efficient systems that can readily survive and operate in these extreme environments without the need for the environmental protection systems.

Relevance / Science Traceability

Relevance to SMD (Science Mission Directorate) is high.

Low temperature survivability is required for surface missions to Titan (-180 deg C), Europa (-220 deg C), Ganymede (-200 deg C), small bodies and comets. Mars diurnal temperatures range from -120 deg C to +20 deg C. For the Europa Clipper baseline concept, with a mission life of 10 years, the radiation environment is estimated at 2.9 megarad total ionizing dose (TID) behind 100 mil thick aluminum. Lunar equatorial region temperatures swing from -180 deg C to +130 deg C during the lunar day/night cycle, and shadowed lunar pole temperatures can drop to -230 deg C.

Advanced technologies for high temperature systems (electronics, electro-mechanical and mechanical) and pressure vessels are needed to ensure NASA can meet its long duration (days instead of hours) life target for its science missions which operate in high temperature and high pressure environments.

S4.05: Contamination Control and Planetary Protection (SBIR)

Lead Center: JPL

Participating Center(s):

Technology Area: 4.0.0 Robotics, Telerobotics and Autonomous Systems

Related Subtopic Pointer(s): S4.02

Scope Description

The planetary protection and contamination control subtopic focuses on mission-enabling and capability-driven technologies to improve NASA's ability to prevent forward and backward contamination. Forward contamination is the transfer of viable organisms from Earth to another body. Backward contamination is the transfer of material posing a biological threat back to Earth's biosphere. NASA is seeking innovative technologies or applications of technologies to facilitate meeting portions of forward and backward contamination requirements to include:

- Improvements to spacecraft cleaning and sterilization that remain compatible with spacecraft materials and assemblies,
- Prevention of re-contamination and cross-contamination throughout the spacecraft lifecycle,
- Improvements to detection and verification of organic compounds and biologicals on spacecraft, to include microbial detection and assessments for viable organism and DNA-based verification technologies to encompass sampling devices, sample processing, and sample analysis pipelines, and
- Active in-situ recontamination/decontamination approaches (e.g., in-situ heating of sample containers to drive off volatiles prior to sample collection) and in-situ/in-flight sterilization approaches (e.g., UV or plasma) for surfaces.
- Enabling end-to-end sample return functions to assure containment and pristine preservation of materials gathered on NASA missions.

For contamination control efforts, understanding contaminants and preventing contamination supports the preservation of sample science integrity and ensures spacecraft function nominally. NASA is seeking analytical and physics-based modeling technologies and techniques to quantify and validate sub-micron particulate contamination, low energy surface material coatings to prevent contamination, and modeling and analysis of particles to ensure hardware and instrumentation meet organic contamination requirements.

Examples of Outcomes

- End-to-end microbial reduction/sterilization technology for larger spacecraft subsystems
- Microbial reduction/sterilization technology for spacecraft components
- Ground/based biological contamination/re-contamination mitigation system that can withstand spacecraft assembly and testing operations
- In-flight spacecraft component-to-component cross contamination mitigation system
- Viable organism and/or DNA sample collection devices, sample processing (e.g. low biomass extraction), and sample analysis (e.g. bioinformatic pipelines for low biomass)
- Real-time, rapid device for detection and monitoring of viable organism contamination on low biomass surfaces or in cleanroom air
- Bioburden spacecraft cleanliness monitors for assessing surface cleanliness throughout flight and surface operations during missions
- DNA-based system to elucidate abundance, diversity, and planetary protection relevant functionality of microbes present on spacecraft surfaces
- An applied molecular identification technology to tag/label biological contamination on outbound spacecraft
- Low surface area energy coatings
- Molecular adsorbers (“getters”)
- Experimental technologies for measurement of outgassing rates lower than 1.0E-15 g/cm2/s with mass-spectrometry, under flight conditions (low and high operating temperatures) and with combined exposure to natural environment (e.g., high-energy radiation, ultraviolet radiation, atomic oxygen exposure)

- Physics-based technologies for particulate transport modeling and analysis for continuum, rarefied and molecular flow environments, with electrostatic, vibro-acoustic, particle detachment and attachment capabilities
- Modeling and analysis technologies for view-factor computation technologies for complex geometries with articulation (e.g., rotating solar arrays, articulating robotic arms)

References

Planetary Protection: https://planetaryprotection.nasa.gov/
Handbook for the Microbial Examination of Space Hardware:
https://searchworks.stanford.edu/view/2569630

Expected TRL or TRL range at completion of the project 2 to 6

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Software, Research

Desired Deliverables Description

Technologies, approaches, techniques, models, and/or prototypes including accompanying data validation reports demonstrating how the product will enable spacecraft compliance with planetary protection and contamination control requirements.

State of the Art and Critical Gaps

Planetary protection state-of-the-art leverages the technologies resulting from the 1960s-1970s Viking spacecraft assembly and test era. The predominant means to control biological contamination on spacecraft surfaces is using some combination of heat microbial reduction processing, solvent cleaning (e.g. isopropyl alcohol cleaning). Notably, vapor hydrogen peroxide is a NASA approved process, but the variability of the hydrogen peroxide concentration, delivery mechanism, and material compatibility concerns still tends to be a hurdle to infuse it on a flight mission with complex hardware and multiple materials for a given component. Upon microbial reduction the hardware then is protected in a cleanroom environment (ISO 8 or better) using protective coverings when hardware is not being assembled or tested. Biological cleanliness is then verified through the NASA standard assay which is a culture-based method. Rapid cleanliness assessments can be performed, but are not currently accepted as a verification methodology, to inform engineering staff about biological cleanliness during critical hardware assembly or tests which include the total adenosine triphosphate (tATP) and limulus amoebocyte lysate (LAL) assays. Terminal sterilization has been conducted with recontamination prevention for in-flight biobarriers employed for the entire spacecraft (Viking) or a spacecraft subsystem (Phoenix spacecraft arm). In addition to the hardware developed approaches for compliance environmental assessments are implemented to understand recontamination potential for cleanroom surfaces and air. While the NASA standard assay is performed on the cleanroom surfaces DNA-based methodologies have been adopted to include 16S and 18S rRNA targeted sequencing while metagenomic approaches are currently undergoing development. Thus, the critical planetary protection gaps include the assessment of DNA from low biomass surfaces (<0.1 ng/uL DNA using current technologies from 1-5m2 of surface), sampling devices that are suitable for low biomass and compounds (e.g. viable organisms, DNA) but also compliant with cleanroom and electrostatic discharge limits, quantification of the widest spectrum of viable organisms, enhanced microbial reduction / sterilization modalities that are compatible with flight materials and a ground- and flight-based recontamination systems.

Contamination Control requirements and practices are also evolving rapidly as mission science objectives targeting detection of organics and life are driving stricter requirements and improved characterization of flight system and science instrument induced contamination. State-of-the-art Contamination Control includes:

- Testing and measurement of outgassing rates down to 3.0E-15 g/cm2/s with mass-spectrometry, under flight conditions (low and high operating temperatures) and with combined exposure to natural environment (high-energy radiation, ultraviolet radiation, atomic oxygen exposure)
- Particulate transport modeling and analysis for continuum, rarefied and molecular flow environments with electrostatic, vibro-acoustic, particle detachment and attachment capabilities.
- Modeling and analysis of molecular return flux using Direct Simulation Monte Carlo (DSMC) and the BGK formulation.

Relevance / Science Traceability

Planetary protection requirements has emerged in recent years with increased interest in investigating bodies with the potential for life detection such as Europa, Enceladus, Mars, etc. and the potential for sample return from such bodies. The development of such technologies would enable missions to be able to be responsive to planetary protection requirements as they would be able to assess viable organisms and establish microbial reduction technologies to achieve acceptable microbial bioburden levels for sensitive life detection instruments to prevent inadvertent “false positives,” to ensure compliance sample return planetary protection and science requirements, and to provide a means to comply with probabilistic based planetary protection requirements for biologically sensitive missions (e.g. outer planets and sample return).

Z2.02: High Performance Space Computing Technology (SBIR)

Lead Center: JPL

Participating Center(s): GSFC

Technology Area: 11.0.0 Modeling, Simulation, Information Technology and Processing

Related Subtopic Pointer(s): S3.08 S5.05 S5.03 H9.07 T6.05 H6.22

Scope Title

Avionics Computing Support

Scope Description

The NASA State-Of-the-Art (SOA) in space computing utilizes 20-year-old technology and is inadequate for future missions. In conjunction with the United States Air Force (USAF), NASA is investing in the development of the High-Performance Spaceflight Computing (HPSC) Chiplet, a radiation-hardened multi-core processor that will improve space computing capabilities by two orders of magnitude. Another joint NASA-USAF project will develop rad-hard, high capacity, high-speed memory components that will likewise improve space computing capabilities by approximately two orders of magnitude. And yet another project, with a planned start date of FY 2019, will start developing a single board computer based on an HPSC-chiplet.

While these efforts will provide an underlying platform, they do not provide the full range of advanced computing capabilities that will be required to support missions currently in the planning stage for the mid-2020s and beyond. Topics of interest include:

- HPSC-compatible Coprocessors: General purpose neural networks and other machine learning accelerators for robotic vision, system health management, and similar applications are needed to meet performance: power requirements in future autonomous robotic systems. Initial design of this application-specific integrated circuit (ASIC) and a validated field-programmable gate arrays (FPGA) implementation of critical portions of the design is desired. A successful SBIR will potentially lead to a Phase 3 award, or alternate funding, to implement the final chiplet.

- Fault Tolerant, Real Time Linux: A flight qualifiable version of Linux for the HPSC Chiplet, capable of supporting parallel and heterogeneous processing for autonomy, robotics and science codes is desired. Initial design of a verifiably reliable, fault tolerant, real time Linux kernel is desired. A successful SBIR will potentially result in a Phase 3 award, or alternate funding, to develop a complete, qualified, operating system.
- Compilers that support Software Implemented Fault Tolerance (SIFT) capabilities (e.g., control flow checking, coordinated checkpoint/rollback, recovery block) for the HPSC Chiplet is desired. A successful SBIR will potentially result in a Phase 3 award, or alternate funding, to implement a complete SIFT-capable software development system.
- Fault tolerant middleware to Support HPSC Chiplet Parallel Processing: Includes math and I/O libraries to support robotic capabilities, autonomy and science processing, and including library routines for Neon Single instruction, Multiple Data (SIMD) processors as well as A53 general purpose processors.
- Technology and languages to enable development of provably correct software.
- Radiation tolerant standard cell libraries for processes below 28nm that are suitable for NASA missions in the natural space environment.

NASA has plans to purchase services for delivery of payloads to the Moon through the Commercial Lunar Payload Services (CLPS) contract. Under this subtopic, proposals may include efforts to develop payloads for flight demonstration of relevant technologies in the lunar environment. The CLPS payload accommodations will vary depending on the particular service provider and mission characteristics. Additional information on the CLPS program and providers can be found at this link: https://www.nasa.gov/content/commercial-lunar-payload-services. CLPS missions will typically carry multiple payloads for multiple customers. Smaller, simpler, and more self-sufficient payloads are more easily accommodated and would be more likely to be considered for a NASA-sponsored flight opportunity. Commercial payload delivery services may begin as early as 2020 and flight opportunities are expected to continue well into the future. In future years it is expected that larger and more complex payloads will be accommodated. Selection for award under this solicitation will not guarantee selection for a lunar flight opportunity.

References

https://www.nasa.gov/press-release/goddard/2017/nasa-selects-high-performance-spaceflight-computing-hpsc-processor-contractor

Expected TRL or TRL range at completion of the project: 4 to 6

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Software

Desired Deliverables Description

For hardware elements, a preliminary design ready for detailed design, fabrication, and production.

State of the Art and Critical Gaps

The SOA in space qualifiable high performance computing has high power dissipation (approximately 18 W) and the SOP in TRL-9 space computing have relatively low performance (between 2 DMIPS to 200 DMIPS at 100 MHz). Neither of these systems provides the performance, power:performance ratio, or the flexibility in configuration, performance, power management, fault tolerance, or extensibility with respect to heterogeneous processor elements. The HPSC Chiplet, currently in development, will provide significantly enhanced capabilities but, as currently defined, lacks a broad range of coprocessors and accelerators (which are supported in the architecture but not planned for implementation) as well as software elements that will be required for use in future missions. This lack of hardware and software ecosystem elements is the focus of this nomination.

Relevance / Science Traceability

HPSC ecosystem is of interest to all major programs in HEOMD (Human Exploration and Operations Mission Directorate) and SMD (Science Mission Directorate). We have had discussions with program and project managers across NASA. Immediate infusion targets include Mars Fetch Rover, WFIRST/Chronograph, Gateway, and SPLICE/Lunar Lander.

Focus Area 12: Entry, Descent, and Landing Systems

Lead MD: STMD

Participating MD(s): HEOMD

The SBIR focus area of Entry, Descent and Landing (EDL) includes the suite of technologies for atmospheric entry as well as descent and landing on both atmospheric and non-atmospheric bodies. EDL mission segments are used in both robotic planetary science missions and human exploration missions beyond Low Earth Orbit, and many technologies have application to emerging commercial space capabilities.

Robust, efficient, and predictable EDL systems fulfill the critical function of delivering payloads to planetary surfaces through challenging environments, within mass and cost constraints. Future NASA missions will require new technologies to break through historical constraints on delivered mass, enable sustained human presence, or to go to entirely new planets and moons. Even where heritage systems exist, no two planetary missions are exactly “build-to-print,” so there are frequently issues of environmental uncertainty, risk posture, and resource constraints that can be dramatically improved with investments in EDL technologies. EDL relies on validated models, ground tests, and sensor technologies for system development and certification. Both new capabilities and improved knowledge are important facets of this focus area.

Because this topic covers a wide area of interests, subtopics are chosen to enhance and or fill gaps in the existing technology development projects. Future subtopics will support one or more of four broad capability areas, which represent NASA’s goals with respect to planetary Entry, Descent and Landing:

- High Mass to Mars Surface
- Precision Landing and Hazard Avoidance
- Planetary Probes and Earth Return Vehicles
- EDL Data Return and Model Improvement

A cross-cutting set of disciplines and technologies will help mature these four capability areas, to enable more efficient, reliable exploration missions.

This year the Entry, Descent and Landing focus area is seeking innovative solutions for:

- Deployable Decelerator Technologies
- Lander Systems Technologies, particularly for the Moon
- EDL Sensors, including those embedded in thermal protection systems and those used for proximity operations and landing
- 3D Weaving Diagnostics
- Diagnostic tools for specialized EDL facilities
- Hot Structure Technology for Aerospace Vehicles

The specific needs and metrics of each of these specific technology developments are described in the subtopic descriptions.

H5.02: Hot Structure Technology for Aerospace Vehicles (SBIR)

Lead Center: MSFC

Participating Center(s): AFRC, JSC, LaRC

Technology Area: 12.0.0 Materials, Structures, Mechanical Systems and Manufacturing

Related Subtopic Pointer(s): Z7.06 S4.04 S3.06 Z2.01 Z7.03 A1.10 T12.05 T12.01

Scope Title
Hot Structure Technology for Aerospace Vehicles

Scope Description

This subtopic encompasses the development of reusable hot structure technology for structural components exposed to extreme heating environments on aerospace vehicles. A hot structure system is a multi-functional structure that can reduce or eliminate the need for a separate thermal protection system (TPS) or active cooling system. The potential advantages of using a hot structure system in place of a TPS with underlying cool structure are: reduced mass, increased mission capability, such as reusability, improved aerodynamics, improved structural efficiency and increased ability to inspect the structure. Hot structure is an enabling technology for reusability between missions or mission phases, such as aerocapture followed by entry, and has been used in prior NASA programs (Space Shuttle Orbiter, Hyper-X, and X-37) on control surfaces and wing leading edges, as well as in Department of Defense programs. Additionally, the development of hot structure technology for combustion-device liquid rocket engine propulsion systems is of great interest.

This subtopic seeks to develop innovative low-cost, damage tolerant, reusable and lightweight hot structure technology applicable to aerospace vehicles exposed to extreme temperatures between 1093° to 2204°C (2000° to 4000°F). These aerospace vehicle applications are unique in requiring the hot structure to carry primary structure vehicle loads and to be reusable after exposure to extreme temperatures during atmospheric entry and/or liquid rocket engine firings. The material systems of interest for use in developing hot structure technology include: advanced carbon-carbon (C-C) materials, ceramic matrix composites (CMC's), or advanced high-temperature refractory metals. Potential applications of hot structure technology include: primary load-carrying aeroshell structures, control surfaces, leading edges, and propulsion system components (such as hot gas valves, combustion chambers, and passively- or actively-cooled nozzle extensions).

Proposals should present approaches to address the current need for improvements in operating temperature capability, toughness/durability, reusability and material system properties. Focus areas should address one or more of the following:

- Improvements in manufacturing processes and/or material designs to achieve repeatable and uniform material properties that should be scalable to actual vehicle components: specifically, material property data obtained from flat-panel test coupons should represent the properties of prototype and flight test articles.
- Material/structural architectures and multifunctional systems providing significant improvements over typical 2D inter-laminar mechanical properties while maintaining in-plane and thermal properties when compared to state-of-the-art C-C or CMC materials. Examples include: incorporating through-the-thickness stitching, braiding or 3D woven preforms.

- Functionally-graded manufacturing approaches to optimize oxidation protection, damage tolerance and structural efficiency, in an integrated hot structure concept that extends performance for multiple cycles up to 2204°C (4000°F).
- Manufacturing process methods that enable a significant reduction in the time required to fabricate materials and components. There is a great need to reduce processing time for hot structure materials and components -- current state-of-the-art fabrication times are often in the range of 6 to 12 months, which can limit the use of such materials. Approaches enabling reduced manufacturing times should not, however, lead to significant reductions in material properties.

Under this subtopic, research, testing, and analysis should be conducted to demonstrate technical feasibility during Phase I and show a path towards Phase II hardware demonstrations. Phase I feasibility studies should also address cost and risk associated with the hot structures technology. At the completion of the Phase I project, in addition to the final report, deliverables should include at least one of the following to aid assessment of technical feasibility: (a) coupons appropriate for thermal and/or mechanical material property tests, (b) arc-jet test specimens, or (c) a subscale nozzle extension test article or analog component. Emphasis should be placed on the delivery of manufacturing demonstration units for NASA testing at the completion of the Phase II contract. In addition, Phase II studies should address scale-up and integration with vehicles that could make use of the developed technology.

Hot structure technology is relevant to the Human Exploration and Operations Mission Directorate (HEOMD), where the technology can be infused into spacecraft and launch vehicle applications. Such technology should provide either improved performance or enable advanced missions requiring re-usability, increased damage tolerance and the durability to withstand long-term space exploration missions. The ability to allow for delivery of larger payloads to various space destinations, such as the lunar south pole, is also of great interest.

The Advanced Exploration Systems (AES) Program would be ideal for further funding a prototype hot structure system and technology demonstration effort. Commercial Space programs, such as Commercial Orbital Transportation Services (COTS), Commercial Lunar Payload Services (CLPS), and Next Space Technologies for Exploration Partnerships (NextSTEP), are also interested in this technology for flight vehicles. Additionally, NASA HEOMD programs that could use this technology include the Space Launch System (SLS) and the Human Landing System (HLS) for propulsion applications.

Potential NASA users of this technology exist for a variety of propulsion systems, including the following:

- Upper stage engine systems, such as those for the Space Launch System,
- In-space propulsion systems, including nuclear thermal propulsion systems,
- Lunar/Mars lander descent/ascent propulsion systems,
- Solid motor systems, including those for primary propulsion, hot gas valve applications, and small separation and/or attitude-control systems, and
- Propulsion systems for the Commercial Space industry, which is supporting NASA efforts.

Finally, the U.S. Air Force is interested in such technology for its Evolved Expendable Launch Vehicle (EELV), ballistic missile and hypersonic vehicle programs. Other non-NASA users include the U.S. Navy, the U.S. Army, the Missile Defense Agency (MDA) and the Defense Advanced Research Projects Agency (DARPA). The subject technology can be both enhancing to systems already in use or under development, as well as enabling for applications that may not be feasible without further advancements in high temperature composite technology.

References

<u>Hypersonic Hot Structures</u>:

Glass, David. "Ceramic matrix composite (CMC) thermal protection systems (TPS) and hot structures for hypersonic vehicles." 15th AIAA International Space Planes and Hypersonic Systems and Technologies Conference. 2008.

Walker, Sandra P., et al. "A Multifunctional Hot Structure Heat Shield Concept for Planetary Entry." 20th AIAA International Space Planes and Hypersonic Systems and Technologies Conference. 2015.

Liquid Rocket Propulsion systems:

"Carbon-Carbon Nozzle Extension Development in Support of In-Space and Upper-Stage Liquid Rocket Engines" paper; Paul R. Gradl and Peter G. Valentine; 53rd AIAA/SAE/ASEE Joint Propulsion Conference, Atlanta, GA; AIAA-2017-5064; July 2017; https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170008949.pdf.

"Carbon-Carbon Nozzle Extension Development in Support of In-Space and Upper Stage Liquid Rocket Engines" presentation charts; Paul R. Gradl and Peter G. Valentine; 53rd AIAA/SAE/ASEE Joint Propulsion Conference, Atlanta, GA; AIAA-2017-5064; July 2017; https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170008945.pdf.

Note: The above references are open literature references. Other references exist regarding this technology, but they are International Traffic in Arms Regulations (ITAR) restricted. Numerous online references exist for the subject technology and projects/applications noted, both foreign and domestic.

Expected TRL or TRL range at completion of the project: 2 to 4

Desired Deliverables of Phase II

Prototypes or components suitable for testing by NASA or Commercial Space partners.

Desired Deliverables Description

At the completion of Phase I project deliverables should include at least one of the following: coupons appropriate for thermal/mechanical material property tests, arc-jet test specimens, or a subscale nozzle extension test article. Emphasis should be on the delivery of manufacturing demonstration units, with representative structural features, for NASA testing at the completion of the Phase II contract.

State of the Art and Critical Gaps

The current state of the art for composite hot structure components is limited primarily to applications with maximum use temperatures in the 1093° – 1600°C (2000° – 2912°F) range. While short excursions to higher temperatures are possible, considerable degradation may occur. Reusability is limited and may require considerable inspection before reuse. Critical gaps or technology needs include: (a) increasing operating temperatures to 1700° – 2204+°C (3092° – 4000+°F); (b) increasing resistance to environmental attack (primarily oxidation); (c) increasing manufacturing technology capabilities to improve reliability, repeatability and quality control; (d) increasing durability/toughness and interlaminar mechanical properties (or introducing 3D architectures); and (e) decreasing overall manufacturing time required.

As an alternative to composites, metallic hot structures may reduce operating temperature requirements to near 1000°C (1832°F) in some applications, while offering greater structural reliability, and should also be pursued. Unfortunately advancements in high temperature metals have been a significant gap.

Relevance / Science Traceability

Hot structure technology is relevant to the Human Exploration and Operations Mission Directorate (HEOMD), where the technology can be infused into spacecraft and launch vehicle applications. Such technology should provide either improved performance or enable advanced missions requiring reusability, increased damage tolerance and the durability to withstand long-term space exploration missions. The ability to allow for delivery of larger payloads to various space destinations, such as the lunar south pole, is also of great interest.

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Finally, the U.S. Air Force is interested in such technology for its Evolved Expendable Launch Vehicle (EELV), ballistic missile, and hypersonic vehicle programs. Other non-NASA users include the U.S. Navy, the U.S. Army, the Missile Defense Agency (MDA), and the Defense Advanced Research Projects Agency (DARPA). The subject technology can be both enhancing to systems already in use or under development, as well as enabling for applications that may not be feasible without further advancements in high temperature composite technology.

Z7.01: Entry Descent & Landing Sensors for Environment Characterization, Vehicle Performance, and Guidance, Navigation and Control (SBIR)

Lead Center: ARC

Participating Center(s): JPL, JSC, LaRC

Technology Area: 9.0.0 Entry, Descent and Landing Systems

Related Subtopic Pointer(s): S3.04 Z7.04 Z7.03 T12.05 S1.01

Scope Description

NASA human and robotic missions to the surface of planetary or airless bodies require Entry, Descent, and Landing (EDL). For many of these missions, EDL represents one of the riskiest phases of the mission. Despite the criticality of the EDL phase, NASA has historically gathered limited engineering data from such missions, and use of the data for real-time Guidance, Navigation and Control (GN&C) during EDL for precise landing (aside from Earth) has also been limited. Recent notable exceptions are the Orion EFT-1 flight test, Mars Entry, Descent, & Landing Instrument (MEDLI) sensor suite, and the planned sensor capabilities for Mars 2020 (MEDLI2 and map-relative navigation). NASA requires EDL sensors to: a) understand the in-situ entry environment b) characterize the performance of entry vehicles, and c) make autonomous and real-time onboard GN&C decisions to ensure a precise landing.

This subtopic describes three related technology areas where innovative sensor technologies would enable or enhance future NASA EDL missions. Proposers may submit solutions to any of these scope areas:

1) High Accuracy, Light Weight, Low Power Fiber Optic or Recession Sensing System for Thermal Protection Systems.
2) Miniaturized Spectrometers for Vacuum Ultraviolet & Mid-wave Infrared In-Situ Radiation Measurements during Atmospheric Entry.

3) Novel Sensing Technologies for EDL GN&C and Small-Body Proximity Operations.

NASA seeks innovative sensor technologies to enable and characterize entry, descent and landing operations on missions to planetary and airless bodies. This subtopic describes three related technology areas where innovative sensor technologies would enable or enhance future NASA EDL missions. Candidate solutions are sought that can be made compatible with the environmental conditions of deep spaceflight, and the rigors of landing on planetary bodies both with and without atmospheres. Proposers may submit to scope areas 1, 2 or 3 below.

1) HIGH ACCURACY, LIGHT WEIGHT, LOW POWER FIBER OPTIC OR RECESSION SENSING SYSTEM FOR THERMAL PROTECTION SYSTEMS.

Current NASA state-of-the-art EDL sensing systems are very expensive to design and incorporate on planetary missions. Commercial fiber optic systems offer an alternative that could result in a lower overall cost and weight, while actually increasing the number of measurements. Fiber optic systems are also immune to Electro-magnetic Interference (EMI) which reduces design and qualification efforts. This would be highly beneficial to future planetary missions requiring Thermal Protection Systems (TPS). In addition, as NASA looks to the future of science missions to the Outer Planets, extreme entry environments will require the new, 3-D woven Heatshield for Extreme Entry Environment Technology (HEEET) TPS recently matured within the Agency. Gathering flight performance data on this new material will be key, particularly the measurement of recession, which was so very important on the Galileo probe mission to Jupiter. Minimizing the sensor intrusion of the outer mold line is critical in this case, because the extreme environment dictates that the TPS be as aerothermally monolithic as possible. In applications to planetary entry vehicles greater than about 1 m diameter, however, the HEEET TPS is expected to contain seams that might be used for accommodating instrumentation. Recession measurements in carbon fiber/phenolic TPS systems like Phenolic Impregnated Carbon Ablator (PICA) and AVCOAT are also of interest. When ablation is not severe and/or rapid, accurate measurements have proven difficult with the historic Galileo-type sensor, which was based on the differential resistance resulting from sensor materials that have charred.

The upcoming Mars 2020 mission will fly the Mars Entry, Descent, and Landing Instrumentation II (MEDLI2) sensor suite consisting of a total of 24 thermocouples, 8 pressure transducers, 2 heat flux sensors, and a radiometer embedded in the TPS. This set of instrumentation will directly inform the large performance uncertainties that contribute to the design and validation of a Mars entry system. A better understanding of the entry environment and TPS performance could lead to reduced design margins enabling a greater payload mass fraction and smaller landing ellipses. Fiber optic sensing systems can offer benefits over traditional sensing system like MEDLI and MEDLI2, and can be used for both rigid and flexible TPS. Fiber optic sensing benefits include, but are not limited to; sensor immunity to EMI, the ability to have thousands of measurements per fiber using Fiber Bragg Grating (FBG), multiple types of measurements per fiber (i.e. temperature, strain, and pressure), and resistance to metallic corrosion.

To be considered against NASA state-of-the-art TPS sensing systems for future flight missions, fiber optic systems must be competitive in sensing capability (measurement type, accuracy, quantity), and Sensor Support Electronics (SSE) mass, size and power. Therefore NASA is looking for a fiber optic system that can meet the following requirements:

Sensing Requirements

- TPS Temperature: Measurement Range: -200 to 1250C (up to 2000C preferred), Accuracy: +/- 5C desired.
- Surface Pressure: Measurement Range: 0-15 psi, Accuracy: < +/-0.5%

Sensor Support Electronics Requirements (including enclosure):

- Weight: 12 lbs or less,

- Size: 240 cubic inches or smaller,
- Power: 15W or less,
- Measurement Resolution: 14-bit or Higher,
- Acquisition Rate per Measurement: 16 Hz or Higher.
- Compatibility with all sensors types, e.g., Temperature, Pressure, Heat Flux, Strain, Radiometer, TPS recession.

For recession measurements in extreme entry environments requiring 3-D woven TPS, NASA is seeking novel concepts that fit into the sensor/electronics architecture described above, and meet the following requirements:

- Up to 5000 W/cm2 heat flux,
- Up to 5 atmospheres of pressure on the vehicle surface,
- Recession measurement accuracy within +/- 1 mm.

For recession measurements in moderate entry environments requiring carbon fiber/phenolic TPS systems, NASA is seeking novel concepts that fit into the sensor/electronics architecture described above, and meet the following requirements:

- Up to 150-2000 W/cm2 heat flux,
- Up to 1 atmosphere of pressure on the vehicle surface,
- Recession measurement accuracy within +/- 1 mm.

2) MINIATURIZED SPECTROMETERS FOR VACUUM ULTRAVIOLET & MID-WAVE INFRARED RADIATION IN-SITU MEASUREMENTS DURING ATMOSPHERIC ENTRY

The current state-of-the-art for flight radiation measurements includes radiometers and spectrometers. Radiometers can measure heating integrated over a wide wavelength range (e.g. MEDLI2 Radiometer), or over narrow-wavelength bands (COMARS+ ICOTOM at 2900 nm and 4500 nm). Spectrometers gather spectrally resolved signal and have been developed for Orion EM-2 (combined Ocean Optics STS units with a range of 190-1100 nm). A spectrometer provides the gold standard for improving predictive models and improving future entry vehicle designs.

For NASA missions through CO2 atmospheres (Venus and Mars), a majority of the radiative heating occurs in the Midwave Infrared range (MWIR: 1500 nm - 6000 nm) [Brandis]. Similarly, for entries to Earth, the radiation is dominated by the Vacuum Ultraviolet (VUV) range (VUV: 100 - 190 nm) [Cruden]. Both of these ranges are outside of those detectable by available miniaturized spectrometers. While laboratory-scale spectrometers and detectors are available to measure these spectral ranges, there are no versions of these spectrometers which would be suitable for integration into a flight vehicle due to lack of miniaturization. This SBIR calls for miniaturization of VUV and Mid-Wave Infrared (MWIR) spectrometers to extend the current state of the art for flight diagnostics.

Advancements in either VUV or MWIR measurements are sought, preferably for sensors with:

- Self-contained with a maximum dimension of ~10 cm or less,
- No active liquid cooling,
- Simple interfaces compatible with spacecraft electronics, such as RS232, RS422, or Spacewire,
- Survival to military spec temperature ranges [-55 to 125C],
- Power usage of order 5W or less.

3) NOVEL SENSING TECHNOLOGIES FOR EDL GN&C AND SMALL BODY PROXIMITY OPERATIONS

NASA seeks innovative sensor technologies to enhance success for EDL operations on missions to other planetary bodies (including Earth's Moon, Mars, Venus, Titan, and Europa). Sensor technologies are also desired to enhance proximity operations (including sampling and landing) on small bodies such as asteroids and comets.

Sensing technologies are desired that determine any number of the following:

- Terrain relative translational state (altimetry/3-axis velocimetry).
- Spacecraft absolute state in planetary/small-body frame (either attitude, translation, or both).
- Terrain characterization (e.g., 3D point cloud) for hazard detection, absolute and/or relative state estimation, landing/sampling site selection, and/or body shape characterization.
- Wind-relative vehicle state and environment during atmospheric entry (e.g., velocity, density, surface pressure, temperature).

Successful candidate sensor technologies can address this call by:

- Extending the dynamic range over which such measurements are collected (e.g., providing a single surface topology sensor that works over a large altitude range such as 1m to >10km, and high attitude rates such as greater than 45° /sec).
- Improving the state-of-the-art in measurement accuracy/precision/resolution for the above sensor needs.
  * Substantially reducing the amount of external processing needed by the host vehicle to calculate the measurements.
- Significantly reducing the impact of incorporating such sensors on the spacecraft in terms of Size, Weight, and Power (SWaP), spacecraft accommodation complexity, and/or cost.
- Providing sensors that are robust to environmental dust/sand/illumination effects.
- Mitigation technologies for dust/particle contamination of optical surfaces such as sensor optics, with possible extensibility to solar panels and thermal surfaces for Lunar, asteroid, and comet missions.
- Sensing for wind-relative vehicle velocity, local atmospheric density, and vehicle aerodynamics (e.g. surface pressures and temperatures).

NASA is also looking for high-fidelity real-time simulation and stimulation of passive and active optical sensors for computer vision at update rates greater than 2 Hz to be used for signal injection in terrestrial spacecraft system test beds. These solutions are to be focused on improving system-level performance Verification and Validation during spacecraft assembly and test.

References

Brandis, A., Cruden, B., White, T., Saunders, D., and Johnston, C. Radiative Heating on the After-Body of Martian Entry Vehicles, AIAA 2015-3111, 45th AIAA Thermophysics Conference, Dallas, TX, 22-26 June 2015.

Cruden, B., Martinez, R., Grinstead, J., and Olejniczak, J. Simultaneous Vacuum-Ultraviolet Through Near-IR Absolute Radiation Measurement with Spatiotemporal Resolution in An Electric Arc Shock Tube, AIAA 2009-4240, 41st AIAA Thermophysics Conference, San Antonio, TX, 22-25 June 2009.

Johnston, C. and Brandis, A. Features of Afterbody Radiative Heating for Earth Entry, Journal of Spacecraft and Rockets, Vol. 52, Issue 1, 15 December 2014.

Expected TRL or TRL range at completion of the project: 3 to 5

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Software, Research

Desired Deliverables Description

Depending on the type of technology submissions, hardware demonstrations of sensors or applicable support hardware (e.g. EDL sensors), or software simulations/analysis of simulated environments (simulation environments for passive and active optical sensors) are acceptable.

State of the Art and Critical Gaps

Active and passive GN&C EDL sensor technologies have been in development over the past decade. Infusion of these capabilities into spaceflight missions requires additional technology advancements to enhance operational performance and dynamic envelop, reduce size, mass, and power, and to address the process of space qualification.

The EDL community has a need to understand the specific contributors to aftbody radiation (especially in CO2 and air); a spectrometer is the next logical step beyond the current state-of-the-art radiometers for EFT-1 and MEDLI2. NASA now requires instrumentation on SMD competed missions involving EDL, and these cost- and mass-constrained missions cannot use the SOA instrumentation. The specific need is for miniaturized spectrometers for in-situ measurements with sensitivity in the VUV or MWIR regions where NASA predicts significant radiation for Earth, Venus, and Mars entries. VUV spectrometers require window operation under vacuum conditions with UV-grade windows for detection of the vacuum ultraviolet. The window materials become increasingly exotic as lower wavelengths are sought. The dispersion of wavelength becomes reduced as spectrometers shrink, which may become an issue for closely spaced features at lower wavelength. Extending the range of miniaturized spectrometers into the MWIR may be limited by the need for extensive cooling and as long wavelengths approach the diffraction limit.

Relevance / Science Traceability

EDL instrumentation directly informs and addresses the large performance uncertainties that drive the design, validation and in-flight performance of planetary entry systems. Improved understanding of entry environments and TPS performance could lead to reduced design margins enabling a greater payload mass-fraction and smaller landing ellipses. Improved real-time measurement knowledge during entry could also minimize the landing dispersions for placing advanced payloads onto the surface of atmospheric and airless bodies.

NASA Science missions are frequently proposed, that include high-speed Earth return (New Frontiers, Discovery, and Mars Sample Return) and Venus and Mars entry. Capsules used for these missions must withstand both convective and radiative aeroheating, and NASA now requires EDL instrumentation for these missions. Current radiative measurement techniques (radiometers) provide only an integrated heating over limited wavelength range; past interpretation of such flight data [Johnston] show the need for spectrally resolved measurements from spectrometers. For Earth and Venus, the radiative component may be the dominant source of heating, and emission comes from the VUV, that NASA currently has no capability to measure. For Mars and Venus, the aftbody radiation is dominated by MWIR. Again, NASA does not have a method to measure MWIR radiation in flight; the current radiometers integrate across several band systems. Miniaturized spectrometers that can measure in VUV and MWIR would have immediate application to SMD planetary missions. Such spectrometers may also inform what ablation species are emitted from the heatshield and backshell during entry.

Z7.03: Deployable Aerodynamic Decelerator Technology (SBIR)

Lead Center: LaRC

Participating Center(s): ARC

Technology Area: 9.0.0 Entry, Descent and Landing Systems

Related Subtopic Pointer(s): Z8.06 Z7.06 H5.02 Z7.04 Z7.01 Z2.01 A1.10 Z7.05

Scope Title

Deployable Aerodynamic Decelerator Technology

Scope Description

Background: NASA is advancing deployable aerodynamic decelerators to enhance and enable robotic and human space missions. Applications include Mars, Venus, Titan, as well as payload return to Earth from Low Earth Orbit. The benefit of deployable decelerators is that the entry vehicle structure and thermal protection system is not constrained by the launch vehicle shroud. It has the flexibility to more efficiently use the available shroud volume, and can be packed into a much smaller volume for Earth departure, addressing potential constraints for payloads sharing a launch vehicle. For Mars, this technology enables delivery of very large (20 metric tons or more) usable payload, which may be needed to support human exploration. The technology also allows for reduced cost access to space by enabling the recovery of launch vehicle assets. This subtopic area solicits innovative technology solutions applicable to deployable entry concepts. Specific technology development areas include:

1) Advancements in textile manufacturing technologies that can be used to simplify production, reduce the mass, or reduce the stowed volume of mechanically deployed structures, inflatable structures, or their flexible thermal protection system. Thermal protection concepts can also lead to improvements in thermal management efficiency of radiant and conductive heat transport at elevated temperatures (exceeding 1200 C). Concepts can be either passive or active dissipation approaches. For smaller scale inflatable systems, less than 1.5 meters in diameter, thin-ply or thin-film manufacturing approaches that can be used to reduce the minimum design gauge are of particular interest for inflatable structures. Focus of Phase 1 development can be subscale manufacturing demonstrations that demonstrate proof of concept and lead to Phase 2 manufacturing scale-up for applications related to Mars entry, Earth return, launch asset recovery, or the emergent small satellite community.

2) Concepts designed to augment the drag or provide guidance control for any class of entry vehicle. Concepts can be either deployable or rigid design systems that are suitable to deployable vehicle designs, including methods that modulate vehicle symmetry or adjust lift for active flight control to improve landing accuracy. Designs that decrease the ballistic coefficient by a factor of two to three times are to be considered. Of particular interest are concepts that can be used to modulate the lift or drag of a vehicle for enhanced control. Phase I proof of concept and preliminary design efforts that will lead to, or can be integrated into, flight demonstration prototypes in a Phase 2 effort are of interest.

3) High temperature capable structural elements to support mechanically deployable decelerators that surpass the performance capability of metallic ribs, joints, and struts. Anticipated systems would include composite elements or hybrid approaches that combine metallic structures with high temperature capable interface materials to improve thermal performance. Phase 1 development can be subscale component demonstrations that lead to Phase 2 scale-up and testing in relevant environments.

References

Hughes, S. J., et al, “Hypersonic Inflatable Aerodynamic Decelerator (HIAD) Technology Development Overview,” AIAA Paper 2011-2524

Bose, D. M, et al, “The Hypersonic Inflatable Aerodynamic Decelerator (HIAD) Mission Applications Study,” AIAA Paper 2013-1389

Hollis, B. R., “Boundary-Layer Transition and Surface Heating Measurements on a Hypersonic Inflatable Aerodynamic Decelerator with Simulated Flexible TPS,” AIAA Paper 2017-3122

Cassell, A., et al, “ADEPT, A Mechanically Deployable Re-Entry Vehicle System, Enabling Interplanetary CubeSat and Small Satellite Missions,” SSC18-XII-08, 32nd Annual AIAA/USU Conference on Small Satellites

Expected TRL or TRL range at completion of the project: 1 to 4

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Software, Research

Desired Deliverables Description

Subscale manufacturing demonstration articles for Phase I that can lead to Phase II manufacturing scale up.

State of the Art and Critical Gaps

The current state of the art for deployable aerodynamic decelerators is limited due to novelty of this technology. Developing more efficient, lighter, and thinner flexible thermal protection system component materials with higher temperature capability could potentially enable more efficient designs and extend the maximum range of use of the concepts. Development of efficient guidance control and drag enhancements concepts for deployable vehicles is enabling technology. Novel and innovative high temperature structural concepts are needed for the mechanically deployed decelerator.

Relevance / Science Traceability

NASA needs advanced deployable aerodynamic decelerators to enhance and enable robotic and human space missions. Applications include Mars, Venus, Titan, as well as payload return to Earth from Low Earth Orbit. HEOMD (Human Exploration and Operations Mission Directorate), STMD (Space Technology Mission Directorate), and SMD (Science Mission Directorate) can benefit from this technology for various exploration missions.

Z7.04: Lander Systems Technologies (SBIR)

Lead Center: MSFC

Participating Center(s): GRC, LaRC

Technology Area: 9.0.0 Entry, Descent and Landing Systems

Related Subtopic Pointer(s): Z13.02 Z7.03 Z7.01 Z8.06 Z2.01 H5.01 Z13.01

Scope Description

Plume/Surface Interaction Analysis & Ground Testing

As NASA and commercial entities prepare to land robotic and crewed vehicles on the Moon, and eventually Mars, characterization of landing environments is critical to identifying requirements for landing systems and engine configurations, instrument placement and protection, and landing stability. The ability to model and predict the extent to which regolith is transported in the vicinity of the lander is also critical to understanding the effects on precision landing sensor requirements and landed assets located in close proximity. Knowledge of the characteristics, behavior, and trajectories of ejected particles and surface erosion during the landing phase is important for designing descent sensor systems that will be effective. Furthermore, although the physics of the atmosphere, gravitational field, and the characteristics of the regolith are different for the Moon, the tools and analysis capability to characterize plume/surface interactions on the Moon will feed forward to Mars.

Therefore, NASA is seeking support in the following areas:

1. ***To increase analysis capability to model and predict the plume/surface interaction and nature and behavior of the ejecta, for NASA and commercial landing.*** Currently, there are negligible amounts of

data collected from planetary robotic landings to develop and validate plume/surface interaction analysis tools. However, the limited data increase the understanding of various parameters, including the various types of surfaces that lead to different cratering effects and plume behaviors. Additionally, the information influences lander design and operations decisions for future missions. Ground testing ("unit tests") is also used to provide data for tool validation. Innovative non-intrusive diagnostic development to measure critical parameters in this discipline are also severely lacking and are needed to advance prediction capability. The current post-landing analysis of planetary landers (on Mars) is of limited applicability in reducing risk to future landers, as it is limited to comparisons with only partially empirically-validated tools. Flight test data do not yet exist in the environments of interest.

2. ***The community needs ground test and flight test data, together with comprehensive Computational Fluid Dynamics (CFD) tools and methods, to devise validated models for different conditions that are applicable to a variety of landing missions.*** A consistent tool set is important for assessing risk and is useful to both the commercial sector and NASA.
3. ***Solutions are sought to alleviate the plume-surface interaction environment.*** Solutions should provide novel approaches for propulsion cluster placements, surface ejecta damage tolerant systems, mitigation shielding, etc. These solutions must be mass-efficient and have minimal interference with vehicle operations.
4. ***Validation data and diagnostic techniques at relevant scales, environments, and degrees of system integration*** are sought to reduce uncertainties in predicted plume-induced environments and subsequently reduce risk to landers and other surface assets. Critical parameters include near-field and far-field particle velocity, trajectories and concentration, erosion rates and transient crater profiles. There are large uncertainties associated with these parameters. Plume-induced environments include cratering, ejecta, aerodynamic destabilization, and elevated convective heating.

Mission needs to consider, in proposing these solutions, include landers with single and multiple engines, both pulsed and throttled systems, landed masses from 400 to 40,000 kg, and both Lunar and Mars destinations.

<u>Innovations for Vehicle Structures</u>

The development of more efficient lander structures and components are sought to improve the mass efficiency of in-space stages and landers. This may include the adoption and utilization of advanced lightweight materials, especially as used in combination with advanced manufacturing to enable reliable, conformal, and lightweight design innovations. Of interest are systems for actively alleviating flight loads and environments, reduce integration complexity, or improve system life, enable reusable landing systems, allow restowage and redeployment of solar arrays for multiple mission usage, and develop mechanisms and couplings for continuous use in the lunar dust environment. Approaches for achieving multifunctional components, repurposing structure for post-flight mission needs, and incorporating design features that reduce operating complexity are also of interest.

<u>Lunar Dust Mitigation</u>

Lunar dust, as experienced during the Apollo program, can have a wide range of deleterious effects on lander subsystems and the people using them. As we head back to the moon with robotic and human landers, the need for effective prevention and/or mitigation measures is needed to ensure long term, nominal operation of lander and surface systems and mission operations. Numerous studies have been performed to characterize dust deposition and potential impacts. Proposals are sought that build on previous studies to better characterize the deposition and impact of dust (see Z13.02 - Dust Tolerant Mechanisms).

NASA has plans to purchase services for delivery of payloads to the Moon through the Commercial Lunar Payload Services (CLPS) contract. Under this subtopic, proposals may include efforts to develop payloads for flight demonstration of relevant technologies in the lunar environment. The CLPS payload accommodations will vary depending on the particular service provider and mission characteristics. Additional information on the CLPS program and providers can be found at this link: https://www.nasa.gov/content/commercial-lunar-payload-services. CLPS missions will typically carry multiple payloads for multiple customers. Smaller, simpler, and more self-sufficient payloads are more easily accommodated and would be more likely to be considered for a NASA-sponsored flight opportunity. Commercial payload delivery services may begin as early as 2020 and flight opportunities are expected to continue well into the future. In future years it is expected that larger and more complex payloads will be accommodated. Selection for award under this solicitation will not guarantee selection for a lunar flight opportunity.

References

Lander Technologies: https://www.nasa.gov/content/lander-technologies

Metzger, Philip, et al. "ISRU implications for lunar and martian plume effects." 47th AIAA Aerospace Sciences Meeting including The New Horizons Forum and Aerospace Exposition. 2009.

Plemmons, D. H., Mehta, M., Clark, B. C., Kounaves, S. P., Peach, L. L., Renno, N. O., ... & Young, S. M. M. (2008). Effects of the Phoenix Lander descent thruster plume on the Martian surface. Journal of Geophysical Research: Planets, 113(E3).

Mehta, M., Sengupta, A., Renno, N. O., Norman, J. W. V., Huseman, P. G., Gulick, D. S., & Pokora, M. (2013). Thruster plume surface interactions: Applications for spacecraft landings on planetary bodies. AIAA journal, 51(12), 2800-2818.

Vangen, Scott, et al. "International Space Exploration Coordination Group Assessment of Technology Gaps for Dust Mitigation for the Global Exploration Roadmap." AIAA SPACE 2016. 2016. 5423.

Expected TRL or TRL range at completion of the project: 3 to 6

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Software, Research

Desired Deliverables Description

Deliverables of all types can be infused into the prospect missions due to early design maturity.

State of the Art and Critical Gaps

The characteristics and behavior of airborne particles during descent is important for designing descent sensor systems that will be effective. Furthermore, although the physics of the atmosphere and the characteristics of the regolith are different for the Moon, the capability to model plume/surface interactions on the Moon will feed forward to Mars, where it is critical for human exploration.

Currently, flight data are collected from early planetary landing, and those data are fed into developmental tools, for validation purposes. The validation data set, as well as the expertise, grows as a result of each mission, and is shared across and applied to all other missions. We gain an understanding of how various parameters, including different types of surfaces, lead to different cratering effects and plume behaviors. The information helps NASA and industry make lander design and operations decisions. Ground testing (“unit tests”) is used early in the development of the capability, to provide data for tool validation.

The current post-landing analysis of planetary landers (on Mars) is performed in a cursory manner with only partially empirically-validated tools, because there has been no dedicated fundamental research investment in this area. Flight test data does not exist, in the environments of interest.

Relevance / Science Traceability

Current and future lander architectures such as:

- Artemis

- Commercial robotic lunar landers
- Planetary mission landers

Z7.05: 3D Weaving Diagnostics (SBIR)

Lead Center: ARC

Participating Center(s):

Technology Area: 9.0.0 Entry, Descent and Landing Systems

Related Subtopic Pointer(s): T12.01 T12.05 Z7.03

Scope Title

3D Weaving Diagnostics for Validation of Uniform Weaving Processes

Scope Description

NASA is utilizing 3D woven materials to develop Woven Thermal Protection Systems (W-TPS). Examples of recent 3D woven Thermal Protection Systems (TPS) projects include: 3D Multifunctional Ablative TPS (3D-MAT) for compression pads on Orion, Adaptive Deployable Entry Placement Technology (ADEPT) looking at a mechanically deployable aeroshell (similar to an umbrella) that utilizes 3D woven carbon fabric between the ribs, and Heatshield for Extreme Entry Environment Technology (HEEET), containing dual-layer 3D weaves to provide mass efficient TPS solutions for extreme entry environment missions such as to Venus, Saturn and the outer planets. The specialized equipment used to weave 3D woven preforms is based on standard textile equipment that is substantially modified to allow hundreds of layers to be interwoven together. As these complex woven structures are scaled up, it is critical to understand the dynamics of the 3D weaving equipment/hardware and how interactions between different components affect the unit cell of the woven structure and ultimately the material properties.

This subtopic area solicits innovative technology solutions applicable to 3-D woven materials. Specific technology development areas include:

1. Advancements in the understanding of the impact of weaving parameters on the properties of the final weave itself. Looking at developing methods to associate measured weave diagnostics (such as warp tension and beat up force) to understand the effects of woven material parameters (such as fiber volume fraction and yarn crimp), to develop tools to predict the impacts of changes in weaving parameters on final material properties (such as stiffness and strength).
2. Understand what damage may be introduced into the yarns during the weaving operation and the impact of that damage on material performance (such as strength). Objective is to further improve the understanding of how/if key aspects/parameters in the weaving operation (warp tension, beat up force, warp or fill yarns per inch) lead to damage of the yarns and develop methods to reduce weaving damage and/or guidelines to reduce the level of damage induced in the yarns.

References

More info for 3D-MAT, ADEPT, HEEET can be found at: https://gameon.nasa.gov/publications/

Expected TRL or TRL range at completion of the project: 3 to 6

Desired Deliverables of Phase II

Prototype, Analysis

Desired Deliverables Description

Phase I: Assessment study of potential diagnostic techniques
Phase II: Prototype instrument demonstration on a weaving machine demonstrating increased control capability

State of the Art and Critical Gaps

NASA is investing in woven thermal protection systems, both rigid and mechanically deployable, which both come from a 3D weave. The mechanical/structural properties of these weaves are a strong function of nuances in the resultant weave microstructure; nuances such as fiber volume fraction and the level of crimp in warp versus weft direction or damage induced in the yarns during weaving. An enhanced understanding of the effects of the weaving operation parameters on the final weave itself would better enable scale-up of weaving processes (thickness and width) and tailoring of weaves to meet specific mission needs (how does a change in warp tension to reduce fiber volume fraction manifest itself in changes to crimp or other parameters). There is also value in understanding if/where the weaving operation induces damage into the yarn and its impact on material properties. The current state of the art is very empirical for understanding the effects of weaving parameters on material performance/damage. For example, it is recognized that increasing crimp can decrease stiffness in a material, but there are not good tools to predict the impacts of changes in weave parameters (such as warp tension) are on the crimp level in a weave and how that will impact the properties of the final material. This makes it difficult to predict the impacts of changes in weave on properties and understand how sensitive the relationships are. The end result is that this lack of knowledge limits the flexibility end users have, and requires substantial amounts of testing to understand if a given change is important or not.

Relevance / Science Traceability

Several potential future missions, outlined in decadal surveys, crewed exploration mission studies, and other supporting analyses, have Entry and Descent (ED)/ Entry, Descent and Landing (EDL) architectures: Mars sample return, high speed crewed return, high mass Mars landers, Venus and gas/ice giant probes. With few exceptions, entry vehicle TPS (Thermal Protection System) for these missions will be composed of materials currently under development and without certification heritage.

NASA planetary exploration programs supporting ED/EDL missions are the intended beneficiaries of this subtopic.

Z7.06: Diagnostic tools for high enthalpy and high temperature materials testing and analysis (SBIR)

Lead Center: ARC

Participating Center(s): LaRC

Technology Area: 9.0.0 Entry, Descent and Landing Systems

Related Subtopic Pointer(s): S4.04 H5.02 Z7.03 A1.08

Scope Title
Optical imaging diagnostics for validation of conventional instrumentation and simulation used to characterize high enthalpy, arc-heated ground test facilities

Scope Description

Advances and new technologies are sought for optical-spectroscopic imaging techniques for NASA's high enthalpy aeroheating test facilities, specifically the Ames Research Center's Arc Jet Complex and Langley Research Center's Hypersonic Materials Environmental Test System (HyMETS). These facilities are used for evaluation of entry system thermal protection materials and structures. Experimental methods for arc jet facility characterization strive to quantify thermodynamic and gas dynamic properties of arc jet flows and serve multiple purposes, such as verification of test conditions (facility operations), validation of arc heater and flow field simulations, and measurement of incident/boundary conditions for material response simulations.

Foremost among these methods are instrumented stream probes and shaped test articles. They are routinely used to measure local heat flux and surface pressure and are tightly integrated with facility operations. Concerns over systematic errors in heat flux measurements have, to date, not been adequately addressed due to a lack of relevant data for validation of the underlying metrology principle – namely the interpreted response of a heat flux sensor to a nominally stable, but unsteady and highly dissociated, gas stream. Development of specialized diagnostic tools which can acquire these validation data, in situ, is the goal of this subtopic scope.

References

Entry Systems Modeling Project: https://gameon.nasa.gov/projects/entry-systems-modeling-esm/

1. G. Palmer, et al., "The Effect of Copper Calorimeter Surface Catalycity on the Predicted Recession of TPS Materials", AIAA 2018-0496
2. O. Chazot, "Experimental Studies on Hypersonic Stagnation Point Chemical Environment", RTO-EN-AVT-142, Experiment, Modeling and Simulation of Gas-Surface Interactions for Reactive Flows in Hypersonic Flights, pp. 13-1 – 13-32
3. A. Nawaz, et al., "Surface Catalysis and Oxidation on Stagnation Point Heat Flux Measurements in High Enthalpy Arc Jets", AIAA 2013-3138
4. A. Gülhan, "Heat Flux Measurements in High Enthalpy Flows", RTO EN-8, Measurement Techniques for High Enthalpy and Plasma Flows, April 2000
5. J. Grinstead, et al., "Consolidated laser-induced fluorescence diagnostic systems for the NASA Ames arc jet facilities", AIAA 2016-4159
6. J.A. Inman, et al., "Nitric Oxide PLIF Measurements in the Hypersonic Materials Environmental Test System (HYMETS)", AIAA Journal Vol. 51, No. 10, pp 2365-2379, October 2013

Expected TRL or TRL range at completion of the project: 3 to 6

Desired Deliverables of Phase II

Prototype, Hardware

Desired Deliverables Description

Phase I: Assessment study of potential diagnostic techniques
Phase II: Prototype instrument demonstration in relevant environment with hardware delivery to NASA

State of the Art and Critical Gaps

Heat flux is undoubtedly the most critical measurement of every arc jet test program as it is used for facility operations, flow field simulation validation, and materials response analyses. Diminished – or unwarranted – confidence in conventional heat flux gauge measurements influences uncertainty in test results and ultimately adds risk to TPS (Thermal Protection System) qualification programs.

In highly dissociated arc jet flows, convective, catalytic, and radiative heat fluxes simultaneously contribute to a heat flux gauge's response. However, response interpretation may not properly account for the microscopic thermodynamic and spatiotemporal characteristics of the incident stream and gas-surface interactions that ultimately govern the response. Potential sources of error and bias are incident flow property unsteadiness and catalytic efficiency uncertainties.

Perturbations and instabilities within the arc heater can persist through nonequilibrium expansion within the nozzle and into the test chamber, possibly resulting in fluctuating flow properties, gradients, and atom fluxes at article surfaces. As flow property gradients are the driving potentials for catalysis, property fluctuations could influence the magnitude of catalytic heat flux. Departures from modeled interpretation cannot be discerned without direct observation, potentially resulting in unknown error and bias in heat flux measurements.

Also contributing to error and bias is the uncertainty in the sensor’s catalytic efficiency. A reduction or augmentation from an assumed value creates an undetectable bias in heat flux measurements with consequences that may not be conservative. Coupled with the potential influence of property gradient fluctuations on catalysis, the modeling assumptions of heat transfer to catalytic surfaces in dissociated flows cannot be validated without additional, independent data sources.

Time-resolved gas property measurement along the stagnation streamline would enable evaluation of the key assumptions of NASA’s heat flux measurement approach. Quantities of particular interest are atomic and molecular species concentrations and temperature. The profiles and statistical variations could verify the conformance to, or reveal the departure from, the modeled theories. The ultimate benefit will be greater confidence in NASA’s use of heat flux gauges.

The above requirements strongly indicate the use of kHz rate, species-selective, ultrafast pulsed laser spectroscopic imaging techniques to advance the state-of-the art. NASA’s current nanosecond laser-induced fluorescence capabilities are inadequate due to insufficient sensitivity for quantitative planar imaging in the highly luminous shock layer ahead of a test model.

Relevance / Science Traceability

Several potential future missions, outlined in decadal surveys, crewed exploration mission studies, and other supporting analyses, have Entry and Descent (ED)/ Entry, Descent and Landing (EDL) architectures: Mars sample return, high speed crewed return, high mass Mars landers, Venus and gas/ice giant probes. With few exceptions, entry vehicle TPS for these missions will be composed of materials currently under development and without certification heritage. Arc jet testing at conditions relevant for certification will invariably be required for each of these proposed missions. Ground testing at more extreme environments for future missions will challenge existing capabilities. There is a compelling need now to bring research-level diagnostic technologies forward to ensure that facility operations can credibly demonstrate required performance to TPS technology projects.

Conventional instrumentation will continue to be the primary source of facility characterization data. The purposes of the advanced techniques are to provide validating evidence for the conventional instrumentation, reveal error and bias in interpretation of heat flux measurements, and ultimately reduce uncertainty in facility performance data provided to test programs.

NASA planetary exploration programs supporting ED/EDL missions are the intended beneficiaries of this subtopic. The first-line project is STMD’s (Space Technology Mission Directorate) Entry Systems Modeling Project.

Scope Title

Advanced instrumentation for NASA's shock tube and ballistic range facilities

Scope Description

NASA is seeking innovative imaging and spectroscopic measurement techniques for NASA’s two specialized-use impulse facilities: the Electric Arc Shock Tube (EAST) and the Hypervelocity Free Flight Aerodynamic Facility (HFFAF). The EAST facility replicates shocked gas environments encountered by entry vehicles transiting planetary atmospheres at hypersonic velocities. Spectroscopic instrumentation is used to characterize the absolute radiance and gas kinetics behind a traveling shock wave. The HFFAF is used for the study of dynamically similar supersonic and hypersonic aerodynamics, transition to turbulence, and laminar and turbulent convective heat transfer. Optical imaging instrumentation is used to characterize aerodynamic forces and moments of scaled models launched through the range. Thermographic and spectral imaging instrumentation is used to characterize spatially resolved heating rates to scaled models.

New electro-optic products and methods enable measurement of quantities beyond current capabilities and improve current practices.

References

Entry Systems Modeling Project: https://gameon.nasa.gov/projects/entry-systems-modeling-esm/

ADEPT Project: https://gcd.larc.nasa.gov/projects-2/deployable-aeroshell-concepts-and-flexible-tps/

Many journal papers, conference proceedings, and technical reports describing the NASA Ames EAST and HFFAF test facilities and research are available in the open literature.

Expected TRL or TRL range at completion of the project: 3 to 6

Desired Deliverables of Phase II

Prototype, Hardware

Desired Deliverables Description

Phase I: Assessment study of potential diagnostic techniques or technology upgrades
Phase II: Prototype instrument demonstration in relevant environment (preferably w/hardware delivery to NASA)

State of the Art and Critical Gaps

The EAST facility's instrumentation acquires data for shocked gas phenomenology and facility performance characterization. Measurements of radiance, absorbance, electron density, and temperature are used for validation of comprehensive radiation transport simulations of planetary atmospheres. Those measurements are primarily acquired using calibrated optical-spectroscopic instruments with sufficient temporal and/or spatial resolution to correlate observed magnitudes with localized, spectrally resolved absolute radiant fluxes or columnar property densities (including electron densities). Ancillary instrumentation is used to measure shock arrival times and transient pressures at the tube wall to establish shock speeds adjacent to the science instruments.

Measurement techniques that correlate observables to atomic and molecular state populations and radiance magnitudes enable validation of radiance models. Emission spectroscopy techniques, which capture the transient characteristics of excited atomic and molecular state populations, have reached a high degree of maturity and efficacy.

However, post-shock electron and ground or other dark state population dynamics also influence shock radiance. Measurement of these states rely on more complicated absorption, induced fluorescence, or scattering (spontaneous and coherent) techniques. The lack of light sources and/or detectors with suitable spectral and temporal characteristics or the challenges of implementation in impulse facilities have limited opportunities for such measurements. Techniques that enable measurement of these states would greatly expand opportunities for radiation transport model validation, particularly for conditions in which self-absorption would influence emission spectroscopy measurements.

For the HFFAF, shadowgraph and schlieren photography are used to provide time-resolved imagery for aerodynamic force and moment analyses of scaled flight vehicles in free flight. A high-speed shutter (40 ns duration) and a spark-gap light source enable images to be captured without motion blur. The shuttering system relies on Kerr cells filled with benzonitrile and a 35 kV pulse shaping and switching network. Advances are sought for the eventual replacement of the 32 heritage light source/shutter systems with components that offer equal or greater performance as well as improved safety and reliability.

Relevance / Science Traceability

Several potential future missions, outlined in decadal surveys, crewed exploration mission studies, and other supporting analyses, have ED/EDL architectures: Mars sample return, high speed crewed return, high mass Mars landers, Venus and gas/ice giant probes. Entry vehicles to these destinations will encounter radiative heating to varying degrees. Radiative heating of a vehicle's back shell has been recognized as a significant concern, so ensuring a full range of diagnostic techniques for expanding flows has become a high priority for the EDL (Entry, Descent, and Landing) community.

Characterizing the aerodynamic stability of emerging deployable drag devices for entry vehicles is also of high importance for future high-mass lander missions. The HFFAF will be a key ground test facility for acquiring crucial free-flight aerodynamic data for study and simulation validation.

NASA planetary exploration programs supporting ED/EDL missions are the intended beneficiaries of this subtopic. Technology development projects supporting these programs are potential beneficiaries of new instrumentation for the EAST and HFFAF.

Focus Area 13: Information Technologies for Science Data

Lead MD: SMD

Participating MD(s): None

NASA Missions and Programs create a wealth of science data and information that are essential to understanding our earth, our solar system and the universe. Advancements in information technology will allow many people within and beyond the Agency to more effectively analyze and apply these data and information to create knowledge. For example, modeling and simulation are being used more pervasively throughout NASA, for both engineering and science pursuits, than ever before. These tools allow high fidelity simulations of systems in environments that are difficult or impossible to create on Earth, allow removal of humans from experiments in dangerous situations, provide visualizations of datasets that are extremely large and complicated, and aid in the design of systems and missions. In many of these situations, assimilation of real data into a highly sophisticated physics model is needed. Information technology is also being used to allow better access to science data, more effective and robust tools for analyzing and manipulating data, and better methods for collaboration between scientists or other interested parties. The desired end result is to see that NASA data and science information are used to generate the maximum possible impact to the nation: to advance scientific knowledge and technological capabilities, to inspire and motivate the nation's students and teachers, and to engage and educate the public.

S5.01: Technologies for Large-Scale Numerical Simulation (SBIR)

Lead Center: ARC

Participating Center(s): GSFC

Technology Area: 11.0.0 Modeling, Simulation, Information Technology and Processing

Related Subtopic Pointer(s): A1.05 S5.03 S5.06

Scope Title
Exascale Computing

Scope Description

NASA scientists and engineers are increasingly turning to large-scale numerical simulation on supercomputers to advance understanding of complex Earth and astrophysical systems, and to conduct high-fidelity aerospace engineering analyses. The goal of this subtopic is to increase the mission impact of NASA's investments in supercomputing systems and associated operations and services. Specific objectives are to:

- Decrease the barriers to entry for prospective supercomputing users
- Minimize the supercomputer user's total time-to-solution (e.g., time to discover, understand, predict, or design)
- Increase the achievable scale and complexity of computational analysis, data ingest, and data communications
- Reduce the cost of providing a given level of supercomputing performance for NASA applications
- Enhance the efficiency and effectiveness of NASA's supercomputing operations and services

The approach of this subtopic is to seek novel software and hardware technologies that provide notable benefits to NASA's supercomputing users and facilities, and to infuse these technologies into NASA supercomputing operations. Successful technology development efforts under this subtopic would be considered for follow-on funding by, and infusion into, NASA's High-End Computing (HEC) projects - the High End Computing Capability project at Ames and the Scientific Computing project at Goddard. To assure maximum relevance to NASA, funded SBIR contracts under this subtopic should engage in direct interactions with one or both HEC projects, and with key HEC users where appropriate. Research should be conducted to demonstrate technical feasibility and NASA relevance during Phase I and show a path toward a Phase II prototype demonstration.

Offerors should demonstrate awareness of the state-of-the-art of their proposed technology, and should leverage existing commercial capabilities and research efforts where appropriate. Open source software and open standards are strongly preferred. Note that the NASA supercomputing environment is characterized by:

- HEC systems operating behind a firewall to meet strict IT security requirements
- Communication-intensive applications
- Massive computations requiring high concurrency
- Complex computational workflows and immense datasets
- The need to support hundreds of complex application codes - many of which are frequently updated by the user/developer.

Projects need not benefit all NASA HEC users or application codes, but demonstrating applicability to an important NASA discipline, or even a key NASA application code, could provide significant value. For instance, a GPU accelerated (or multi-core) planetary accretion code such as LIPAD (Lagrangian Integrator for Planetary Accretion and Dynamics) could be one possible project.

The three main technology areas of S5.01 are aligned with three objectives of the National Strategic Computing Initiative (NSCI) announced by the White House in July 2015. The overarching goal of NSCI is to coordinate and accelerate U.S. activities in HEC, including hardware, software, and workforce development, so that the U.S. remains the world leader in HEC technology and application. NSCI charges every agency that is a significant user of HEC to make a significant contribution to this goal. This SBIR subtopic is an important part of NASA's contribution to NSCI. See https://www.nitrd.gov/nsci/index.aspx for more information about NSCI. The three main elements of S5.01 are:

- Many NASA science applications demand much faster supercomputers. This area seeks technologies to accelerate the development of an efficient and practical exascale computing system (10^{18} operations per second). Innovative file systems that leverage node memory and a new exascale operating system geared toward NASA applications are two possible technologies for this element. At the same time, this area calls for technology to support co-design (i.e., concurrent design) of NASA applications and exascale supercomputers, enabling application scaling to billion-fold parallelism while dramatically increasing memory access efficiency. This supports NSCI Objective 1. (Accelerating delivery of a capable exascale computing system that integrates hardware and software capability to deliver approximately 100 times the performance of current 10 petaflop systems across a range of applications representing government needs.)

- Data analytics is becoming a bigger part of the supercomputing workload, as computed and measured data expand dramatically, and the need grows to rapidly utilize and understand that data. This area calls for technologies that support convergence of computing systems optimized for modeling & simulation and those optimized for data analytics (e.g., data assimilation, data compression, image analysis, machine learning, visualization, and data mining). In situ data analytics that can run in-memory side-by-side with the model run is another possible technology for this element. This supports NSCI Objective 2. (Increasing coherence between the technology base used for modeling and simulation and that used for data analytic computing.)
- Presently it is difficult to integrate cyberinfrastructure elements (supercomputing system, data stores, distributed teams, instruments, mobile devices, etc.) into an efficient and productive science environment. This area seeks technologies to make elements of the supercomputing ecosystem much more accessible and composable, while maintaining security. This supports NSCI Objective 4. (Increasing the capacity and capability of an enduring national HPC ecosystem by employing a holistic approach that addresses relevant factors such as networking technology, workflow, downward scaling, foundational algorithms and software, accessibility, and workforce development.)

References:

Exascale Computing

https://www.nas.nasa.gov/hecc/about/hecc_project.html (NASA High-End Computing Capability Project)

https://www.nitrd.gov/nsci/index.aspx (The National Strategic Computing Initiative)

Expected TRL or TRL range at completion of the project: 5 to 7

Desired Deliverables of Phase II:
Prototype Software

Desired Deliverables:

Expected outcomes are to improve the productivity of NASA's supercomputing users, broaden NASA's supercomputing user base, accelerate advancement of NASA science and engineering, and benefit the supercomputing community through dissemination of operational best practices.

State of the Art and Critical Gaps:

The SOA and the critical gaps of the three technologies areas are: 1. NASA science requires at least 100X more powerful supercomputers and 1000X higher application parallelism in 10 years, at the same power. 2. Current technologies for high-fidelity computational simulations and data analytics are distinct, and interfacing them is inefficient. 3. It is difficult to integrate cyberinfrastructure elements (supercomputing, data stores, distributed teams, instruments, mobile devices, etc.).

Relevance/Science Traceability:

Virtually all high-end computing systems and applications can benefit from the deliverables of this subtopic. As the demand for high-end computing continue to grow, there is an increasing need for the solicited technologies in both the government and the industry.

S5.03: Accelerating NASA Science and Engineering through the Application of Artificial Intelligence (SBIR)

Lead Center: GSFC

Participating Center(s): ARC, JPL, LaRC

Technology Area: 11.0.0 Modeling, Simulation, Information Technology and Processing

Related Subtopic Pointer(s): T11.04 H9.03 H10.02 T4.04 H6.22 S5.04 S5.01 H9.07 Z2.02 S5.06 A3.02

Scope Title

Accelerating NASA Science and Engineering through the Application of Artificial Intelligence

Scope Description

NASA researchers are increasingly using Artificial Intelligence (AI) technologies across science and engineering to address questions that previously could not be studied, in order to open up new insights. While many problems can be addressed with AI, the adoption of these techniques and technologies has been slow due to the large learning curve associated with the application of these technologies, the applicability of commercial tools to specific problems of interest for NASA, and the high level of effort to create training sets. The goal of this subtopic is to overcome these challenges and accelerate NASA science and engineering through the development and/or application of tools and technologies that use AI, including Machine Learning (ML), Deep Learning (DL), and more. The expected outcomes of this subtopic are tools and technologies that use AI that lead to improved science and engineering, and that lead to advancements in operational capabilities for remote sensing instruments and platforms.

The specific objectives of this subtopic include the following. Innovative proposals using AI are being sought to solve these unique problems across NASA science. Proposals MUST be in alignment with existing and/or future NASA programs and address or extend a specific need or question for those programs. Examples of AI solutions to NASA problems include:

- Mission Operations with long latency communications in deep space environments where the models of the destinations are not well known. Examples of these missions include rovers/instruments on Mars2020 and the Europa Lander.
    - Advanced autonomy with the ability for instruments to learn at the edge
    - Fault detection and recovery
    - Anomaly detection for instruments or platforms
    - Onboard/embedded machine learning for remote sensing platforms
- Data fusion and predictions across multiple data sets using AI, examples include
    - Enhanced geoeffective space-weather predictions
    - Creation of a global product from the fusion of multiple satellite inputs for areas such as carbon science or aerosols
    - Downscaling lower-resolution images to higher resolutions, either from previous missions or through combination of multiple data sets and in-situ data
- Augmenting automatic image analysis, including registration, classification, segmentation, and/or change detection. Examples include
    - Identification of spatial patterns to better determine calibration factors across multiple instruments or for detecting instrument degradation
    - The detection of transient events in astronomical imagery

- The detection of burned areas from Earth imagery

Research proposed to this subtopic should demonstrate technical feasibility during Phase I, and in partnership with scientists and/or engineers, show a path toward a Phase II prototype demonstration, with significant communication with missions and programs to later plan a potential Phase III infusion. It is highly desirable that the proposed projects lead to solutions that will be infused into NASA programs and projects.

Tools and products developed under this subtopic may be developed for broad public dissemination or used within a narrow community. These tools can be plug-ins or enhancements to existing software, on-line data/computing services, or new stand-alone applications or web services, provided that they promote interoperability and use standard protocols, file formats, and Application Programming Interfaces (APIs).

References

Most Recent Decadal Surveys: https://science.nasa.gov/about-us/science-strategy/decadal-surveys

Mission to Europa - Europa Lander: https://www.jpl.nasa.gov/missions/europa-lander/

Mars 2020 Mission: https://mars.nasa.gov/mars2020/

Global Modeling and Assimilation Office: https://gmao.gsfc.nasa.gov/

NASA Goddard Institute for Space Studies: https://www.giss.nasa.gov/

NASA Earth Science Data: https://earthdata.nasa.gov/

NASA Center for Climate Simulation: https://www.nccs.nasa.gov/

NASA High-End Computing (HEC) Program: https://www.hec.nasa.gov/

Expected TRL or TRL range at completion of the project: 4 to 6

Desired Deliverables of Phase II

Prototype, Software, Research

Desired Deliverables Description

Tools and products developed under this subtopic may be developed for broad public dissemination or used within a narrow scientific community. These tools can be plug-ins or enhancements to existing software, on-line data/computing services, or new stand-alone applications or web services, provided that they promote interoperability and use standard protocols, file formats, and Application Programming Interfaces (APIs).

The desired outcomes for this subtopic include: (1) new or accelerated science and engineering products, (2) training data sets and trained models specifically for a given problem but that can also be used as a basis for furthering other science and engineering research and development, and (3) software algorithms and capabilities developed during the SBIR work would be used and infused in NASA science projects and potentially used to develop new missions.

State of the Art and Critical Gaps

NASA science and engineering have only just begun making use of Artificial Intelligence (AI) technologies (which includes both machine learning and deep learning). Emerging computational platforms now provide significant improvements in computing capabilities to enable AI to be applied to a wide variety of applications in science and engineering. These emerging computational capabilities have the potential to dramatically speed up AI calculations, and these systems are even being used as the reference architecture for Exascale high performance computing systems.

The current applications of AI across NASA science and engineering are just beginning, and the technologies are difficult to use with significant barriers to entry. This has dramatically slowed the adoption of AI across NASA.

Relevance / Science Traceability

Broad applicability across throughout the decadal surveys

Specific missions include the Europa Lander, Mars2020, and more:

- Global Modeling and Assimilation Office (GMAO) Assimilation - Augment Earth system modeling or data assimilation
- Carbon Cycle Ecosystems Office (CCOE) - Wide variety of applications given the diversity of data sets from sparse in-situ to global satellite measurements
- Earth Observing System Data and Information System (EOSDIS)/ Distributed Active Archive Centers (DAACs) - Harnessing the potential for new discoveries across the wide array of observation data
- Earth Science Technology Office (ESTO/AIST) - New technology and services to exploit NASA and non-NASA data
- Computational and Information Sciences and Technology Office (CISTO - Code 606) - Technologies used for new data science
- NASA Center for Climate Simulation (NCCS - Code 606.2) - Building applications toward exascale computing

S5.04: Integrated Science Mission Modeling (SBIR)

Lead Center: JPL

Participating Center(s): GSFC

Technology Area: 11.0.0 Modeling, Simulation, Information Technology and Processing

Related Subtopic Pointer(s): T11.04 S5.03 S5.05 T11.03

Scope Title
Innovative System Modeling Methods and Tools

Scope Description

NASA seeks innovative systems modeling methods and tools addressing the following needs:

- Define, design, develop, and execute future science missions by developing and utilizing advanced methods and tools that empower more comprehensive, broader, and deeper system and subsystem modeling, while enabling these models to be developed earlier in the lifecycle. Ideally, the proposed solutions should leverage MBSE (Model-Based Systems Engineering)/SysML (System Markup Language) approaches being piloted across NASA, allow for easier integration of disparate model types, and be compatible with current agile design processes.
- Enable disciplined system analysis for the design of future missions, including modeling of decision support for those missions and integrated models of technical and programmatic aspects of future missions.
- Evaluate technology alternatives and impacts, science valuation methods, and programmatic and/or architectural trades.

Specific areas of interest are listed below. Proposers are encouraged to address more than one of these areas with an approach that emphasizes integration with others on the list:

1. Conceptual phase models and tools that allow design teams to easily develop, populate, and visualize very broad, multidimensional trade spaces; methods for characterizing and selecting optimum

candidates from those trade spaces, particularly at the architectural level. There is specific interest in models and tools that facilitate comprehensive comparison of architectural variants of systems.

2. Capabilities for rapid generation models of function or behavior of complex systems, at either the system or the subsystem level. Such models should be capable of eliciting robust estimates of system performance given appropriate environments and activity timelines, and should be tailored:
    a. To support emerging usage of autonomy, both in mission operations and flight software as well as in growing usage of auto-coding.
    b. To operate within highly distributed, collaborative design environments, where models and/or infrastructure that support/encourage designers are geographically separated (including Open Innovation environments). This includes considerations associated with near-real-time (concurrent) collaboration processes and associated model integration and configuration management practices.
    c. To be capable of execution at variable levels of fidelity/uncertainty. Ideally, models should have the ability to quickly adjust fidelity to match the requirements of the simulation (e.g., from broad-and-shallow to in-depth and back again).
3. Target models (e.g., phenomenological or geophysical models) that represent planetary surfaces, interiors, atmospheres, etc., and associated tools and methods that allow for integration into system design/process models for simulation of instrument responses. These models may be algorithmic or numeric, but should be useful to designers wishing to optimize remote sensing systems for those planets.

Note that this topic area addresses a broad potential range of science mission-oriented modeling tools and methods. This includes the integration of these tools into broader model-based engineering frameworks, and also includes proposals with MBSE/SysML as the primary focus.

References

Large Ultraviolet Optical Infrared Surveyor (LUVOIR): https://asd.gsfc.nasa.gov/luvoir/

Origins Space Telescope (OST): https://asd.gsfc.nasa.gov/firs/

Habitable Exoplanet Observatory (HabEx): https://www.jpl.nasa.gov/habex/

Lynx: https://wwwastro.msfc.nasa.gov/lynx/

Laser Interferometer Space Antenna (LISA): https://lisa.gsfc.nasa.gov/

Wide Field Infrared Survey Telescope (WFIRST): https://www.nasa.gov/content/goddard/wfirst-wide-field-infrared-survey-telescope

Mars Exploration/Program & Missions: https://mars.nasa.gov/programmissions/

JPL Missions: https://www.jpl.nasa.gov/missions/

Expected TRL or TRL range at completion of the project: 3 to 5

Desired Deliverables of Phase II

Prototype, Software

Desired Deliverables Description

At the completion of Phase 2, NASA desires a working prototype suitable for demonstrations with "real" data to make a compelling case for NASA usage. Use and development of the model - including any and all work performed to verify and validate it - should be documented.

State of the Art and Critical Gaps

There currently are a variety of models, methods, and tools in use across the Agency and with our industry partners. These are often custom, phase-dependent, and poorly interfaced to other tools. The disparity between the creativity in the early phases and the detail-oriented focus in later phases has created phase transition boundaries, where missions not only change teams but tools and methods as well. We aim to improve this.

As NASA continues its move into greater use of models for formulation and development of NASA projects and programs, there are recurring challenges to address. This sub-topic focuses on encouraging solutions to these cross-cutting modeling challenges. These cross-cutting challenges include: greater modeling breadth (e.g., cost/schedule), depth (scalability), variable fidelity (precision/accuracy vs computation time), trade space exploration (how to evaluate large numbers of options), and processes that link them together. The focus is not on specific tools, but demonstrations of capability and methodologies for achieving the above.

The explosion of MBX (Model Based Everything) has led to a proliferation of models, modeling processes, and the integration/aggregation thereof. The model results are often combined with no clear understanding of the fidelity/credibility. While some NASA folks are looking for greater accuracy and "single source of truth," others are looking for the generation and exploration of massive trade spaces. Both greater precision and greater robustness will require addressing the cross-cutting challenges cited above.

Relevance / Science Traceability

Several concept/feasibility studies for potential large (flagship) Astrophysics missions are in progress: LUVOIR, OST, HabEx and Lynx. Following the 2020 Astrophysics decadal rankings, one of these will likely proceed to early Phase A where the infusion of new and advanced systems modeling tools and methods would be a potential game-changer in terms of rapidly navigating architecture trades, requirements development and flow-down, and design optimization.

A variety of planetary missions requires significant modeling and simulation across a variety of possible trade spaces. The portions of this topic area focused on breadth and variable fidelity will support them.

S5.06: Space Weather R2O/O2R Technology Development (SBIR)

Lead Center: GSFC

Participating Center(s): JPL, JSC, LaRC, MSFC

Technology Area: 11.0.0 Modeling, Simulation, Information Technology and Processing

Related Subtopic Pointer(s): T5.03 S3.08 S5.03 T6.05 S1.06 S4.04 S5.01

Scope Title

Space Weather R2O/O2R Technology Development

Scope Description

Space weather has the potential to disrupt telecommunications, aircraft and satellite systems, electric power subsystems, and position, navigation, and timing services. Given the importance of these systems to our national well-being, NASA’s Heliophysics Division invests in activities to improve the understanding of these phenomena and to enable new monitoring, prediction, and mitigation strategies.

The national direction for this work is organized by the Space Weather Operations, Research, and Mitigation (SWORM) Working Group, which is a Federal interagency coordinating body organized under the Space Weather, Security, and Hazards (SWSH) Subcommittee. The SWSH is a part of the National Science and Technology Council (NSTC) Committee on Homeland and National Security, organized under the Office of

Science and Technology Policy (OSTP). The SWORM coordinates Federal Government departments and agencies to meet the goals and objectives specified in the National Space Weather Strategy and Action Plan released in March 2019.

NASA's role under the National Space Weather Strategy and Action Plan is to provide increased understanding of the fundamental physics of the Sun-Earth system through space-based observations and modeling, the development of new space-based space weather technologies and missions, and monitoring of space weather for NASA's space missions. This includes research that advances operational space weather needs.

This subtopic solicits new, enabling space weather technologies as part of NASA's response to these national objectives. While this subtopic will consider all concepts demonstrably related to NASA's Research-to-Operations/Operations-to-Research (R2O/O2R) responsibilities outlined in the Strategy and Action Plan, five areas have been identified for priority development:

(1) Space Weather Forecasting Technologies and Techniques: Innovative technologies and techniques are solicited that explore and enable the transition of tools, models, data, and knowledge from research to operational environments. This includes the preparation and validation of existing science models that may be suitable for transition to operational use. Coordination with existing NASA capabilities, such as the Space Radiation Analysis Group (SRAG) at Johnson Space Center (JSC), the Community Coordinated Modeling Center (CCMC) at GSFC, and the Short-term Prediction Research and Transition (SPoRT) Center at Marshall Space Flight Center (MSFC), is appropriate. Areas of special interest include, but are not limited to:

- Lunar space environment characterization tools that can be employed by NASA to enhance protection of crewed and uncrewed missions to cis-lunar and lunar surface missions;
- Specifications and/or forecasts of the energetic particle and plasma conditions encountered by spacecraft within Earth's magnetosphere, as well as products that directly aid in spacecraft anomaly resolution, and end-users such as spacecraft operators;
- Approaches that potentially lead to a 2-3 days forecasting of atmospheric drag effects on satellites and improvement in the quantification of orbital uncertainties in LEO altitude ranges (up to ~2000 km);
- Techniques that enable the characterization and prediction of ionospheric variability that induces scintillations, which impact communication and global navigation and positioning systems;
- Longer-range (2-3 days) forecasting of SPEs (Solar Particle Events) and an improved all-clear SPE forecasting capability.

(2) Space Weather Advanced Data-Driven Discovery Techniques: A particular challenge is to combine the sparse, vastly distributed data sources available with realistic models of the near-Earth space environment. Data assimilation and other cutting-edge data-driven discovery innovations are solicited that enable tools and protocols for the operational space weather community. Priority will be given to proposals that:

- Develop data assimilation space weather applications or technologies desired by established space weather operational organizations;
- Integrate data from assets that typically do not share similar time series, utilize different measurement techniques (e.g., imaging vs in-situ particles and fields), or are distributed throughout the heliosphere;
- Provide new data driven operational forecasting tools that can be straightforwardly validated by the CCMC or another equally robust validation methodology; and/or,
- Integrate underutilized resources (e.g. space-based radio occultation for ionospheric specification or U.S. Geological Survey (USGS) ground conductivity measurements related to geomagnetically induced currents).

(3) Space Weather Benchmarks: The Heliophysics System Observatory (HSO) data archives include a vast array of spacecraft observations suitable for the development of space weather benchmarks, which are the set of characteristics against which space weather events are measured. This includes refining the Phase 1 Benchmarks that were released by the National Science and Technology Council in 2018 for induced geo-electric fields, ionizing radiation, ionospheric disturbance, solar radio bursts, and upper atmospheric expansion. These benchmarks should be in a form useful to the owners and operators of systems and assets that contribute to critical national functions. Innovations to produce and/or further refine these benchmarks are solicited, as are concepts for future creative approaches utilizing new data types or models that could become available.

(4) Space Weather Mitigation Technologies: The 2019 National Space Weather Strategy and Action Plan specifically calls out the need to test, evaluate, and deploy technologies and devices to mitigate the effects of space weather on communication systems, geomagnetic disturbances on the electrical power grid, or radiation events on satellites. It also includes the development of processes to improve the transition of research approaches to operations.

(5) Space Weather Instrumentation: Heliophysics science relies on a wide variety of instrumentation for its research and often makes its data available in near-real-time for space weather forecasting purposes. Concepts are solicited for instrumentation concepts, flight architectures, and reporting systems that enable enhanced, more informative, robust, and effective measurements for space weather monitoring and forecasting systems. Opportunities for improving measurements include increased spatial and temporal resolution, fidelity, promptness, and measurement system reliability. This includes the miniaturization of existing systems and/or technologies deployable as an array of CubeSats. In order to be considered for investment, SBIR technologies should demonstrate comparable, or better, precision and accuracy when compared to the current state-of-the art. Further, SBIR instrument designs should avoid duplicating current NASA research spacecraft arrays or detector systems including those currently in formulation or development (e.g. Interstellar Mapping and Acceleration Probe (IMAP), Geospace Dynamics Constellation (GDC), Medici, Explorer concepts, etc.).

Proposals must demonstrate an understanding of the current state-of-the-art, describe how the proposed innovation is superior, and provide a feasible plan to develop the technology and infuse into a specific activity listed within the National Space Weather Strategy and Action Plan.

References

Executive Order 13744-- Coordinating Efforts to Prepare the Nation for Space Weather Events: https://www.federalregister.gov/documents/2016/10/18/2016-25290/coordinating-efforts-to-prepare-the-nation-for-space-weather-events

The Space Weather Operations, Research, and Mitigation (SWORM) Working Group is a Federal interagency coordinating body organized under the Space Weather, Security, and Hazards (SWSH) Subcommittee. THE SWSH is a part of the National Science and Technology Council (NSTC) Committee on Homeland and National Security, organized under the Office of Science and Technology Policy (OSTP). The SWORM coordinates Federal Government departments and agencies to meet the goals and objectives specified in the National Space Weather Strategy and Action Plan released in March 2019. See: https://www.sworm.gov/

The White House Executive Office of Science and Technology Policy released the National Space Weather Strategy and Action Plan on March 26th, 2019, during the National Space Council meeting in Huntsville, Alabama. The announcement was made by the Office of Science and Technology Policy Director, Kelvin K. Droegemeier. This strategy and action plan is an update to the original National Space Weather National Space Weather Strategy and Space Weather Action Plan, released in October 2015. See: https://www.whitehouse.gov/wp-content/uploads/2019/03/National-Space-Weather-Strategy-and-Action-Plan-2019.pdf

Space Weather Phase 1 Benchmarks:
https://www.sworm.gov/publications/2018/Space-Weather-Phase-1-Benchmarks-Report.pdf

An Executive Order (EO) on Coordinating National Resilience to Electromagnetic Pulses (EMP) was released by the White House on March 26, 2019. The EO identifies the disruptive impacts an EMP has on technology and critical infrastructure systems, whether the EMP is human-made or naturally occurring. The EO outlines how the Federal Government will prepare for and mitigate the effects of EMPs by an efficient and cost-effective approach.

See: https://www.whitehouse.gov/presidential-actions/executive-order-coordinating-national-resilience-electromagnetic-pulses/

Expected TRL or TRL range at completion of the project 3 to 8

Desired Deliverables of Phase II

Prototype, Hardware, Software

Desired Deliverables Description

Space weather is a broad umbrella encompassing science, engineering, applications and operations. The ultimate goal of this SBIR is to generate products or services (“deliverables”) that enable end-user action. The deliverables can be applied, for example, to space weather hazard assessments, real-time situational awareness, or to plan protective mitigation actions. Deliverables can be in the form of new data, new techniques new instrumentation, or predictive models that are prepared/validated for transition into operations.

State of the Art and Critical Gaps

We do not yet know how to predict what needs to be predicted; we do not yet know how quantitatively good/bad our operational capabilities are (metrics); mechanisms do not yet exist to enable a broad range of the community to participate in the improvement of operational models; the research environment advances understanding rather than the improvement of operational products.

Space weather poses a constant threat to the Nation’s critical infrastructure, our satellites in orbit, and our crewed and uncrewed space activities. Extreme space weather events can cause substantial harm to our Nation’s security and economic vitality. Preparing for space weather events is an important aspect of American resilience that bolsters national and homeland security and facilitates continued U.S. leadership in space A robust space weather program and its associated forecasting capabilities are essential for NASA’s future exploration success.

Relevance / Science Traceability

This SBIR subtopic enables NASA to demonstrate progress against NASA Goal 1.4: Understand the Sun and its interactions with Earth and the solar system, including space weather.

These applied research projects directly address NASA's role within the Space Weather Operations, Research, and Mitigation (SWORM) Working Group, which is a Federal interagency coordinating body organized under the Space Weather, Security, and Hazards (SWSH) Subcommittee. The SWSH is a part of the National Science and Technology Council (NSTC) Committee on Homeland and National Security, organized under the Office of Science and Technology Policy (OSTP). The SWORM coordinates Federal Government departments and agencies to meet the goals and objectives specified in the National Space Weather Strategy and Action Plan released in March 2019.

The Heliophysics Space Weather Science and Applications (SWxSA) Program establishes an expanded role for NASA in space weather science under single element. It is consistent with the recommendation of the NRC Decadal Survey and the OSTP/SWORM 2019 National Space Weather Strategy and Action Plan. It competes ideas and products, leverages existing agency capabilities, collaborates with other agencies, and fosters partnership with user communities. The SWxSA program is distinguishable from other heliophysics research elements in that it is specifically focused on investigations that significantly advance understanding of space weather and then apply this progress to enable more accurate characterization and predictions with longer lead time. The Heliophysics Living with a Star (LWS) Program has established a path forward to meet the NASA's obligations to the research relevant to space weather and is a significant source of input to SWxSA.

Further involvement by the emerging Heliophysics space weather commercial community has the potential to significantly advance the space weather application obligations portion of the mandate.

Astronauts are not protected by the Earth's atmosphere and are exposed to space radiation such as galactic cosmic rays and solar energetic particles. A robust space weather program and associated forecasting capabilities is essential for NASA's future exploration success.

Focus Area 14: On-orbit Servicing, Assembly, and Manufacturing (OSAM)

Lead MD: STMD

Participating MD(s): STTR

NASA is seeking technological innovations that will accelerate development and adoption of advanced manufacturing and modular assembly technologies supporting a wide range of NASA Missions. NASA has an immediate need for more affordable and more capable materials and processes across its unique missions, systems, and platforms. Cutting-edge manufacturing technologies offer the ability to dramatically increase performance and reduce the cost of NASA's programs. The ability to improve cost, launch mass, system resiliency and extended life time by advancing technologies to enable large structures that can be deployed, assembled/constructed, reconfigured and serviced in-space or on planetary surfaces is also imperative to NASA's Missions. In the areas of manufacturing, this topic is focused on technologies for both the ground-based advancements and in-space manufacturing capabilities required for sustainable, long-duration space missions to destinations such as Mars. The terrestrial subtopic areas concentration is on research and development of advanced metallic materials, processes and additive manufacturing technologies for their potential to increase the capability and affordability of engines, vehicles, space systems, instruments and science payloads by offering significant improvements over traditional manufacturing methods. Technologies should facilitate innovative physical manufacturing processes combined with the digital twin modeling and simulation approach that integrates modern design and manufacturing. The in-space manufacturing focus area includes: a) manufacturing and recycling in an intravehicular environment (for production of spare parts and to achieve logistics reductions); b) manufacturing of large scale structures with dimensions exceeding current payload fairings with additive manufacturing in the external space environment; and, c) repair and assembly of structures using joining technologies. In addition, advances in lighter-weight metals processing (on ground and in-space) will enable the delivery of higher-mass payloads to Mars and beyond. In order to achieve necessary reliabilities and ensure parts meet requirements for intended use scenarios, development of in situ process assessment, feedstock control and monitoring, and volumetric inspection capabilities are urgently needed. This topic also includes autonomous assembly of structures in space, focused on four critical aspects including autonomy, system modularity, metrology, and modeling & simulation. The hardware and software components of an in-space assembled structure must be modular to facilitate servicing, component replacement, and reconfiguration of the spacecraft. Research should be conducted to demonstrate technical feasibility and prototype hardware development during Phase I and show a path toward Phase II hardware and software demonstration and delivering an engineering development unit for NASA testing at the completion of the Phase II that could be turned into a proof-of-concept system for flight demonstration. To understand the full technology needs and requests see the detailed topic and subtopic descriptions.

T12.06: Extensible Modeling of Additive Manufacturing Processes (STTR)

Lead Center: JPL

Participating Center(s): None

Technology Area: 12.0.0 Materials, Structures, Mechanical Systems and Manufacturing

Related Subtopic Pointer(s): Z4.04

Scope Title

Process Modeling of Additive Manufacturing

Scope Description

The subtopic of modeling of additive processes is highly relevant to NASA as NASA is currently on a path to implement additive processes in space flight systems with little or no ability to model the process and thereby predict the results. In order to reliably use this process with a variety of materials for space flight applications, NASA has to have a much deeper understanding of the process. NASA is currently considering these processes for the Mars Oxygen In-Situ Resource Utilization Experiment (MOXIE), Scanning Habitable Environments with Raman & Luminescence for Organics & Chemicals (SHERLOC), ion engines and other spacecraft structural and multi-functional applications. Additive manufacturing of development and flight hardware with metallic alloys is being developed by NASA and its various partners for a variety of spacecraft applications. These components are expected to see extreme environments coupled with a need for high-reliability (e.g., manned spaceflight), which requires a deeper understanding of the manufacturing processes. Modeling of the additive processes to provide accurate dimensional designs, preferred micro-structures that are defect-free is a significant challenge that would dramatically benefit from a joint academic-industry approach. The objective would be to create process models that are compatible with current alloys systems and additive manufacturing equipment which will provide accurate prediction of outcomes from a variety of additive manufacturing process parameters and materials combinations. The primary alloys of interest to NASA at this time include: Inconel 625 & 718, stainless steels, such as 304 and 316, Al10SiMg, Ti-6Al-4V, and copper alloys (GrCop-84). It is desired that the modeling approach address a focused material system, but be readily adaptable to eventually accommodate all of these materials. Therefore, the model should incorporate modest parameter changes coupled with being easily extensible for future alloys of interest to NASA. NASA is interested in modeling of the Selective Laser Melting (SLM), Electron Beam Melting (EBM) and Laser Engineered Net Shaping (LENS) processes.

References

Stranza, M. et al., Materials Letters, accepted (https://doi.org/10.1016/j.matlet.2018.07.141)

Vision 2040: A Roadmap for Integrated, Multiscale Modeling and Simulation of Materials and Systems, NASA/CR—2018-219771

Keller, T. et al., Acta Materiala, (https://doi.org/10.1016/j.actamat.2017.05.003)

Expected TRL or TRL range at completion of the project

Proposed technologies should mature to TRL 1 to 2 by the end of Phase II effort.

Desired Deliverables of Phase II

Software

Desired Deliverables Description

A functional process model covering the specific area by the proposer, using open source or code shared with the Agency.

State of the Art and Critical Gaps

Additive manufacturing will be used for space flight applications. NASA, and its suppliers, currently have very little knowledge of what is happening with these processes. Modeling of these additive processes is essential for NASA to be able to use these processes reliably. NASA is currently working on a specification for these processes and modeling would help that effort as well.

Relevance / Science Traceability

Process modeling of additive manufacturing is relevant to Human Exploration and Operations Mission Directorate (HEOMD), Science Mission Directorate (SMD)), and Space Technology Mission Directorate (STMD), all of which have extant efforts in additive manufacturing. HEOMD is focusing heavily on the use of additive manufacturing for propulsion systems (e.g. RS-25, RL10) for SLS, SMD is using additive manufacturing on the Planetary Instrument for X-ray Lithochemistry (PIXL) on the Mars 2020 mission, the Psyche Mission, as well as various ESI initiatives through STMD.

Z3.03: Development of material joining technologies and large-scale additive manufacturing processes for on-orbit manufacturing and construction (SBIR)

Lead Center: MSFC

Participating Center(s): GSFC, LaRC

Technology Area: 12.0.0 Materials, Structures, Mechanical Systems and Manufacturing

Related Subtopic Pointer(s): Z4.05 S2.02 H8.01 Z4.03 T12.01 Z4.04 Z3.04 H5.01 Z3.05

Scope Title

Development of Material Joining Technologies for On-Orbit Manufacturing and Construction

Scope Description

Technology development efforts are required to enable On-Orbit Servicing, Assembly, and Manufacturing (OSAM) for commercial satellites, robotic science, and human exploration. OSAM is an emerging national initiative to transform the way we design, build, and operate in space. The goal of the initiative is to develop a strategic framework to enable robotic servicing, repair, assembly, manufacturing, and inspection of space assets.

An in-space material joining capability is an important supporting technology for the long duration, long endurance space missions that NASA will undertake beyond the International Space Station (ISS). Historically structures in space have been assembled using mechanical fastening techniques and modular assembly. Structural designs for crewed habitats, space telescopes, antennas, and solar array reflectors are primarily driven by launch considerations such as payload faring dimensions and vibrational loads experienced during ascent. An in-space material joining capability can potentially eliminate constraints on the system imposed by launch, enabling the construction of larger, more complex and more optimized structures. Material joining is an essential complementary capability to large scale additive manufacturing technologies being developed by NASA and commercial partners. Material joining is also a critical capability for repair scenarios (ex. repair of damage to a structure from micrometeorite impacts).

This subtopic seeks innovative engineering solutions to robotically join materials, fully or semi-autonomous, for manufacturing in the external space environment. Current State-Of-the-Art (SOA) terrestrial joining methods such and laser beam, electron beam, brazing, friction/ultrasonic stir and arc welding should be modified with an effort to reduce the footprint, mass and power requirements for on-orbit applications.

Phase I is a feasibility study and laboratory proof of concept of a robotic welding process and system for external in-space manufacturing applications. Targeted applications for this technology include joining and repair of components at the subsystem level, habitat modules, trusses, solar arrays, and/or antenna reflectors.

The need to repair a damaged structure may require the need to not only join material but cut and remove material. A single process with the ability to not only join material but also cut/remove material is a priority. The Phase I effort should provide a laboratory demonstration of the joining process and its applicability to aerospace grade metallic materials and/or thermoplastics, focusing on joint configurations which represent the priority in-space joining applications identified above. Work under Phase I will inform preliminary design of a mobile welding unit and a concept of operations for how the system would be deployed and operate in the space environment, with a focus on specific scenarios: for example, repair of a metal panel following micrometeorite damage, longitudinal joining of two metal curved panels, and joining of a truss to an adjacent truss. The Phase I should also provide an assessment of the proposed process operational capabilities (for example: classes of materials which can be welded with the process, joint configurations which can be accommodated, and any expected impacts of the microgravity environment on joint efficiency relative to terrestrial system operation), volume, and power budget. A preliminary design and concept of operations are also deliverables under the phase I. Concepts for ancillary technologies such as post-process inspection, in-situ monitoring, or robotic arms for manipulation of structures to be joined may also be included in the Phase I effort.

Phase I requires a demonstration/proof of concept that: a) the process selected enables high-value applications of in-space welding for repair and assembly and b) system shows potential for being operated remotely with very little intervention/setup. Phase II includes finalization of the design and demonstration of a ground-based prototype system. Phase III would seek to evolve the technology toward a flight demonstration, either via a system mounted externally on ISS, Gateway, Restore-L or as a free-flyer.

References

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Tamir, David, et al. "In-Space Welding: Visions and Realities." 1993.

Paton, Boris Evgen’evich, and V. F. Lapchinskiĭ. Welding in space and related technologies. Cambridge International Science Publishing, 1997.

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S. Carioscia, B. A. Corbin, and B. Lan, "Roundtable Proceedings: Ways Forward for On-Orbit Servicing, Assembly, and Manufacturing (OSAM) of Spacecraft", 2018.

Expected TRL or TRL range at completion of the project: 4 to 5

Desired Deliverables of Phase II

Prototype, Hardware

Desired Deliverables Description

Phase I: laboratory demonstration/proof of concept of joining capability for external in-space manufacturing, initial design of system

Phase II: ground-based prototype system

Phase III: flight demonstration (Gateway, IRMA, Restore-L or free-flyer)

State of the Art and Critical Gaps

External in-space manufacturing has primarily focused on fabrication of structures in the space environment. Material joining is an essential supporting technology to these capabilities. Research on joining tapered off to some extent following the cancellation of the In-Space Welding Experiment (ISWE) for space shuttle. With the emergence of the OSAM initiative, a renewed interest and focus on manufacturing structures in the space environment as an enhancing capability for long duration missions and as a way to remove design constraints imposed by payload fairings and launch loads, additional work on development of an in-space material joining capability should be a priority. In-space joining represents an essential complementary technology to in-space fabrication techniques.

Relevance / Science Traceability

ISS, Gateway, Restore-L, ISAT, IRMA

Scope Title

Development of Large-Scale Additive Manufacturing Processes for On-Orbit Manufacturing and Construction

Scope Description

Technology development efforts are required to enable On-Orbit Servicing, Assembly, and Manufacturing (OSAM) for commercial satellites, robotic science, and human exploration. OSAM is an emerging national initiative to transform the way we design, build, and operate in space. The goal of the initiative is to develop a strategic framework to enable robotic servicing, repair, assembly, manufacturing, and inspection of space assets.

The ability to additively manufacture large scale structures in-space in an enabling capability needed to fully realize the game changing impacts of on-orbit servicing, assembly and manufacturing. Current state of the art on-orbit manufacturing systems are constrained to a build volume similar to terrestrial additive manufacturing processes with a build volume. Structural designs for crewed habitats, space telescopes, antennas, and solar array reflectors are primarily driven by launch considerations such as payload faring dimensions and vibrational loads experienced during ascent. A large-scale, free-form additive manufacturing capabilities can potentially eliminate constraints on the system imposed by launch, enabling the construction of larger, more complex and more optimized structures.

This subtopic seeks innovative engineering solutions to robotically fabricate and/or repair large structures, fully or semi- autonomous, in the external space environment. Current SOA terrestrial large-scale additive manufacturing processes such as wire-fed directed energy deposition and additive friction stir should be modified with an effort to reduce the footprint, mass and power requirements for on-orbit applications.

Phase I is a feasibility study and laboratory proof of concept of a robotic large-scale additive manufacturing process and system for external in-space manufacturing applications. Targeted applications for this technology include fabrication of truss structures, build-up of structural material for retrofitting spent tanks to habitat modules, and/or solar arrays back planes. Additional targeted applications include the repair of structures such as spacecrafts and/or payloads damaged during the ascent stage, habitat modules with micrometeoroid impact, and out-of-service components due to unforeseen circumstances and/or scheduled repairs. The Phase I effort should provide a laboratory demonstration of the manufacturing process and its applicability to aerospace grade metallic materials, focusing on structures which represent the priority in-space manufacturing applications identified above. Work under Phase I will inform preliminary design of a robotic additive manufacturing process and a concept of operations for how the system would be deployed and operate in the space environment. The Phase I should also provide an assessment of the proposed process operational capabilities, volume, and power budget. A preliminary design and concept of operations are also deliverables under the Phase I. Concepts for ancillary technologies such as post-process inspection, in-situ monitoring, or robotic arms for manipulation of structures to be fabricated may also be included in the Phase I effort.

Phase I requires a demonstration/proof of concept that: a) the process selected enables high-value applications of in-space fabrication of large-scale structures and b) system shows potential for being operated remotely with very little intervention/setup. Phase II includes finalization of the design and demonstration of a ground-based prototype system. Phase III would seek to evolve the technology toward a flight demonstration, either via a system mounted externally on ISS, Gateway, Restore-L or as a free-flyer.

References

G. J. Clinton, R, “NASA’s In Space Manufacturing Initiatives: Conquering the Challenges of In-Space Manufacturing,” 2017. [Online]. Available: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170011108.pdf [Accessed: 10-Oct-2019].

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S. Carioscia, B. A. Corbin, and B. Lan, "Roundtable Proceedings: Ways Forward for On-Orbit Servicing, Assembly, and Manufacturing (OSAM) of Spacecraft", 2018.

Expected TRL or TRL range at completion of the project: 4 to 5

Desired Deliverables of Phase II

Prototype

Desired Deliverables Description

Phase I: laboratory demonstration/proof of concept of large-scale additive manufacturing system for external in-space manufacturing, initial design of system

Phase II: ground-based prototype system including autonomous capability

Phase III: flight demonstration (Gateway, IRMA, Restore-L or free-flyer)

State of the Art and Critical Gaps

External in-space manufacturing has primarily focused on fabrication of 3D printed truss structures and beams. The In-Space Robotic Manufacturing and Assembly Project funded by the STMD (Space Technology Mission Directorate) Technology Demonstration Mission Program is planning the demonstration of 3D printed truss structures and beams. The technology advancement to multiple degrees of freedom, large-scale fabrication of structures is a priority for on-orbit manufacturing.

Relevance / Science Traceability

ISS, Gateway, Outpost, IRMA, Restore-L

Z3.04: Autonomous Modular Assembly Technology for OSAM (SBIR)

Lead Center: LaRC

Participating Center(s): MSFC

Technology Area: 4.0.0 Robotics, Telerobotics and Autonomous Systems

Related Subtopic Pointer(s): Z3.03 T11.04 Z3.05

Scope Title
Autonomous Modular Assembly Technology for On-Orbit Servicing, Assembly and Manufacturing (OSAM)

Scope Description

As NASA seeks to extend its presence into deep space, ground-based human intelligence applied to supervision, control, and intervention of operations will no longer be viable due to system and mission complexity and communication delays. Therefore, trusted and certified-safe autonomous systems with machine intelligence and robotic capabilities of responding to both nominal and unexpected situations will be needed. These systems should be capable of:

- Sensing and perception

- Acquiring measurements on-orbit or on planetary surfaces
- Achieving situational awareness
- Making decisions
- Taking action
- Teaming with humans and other machine agents
- Using experiential data to update capabilities
- Verifying autonomy algorithms and behavior
- Validating as-assembled structure shape and interface integrity

As such, autonomy, system modularity, metrology, and modeling & simulation are four critical aspects required to enable On-Orbit Servicing, Assembly, and Manufacturing (OSAM). The hardware and software components of an in-space assembled structure must be modular to facilitate servicing, component replacement, and reconfiguration of the spacecraft. Assembly by autonomous robots can reduce the workload on astronauts and ground crew as well as mitigate inefficiencies due to communication delays associated with teleoperation. The OSAM paradigm requires multiple autonomous agents to collaborate in a complex, dynamic environment. These agents will need to accurately perceive both their environment (the worksite) and each other in order to efficiently allocate tasks, plan trajectories, and respond to disturbances all in the presence of uncertainties such as unknown payload characteristics and unmodeled effects.

Modular structures will increase ease of access to space. Modular platforms could host flight hardware and share power, data, Guidance, Navigation and Control (GN&C), and thermal regulation capabilities. Under this paradigm, technology demonstrations could be carried out without the need to design and operate an entire spacecraft. Modules could simply occupy space on the already existing platform. This constitutes a plug-and-play architecture which will require a common interface between modules such that required structural loads can be supported as well as power, data, and other services.

Modeling & simulation of structures and assembly agents is necessary for verifying autonomous agent algorithms and behavior used for structures that cannot be assembled on the ground.

Accurate sensing of complex and uncertain environments is necessary to provide autonomous agents with situational awareness to accomplish assembly tasks. Validation of the autonomous system behavior and in-space assembled structure accuracy in-situ will require in-space metrology capabilities.

The scope of this subtopic includes modular hardware and software systems:

- ***Element 1*****:** Algorithms and software for sensing, planning and control of both autonomous robots and mission/task management agents
- ***Element 2*****:** Novel hardware designs (modular robots and structures)
- ***Element 3*****:** Hardware and software for global (worksite scale) metrology systems for accurately sensing agent and structure pose within an on-orbit or lunar assembly worksite
- ***Element 4*****:** Novel approaches to dynamics-based mathematical modeling for complex rigid-body connections and independent verification and validation for dynamics-based rigid multi-body mathematical models

Specific subjects to be considered include

- ***Heterogeneous multi-agent planning and control*****:** Algorithms for collaboration on shared tasks for assembly of large modular space structures; task allocation amongst multiple agents; trajectory planning through the worksite and real-time updating of tasks and trajectories to respond to unplanned scenarios; robust and adaptive control for guaranteed performance or graceful degradation of performance for robotic manipulators and/or novel assembly agents; teaming of humans and machines for planning, validation, and post-assembly analysis

- ***Strategies and solutions for error detection and correction during the assembly process***: Perception systems and/or classification algorithms independent from the assembly agent for verifying assembly steps and characterizing assembly errors. Fault/anomaly detection, diagnosis, and response to restore nominal operations or derive an acceptable alternative goal
- ***Metrology systems***: Global metrology systems or sensing tools that can map a worksite to facilitate agent and structure assembly path-planning for real-time task management and situational awareness and facilitate verification and validation of assembly tasks. A scalable system that can accurately measure structures at an in-space (orbital or surface) worksite with a focus on minimal supporting infrastructure is desired. Concepts with potential for integration and repurposing after construction are favored.
- ***Modular structures, systems, and tools***: Deployables that are rigidizable by an accompanying in-situ system (i.e. trusses or functional modules), can be serviced (due to modularity), are capable of moving along truss structures of variable geometries, and/or can interface with agents or be stored/stowed at a worksite where the agent mostly acts as a driver for a mobility system. Of particular interest are approaches to efficiently connect truss modules together. Hardware concepts that support the interconnection of modules in the 100 – 5,000 kg range using some form of space robotics. The objective is to minimize the parasitic mass of the completed spacecraft from the modularity features that are required for inter-module assembly. Features can be added and removed to reduce this parasitic mass. Proposals are preferred that include features to connect both electrical (power and data) and structural features, noting that the connections can occur sequentially. Joining strategies that support fluid connections are of interest but not necessary to be responsive to this subtopic area. The structural connection should occur at a minimum of 3 discrete locations fixing the rigid body motion of the 2 modules in all 6 degrees of freedom while isolating (minimizing) forces resulting from thermal induced strain between the modules consistent with a LEO orbit. The three (or more) connections do not have to occur simultaneously.
- ***Modeling & simulation***: Novel approaches to dynamics-based mathematical modeling for complex rigid-body connections with nonlinear effects (for example, slider, ball, or slot connections) and independent verification and validation for dynamics-based rigid multi-body mathematical models. Of particular interest are accurate dynamics-based models for joining of modules on-orbit or in planetary environments.

References

- NASA in-Space Assembled Telescope (iSAT) Study: https://exoplanets.nasa.gov/exep/technology/in-space-assembly/iSAT_study/
- NASA Raven: https://www.nasa.gov/mission_pages/station/research/experiments/explorer/Investigation.html?#id=1734
- NASA Robotic Refueling Mission (RRM3): https://sspd.gsfc.nasa.gov/RRM3.html
- NASA Restore-L: https://sspd.gsfc.nasa.gov/restore-L.html
- NASA Dragonfly: https://www.nasa.gov/mission_pages/tdm/irma/nasas-dragonfly-project-demonstrates-robotic-satellite-assembly-critical-to-future-space.html
- Autonomous Systems NASA Capability Overview: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20180007804.pdf

Expected TRL or TRL range at completion of the project: 3 to 5

Desired Deliverables of Phase II

Hardware, Software

Desired Deliverables Description

- Software implementations and documentation verifying the efficacy of the designed algorithms
- Physical prototypes and documentation for the designed hardware

State of the Art and Critical Gaps

As humans venture into deeper space, communication latency will increase to the point that autonomous operations are crucial. Current technologies for autonomous robots are low TRL, application specific, and fragile with respect to environmental uncertainties. To enable OSAM, these technologies must be made more resilient. Many interesting ideas exist in academia, but have yet to be made into a viable product.

Existing interfaces for modular trusses are purely structural. A critical gap is the development of interfaces that can exchange power, data, and other services over the interface.

Relevance / Science Traceability

Achieving a robust and resilient autonomous solution for OSAM requires the intersection of many disciplines including mechanical and electrical systems, robotics, dynamics modeling, control theory, and computer science. NASA goals that would directly benefit from this work are future lunar exploration missions, including sustained human presence on the moon and persistent space platforms.

Z3.05: Satellite Servicing Technologies (SBIR)

Lead Center: GSFC

Participating Center(s): LaRC, MSFC

Technology Area: 4.0.0 Robotics, Telerobotics and Autonomous Systems

Related Subtopic Pointer(s): S3.04 H9.03 Z5.04 Z3.04 Z3.03

Satellite servicing technology developments are needed to enable robotic science and human exploration missions that are sustainable, affordable, and resilient and may not be realizable based on current approaches to space systems design, launch, and operations. The focal areas for technology development are remote inspection, relocation, refueling, repair, replacement of equipment, and augmentation of existing on-orbit assets. The intended application for these technology developments are servicing, assembly, exploration, sample return, and mission extension.

This subtopic seeks two specific technologies that will enhance satellite servicing by: 1) providing improved sensing/perception during close proximity robotic manipulator operations; and 2) providing a mechanical swivel for use with liquid hypergolic oxidizer propellant.

Scope 1 Title: Development of low mass low power proximity sensor for satellite servicing

The first technology scope covers small robot proximity range sensor which can be mounted at the end of a robotic arm and provide mm-class range performance inside of a few cm, for measurement of range from the sensor to an arbitrary object. Restore-L autonomous capture utilizes only cameras for this operation, a sensing modality which cannot enable “capture before contact” or soft-capture of a legacy vehicle. A direct ranging sensor, operating at high frequency (>10Hz) would greatly enhance this operation, and enable many other autonomous robotic operations.

Phase 1 proposals are expected to identify options, or develop prototypes, and test potential sensor options in laboratory demonstrations at various distances from centimeters to contact, and with typical satellite external surface materials including multi-layer insulation blankets, launch vehicle interfaces (marman rings), and other materials found on or near space grapple or grasp fixtures. Phase I proof of concept and preliminary design efforts that will lead to, or can be integrated into, flight demonstration prototypes in a Phase 2 effort are of interest.

Scope 2 Title: Mechanical swivel for liquid hypergolic oxidizer propellant

The second technology scope concerns the selection or development of materials, and subsequent design and test of mechanisms capable of introducing a mechanical swivel in the fluid lines of a liquid hypergolic oxidizer propellant system. While Restore-L does not plan to transfer Oxidizer, other refueling missions will need to do so. One option for this transfer includes a flexible hose with no dynamic seals, and therefore limited dexterity and ability to accommodate a large variety of clients (for example, imagine an automobile gas station hose with no swivel – filling the tank with a more than one specific vehicle would be very challenging). Introduction of a dynamic seal and swivel would greatly expand the ability of such a system to accommodate multiple clients and fluid coupler locations. This flexibility is essential for the commercial refueling business case, which must amortize the cost of the refueler over many clients and configurations.

Phase 1 proposals are expected to develop a mechanical swivel joint that can be utilized for fluid transport with flow rates in the range of 2-20 kg / min and maximum expected operating pressure of 500 psia with a low quantity of dynamic cycles (<10) with exposure to liquid hypergolic oxidizer propellant (N2O4 MON-3), and also varying degrees of prior accelerated radiation exposure to softgoods to assist with determining possible on-orbit life cycle use estimates. Phase I proof of concept and preliminary design efforts that will lead to, or can be integrated into, flight demonstration prototypes in a Phase 2 effort are of interest.

References

Fourth Technology Transfer Industry Day; Plan to Facilitate Commercial On-Orbit Robotic Servicing, Assembly and Manufacturing (OSAM) - Federal Business Opportunities: Opportunities, National Aeronautics Space Administration, 30 July 2019, www.fbo.gov/index.php?s=opportunity&mode=form&id=1f59d52003a1a1538aba9975a854ec9e&tab=core&tabmode=list& .

Reed, Benjamin B. "On-Orbit Satellite Servicing Study Project Report." *Satellite Servicing Projects* Division, NASA, Oct. 2010, On-Orbit Satellite Servicing Study Project Report.

Expected TRL or TRL range at completion of the project: 2-4

Desired Deliverables Description

Scope 1: Proximity sensor with mass < 0.25 kg, range 20 cm to 0.5 cm, precision better than 0.5 mm, power less than 3 W at 10 hz update rate.

Scope 2: A mechanical swivel joint that can be utilized for fluid transport with flow rates in the range of 2-20 kg / min and maximum expected operating pressure of 500 psia with a low quantity of dynamic cycles (<10) maintaining a leak rate better than 1x10^-5 sscs gHe with exposure to liquid hypergolic oxidizer propellant (N2O4 MON-3), and also varying degrees of prior accelerated radiation exposure to softgoods to assist with determining possible on-orbit life cycle use estimates. Laboratory demonstration would involve determining top material selection (metal and latest available Teflon or polymer), fabrication of small test unit, and post-exposure GHe precision leak testing utilizing as much of existing standardized testing infrastructure as possible (NASA STD 6001 Test 15, etc.).

State of the Art and Critical Gaps

Scope 1: Mass is critical at the end of robotic arms during autonomous capture. Having knowledge of the distance from the end of the arm to the adjacent free flying satellite would reduce the risk of a collision or missed capture.

Scope 2: Dynamic seals exist today for chemical fuel propellants (hydrazine, monomethyl hydrazine, etc.), however there is no known oxidizer seal that can meet the requirements listed above.

Relevance / Science Traceability

Restore-L, ISS, Gateway, Artemis, iSAT, commercial refueling.

Each of the technologies are considered key for satellite servicing. These technologies could be applicable to the Restore-L mission as well as other potential servicing missions, platform demonstrations, or smallsats. These technologies could also be applicable to refueling at Artemis.

Focus Area 15: Materials, Materials Research, Structures, and Assembly

Lead MD: STMD

Participating MD(s): HEOMD, STTR

As NASA strives to explore deeper into space than ever before, lightweight structures and advanced materials have been identified as a critical need. The Lightweight Materials, Structures, Advanced Assembly and Construction focus area seeks innovative technologies and systems that will reduce mass, improve performance, lower cost, be more resilient and extend the life of structural systems. Reliability will become an enabling consideration for deep space travel where frequent and rapid supply and resupply capabilities are not possible.

Improvement in all of these areas is critical to future missions. Applications include structures and materials for launch, in-space and surface systems, deployable and assembled systems, integrated structural health monitoring (SHM) and technologies to accelerate structural certification. Since this focus area covers a broad area of interests, specific topics and subtopics are chosen to enhance and or fill gaps in the space and exploration technology development programs as well as to complement other mission directorate structures and materials needs.

H5.01: Lunar Surface Solar Array Structures (SBIR)

Lead Center: LaRC

Participating Center(s): GRC

Technology Area: 12.0.0 Materials, Structures, Mechanical Systems and Manufacturing

Related Subtopic Pointer(s): Z3.03 S3.01 Z7.04 Z1.03 Z13.02 Z13.01

Scope Description

NASA intends to land near the lunar south pole (between 85-90 S latitude) by 2024 in Phase 1 of the Artemis Program, and then to establish a sustainable long-term presence by 2028 in Phase 2. At exactly the lunar south pole (90 S), the Sun elevation angle varies between -1.5 deg and 1.5 deg during the year. At 85 S latitude, the elevation angle variation increases to between -6.5 deg and 6.5 deg. These persistently shallow sun grazing angles result in the interior of many polar craters never receiving sunlight while some nearby elevated ridges and plateaus receive sunlight up to 100% of the time in the summer and up to about 70% of the time in the winter. For this reason, these elevated sites are promising locations for human exploration and settlement because they avoid the excessively cold 14-day nights found elsewhere on the Moon while providing nearly continuous sunlight for site illumination, moderate temperatures, and solar power [Refs. 1-2].

This subtopic seeks structural and mechanical innovations for 10+ kW lightweight solar arrays near the south pole for powering landers, In-Situ Resource Utilization (ISRU) equipment, lunar bases, and rovers, and that can deploy and retract at least 5 times. Retraction will allow solar array hardware to be relocated, repurposed, or refurbished and possibly also to minimize nearby rocket plume loads and dust accumulation. Also, innovations to raise the bottom of the solar array by up to 10 m to reduce shadowing from local terrain are of interest [Ref. 3]. Suitable innovations and variations of existing array concepts [e.g., Ref. 4] are of special interest.

Design guidelines for these deployable/retractable solar arrays are:

- Deployed area: 35 m^2 (10 kW) initially; up to 140 m^2 (40 kW) eventually per unit.
- Single-axis sun tracking about the vertical axis.
- Adjustable leveling to within 10 deg of vertical.
- Retractable for relocating, repurposing, or refurbishing.
- Number of deploy/retract cycles in service: >5; stretch goal >10.
- Optional 10 m height extension boom to reduce shadowing from local terrain.
- Lunar dust, radiation, and temperature resistant mechanical and electrical components.
- Factor of safety of 1.5 on all components.
- Specific mass: >150 W/kg at 35 m^2; >100 W/kg at 140 m^2.
- Specific packing volume: >60 kW/m^3 at 35 m^2; >40 kW/m^3 at 140 m^2.
- Lifetime: >15 years.

Suggested areas of innovation include:

- Novel packaging, deployment, retraction, and modularity concepts.
- Lightweight, compact components including booms, ribs, substrates, and mechanisms.
- Novel actuators for telescoping solar arrays with tubular segments of ~4 m length and ~0.2 m diameter such as gear/rack, piezoelectric, ratcheting, or rubber-wheel drive devices.
- Mechanisms with exceptionally high resistance to lunar dust.
- Load-limiting devices to avoid damage during deployment, retraction, and solar tracking.
- Optimized use of advanced lightweight materials (but not materials development).
- Validated modeling, analysis, and simulation techniques.
- High-fidelity, functioning laboratory models and test methods.
- Scaled flight hardware for demonstration on small or mid-size landers.
- Modular and adaptable solar array concepts for multiple lunar surface use cases.
- Completely new concepts; e.g., thinned “rigid panel” or 3D printed solar arrays, non-rotating telescoping “chimney” arrays, or lightweight reflectors to redirect sunlight onto solar arrays or into dark craters.

Proposals should emphasize structural and mechanical innovations, not photovoltaics, electrical, or energy storage innovations, although a complete solar array systems analysis is encouraged. If solar concentrators are proposed, strong arguments must be developed to justify why this approach is better from technical, cost, and risk points of view over unconcentrated planar solar arrays.

In Phase I, contractors should prove the feasibility of proposed innovations using suitable analyses and tests. In Phase II, significant hardware or software capabilities that can be tested at NASA should be developed to advance their Technology Readiness Level (TRL). TRL at the end of Phase II of 4 or higher is desired.

NASA has plans to purchase services for delivery of payloads to the Moon through the Commercial Lunar Payload Services (CLPS) contract. Under this subtopic, proposals may include efforts to develop payloads for flight demonstration of relevant technologies in the lunar environment. The CLPS payload accommodations will vary depending on the particular service provider and mission characteristics. Additional information on the CLPS program and providers can be found at this link: https://www.nasa.gov/content/commercial-lunar-payload-services. CLPS missions will typically carry multiple payloads for multiple customers. Smaller, simpler, and more self-sufficient payloads are more easily accommodated and would be more likely to be considered for a NASA-sponsored flight opportunity. Commercial payload delivery services may begin as early as 2020 and flight opportunities are expected to continue well into the future. In future years it is expected that larger and more complex payloads will be accommodated. Selection for award under this solicitation will not guarantee selection for a lunar flight opportunity.

References

1. Burke, J., “Merits of a Lunar Pole Base Location,” in Lunar Bases and Space Activities of the 21st Century, Mendell, W. (editor), 1985, https://www.lpi.usra.edu/publications/books/lunar_bases/
2. Fincannon, J., “Characterization of Lunar Polar Illumination from a Power System Perspective,” NASA TM-2008-215186, May 2008, https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20080045536.pdf.
3. Mazarico, E. et al., “Illumination Conditions of the Lunar Polar Regions Using LOLA Topography,” Icarus, February 2011, https://doi.org/10.1016/j.icarus.2010.10.030.
4. McEachen, M. et al., “Compact Telescoping Array: Advancement from Concept to Reality,” AIAA Paper 2018-1945, January 2018, https://doi.org/10.2514/6.2018-1945.

Expected TRL or TRL range at completion of the project: 4 to 5

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Software, Research

Desired Deliverables Description

In Phase I, contractors should prove the feasibility of proposed innovations using suitable analyses and tests. In Phase II, significant hardware or software capabilities that can be tested at NASA should be developed to advance their Technology Readiness Level (TRL). TRLs at the end of Phase II of 4 or higher are desired.

State of the Art and Critical Gaps

Deployable solar arrays power almost all spacecraft, but they primarily consist of hinged, rigid panels. This traditional design is too heavy and packages too inefficiently for larger sizes of arrays above about 20 kW. Furthermore, there is usually no reason to retract the arrays in space, so self-retractable solar array concepts are unavailable except for rare exceptions such as the special-purpose International Space Station (ISS) solar array wings. In recent years, several lightweight solar array concepts have been developed but none of them have motorized retraction capability either. The critical technology gap filled by this subtopic is a lightweight, vertically deployed, retractable 10+ kW solar arrays for the surface power for ISRU, lunar bases, dedicated power landers and rovers.

Relevance / Science Traceability

Robust, lightweight, redeployable solar arrays for lunar surface applications are a topic of great current interest to NASA on its path back to the moon. New this year, the subtopic extends the focus area from landers to other powered elements of the lunar surface architecture along with refined design guidelines. There are likely several infusion paths into ongoing and future lunar surface programs, both within NASA and also with commercial entities currently exploring options for a variety of lunar surface missions. Given the focus on the lunar South Pole, NASA will need vertically deployed and retractable solar arrays that generate 10-40 kW of power. 10 kW class solar array structures are also applicable for Science Mission Directorate (SMD) ConOps on the Moon to charge a Mars Science Laboratory (MSL)-class rover.

T12.01: Thin-Ply Composite Technology and Applications (STTR)

Lead Center: LaRC

Participating Center(s): GRC

Technology Area: 12.0.0 Materials, Structures, Mechanical Systems and Manufacturing

Related Subtopic Pointer(s): Z4.03 Z7.05 Z3.03 T12.05 T8.04 H5.02

Scope Description

The use of thin-ply composites is one area of composites technology that has not yet been fully explored or exploited. Thin-ply composites are those with cured ply thicknesses below 0.0025 in., and commercially available prepregs are now available with ply thicknesses as thin as 0.00075 in. By comparison, a standard-ply-thickness composite would have a cured ply thickness of approximately 0.0055 in. or greater. Thin-ply composites hold the potential for reducing structural mass and increasing performance due to their unique structural characteristics, which include (when compared to standard-ply-thickness composites):

- Improved damage tolerance.
- Resistance to microcracking (including cryogenic-effects).
- Improved aging and fatigue resistance.
- Reduced minimum-gage thickness.
- Thinner sections capable of sustaining large deformations without damage.
- Increased scalability of structures.

The particular capabilities requested for potential Phase I proposals in this subtopic in line with the critical gaps between the state of the art and the technology needed are:

- New processing methods for making repeatable, consistent, high quality thin-ply carbon-fiber prepreg materials, (i.e., greater than 55% fiber density with low degree of fiber twisting, misalignment and damage, low thickness non-uniformity and minimal gaps in the material across the width) using currently used and commercially available fiber/matrix combinations. The intent of this requirement is to provide thin-ply prepreg material with the same quality as the standard-ply material of the same material system in order to facilitate substitution of thin-ply into structural concepts, and while continuous fiber forms are sought, this does not preclude development of new and novel prepreg material forms. Prepreg product forms of interest have area weights below 60 g/m2 for unidirectional tape with tape widths between 6 and 300 mm wide, and below 120 g/m2 for woven/braided prepreg materials. Matrices of interest include both toughened epoxy resins for aeronautics applications, and resins qualified for use in space.

- Development of novel low creep and low stress relaxation polymer thin-ply composites for inflatable and rollable/foldable space structures. Amongst others, approaches of interest are: designing new molecular structures showing high restriction of distortion of atomic bond angle under stress; controlling cross-linking density by reactive functional groups of molecular chains to keep a good balance between restriction of molecular rearrangement and material brittleness; restricting large scale rearrangements of polymer molecules by second phase of components; and securing strong interfaces between reinforcing fibers and polymer matrix by chemical bonding or fiber sizing improvements to prevent fibers and polymer molecules slippage under load. The temperature dependent viscoelastic-plastic properties of the developed thin-ply material shall be characterized to predict the long-term behavior of the system under continuous loading.
- Fabrication of large, thin-gauge structures, such as deployable/rollable thin-shell booms or wing skins, are often limited in size by autoclave constraints. Innovative out-of-autoclave processing methods for thin-gauge structures are sought to facilitate the production of large structures. Additionally, the innovative method shall guarantee the curing process variables (temperature, pressure, etc.) are uniform over the long parts to achieve better final products with less process-related defects and part-to-part variability.
- Cure-induced deformation of thin composite structures such as the spring-in effect is a known phenomenon that affects part accuracy during fabrication. Simulation software compatible with general purpose finite element environments such as ABAQUS or ANSYS for predictions of the manufacturing process-induced deformations and residual stresses are sought. These software tools should be tailored to the modeling needs of thin-ply composite structures, especially for structures with a final thickness under 1.5 mm. In addition, simulation capability of sequential multi-step processes (cure and post-bonding) as well as complex process (composite sections co-cure and/or co-bond) are of special interest. The goal is to develop recommendations for geometric tool compensation, as well as cure cycles and tooling that meets cure cycle specifications.
- Fracture mechanics models for thin-shell, thin-ply polymer composites subjected to large continuous and cyclic bending strains (>2%) for which the nonlinear and viscoelastic-plastic response of the material plays an important role on the damage initiation and progression in the foldable/rollable/deformable structural member. Multi-scale failure models for spread-tow woven/braided lamina, as well as laminates that combine these with spread-tow unidirectional plies are sought. The study of material creep rupture, thermal fatigue, mechanical fatigue and resin micro-cracking at lower strains (< 1%), as related to environmental ageing, durability and dimensional stability of the final thin-ply composite structure is of special interest as part of a larger goal to qualify thin-shell, flexible composite structures for space flight.
- Testing and micromechanics models capable of identifying damage initiation and growth for hybrid thin-ply composites are sought. Specifically, methods for composites comprising thin and standard unidirectional plies, and composites combining different forms, such as combining unidirectional plies with woven or braided plies of the same or dissimilar areal weights.

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Expected TRL or TRL range at completion of the project: 4 to 5

Desired Deliverables of Phase II

Prototype, Analysis, Software, Research

Desired Deliverables Description

The Phase II deliverables will depend on the aspect addressed, but in general will be manufacturing processes, documentation of the analytical foundation and process, maturing the necessary design/analysis codes, and validation of the approach through design, build, and test of an article representative of a component/application of interest to NASA.

State of the Art and Critical Gaps

Thin-ply composites are attractive for a number of applications in both aeronautics and space as they have the potential for significant weight savings over the current state-of-the-art standard-ply materials due to improved performance. For example, preliminary analyses show that the notched strength of a hybrid of thin and standard ply layers can increase the notched tensile strength of composite laminates by 30%. Thus, selective incorporation of thin plies into composite aircraft structures may significantly reduce their mass. There are numerous possibilities for space applications. The resistance to microcracking and fatigue makes thin-ply composites an excellent candidate for a deep-space habitation structure where hermeticity is critical. Since the designs of these types of pressurized structures are typically constrained by minimum gage considerations, the ability to reduce that minimum gage thickness also offers the potential for significant mass reductions. For other space applications, the reduction in thickness enables: thin-walled, deployable structural concepts only a few plies thick that can be folded/rolled under high strains for launch (and thus have high packaging efficiencies) and deployed in orbit; and, greater freedom in designing lightweight structures for satellite buses, landers, rovers, solar arrays, and antennas. For these reasons, NASA is interested in exploring the use of thin-ply composites for aeronautics applications requiring very high structural efficiency, for pressurized structures (such as habitation systems and tanks), for lightweight deep-space exploration systems, and for low-mass high stiffness deployable space structures (such as rollable booms or foldable panels, hinges or reflectors).

There are many needs in development, qualification and deployment of composite structures incorporating thin-ply materials – either alone or as a hybrid system with standard ply composite materials. In particular, there is substantial interest in proposals that address manufacturability and production of composite structures utilizing thin-ply composites that at minimum develop the process and plan for the production of one prototype in Phase 1, and demonstrate reproducibility of prototype manufacturing and key parameter validation of repeated samples in Phase 2. Available predictive manufacturing-cure-induced deformation/residual stress software uses solid finite elements to represent the composite plies and those result in high aspect ratios elements when thin-ply materials are used, which ultimately derive in computationally expensive models or loss of convergence. New ways of modeling thin-ply materials are thus needed on these specialized software, particularly for complex-shaped, thin-shell structures just a few plies thick. Another area requiring development is in fracture initiation/progression mechanism models, efficient homogenization methods for spread-tow textile fabrics and hybrid (textile and unidirectional plies) laminates that include viscoelastic-viscoplastic and thermo-mechanical response, and new large deformation testing and analysis methods adapted for thin-ply composites subjected to high bending strains (>1.5%) for foldable and/or rollable thin-shell structures. Finally, polymer matrix composites subjected to high strains for a long-period of time are particularly susceptible to stress relaxation or creep. New thin-ply polymer composites materials for space applications tailored for low relaxation/creep response under large bending deformations and high strains, such as for rollable or foldable thin-shell structures, are needed.

Relevance / Science Traceability

The most applicable Aeronautics Research Mission Directorate (ARMD) program is Advanced Air Vehicles Program (AAVP), and within that is Advanced Air Transport Technologies (AATT). Additional projects withing AAVP that could leverage this technology are: Commercial Supersonic Technology (CST), Hypersonic Technology (HT), and Revolutionary Vertical Lift Technologies (RVLT). Projects within Transformative

Aeronautics Concepts Program (TACP) could also benefit. That is, any project in need of lightweight structures can benefit from the thin-ply technology development.

Within Space Technology Mission Directorate (STMD), projects with deployable composite booms, landing struts, foldable reflectors, and other very lightweight structures can benefit from the thin-ply technology.

T12.05: Deposition and Curing of Thermoset Resin Mixtures for Thermal Protection (STTR)

Lead Center: JSC

Participating Center(s): ARC, GSFC, LaRC

Technology Area: 12.0.0 Materials, Structures, Mechanical Systems and Manufacturing

Related Subtopic Pointer(s): S3.06 Z2.01 T12.01 H5.02 Z7.05 Z7.01 Z4.04

Scope Description

NASA has a need to significantly improve the manufacturing processes of Thermal Protection Systems (TPS) used in human-rated spacecraft with the intention of reducing cost and improving quality and system performance. The fabrication and installation of current TPS are labor intensive, cost prohibitive, and result in many seams between the segments. Future human missions to Mars will require the landing of large-mass payloads on the surface, and these large entry vehicles will require large areas of TPS to protect the structure. A sustained lunar presence will require the development of Lunar-return vehicles which will also need TPS. In order to reduce the cost and complexity of these vehicles, new TPS materials and compatible additive manufacturing techniques are being developed such that thermoset-resin based mixtures can be deposited, bonded and cured on spacecraft structures with automated systems. Typically, these thermoset resin systems are filled with fibers, microballoons, rheology modifiers and other additives. Technologies are sought to mix and feed, and then deposit and cure these highly filled thermoset resin mixtures on the flight structure. Basic requirements and goals for the material system are provided in the references.

This subtopic seeks to develop the materials and subsystems needed to design, fabricate and operate an automated production process for TPS. The technologies needing development include:

1. Compatible thermoset resin mixtures, extruder and tool-path algorithms to produce uniform printed and cured TPS material with voids/flaws less than 1/8”.
2. Printable resins yielding TPS materials with low coefficient of thermal expansion. Approaches could include additives to thermoset resin mixtures or alternate material systems potentially with imbedded and longer fibers.
3. Capability to vary the resin-mixture composition during the layer deposition to produce an insulative layer at the structure and a more robust layer on the outer surface.
4. Scalable material feed systems to transport the material to the extruder head(s). Mixing the raw materials in the feed system is desirable.
5. Cure/set the highly filled thermoset resin mixture on the flight structure without the need for large ovens. Curing can be accomplished by chemical composition and/or external energy sources, such as, but not limited to, radio frequency (RF) generators, ultraviolet (UV) lights, etc.
6. Processes and subsystems to ensure a good bond between the deposited material and high-temperature carbon-fiber composite structures.

During Phase I, the focus should be to develop and demonstrate, on a small scale, a solution to at least one of the technologies described above using a candidate thermoset resin mixture. Concepts for the other technologies should be developed during Phase I and then further developed and demonstrated in Phase II.

References

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Expected TRL or TRL range at completion of the project: 2 to 4

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Research

Desired Deliverables Description

Phase I deliverables should include a small scale demonstration of the resin mixture printing and curing process and also include printed and cured material samples for testing. The goal deliverables for Phase II would include the demonstration of a prototype system with a clear path for scale up to production of a full-size heat shield and the demonstrated capability to print, cure and bond acceptable TPS materials on a small, non-planar composite structure.

State of the Art and Critical Gaps

Current state of the art (SOA) for manufacturing and installing thermal protection on NASA space vehicles is too labor intensive and too costly. Furthermore, the heat shield designs are constrained by manufacturing processes that result in segmented blocks with gap fillers that create flight performance issues. To develop an automated additive manufacturing process for spacecraft heat shields that are monolithic, the development of the materials and technologies to deposit and cure the materials on the flight structures are needed.

Relevance / Science Traceability

Both Human Exploration and Operations Mission Directorate (HEOMD) and Science Mission Directorate (SMD) would benefit from this technology. All missions that include a spacecraft that enters a planetary atmosphere require TPS to protect the structure from the high-heating associated with hypersonic flight. Improved performance and lower cost heat shields benefit the development and operation of these spacecraft. Human missions to the moon and Mars would benefit from this technology. Commercial Space programs would also benefit from TPS materials and manufacturing processes developed by NASA.

Z4.04: Real Time Defect Detection, Identification and Correction in Wire-Feed Additive Manufacturing Processes (SBIR)

Lead Center: LaRC

Participating Center(s): MSFC

Technology Area: 12.0.0 Materials, Structures, Mechanical Systems and Manufacturing

Related Subtopic Pointer(s): Z4.05 H8.01 Z3.03 T2.04 A1.04 T12.05 Z8.10 T12.06

Scope Title

Development of Real Time Defect Detection, Identification and Correction in Wire-Feed Additive Manufacturing Processes

Scope Description

Additive Manufacturing (AM) (also referred to here as 3D printing) offers the ability to build light-weight components that are optimally suited for use in aerospace applications. Significant strides have been made in the development of AM with 3D printed components now being part of active aircraft and spacecraft[1,2,3]. While the use of AM has enabled non-traditional designs and decreased part counts, full inspection of each component is typically required post-build to determine fitness for the final application. Complex geometries, rough as-built surface finishes, and porosity can hinder inspection. If 100% inspection is not possible, proof test logic or some other method of proving fitness for use must be applied[4]. Defects that occur can force a complete reprint. The ultimate promise of AM is to enable on-demand production of customized unique components. For utility in space applications, printed parts have to be fully functional with zero to minimal post processing. Ideally, parts need to be built with acceptable form, fit, and function the first time, with sufficient documentation to allow direct entry into service. To enable the full realization of the potential of 3D printing, a capability for closed loop control of the process that integrates *in situ* monitoring, real-time defect detection and identification, & print parameter modification is required.

Wire-feed or extrusion type AM, with its relative simplicity, wide range of feedstocks and build volume flexibility is a popular 3D printing technique that is well suited to space applications [6]. Fused Filament Fabrication (FFF) and Electron Beam Free Form Fabrication (EBF[3]) are useful examples of wire-feed processes to illustrate the limitations placed on AM by presently available design and process control tools. After designing an object using 3D modeling software, the geometry is passed to a slicing and tool path planning code, which generates the list of instructions needed by the printing hardware. Once received by the printer, no further modifications or corrections can be made, and the process continues to completion.

Proposals are invited to advance the manufacturing technology by incorporating an *in situ* defect detection and correction capability into wire-feed or extrusion type metallic, plastic or composite AM.

In Phase I, contractors should prove the feasibility of integrating sensor feedback with appropriate software tools and computation resources to be able to detect defects during fabrication of parts with complex geometries, evaluating the potential impact of the defects to the part performance and the correction of those defects. Solutions sought include the software that can be integrated into the 3D printing workflow, hardware requirements to run that software for real-time data processing and sensors capable of operating in the build environment to provide data also in real time. The proposed approach should be demonstrable at least on the coupon scale for shapes such as circles or boxes.

Phase II, should demonstrate the feasibility of Phase I concepts to arrive at closed loop solutions to build parts in which information on the processing generated from gathering and analyzing sensor data is used for the prediction of part performance, unique to each individual part, as it is being built. Incorporation of defect correction during fabrication, rather than requiring a print to be scrapped and restarted should be demonstrated on sample parts.

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3. https://www.rocketlabusa.com/news/updates/rocket-lab-celebrates-100th-rutherford-engine-build/ [Rocket Lab News release -"Rocket Lab Celebrates 100th Rutherford Engine Build"]
4. https://www.nasa.gov/sites/default/files/atoms/files/msfcstd3716baseline.pdf [MSFC Technical Standard EM20 "Standard for Additively Manufactured Spaceflight Hardware by Laser Powder Bed Fusion in Metals" - MSFC-STD-3716]
5. https://www.thefabricator.com/additivereport/blog/wire-feed-3d-printing-grows-in-popularity [the Additive Report- "Wire-feed 3D printing grows in popularity"]

6. https://www.ibm.com/blogs/internet-of-things/iot-3d-printing-quality-manufacturing/ [IBM Internet of Things blog – "Why quality is the obstacle to mass adoption of 3D printing"]

7. https://cdn.eos.info/839090ec135565bc/b6a6ac17dca9/EOS_Whitepaper_Monitoring.pdf [Lukas Fuchs, Christopher Eischer, EOS GmbH Whitepaper - "In-process monitoring systems for metal additive manufacturing"]

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Expected TRL or TRL range at completion of the project: 2 to 3

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Software, Research

Desired Deliverables Description

In Phase I, concept studies documenting the feasibility of incorporating sensor data feedback and appropriate software tools and computation resources to be used to detect defects during fabrication of parts with complex geometries, evaluating the potential impact of the defects on the performance of the parts and the correction of those defects.

Phase II, scale demonstration of a printer with closed loop control that incorporates defect detection, identification and correction during fabrication. The complexity of defects that are detected and corrected as well as the size of the parts should demonstrate the challenges that would come up in full-scale use of the control processes. Printed part sizes should be at least 10 cm per side for cubes with detectable defects down to the mm scale or smaller. The defects should have a demonstrable effect on the part performance, such as a decrease in mechanical properties that is then corrected for by the process.

State of the Art and Critical Gaps

Additive Manufacturing is seeing rapidly expanding applications in many areas including in aerospace. Despite this growth in AM, fulling its full potential has always been limited by quality control issues and certification of the manufactured parts as each component that is built is unique[6]. Some work has begun to add defect detection and correction to powder based manufacturing processes such as Direct Metal Laser Sintering (DMLS)[7,8] and wire-feed AM[9]. There has however not been the requisite advance in ensuring that defect detection and identification is coupled with the real-time correction of those defects and ensuring final performance of the manufacture part in a particular application.

Gap: Real-time defect detection, identification and correction in AM processes, which would ensure the performance of the as-printed parts without relying on post production inspection processes, with parts built with acceptable form, fit, and function the first time, with sufficient documentation to allow direct entry into service has not been demonstrated.

Relevance / Science Traceability

This topic fits under STMD (Space Technology Mission Directorate). It supports Advanced Manufacturing of Lightweight Structures. Enhancing quality control in AM opens up its use in many industrial applications as well as for NASA use. In particular, in-space use of AM in future Gateway, Lunar and Mars exploration missions will require that parts that are produced are ready for use as-produced since there will be limitations in availability of material for re-printing as well as crew time and equipment for post-printing inspection.

Z4.05: Nondestructive Evaluation (NDE) Sensors, Modeling, and Analysis (SBIR)

Lead Center: LaRC

Participating Center(s): ARC, GSFC

Technology Area: 8.0.0 Science Instruments, Observatories & Sensor Systems

Related Subtopic Pointer(s): Z4.04 S1.06 S1.09 Z3.03 T11.04

Scope Description

NASA's Non-Destructive Evaluation (NDE) SBIR subtopic will address a wide variety of NDE disciplines. These disciplines include but are not limited to Structural Health Monitoring (SHM), Novel NDE Sensor Development and NDE Modeling and analysis. All three of these disciplines can be used on aerospace structures and materials systems including but not limited to Inconel, Titanium, Aluminum, Carbon Fiber, Avcoat, ATB-8, Phenolic Impregnated Carbon Ablator (PICA) and thermal blanket structures. Sensor systems, SHM and modeling can target any set of these materials in common aerospace configurations such as Micro-Meteoroids and Orbital Debris (MMOD) shielding, Truss Structures and Stiffened Structures. In addition NDE can target material and material systems in a wrought state, in process and NDE techniques that could be used to inspect additively manufactured components would be favored. Current NDE computational tools do not have sufficient resolution to provide representation on the order of Finite Element Model (FEM) models allowing for Digital Twin. Depending on the size of the critical flaw in the material system / structure this resolution can range from 500nm to 100cm realistically. As NDE tool resolution grows larger volumes of data are created and thus new computational tools are required. At the same time, low cost emerging computational hardware, such as Graphics Processing Units (GPUs), is enabling the growing use of advanced physics based models for improved NDE inspection and for advanced data analysis methods such as Machine Learning. In addition as NASA strives to go deeper and longer new tools need to be developed in order to support long duration space flight.

<u>NDE sensors and data analysis:</u>

Technologies enabling the ability to perform inspections on large complex structures will be encouraged. Technologies should provide reliable assessments of the location and extent of damage. Methods are desired to perform inspections in areas with difficult access in pressurized habitable compartments and external environments for flight hardware. Many applications require the ability to see through assembled conductive and/or thermal insulating materials without contacting the surface.

Techniques that can dynamically and accurately determine position and orientation of the NDE sensor are needed to automatically register NDE results to precise locations on the structure. Advanced processing and displays are needed to reduce the complexity of operations for astronaut crews who need to make important assessments quickly. NDE inspection sensors are needed for potential use on free-flying inspection platforms. Integration of wireless systems with NDE may be of significant utility. It is strongly encouraged that proposals provide an explanation of how the proposed techniques and sensors will be applied to a complex structure. Examples of structural components include but are not limited to multi-wall pressure vessels, batteries, tile, thermal blankets, micrometeoroid shielding, International Space Station (ISS) Radiators or aerospace structural components.

Additionally, techniques for quantitative data analysis of sensor data are desired. It is also considered highly desirable to develop tools for automating detection of material Foreign Object Debris (FOD) and/or defects and evaluation of bondline and in-depth integrity for light-weight rigid and/or flexible ablative materials are sought. Typical internal void volume detection requirements for ablative materials are on the order of less than 6mm and bondline defect detection requirements are less than 25mm.

Additive manufacturing is rapidly becoming a manufacturing method targeting fracture critical components and as such NDE requirements will become more stringent. Additively manufactured components represent a novel challenge for NDE due to the layering nature of the process and it effect on diffracting energy sources. Additive manufacturing also offers an additional chance for in-process inspection. Development of NDE techniques, sensors and methods addressing these issues would be highly desired. But techniques addressing weld inspection will also be considered. Most of the aerospace components will be metallic in nature and critical flaws are on the range of 1mm or smaller and can be volumetric or fracture like in nature.

Structural Health Monitoring (SHM):

Future manned space missions will require spacecraft and launch vehicles that are capable of monitoring the structural health of the vehicle and diagnosing and reporting any degradation in vehicle capability. This subtopic seeks new and innovative technologies in Structural Health Monitoring (SHM) and Integrated Vehicle Health Management (IVHM) systems and analysis tools.

Techniques sought include modular/low mass-volume systems, low power, low maintenance systems, and systems that reduce or eliminate wiring, as well as stand-alone smart-sensor systems that provide processed data as close to the sensor as practical and systems that are flexible in their applicability. Examples of possible system are: Surface Acoustic Wave (SAW)-based sensors, passive wireless sensor-tags, flexible sensors for highly curved surfaces direct-write film sensors, and others. Damage detection modes include leak detection, ammonia detection, micrometeoroid impact and others. Reduction in the complexity of standard wires and connectors and enabling sensing functions in locations not normally accessible with previous technologies is also desirable. Proposed techniques should be capable of long term service with little or no intervention. Sensor systems should be capable of identifying material state awareness and distinguish aging related phenomena and damage related conditions. It is considered advantageous that these systems perform characterization of age-related degradation in complex composite and metallic materials. Measurement techniques and analysis methods related to quantifying material thermal properties, elastic properties, density, microcrack formation, fiber buckling and breakage, etc. in complex composite material systems, adhesively bonded/built-up and/or polymer-matrix composite sandwich structures are of particular interest. Some consideration will be given to the IVHM /SHM ability to survive in on-orbit and deep space conditions, allow for additions or changes in instrumentation late in the design/development process and enable relocation or upgrade on orbit. System should allow NASA to gain insight into performance and safety of NASA vehicles as well as commercial launchers, vehicles and payloads supporting NASA missions. Inclusion of a plan for detailed technical operation and deployment is highly favored.

NDE Modeling:

Technologies sought under this SBIR include near real-time realistic NDE and SHM simulations and automated data reduction/analysis methods for large data sets. Simulation techniques will seek to expand NASA's use of physics based models to predict inspection coverage for complex aerospace components and structures and to utilize inverse methods for improved defect characterization. Analysis techniques should include optimized automated reduction of NDE/SHM data for enhanced interpretation appropriate for detection/ characterization of critical flaws in space flight structures and components, and may involve methods such as machine learning, domain transformation, etc. NASA's interest area is light weight structural materials for space flight such as composites and thin metals. Future purposes will include application to long duration space vehicles, as well as validation of SHM systems.

Techniques sought include advanced material-energy interaction (i.e., NDE) simulations for high-strength lightweight material systems and include energy interaction with realistic damage in complex 3D component geometries (such as bonded/built-up structures). Primary material systems can include metals but it is highly desirable to target composite structures. NDE/SHM techniques for simulation can include ultrasonic, laser, Micro- wave, Terahertz, Infrared, X-ray, X-ray Computed Tomography, Fiber Optic, backscatter X-Ray and eddy current. It is assumed that any data analysis methods will be focused on NDE techniques with high resolution high volume data. Modeling efforts should be physics based and it is desired they can account for material aging characteristics and induced damage, such as micrometeoroid impact. Examples of damage states of interest include delamination, microcracking, porosity, fiber breakage. Techniques sought for data reduction/interpretation will yield automated and accurate results to improve quantitative data interpretation to reduce large amounts of NDE/SHM data into a meaningful characterization of the structure. It is advantageous to use co-processor/accelerator based hardware [e.g., GPUs, Field Programmable Gate Arrays FPGA)] for simulation and data reduction. Combined simulation and data reduction/interpretation techniques should demonstrate ability to guide the development of optimized NDE/SHM techniques, lead to improved inspection coverage predictions, and yield quantitative data interpretation for damage characterization.

References:

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Gregory, E. D.; and Juarez, P. D.: In-situ Thermography of Automated Fiber Placement Parts: Review of Progress in Quantitative Nondestructive Evaluation. Presented at QNDE - Review of Progress in Quantitative NDE, July 17-21, 2017, Provo, Utah.

Gregory, E. D.; Campbell Leckey, C. A.; and Schneck, W. C.: A Versatile Simulation Framework for Elastodynamic Modeling of Structural Health Monitor

Expected TRL or TRL range at completion of the project: 1 to 6

Desired Deliverables of Phase II

Working prototype or software of proposed product, along with full report of development, validation, and test results.

Desired Deliverables Description

Phase I Deliverables - For NDE sensors focused proposals, lab prototype and feasibility study or software package including applicable data or observation of a measurable phenomenon on which the prototype will be built. For NDE modeling focused proposals, feasibility study, including demonstration simulations and data interpretation algorithms, proving the proposed approach to develop a given product (TRL 2-4). Inclusion of a proposed approach to develop a given methodology to Technology Readiness Level (TRL) of 2-4. All Phase I's will include minimum of short description for Phase II prototype/software. It will be highly favorable to include description of how the Phase II prototype or methodology will be applied to structures.

Phase II Deliverables - Working prototype or software of proposed product, along with full report of development, validation, and test results. Prototype or software of proposed product should be of Technology Readiness Level (TRL 5-6). Proposal should include plan of how to apply prototype or software on applicable structure or material system. Opportunities and plans should also be identified and summarized for potential commercialization.

State of the Art and Critical Gaps

NDE Tools for flight still do not have sufficient resolution to provide representation on the order of Finite Element Models (FEM) allowing for Digital Twin. Also as NDE tools grow and sensors get faster larger volumes of data are created and thus new computational tools are required. At the same time, low cost emerging computational hardware, such as GPUs, is enabling the growing use of advanced physics based models for improved NDE inspection and for advanced data analysis methods such as Machine Learning. Development of new techniques are enabling Orion to meet its 100% inspected mission directive. In addition as NASA strives to go deeper and longer new tools need to be developed in order to support long duration space flight.

Relevance / Science Traceability

Several missions could benefit from technology developed in the Area of nondestructive evaluation. Currently NASA is returning to manned space flight. The Orion/Space Launch System and Artemis program has continuing to have inspection difficulties and continued development and implementation of NDE tools will serve to keep our missions flying safely. Currently Orion is using several techniques and prototypes that have been produced under the NDE SBIR topic. Space Launch System is NASA’s next heavy lift system. Capable of sending hundreds of metric tons into orbit. Inspection of the various systems is on-going and will continue to have challenges such as verification of the friction stir weld on the fuel tanks. As NASA continues to push in deeper space smart structures that are instrumented with structural health monitoring system can provide real time mission critical information of the status if the structure.

Focus Area 16: Ground & Launch Processing

Lead MD: HEOMD

Participating MD(s): STTR

Ground processing technology development prepares the agency to test, process and launch the next generation of rockets and spacecraft in support of NASA's exploration objectives by developing the necessary ground systems, infrastructure and operational approaches.

This topic seeks innovative concepts and solutions for both addressing long-term ground processing and test complex operational challenges and driving down the cost of government and commercial access to space. Technology infusion and optimization of existing and future operational programs, while concurrently maintaining continued operations, are paramount for cost effectiveness, safety assurance, and supportability.

A key aspect of NASA's approach to long term sustainability and affordability is to make test, processing and launch infrastructure available to commercial and other government entities, thereby distributing the fixed cost burden among multiple users and reducing the cost of access to space for the United States.

Unlike previous work focusing on a single kind of launch vehicle such as the Saturn V rocket or the Space Shuttle, NASA is preparing common infrastructure to support several different kinds of spacecraft and rockets that are in development. Products and systems devised at a NASA center could be used at other launch sites on earth and eventually on other planets or moons.

Specific emphasis to substantially reduce the costs and improve safety/reliability of NASA's test and launch operations includes development of ground test and launch environment technology components, system level ground test systems for advanced propulsion, autonomous control technologies for fault detection, isolation, and recovery, including autonomous propellant management, and advanced instrumentation technologies including Intelligent wireless sensor systems.

H10.01: Advanced Propulsion Systems Ground Test Technology (SBIR)

Lead Center: SSC

Participating Center(s): KSC

Technology Area: 13.0.0 Ground and Launch Systems Processing

Related Subtopic Pointer(s): T2.04 Z10.03

Scope Title

Advanced Propulsion Test Technology Development

Scope Description

Rocket propulsion development is enabled by rigorous ground testing to mitigate the propulsion system risks that are inherent in spaceflight. This is true for virtually all propulsive devices of a space vehicle including liquid and solid rocket propulsion, chemical and non-chemical propulsion, boost stage, in-space propulsion and so forth. It involves a combination of component and engine-level testing to demonstrate the propulsion devices were designed to meet the specified requirements for a specified operational envelope over robust margins and shown to be sufficiently reliable prior to its first flight.

This topic area seeks to develop advanced ground test technology components and system level ground test systems that enhance Chemical and Advanced Propulsion technology development and certification. The goal is to advance propulsion ground test technologies to; enhance environment simulation, minimize test program time, cost and risk; and meet existing environmental and safety regulations. It is focused on near-term products that augment and enhance proven, state-of-the-art propulsion test facilities. This project is especially interested in ground test and launch environment technologies with potential to substantially reduce the costs and improve safety/reliability of NASA's test and launch operations.

In particular, technology needs include stable combustion of oxygen and hydrogen in a low pressure duct, developing robust materials, and advanced instruments and monitoring systems capable of operating in extreme temperature and harsh environments.

This subtopic seeks innovative technologies in the following areas:

- Design of technology/techniques for oxygen injection into a duct that assures stable combustion with hot (>1700°R) hydrogen at low pressure (<25 psia), having an oxidizer to fuel mixture ratio of 9 for an oxygen flow rate of approximately 2.7 lbm/sec. This technology solution must be extensible to a system having an oxygen flow rate of approximately 270 lbm/sec.
- Devices for measurement of pressure, temperature, strain and radiation in a high temperature and/or harsh environment.
- Development of innovative rocket test facility components (e.g., valves, flowmeters, actuators, tanks, etc.) for ultra-high pressure (>8000 psi), high flow rate (>100 lbm/sec) and cryogenic environments.
- Robust and reliable component designs which are oxygen compatible and can operate efficiently in high vibro-acoustic, environments.
- Advanced materials to resist high-temperature (<4400°F), hydrogen embrittlement and harsh environments.
- Tools using computational methods to accurately model and predict system performance that integrate simple interfaces with detailed design and/or analysis software, are required. Stennis Space Center (SSC) is interested in improving capabilities and methods to accurately predict and model the transient fluid structure interaction between cryogenic fluids and immersed components to predict the dynamic loads and frequency response of facilities.
- Improved capabilities to predict and model the behavior of components (valves, check valves, chokes, etc.) during the facility design process are needed. This capability is required for modeling components in high pressure (to 12,000 psi), with flow rates up to several thousand lb/sec, in cryogenic environments and must address two-phase flows. Challenges include: accurate, efficient, thermodynamic state models; cavitation models for propellant tanks, valve flows, and run lines; reduction in solution time; improved stability; acoustic interactions; fluid-structure interactions in internal flows.

For all above technologies, research should be conducted to demonstrate technical feasibility during Phase I and show a path towards Phase II hardware/software demonstration with delivery of a demonstration unit or software package for NASA testing at the completion of the Phase II contract.

References

https://www.nasa.gov/centers/stennis/home/index.html

https://technology.ssc.nasa.gov/

Expected TRL or TRL range at completion of the project: 4 to 6

Desired Deliverables of Phase II

Prototype, Hardware, Software

Desired Deliverables Description

For all above technologies, research should be conducted to demonstrate technical feasibility during Phase I and show a path toward Phase II hardware/software demonstration, with delivery of a demonstration unit or software package for NASA testing at the completion of the Phase II contract.

State of the Art and Critical Gaps

This subtopic seeks to provide technological advances that provide the ability to test next generation rocket propulsion systems while reducing costs, increasing efficiencies and improving safety/reliability within the static rocket engine test environment. Specifically, the goal is to reduce costs of propellants and other fluids;

reduce logistics costs; reduce times required for ground processing and launch; reduced mission risk; and reduced hazards exposure to personnel.

There is a broad range of technologies needed to support rocket propulsion testing. Dynamic fluid flow simulation is used to characterize and model the facility performance in a highly dynamic environment with NASA, Department of Defense (DoD) and commercial customers. Multiple issues remain with modeling combustion instabilities and component/facility performance. These issues can have catastrophic results if not understood completely. New test programs will require the materials to withstand extreme temperatures and harsh environments. Next generation testing requires the ability to produce very high temperature hydrogen at high near-continuous flow rates to verify component and facility performance. The extreme and harsh environment also requires advancements in mechanical components and instrumentation.

Relevance / Science Traceability

Subtopic is relevant to the development of liquid propulsion systems development and verification testing in support of the Human Exploration and Mission Operations Directorate (HEOMD), all test programs at SSC and other propulsion system development centers.

H10.02: Autonomous Operations Technologies for Ground and Launch Systems (SBIR)

Lead Center: KSC

Participating Center(s): ARC, LaRC, SSC

Technology Area: 4.0.0 Robotics, Telerobotics and Autonomous Systems

Related Subtopic Pointer(s): S5.03 S5.05

Scope Description

Autonomous Operations Technologies (AOT) are required to reduce operations and maintenance (O&M) costs of ground and payload processing operations on ground, and to increase ground systems availability to support mission operations. These technologies will also be required for extended surface O&M on the Moon and Mars. Furthermore, AOT are required in activities where human intervention/interaction/presence needs to be minimized, such as in hazardous locations/operations and in support of remote operations.

AOT performs functions such as systems and components' fault prediction and diagnostics, anomaly detection, fault detection and isolation, and enables various levels of autonomous control and recovery from faults, where recovery may include system repair and/or reconfiguration. AOT are enabled by Health Management (HM) technologies, methodologies, and approaches; command, monitoring and control architectures; computing architectures; software for decision-making and control; and intelligent components and devices.

AOT will be integrated in activities performed by rocket engine test facilities, propellant servicing systems, and processing and launch of vehicles and payloads. AOT will complement In-Situ Resources Utilization (ISRU) operations. AOT will enable surface O&M, which requires high degree of autonomy and reliability for unattended operations during extended periods of time. AOT enables Autonomous Propellant Management (APM), which requires unattended or minimally attended storage, transfer, monitoring, and sampling of cryogenic propellants, or other propellants use in launch systems. APM includes pre-planned nominal processes, such as vehicle fill and drain, as well as contingency and off-nominal processes, such as emergency safing, venting and system reconfiguration.

AOT will enable the autonomous command, monitoring and control of the overall system, resulting from the integration of loading systems and all other associated support systems involved in the loading process. AOT will also support tasks such as systems setup, testing and checkout, troubleshooting, maintenance, upgrades and repair. These additional tasks drive the need for autonomous element-to-element interface connection and separation, multi-element inspection, and recovery of high value cryogenic propellants and gases to avoid system losses.

The AOT autonomy software will include both prerequisite control logic (PCL) and reaction control logic (RCL) programming, and may utilize some form of machine learning, neural network or other form of artificial intelligence to adapt to degraded system components or other form of off-nominal conditions.

In addition to cryogenic and other propellants, propellant management systems may utilize additional commodities to prepare a vehicle for launch, such as high pressure gases for purges, pressurization, or conditioning, and may include power and data interfaces with the vehicle to configure vehicle valves or other internal systems and utilize on-board instrumentation to gain visibility into the vehicle during loading.

Specifically, this subtopic seeks the:

- Standardization of architectures and interfaces
- Standardization of ground systems design (design for maintainability, commonality, reusability)
- Development of ground technologies for automated/autonomous cryogenic loading and servicing of commodities for ground and lunar payloads
- Development of high-fidelity physics-based cryogenic-thermal models and simulations capable of real-time and faster than real-time performance
    - Development of high-fidelity models and simulations for complex payload systems
    - Development of automated/autonomous algorithms for ground systems applications
    - Development of Test and Evaluation (T&E), and verification and validation (V&V) methods for automated/autonomous algorithms, models and simulations
- Development of technologies for ground systems Health Determination and Fault Management
    - Prediction, prognosis and anomaly detection algorithms and applications
    - Detection, isolation, and recovery of systems and components faults and degradation
    - Development of Test and Evaluation (T&E), and verification and validation (V&V) methods for Health Determination and Fault Management algorithms and applications
- Development of technologies for automated/autonomous Planning and Scheduling (P&S)
    - Automated/Autonomous Assets management tools and applications
    - Scheduling and prioritization algorithms and applications
    - Human-machine information interactions
- Development of technologies for automated/autonomous Inspection, Maintenance and Repair
    - Use of robotic caretakers for inspection, maintenance and repair needs
    - Self-diagnosis in systems and components (Condition Based Maintenance)
- Development of technologies for enhanced Logistics and Reliability
    - Optimization/Reduction of logistics needs (design for maintainability, commonality, reusability)
    - Commonality of maintenance equipment, tools and consumables
    - Automated/autonomous assets and personnel location and condition
    - Intelligent Devices (sensors, actuators and electronics with self-diagnosis capabilities, calibration on demand, self-healing capabilities, etc.)

For all above technologies, research should be conducted to demonstrate technical feasibility during Phase I; show a path toward Phase II demonstration; deliver a demonstration package for NASA testing in operational or analog test environments at the completion of the Phase II contract. Successful Phase II technologies will be candidates for integration and demonstration in the existing Advanced Ground Systems Maintenance (AGSM) Integrated Health Management (IHM) Architecture, deployed at Kennedy Space Center (KSC).

References

NASA Technology Roadmaps (https://www.nasa.gov/offices/oct/home/roadmaps/index.html)

NASA Strategic Space Technology Investment Plan (https://www.nasa.gov/sites/default/files/atoms/files/strategic_space_technology_investment_plan_508.pdf)

Expected TRL or TRL range at completion of the project: 5 to 8

Desired Deliverables of Phase II

Prototype, Hardware, Software

Desired Deliverables Description

Phase I Deliverables - Research, identify and evaluate candidate technologies or concepts for systems and components fault detection, isolation and recovery, fault prediction and diagnosis, and decision-making algorithms for control to enable autonomy of ground systems. Demonstrate the technical feasibility and show a path towards a demonstration. Concept methodology should include the path for adaptation of the technology, infusion strategies (including risk trades) and business model. It should identify improvements over the current state of the art for both operations and systems development and the feasibility of the approach in a multi-customer environment. Bench or lab-level demonstrations are desirable. Deliverables must include a report documenting findings.

Phase II Deliverables - Emphasis should be placed on developing, prototyping and demonstrating the technology under simulated operational conditions using analog earth-based systems including dynamic events such as commodity loading, disconnect or engine testing. Deliverables shall include a report outlining the path showing how the technology could be matured and applied to mission-worthy systems, functional and performance test results and other associated documentation. Deliverable of a functional prototype (software and hardware) is expected at the completion of the Phase II contract. The technology concept at the end of Phase II should be at a TRL of 6 or higher.

State of the Art and Critical Gaps

There are presently critical gaps between state-of-the-art and needed technology maturation levels as follows:

1) High-fidelity, physics-based, cryogenic-thermal simulations with real-time and faster than real-time performance (Current TRL is 5; Required TRL is 9)
2) Simulation Component libraries to support rapid prototyping of cryogenic-thermal models (Current TRL is 5; Required TRL is 9)
3) Supervisory control software for autonomous control and recovery of propellant loading systems and infrastructure (Current TRL is 5; Required TRL is 9)
4) Software development tools to support rapid prototyping of autonomous control applications (Current TRL is 5; Required TRL is 9)
5) Architecture for integrated autonomous operations (Current TRL is 5; Required TRL is 9)

Relevance / Science Traceability

In addition to reducing O&M costs in ground operations, this subtopic provides Human Exploration Operations Mission Directorate (HEOMD) with an on-ramp for technologies that enable the unattended setup, operation and maintenance of ground systems and systems on the surfaces of other planets and moons. With the recently directive from the President to accelerate the landing of astronauts on the Moon and provide sustainable presence after 2028, these technologies have become more relevant. These types of technology development are identified in the NASA Strategic Technology Area (TA) roadmaps, published by the Office of the Chief Technologist, under TA4 - Robotics and Autonomous Systems, and TA13- Ground and Launch Systems roadmaps.

This subtopic produces technologies which will also be of use to the Space Technology Mission Directorate (STMD) program. Autonomous strategies have crosscutting value in other applications and with other mission directorates.

T13.01: Intelligent Sensor Systems (STTR)

Lead Center: SSC

Participating Center(s):

Technology Area: 4.0.0 Robotics, Telerobotics and Autonomous Systems

Related Subtopic Pointer(s): S5.05 S1.09 Z8.10 A2.01

Scope Title

Advanced Instrumentation for Rocket Propulsion Testing

Scope Description

Rocket propulsion system development is enabled by rigorous ground testing to mitigate the propulsion system risks inherent in spaceflight. Test articles and facilities are highly instrumented to enable a comprehensive analysis of propulsion system performance. Advanced instrumentation has the potential for substantial reduction in time and cost of propulsion systems development, with substantially reduced operational costs and evolutionary improvements in ground, launch and flight system operational robustness.

Advanced instrumentation would provide a wireless, highly flexible instrumentation solution capable of measurement of heat flux, temperature, pressure, strain, and/or near-field acoustics. Temperature and pressure measurements must be acquired from within the facility mechanical systems or the rocket engine itself. These sensors would be capable of addressing multiple mission requirements for remote monitoring such as vehicle health monitoring in flight systems, autonomous vehicle operation, or instrumenting inaccessible measurement locations, all while eliminating cabling and auxiliary power. Rocket propulsion test facilities also provide excellent test beds for testing and using the innovative technologies for possible application beyond the static propulsion testing environment.

This subtopic seeks to develop advanced wireless instrumentation capable of performing some processing, gathering sensory information and communicating with other connected nodes in the network. Sensor systems should have the ability to provide the following functionality:

- Acquisition and conversion to engineering units for quantifying heat flux, temperature, pressure, strain, and/or near-field acoustics such that it contributes to rocket engine system performance analysis within established standards for error and uncertainty.
- Capable of in-place calibrations with The National Institute of Standards and Technology (NIST) traceability.
- Collected data must be time stamped to facilitate analysis with other collected data sets.
- Transfer data in real-time to other systems for monitoring and analysis.
- Interface to flight qualified sensor systems, which could be used for multi-vehicle use.

- Determine the quality of the measurement and instrument state-of-health.
- Self-contained to collect information and relay measurements through various means by a sensor-web approach to provide a self-healing, auto-configuring method of collecting data from multiple sensors, and relaying for integration with other acquired data sets.
- Function reliably in extreme environments, including rapidly changing ranges of environmental conditions, such as those experienced in space. These ranges may be from extremely cold temperatures, such as cryogenic temperatures, to extremely high temperatures, such as those experienced near a rocket engine plume.

References

Fernando Figueroa, Randy Holland, David Coote, "NASA Stennis Space Center integrated system health management test bed and development capabilities," Proc. SPIE 6222, Sensors for Propulsion Measurement Applications, 62220K (10 May 2006);

J. Schmalzel ; F. Figueroa ; J. Morris ; S. Mandayam ; R. Polikar, "An architecture for intelligent systems based on smart sensors," IEEE Transactions on Instrumentation and Measurement (Volume: 54 , Issue: 4 , Aug. 2005)

S. Rahman, R. Gilbrech, R. Lightfoot, M. Dawson, "Overview of Rocket Propulsion Testing at NASA Stennis Space Center," NASA Technical Report SE-1999-11-00024-SSC

David J. Coote, Kevin P. Power, Harold P. Gerrish, and Glen Doughty. "Review of Nuclear Thermal Propulsion Ground Test Options", 51st AIAA/SAE/ASEE Joint Propulsion Conference, AIAA Propulsion and Energy Forum, (AIAA 2015-3773)

H. Ryan, W. Solano, R. Holland, W. Saint Cyr, S. Rahman, "A future vision of data acquisition: distributed sensing, processing, and health monitoring," IMTC 2001. Proceedings of the 18th IEEE Instrumentation and Measurement Technology Conference. Rediscovering Measurement in the Age of Informatics (Cat. No.01CH 37188)

https://www.nasa.gov/sites/default/files/atoms/files/propulsion_testing.pdf

https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20040053475.pdf

https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20090026441.pdf

https://www.nasa.gov/centers/wstf/pdf/397001main_Prop_test_data_acq_cntl_sys_DACS_doc.pdf

Expected TRL or TRL range at completion of the project: 3 to 6

Desired Deliverables of Phase II

Prototype, Hardware, Software

Desired Deliverables Description

For all above technologies, research should be conducted to demonstrate technical feasibility during Phase I and show a path towards Phase II hardware/software demonstration with delivery of a demonstration unit or software package for NASA testing at the completion of the Phase II contract.

State of the Art and Critical Gaps

Highly modular, remote sensors are of interest to many NASA tests and missions. Real-time data from sensor networks reduces risk and provides data for future design improvements. Wireless sensors offer a highly flexible solution for scientists and engineers to collect data remotely. They can be used for thermal, structural and acoustic measurement of systems and subsystems and also provide emergency system halt instructions in the case of leaks, fire or structural failure. Other examples of potential NASA applications include 1) measuring temperature, strain, voltage and current from power storage and generation systems, 2) measuring pressure, strain and temperature in pumps and pressure vessels and 3) measuring strain in test structures, ground support equipment and vehicles, including high-risk deployables.

There are many other applications that would benefit from increased, real-time sensing in remote, hard-to-test locations. For example, sensor networks on a vehicle body can give measurement of temperature, pressure, strain and acoustics. This data is used in real time to determine safety margins and test anomalies. The data is also used post-test to correlate analytical models and optimize vehicle and test design. Because these sensors are small and low mass, they can be used for ground test and for flight. Sensor module miniaturization will further reduce size, mass and cost.

No existing wireless sensor network option meets NASA's current needs for flexibility, size, mass and resilience to extreme environments.

Relevance / Science Traceability

This subtopic is relevant to the development of liquid propulsion systems development and verification testing in support of the Human Exploration and Mission Operations Directorate. Supports all test programs at Stennis Space Center (SSC) and other propulsion system development centers. Potential advocates are the Rocket Propulsion Test (RPT) Program Office and all rocket propulsion test programs at SSC.

Focus Area 17: Thermal Management Systems

Lead MD: STMD

Participating MD(s): SMD

From the smallest satellite to the most complicated human rated spacecraft, thermal is seen as an enabling function to a vehicle. Temperatures must be maintained within design limits, whether those be cryogenic systems for science instruments, or comfortable shirt sleeve operations temperatures for crew missions. As missions evolve and waste energy rejection becomes more of a demand, NASA seeks components for both active and passive thermal systems. Such components complete the thermal cycle which includes waste energy acquisition, transport, rejection/storage, and insulation. The intended goal for any advanced thermal development is to enable new mission concepts while maintaining minimal impact to thermal system mass, volume, and power to maintain a spacecraft at specific temperature limits.

S3.06: Thermal Control Systems (SBIR)

Lead Center: GSFC

Participating Center(s): JPL, LaRC, MSFC

Technology Area: 14.0.0 Thermal Management Systems

Related Subtopic Pointer(s): T12.05 H5.02 Z2.01 Z13.01

Future spacecraft and instruments for NASA's Science Mission Directorate (SMD) will require increasingly sophisticated thermal control technology. Innovative proposals for the cross-cutting thermal control discipline are sought in the following areas/scopes. Research should be conducted to demonstrate technical feasibility during Phase I and show a path toward a Phase II hardware demonstration. Phase II should deliver a demonstration unit for NASA testing at the completion of the Phase II effort.

Scope Title
Dust Mitigation Thermal Coatings

Scope Description

Thermal coatings are an integral part of a space mission and are essential to the survivability of the spacecraft and instrument. Coating of the radiator with desired emissivity and absorptivity on the radiator surface provides a passive means for instrument temperature control. The utilization of variable emittance devices further enables active control of the instrument temperature when the heat output from the instrument or the thermal environment of the radiator changes. With NASA's new initiative to return to the moon, a new coating technology that will keep surfaces clean and sanitary is needed. New coating formulations utilizing durable, anti-contamination and self-cleaning properties that will disallow the accumulation of dust, dirt and foreign materials are highly desirable. These coatings can have low absorptance and high IR emittance properties or be transparent for use on existing thermal coating systems. The goal of this technology is to preserve optimal long-term performance of spacecraft and habitation components and systems.

References

The following website provides links to some references for dust mitigation coatings such as lotus thermal coatings:

https://ntrs.nasa.gov/search.jsp?R=20150020486

Expected TRL or TRL range at completion of the project: 2 to 5

Desired Deliverables of Phase II

Prototype, Analysis, Hardware

Desired Deliverables Description

- Successfully develop the formulations of the coating that leads to the desired dust mitigation.
- Samples of the hardware for further testing at NASA facilities.
- Results of performance characterization tests.
- Results of stability test of the coating formulations and its mechanical durability test under the influence of simulated space and lunar environmental conditions.
- Final report.

State of the Art and Critical Gaps

There are limited options for durable, stable thermal control coatings that are dust shedding in charging environments. Current state of the art, sprayable radiation stable coatings are able to coat complex, irregular surfaces, but they are porous and will become imbedded with dust and particulates. Other surface films tend to be less optically stable and may charge in the plasma environment thereby attracting lunar regolith to their surfaces. Mirrors have the limitations of requiring flat surfaces and are not conformal in nature. Currently, no single thermal control surface appears to provide stability, durability, and meet optical property requirements for sustained durations in space and lunar environments.

Relevance / Science Traceability

Many Science Mission Directorate (SMD) missions will greatly benefit from this dust mitigation thermal coating technology: any lunar-relating project, and projects involved with robotic science rovers and landers.

Scope Title

Heat Pumps for High Temperature Sink Environments

Scope Description

Operations in extreme environments where the environment sink temperature exceeds spacecraft hardware limits will require active cooling if long duration survivability is expected. Robotic science rovers operating on the Lunar surface over diurnal cycles face extreme temperature environments. Landers with clear views to sky can often achieve sufficient heat rejection with a zenith or, if sufficiently far from the equator, an anti-sun facing radiator. However, science rovers must accommodate random orientations with respect to the surface and Sun. Terrain features can then result in hot environment sink temperatures beyond operating limits, even with shielded and articulated radiator assemblies. Lunar dust degradation on radiator thermo-optical properties can also significantly affect effective sink temperatures. During the Lunar night, heat rejection paths must be turned off to preclude excessive battery mass or properly routed to reclaim nuclear-based waste heat.

Science needs may drive rovers to extreme terrains where steady heat rejection is not otherwise possible. The paradigm of swarms or multiple smaller rovers enabled by commercial lander opportunities will need to leverage standard rover bus designs to permit flexibility. A heat pump provides the common extensibility for thermal control over the lunar diurnal. Active cooling systems or heat pumps are commonly used on spacecraft. Devices used include mechanical cryocoolers and thermoelectric coolers. For higher loads, vapor compression systems have been flown and, more recently, reverse turbo Brayton-cycle coolers are being developed under NASA's Game Changing program for high load, high temperature lift cryocoolers. However, technology gaps exist for mid-range heat pumps that are suitable for small science rovers where internal heat dissipation may range from 20 Watts to 100 Watts.

References

Apollo Lunar Roving Vehicle Documentation: https://www.hq.nasa.gov/alsj/alsj-LRVdocs.html

Apollo Experience Report - Thermal Design of Apollo Lunar Surface Experiments Package - https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19720013192.pdf

Thermal Considerations for Designing the Next Lunar Lander: https://aip.scitation.org/doi/10.1063/1.2437438

Expected TRL or TRL range at completion of the project: 2 to 5

Desired Deliverables of Phase II

Prototype, Analysis, Research

Desired Deliverables Description

- Conceptual design
- Physics-based analysis or model
- Proof-of-concept hardware
- Final report

State of the Art and Critical Gaps

Specifically, heat pump systems are needed for the following:

- Temperature lift from a cold-side at < 50 deg. C to an environmental sink temperature as high as 75 deg. C (temperature lift of 50 deg. C or heat rejection rate of 230 W/m^2), with a system coefficient of performance > 2.5.
- System should be tolerant of being powered down during the lunar night and re-started during the day reliably over multiple diurnals.
- Exported vibrations, if any, should be minimal for compatibility with science instruments.

Novel heat pump systems are desired. Enabling improvements over state-of-the-art systems are also welcome.

Relevance / Science Traceability

NASA's lunar initiative and Planetary Science Division form the primary customer base for this technology. Missions that directly address the NRC's Planetary Science Decadal Survey are included.

Scope Title

Software Improvements for Integrated Thermal-Structural-Optical Performance Analysis

Scope Description

Sensitive optical components and systems, as are frequently used on science missions, require structural, thermal, and optical performance (STOP) analysis in their design process to validate optical system performance in expected mission environments. This analysis often utilizes models generated in software unique to each field. The models, or their outputs, are transferred between analysts, creating iterative and time consuming design cycles. Software packages do exist that provide multiphysics analysis or coupling between analysis programs; however, the packages can be difficult to learn/implement and cost prohibitive. A new software is needed that can provide concurrent (or near concurrent) analysis using analysis programs in use by NASA, is straightforward to learn, and can be used by the growing number of low cost flight programs.

References

Nearly all spacecraft with optical components require some level of STOP analysis.

Structural-Thermal-Optical performance (STOP) Analysis:
https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20150017758.pdf

Expected TRL or TRL range at completion of the project: 5 to 9

Desired Deliverables of Phase II

Analysis, Software

Desired Deliverables Description

A successful STOP analysis software program will be applicable to any optical system and capable of interfacing with mechanical, structural, thermal, and optical analysis software used at NASA to provide concurrent (or near concurrent) analysis capability by users of the various disciplines. Additionally, the software must be straightforward to use and easy to learn.

State of the Art and Critical Gaps

STOP analyses have traditionally required a time-consuming, iterative approach where models, or their outputs, have been transferred among the respective structural, optical, and thermal analysts. Recently, multi-physics software package have become available that can centralize the analysis into one program. However, these can be cumbersome to learn, lack heritage, and can be cost-prohibitive to use.

Relevance / Science Traceability

Any mission/project in which optical components or systems are used will require STOP analyses to be completed. As such, a general, integrated, and easy-to-use STOP software is a common desire among engineers of different disciplines.

Scope Title

Advanced Manufacturing of Loop Heat Pipe Evaporator

Scope Description

A loop heat pipe (LHP) is a very versatile heat transport device that has been used on many spacecraft. At the heart of the LHP is the evaporator and reservoir assembly. During the manufacturing, tedious processes are required to machine the porous primary wick and insert into the evaporator, and both ends of the wick need to be sealed for liquid and vapor separation. One commonly used method for vapor seal is to use a bimetallic knife edge joint, which is more prone to failure over long term exposure to thermal cycles and shock and vibration. These tedious manufacturing processes add to the cost of the traditional LHP. A new manufacturing technique that will allow the primary wick to be welded directly to the reservoir without the use of a knife-edge seal is needed in order to reduce the cost and enhance the reliability.

References

Richard, Bradley, et al., "Loop Heat Pipe Wick Fabrication via Additive Manufacturing," NASA Thermal & Fluid Analysis Workshop, August 21-25, 2017, Marshall Space Flight Center, Huntsville, AL

Expected TRL or TRL range at completion of the project: 4 to 6

Desired Deliverables of Phase II

Prototype, Analysis, Hardware

Desired Deliverables Description

- Successfully develop advanced techniques to manufacture the LHP evaporator and reservoir assembly.
- Demonstrate the performance of the evaporator/reservoir performance in an LHP setup.
- Final report.

State of the Art and Critical Gaps

The LHP evaporator contains a porous wick which provides the capillary pumping capability to sustain the fluid flow in the loop. The smaller the size, the higher the capillary pumping capability. On the other hand, the smaller the pore size, the higher the flow resistance which must be overcome by the capillary force. Traditional sintered metal wicks have a pore size on the order of 1 micron and porosity around 0.4-0.6. In order to replace the traditional porous wick, the new wick produced by the advanced manufacturing technology must have comparable pore size and porosity. The smallest pore size currently produced by direct metal laser sintering is on the order of 10 microns.

Relevance / Science Traceability

Traditional LHPs are used on many NASA missions including ICESat (Ice, Cloud, and Land Elevation Satellite), ICEsat-2, Swift, Aura, Geostationary Operational Environmental Satellite (GOES), Geostationary Operational Environmental Satellite-R Series (GOES-R), and Surface Water and Ocean Topography (SWOT). Similar future SMD missions, especially those using small satellites, can greatly benefit from this technology.

Scope Title

Approaches and Techniques for Lunar Surface Payload Survival

Scope Description

The lunar environment poses significant challenges to small, low power (~100W or less) payloads, rovers, and landers required for lunar science. The lunar day/night cycle is approximately one earth month. During that time, surface temperatures on the lunar surface can reach 400K at local solar noon or drop to below 100K during the lunar night, even colder in permanently shadowed regions. These hot and cold conditions can last several earth days due to the slow rotation of the moon or permanently in shadowed craters. Lunar dust deposited on heat rejection surfaces and coatings will increase the heat absorbed from the Sun, thus reducing the effectiveness of radiators for heat rejection. The lunar gravity, which is 1/6th of the Earth's, will limit the ability of typical low power heat transport devices.

This call seeks to solicit innovative proposals to enable lunar science in the difficult lunar environment. Some technologies may include, but are not limited to, active loops that may be turned off and are freeze tolerate, zero or low power heat generation sources, high thermal capacitance thermal storage, advanced insulation, passive switching. Technologies should show substantial increase over the state-of-the-art. Considerations include power usage in day and night/shadow, mass, heat transport when turned on, heat leak when turned off, sensitivity to lunar topography and orientation, etc.

References

NASA Prepares for Performing New Science on the Moon: https://www.jpl.nasa.gov/news/news.php?release=2007-068

Destination Moon: A History of the Lunar Orbiter Program - Chapter II: Toward A Lightweight Lunar Orbiter –

The Surveyor Program: https://history.nasa.gov/TM-3487/ch2-1.htm

The Surveyor Program: https://www.lpi.usra.edu/lunar/missions/surveyor/

Missions - Lunokhod 01: https://solarsystem.nasa.gov/missions/lunokhod-01/in-depth/

Missions - Lunokhod 02: https://solarsystem.nasa.gov/missions/lunokhod-02/in-depth/

Expected TRL or TRL range at completion of the project: 3 to 4

Desired Deliverables of Phase II

Prototype, Analysis, Hardware

Desired Deliverables Description

Thermal management approaches, techniques, and hardware components to enable the accommodation of lunar temperature extremes encountered in the lunar environment.

State of the Art and Critical Gaps

Missions like Surveyor and Lunokhod hibernated during the night or reduced operational power near noon, in attempts to survive single or multiple lunar cycles. ALSEP's (Apollo Lunar Surface Experiments Package) were deployed on several Apollo missions and had select experiments that operated for many lunar cycles. However, both Lunokhod and ALSEP benefited from radioisotope heat and power sources, which are either too expensive or not likely to be available for near term future lunar science experiments. In fact, most modern lunar surface mission planning is based on solar power and batteries and typically avoids the challenges associated with surviving the full lunar cycle or shadowed regions.

While interest in lunar science and the development of abilities to deliver payloads to the lunar surface are resurgent, the capability to operate through the entire lunar environment is critical. In the absence of perpetual power supplies like RTG's, thermal management approaches to accommodate the lunar extremes, extended day/night cycles, and shadowed regions are seen as enabling.

Relevance / Science Traceability

SMD lunar surface science investigations will employ small, low power payloads that will require advanced thermal control approaches and techniques to survive and operate for extended duration through extreme thermal environments on the lunar surface.

NASA has plans to purchase services for delivery of payloads to the Moon through the Commercial Lunar Payload Services (CLPS) contract. Under this subtopic, proposals may include efforts to develop payloads for flight demonstration of relevant technologies in the lunar environment. The CLPS payload accommodations will vary depending on the particular service provider and mission characteristics. Additional information on the CLPS program and providers can be found at this link: https://www.nasa.gov/content/commercial-lunar-payload-services. CLPS missions will typically carry multiple payloads for multiple customers. Smaller, simpler, and more self-sufficient payloads are more easily accommodated and would be more likely to be considered for a NASA-sponsored flight opportunity. Commercial payload delivery services may begin as early as 2020 and flight opportunities are expected to continue well into the future. In future years it is expected that larger and more complex payloads will be accommodated. Selection for award under this solicitation will not guarantee selection for a lunar flight opportunity.

Z2.01: Spacecraft Thermal Management (SBIR)

Lead Center: JSC

Participating Center(s): GRC, GSFC, JPL, MSFC

Technology Area: 14.0.0 Thermal Management Systems

Related Subtopic Pointer(s): T12.05 H5.02 Z7.03 Z13.01 Z1.03 Z7.04 S3.02 S3.06 Z8.09

Scope Description

NASA seeks new technologies that will facilitate low mass and highly reliable thermal control systems for the exploration of our solar system. This solicitation specifically targets new technologies and methods for two-phase mechanically pumped deployable radiators, novel three-way valves that can operate as either mix or split single phase fluid flow passively, global access lunar lander technologies, and improved integrated human thermal modeling. Proposed improvements are expected to demonstrate analytical and/or empirical proof-of-concept results at the end of Phase I and delivery of a prototype (or better) at the end of Phase II.

<u>Two-Phase Deployable Radiators:</u>

NASA seeks novel deployable radiator designs for two-phase (vapor/liquid) mechanically pumped fluid loop system that provide passive turn-down capability via stagnation and freeze of the ammonia working fluid in the radiator condenser (three-phase compatible design). A stretch goal of compatibility with other working fluids is acceptable. Proposed technologies must address all of the following design goals:

- Condensing radiators with passive, variable heat rejection turn-down capability of greater than 200:1 achieved through partial to complete coolant freezing and built-in flow bypass
- Compatible with a segmented radiator design where panels are one-time deployable
- Mass goal of < 8 kg/m^2 including fluid and deployable hardware
- Scalable design up to 3 m^2 consisting of 1 m^2 panels
- Materials and structures should be compatible with 15-year life in environments ranging from low Lunar orbit, Jupiter orbit (radiation exposure), and inner to outer planet exploration (temperature exposures)
- Working pressures and freeze-tolerance turn-down technologies should assume ammonia as the working fluid

<u>Passive Three-Way Valves:</u>

NASA seeks novel three-way valves that can operate as either a mixing valve (two liquid input ports and one liquid output port) or splitting valve (one liquid input port and two liquid output ports) that can be used to passively control loop temperatures by the degree fraction of radiator bypass. Such miniature passive thermal control valves could find use in a number of single-phase mechanically pumped fluid thermal control systems. Proposed technologies must address the following design goals:

- Design shall autonomously operate without power
- <0.1% flow rate through the shut off port, with a goal of having a provision for no leakage/adjustable leakage through the use of a pre-installed orifice
- Control range of 5-10 ^oC, with pre-adjustable set-point control
- Operational temperature limits -55 ^oC to 90 ^oC, non-operational limits of -55 ^oC to 125 ^oC
- Designs shall be compatible with FC-72 working fluid as well as those used on the ISS thermal control loops (water and ammonia). Retrofit of soft goods are acceptable.
- Mass desire <250 grams (maximum mass 500 g)
- Unit volume <50 cm^3 (maximum 100 cm^3)
- Leak rate $1x10^{-6}$ scc/s gHe at 200 PSIA
- Minimum 4000 full actuation cycles, desired 17,500 cycles
- Rad hard to 300 krad
- 200 psia maximum expected operating pressure, 200 psia proof pressure, 800 psia burst pressure
- Pressure drop <1.5 psi at 1.5 liters per minute of FC-72 working fluid

Global Access Lunar Technology Development:

NASA is seeking focused efforts to develop large human class lunar lander technologies. Technologies should address a gap associated to long duration habitation on the lunar surface where temperatures range from -193° C in shadow regions (including night) to 120° C at the subsolar point. System technologies should be orientation insensitive; for example, lander side mounted radiators must provide their function regardless of lunar surface temperature condition. Technologies are needed that allow a single vehicle design to operate in all these environments. Technologies should address reduction in mass, volume, and power usage relative to current solutions. Adding heaters can add significant vehicle mass to accommodate an additional power source and are not considered a novel architecture approach. Proposed radiator technologies should also address Micrometeoroid and Orbital Debris (MMOD) robustness and protection potential where appropriate.

Examples of other challenges to address in this area include: the deposition of dust on radiators leading to degraded optical properties, contamination insensitive evaporators/sublimators to enable long mission life, and self-healing coolant tubes for MMOD impact resilience.

Technologies should be suitable for use in medium sized landers that operate near 1 kW average heat dissipation capacity. Proposed technologies should also be extensible to human class landers that will have variable heat loads, and average loads between 3-6 kW. All technologies should support a minimum flight duration of 5 years and be compatible with the encountered aerospace environment.

This subtopic is different from S3.06 subtopic, which is focused on thermal control technologies for payloads and smaller robotic landers.

Human Thermal Modeling:

Human thermal analysis for space applications has primarily focused on Extravehicular Activity (EVAs), and typically utilized standalone tools for these short duration assessments. As NASA moves beyond low earth orbit to long duration missions, crew member induced loads to an exploration vehicle's thermal control, environmental control, and life support systems need conjugate analytical assessments between crew and vehicle to determine the most mass efficient capacity for these systems. Additionally, these missions will require an exercise prescription at high metabolic rates for the crew which drives the system sizing for CO2, water (vapor and liquid), and metabolic heat removal. The provided human thermal model should be capable of interfacing with Systems Improved Numerical Differencing Analyzer (SINDA) compatible analysis tools to enable conjugate assessments of crew-induced loads and vehicle thermal control systems.

NASA has plans to purchase services for delivery of payloads to the Moon through the Commercial Lunar Payload Services (CLPS) contract. Under this subtopic, proposals may include efforts to develop payloads for flight demonstration of relevant technologies in the lunar environment. The CLPS payload accommodations will vary depending on the particular service provider and mission characteristics. Additional information on the CLPS program and providers can be found at this link: https://www.nasa.gov/content/commercial-lunar-payload-services. CLPS missions will typically carry multiple payloads for multiple customers. Smaller, simpler, and more self-sufficient payloads are more easily accommodated and would be more likely to be considered for a NASA-sponsored flight opportunity. Commercial payload delivery services may begin as early as 2020 and flight opportunities are expected to continue well into the future. In future years it is expected that larger and more complex payloads will be accommodated. Selection for award under this solicitation will not guarantee selection for a lunar flight opportunity.

References

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Kandilian, R., Bhandari, P., and Mastropietro, A.J. (2018). Thermal and Flow Analysis of Europa Clipper Thermal Control Valves. NASA Thermal and Fluids Analysis Workshop, TFAWS18-AT-14.

Chen, W., Conboy, R., Daines, G., Fogg, D. (2017). A Robust Two-Phase Pumped Loop with Multiple Evaporators and Multiple Radiators for Spacecraft Applications. ICES-2017-221.

Hartenstine, J., Walker, K., and Anderson W. (2012). Passive Control of a Loop Heat Pipe with Thermal Control Valve for Lunar Lander Application. AIAA 2012-3542.

Stephan, R. (2011). Overview of the Altair Lunar Lander Thermal Control System Design and the Impacts of Global Access. AIAA 2011-5001.

Ewert, M.K. (1993). Investigation of Lunar Base Thermal Control System Options. *SAE Transactions, J. of Aerospace.* 102(1), 829-840.

Nyberg, K. L., Diller, K. R., & Wissler, E. H. (2001). Model of human/liquid cooling garment interaction for space suit automatic thermal control. *Journal of biomechanical engineering*, *123*(1), 114-120.

Wissler, E. H. (1964). A mathematical model of the human thermal system. *The Bulletin of mathematical biophysics*, *26*(2), 147-166.

Kuznetz, L. H. (1979). A two-dimensional transient mathematical model of human thermoregulation. *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology*, *237*(5), R266-R277.

Stolwijk, J. A. J., & Hardy, J. D. (1966). Temperature regulation in man—a theoretical study. *Pflüger's Archiv für die gesamte Physiologie des Menschen und der Tiere*, *291*(2), 129-162.

Stolwijk, J. A. (1971). A mathematical model of physiological temperature regulation in man. NASA CR-1855.

Expected TRL or TRL range at completion of the project: 3 to 5

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Software

Desired Deliverables Description

Phase I awards are expected to provide a proof-of-concept analysis and supporting hardware/software which demonstrates the ability of the organization to meet the goals stated in the solicitation.

At the culmination of a Phase II contract, deliverables would include math modeling that has been correlated to test data, raw and reduced test data, and delivery of the new hardware or software package to NASA.

State of the Art and Critical Gaps

These focus areas strive to reduce mass, volume, and power of a thermal control system in the next generation of robotic and human class spacecrafts. These improvements may come through either novel hardware solutions or modernization of software tools used to assess human vehicle interactions. The current state-of-the-art (SOA) in thermal control results in vehicle power and mass impact of greater than 25-30% due to old technologies still in use. Furthermore, as missions become more variable (dormancy, environments, etc.) the need for intelligent control (both actively and passively) within the thermal control system becomes more apparent. As science payloads continue to decrease in size, increase in power, and require precise temperature control, all of which cannot be provided by traditional thermal control methods due to vehicle level impacts of mass/volume and power.

Relevance / Science Traceability

- Gateway
- Europa Clipper/Lander
- Lunar Lander
- Long duration habitats (moon, mars. etc.)

Focus Area 18: Air Vehicle Technology

Lead MD: ARMD

Participating MD(s): STTR

This focus area includes tools and technologies that contribute to both the Advanced Air Vehicles Program (AAVP) and the Transformative Aeronautics Concepts Program (TACP) encompassing technologies in all six Strategic Thrusts within the NASA Aeronautics Mission Directorate (ARMD). AAVP studies, evaluates and develops technologies and capabilities for new aircraft systems, and also explores far-future concepts that hold promise for revolutionary air-travel improvements. Innovative AAVP design concepts for advanced vehicles integrate technologies focus on fuel burn, noise, emissions and intrinsic safety. The goal: to enable new aircraft to fly safer, faster, cleaner, quieter, and use fuel far more efficiently. Partnering with industry, academia, and other government agencies, AAVP pursues mutually beneficial collaborations to leverage opportunities for effective technology transition. TACP encourages revolutionary concepts, creates the environment for researchers to experiment with new ideas, performs ground and small-scale flight tests, and drives rapid turnover into potential future concepts to enable aviation transformation. Research is organized to aggressively engage both the traditional aeronautics community and non-traditional partners. Although TACP focuses on sharply focused studies, the program provides flexibility for innovators to assess new-technology feasibility and provide the knowledge base for radical aeronautics advances.in noise reduction technology.

A1.01: Aeroelasticity and Aeroservoelastic Control (SBIR)

Lead Center: LaRC

Participating Center(s): AFRC

Technology Area: 15.0.0 Aeronautics

Related Subtopic Pointer(s): A1.05

Scope Title

Aeroelasticity and Aeroservoelasticity for Advanced Configurations

Scope Description

The technical discipline of aeroelasticity is a critical ingredient necessary in the design process of a flight vehicle for maintaining optimal performance while ensuring freedom from aeroelastic and aeroservoelastic instabilities. This discipline requires a thorough understanding of the complex interactions between a flexible structure and the steady and unsteady aerodynamic forces acting on the structure, with interactive control systems for flight vehicle performance and stability. Predicting the aeroelastic response of emerging evolutionary and revolutionary vehicle concepts, which include new vehicle configurations, new structures, and/or new materials, is not an easy task. Aeroelastic prediction and testing methods must evolve and expand together with these vehicle concepts. The use of lightweight flexible structures, the development of new airframes, and the intentional exploitation of aeroelastic response phenomena require a comprehensive understanding of the aeroelasticity involved if they are to succeed. Both enhancements to current methodologies/codes and new methodologies/codes that enable evaluation and understanding of new concepts are needed to keep pace with the state of the art in vehicle technology and to fill critical gaps in understanding these complex vehicles.

The fundamental aeronautics work for the Aeroelasticity and Aeroservoelastic Control Subtopic is focused on active/adaptive aerostructural control for lightweight flexible structures, specifically related to load distribution, flutter prediction and suppression, gust load prediction and alleviation, and aeroservoelasticity for Ultra-Efficient and Supersonic Commercial Vehicles. The program's work on aeroservoelasticity includes conduct of broad-based research and technology development to obtain a fundamental understanding of aeroelastic and unsteady-aerodynamic phenomena experienced by aerospace vehicles in subsonic, transonic, supersonic, and hypersonic speed regimes. The subtopic content includes theoretical aeroelasticity, experimental aeroelasticity, and advanced aeroservoelastic concepts. Of interest are:

- Aeroelastic, aeroservoelastic, and unsteady aerodynamic analyses at the appropriate level of fidelity for the problem at hand
- Aeroelastic, aeroservoelastic, and unsteady aerodynamic experiments to validate methodologies and to gain valuable insights available only through testing
- Development of computational-fluid-dynamic (CFD), computational-aeroelastic and computational-aeroservoelastic analysis tools that advance the state of the art in aeroservoelasticity through novel and creative application of aeroelastic knowledge

Specific subjects to be considered include:

- Development of aerostructural control design methodologies that include CFD steady and unsteady aerodynamics, flexible structures, and active control systems
- Development of efficient methods to generate mathematical models of wind-tunnel models and flight vehicles for performing aeroservoelastic studies
- Development of CFD-based methods (reduced-order models) for aeroservoelastic models and simulation that can be used to predict gust loads, ride quality issues, flight dynamics stability, and aerostructural control issues
- Development of novel aeroservoelastic sensing and control approaches, including active/adaptive control concepts and architectures that employ smart materials embedded in the structure and aerodynamic sensing and control schemes for suppressing aeroelastic instabilities and improving performance

- Development of techniques that support simulations, ground testing, wind tunnel tests, and flight experiments for aerostructural control of aeroservoelastic phenomena

References

Links to program/project websites:

1) Aeronautics Research Mission Directorate's (ARMD) Advanced Air Vehicles Program (AAVP): https://www.nasa.gov/aeroresearch/programs/aavp
2) ARMD's Transformative Aeronautics Concepts Program (TACP): https://www.nasa.gov/aeroresearch/programs/tacp
3) ARMD's Flight Demonstrations and Capabilities (FDC) Project under the Integrated Aviation Systems Program (IASP): https://www.nasa.gov/aeroresearch/programs/iasp/fdc
4) X-56 Flight Project: https://www.nasa.gov/centers/armstrong/research/X-56/index.html

Information related to evolutionary and revolutionary flight vehicle concepts/configurations that are on the drawing board or already being tested:

1) Truss-Braced Wing: https://www.sae.org/news/2019/01/boeing-and-nasa-unveil-lightweight-ultra-thin-more-aerodynamic-transonic-truss-braced-wing-concept
2) Blended Wing Body: https://www.nasa.gov/centers/dryden/multimedia/imagegallery/X-48C/ED12-0255-51.html
3) Joined Wing: https://www.nasa.gov/centers/langley/multimedia/iotw-tdt-wing.html
4) X-57: https://www.nasa.gov/image-feature/milestone-achieved-as-x-57-mod-ii-takes-shape
5) X-59: https://www.nasa.gov/image-feature/a-look-inside-the-x-59-quesst-cockpit

Expected TRL or TRL range at completion of the project: 3 to 5

A1.02 Quiet Performance - Aircraft Propulsion Noise (SBIR)

Lead Center: GRC

Participating Center(s): LaRC

Technology Area: 15.0.0 Aeronautics

Related Subtopic Pointer(s): A1.06 A3.03

Scope Description

Innovative methods and technologies are necessary for the design and development of efficient, environmentally acceptable aircraft. In particular, for passenger aircraft, the impact of aircraft noise on communities around airports is the predominant limiting factor on the growth of the nation's air transportation system. Reductions in aircraft noise could lead to wider community acceptance, lower airline operating costs where noise quotas/fees are employed, and increased potential for air traffic growth on a global scale.

Therefore, in support of the Advanced Air Vehicles Program (AAVP), Integrated Aviation Systems Program (IASP), and Transformative Aeronautics Concepts Program (TACP), improvements in technologies and methods for aircraft propulsion noise prediction, diagnostics, and reduction for both subsonic and supersonic aircraft are sought. Innovations in the following specific areas are solicited:

<u>Noise Reduction</u>

- Advanced liners including broadband liners (i.e., liners capable of appreciable sound absorption over at least two octaves) and low-frequency liners (i.e., liners with optimum absorption frequencies half of the current ones but without increasing liner depth); engine hot-section liners;

- Low-noise propulsor concepts that are significantly quieter than the current generation fans and open rotors;
- Concepts for active control of propulsion broadband noise sources including fan, open rotor, jet, compressor, combustor, and turbine;
- Adaptive flow and noise control technologies including smart structures and materials for inlets, nozzles, and low-drag liners;
- Concepts to mitigate the effects of distorted inflow on propulsor noise;

Noise Prediction

- High-fidelity fan and turbine noise prediction models including Large Eddy Simulation of broadband noise, 3D fan and turbine acoustic transmission models for tone and broadband noise;
- Accurate models for prediction of installed noise for jet surface interaction, fan inlet distortion, and open rotors;

Noise Diagnostics

- Tools/Technologies for quantitative characterization of fan in-duct broadband noise in terms of its spatial and temporal content;
- Phased array and acoustical holography techniques to measure realistic propulsion noise sources in low-signal-to-noise ratio wind tunnel environments;
- Characterization of fundamental jet noise sources and structures;
- Innovative measurement of radiated acoustic fields from aeroacoustic sources;
- Novel and robust combustion noise measurement techniques.

References

AAVP - Advanced Air Transport Technology (AATT) Project:
https://www.nasa.gov/aeroresearch/programs/aavp/aatt

AAVP - Commercial Supersonic Technology (CST) Project:
https://www.nasa.gov/aeroresearch/programs/aavp/cst

TACP - Transformational Tools and Technologies (TTT) Project:
https://www.nasa.gov/aeroresearch/programs/tacp/ttt

Expected TRL or TRL range at completion of the project: 2 to 5.

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Software, Research

Desired Deliverables Description

Concepts and technologies that demonstrate a potential for engine component noise reduction, or demonstrate characteristics that could be incorporated into a more sophisticated noise control solution for aircraft engines.

State of the Art and Critical Gaps

Current state-of-the-art solutions for propulsion noise reduction rely heavily on relatively modest changes to the engine architecture and/or passive noise reduction technologies such as acoustic liners, blade/vane count optimization, or vane sweep and/or lean. They do not incorporate advanced materials, adaptive mechanisms, or active noise control systems that can modify the acoustic performance of the component(s) of interest based on the noise state of the engine or aircraft. Such materials, mechanisms, and systems are currently at various stages of maturity, but in general they have not been sufficiently developed to meet certifiability, reliability, and robustness criteria. Novel material systems that could be applied to engine component noise sources are needed, such as shape memory alloy actuators, or active or adaptive systems. High-fidelity numerical tools are beginning to be used for predicting engine component noise. However, they remain too resource-intensive for routine use for design and analysis work. Medium-fidelity prediction tools that can be used for rapid-turn-around evaluations at design and analysis stages are highly desirable. Advanced flow and noise diagnostic techniques that can provide more direct linkage between the noise generating flow features and/or provide more detailed spatio-temporal descriptions of the sound field are also much needed.

Relevance / Science Traceability

AAVP: The Advanced Air Transport Technology (AATT) and Commercial Supersonic Technology (CST) Projects would benefit from noise reduction technologies that could reduce the aircraft noise footprint at landing and takeoff. Configurations with novel engine placement, such as above the fuselage, can reduce the noise footprint, but technologies are needed to efficiently model the performance and noise impacts of these novel engine installations.

TACP: The Transformational Tools and Technologies (TTT) Project would benefit from tool developments to enhance the ability to consider acoustics earlier in the aircraft design process. The TTT project would also benefit from the development and demonstration of simple material systems, such as advanced liner concepts with reduced drag or adaptive material and/or structures that reduce noise, as these component technologies could have application in numerous vehicle classes in the AAVP portfolio, including subsonic and supersonic transports as well as vertical lift vehicles.

A1.03: Low Emissions/Clean Power - Environmentally Responsible Propulsion (SBIR)

Lead Center: GRC

Participating Center(s): LaRC

Technology Area: 1.0.0 Launch Propulsion Systems

Related Subtopic Pointer(s):

Scope Description

Environmentally Responsible Propulsion allows high turbine engine performance with lower pollution and quiet engines.

Achieving low emissions and finding new pathways to cleaner power are critical for the development of future air vehicles. Vehicles for subsonic and supersonic flight regimes will be required to operate on a variety of certified aircraft fuels and emit extremely low amounts of gaseous and particulate emissions to satisfy increasingly stringent emissions regulations. Future vehicles will be more fuel-efficient which will result in smaller engine cores operating at higher pressures. Future combustors will also likely employ lean burn concepts which are more susceptible to combustion instabilities. Fundamental combustion research coupled with associated physics based model development of combustion processes will provide the foundation for technology development critical for these vehicles.

Development of measurement techniques for characterizing aircraft engine particle emissions in the 10 to 200 nanometer (nm) particle diameter size range including:

- Absorbing aerosol standard for the quantitative calibration of optically-based soot mass sensors
- Size-dependent mass concentrations of volatile (e.g., hydrocarbons, sulfuric acid) and non-volatile particles (e.g., black carbon or soot)

- Measurements carried out at high sample line pressures relevant for sector combustor studies and low pressures relevant for flight studies

Environmentally Responsible Propulsion includes all of the following potential research areas:
Detectors (see also Sensors); Conversion; Generation; Sources (Renewable, Nonrenewable); Characterization; Models & Simulations (see also Testing & Evaluation); Thermal Imaging (see also Testing & Evaluation); Fluids; Metallics; Nanomaterials; Organics/Biomaterials/Hybrids.

References

https://www.nasa.gov/aeroresearch/programs/tacp/ttt

https://www.nasa.gov/aeroresearch/programs

NASA Glenn Combustor Facilities: https://www1.grc.nasa.gov/facilities/erb/combustor/

NASA Langley Aerosol Research Group: https://science.larc.nasa.gov/large/aeronautics.html

Expected TRL or TRL range at completion of the project: 2 to 5.

Desired Deliverables of Phase II

Prototype, Analysis, Software, Research

Desired Deliverables Description

A major deliverable will be computer simulation software to predict the best and most effective combustor configurations. Another deliverable would be prototype flow control devices to control combustor efficiency. Sensor development for monitoring engine emissions and sound levels would be another deliverable.

State of the Art and Critical Gaps

Combustion involves multi-phase, multi-component fuel, turbulent, unsteady, 3-D, reacting flows where much of the physics of the processes are not completely understood. Computational Fluid Dynamics (CFD) codes used for combustion do not currently have the predictive capability that is typically found for non-reacting flows. Low emissions combustion concepts require very rapid mixing of the fuel and air with a minimum pressure loss to achieve complete combustion in the smallest volume. Areas of specific interest where research is solicited include:

- Development of laser-based diagnostics for quantitative spatially and temporally resolved measurements of fuel/air ratio in reacting flows at elevated pressure.
- Development of ultra-sensitive instruments for determining the size-dependent mass of combustion generated particle emissions.
- Low emissions combustor concepts for small high pressure engine cores.
- Development of miniature high-frequency fuel modulation valve for combustion instability control able to withstand the surrounding high-temperature air environment.

Relevance / Science Traceability

All of Aeronautic Research Mission Directorate (ARMD), Transformational Tools and Technologies (TTT), etc.

Achieving low emissions and finding new pathways to cleaner power are critical for the development of future air vehicles. Vehicles for subsonic and supersonic flight regimes will be required to operate on a variety of certified aircraft fuels and emit extremely low amounts of gaseous and particulate emissions to satisfy increasingly stringent emissions regulations. Future vehicles will be more fuel-efficient which will result in smaller engine cores operating at higher pressures. Future combustors will also likely employ lean burn concepts which are more susceptible to combustion instabilities.

Infusion / Commercial Potential: These developments will impact future aircraft engine combustor designs (lower emission, control instabilities) and may have commercial applications in other gas-turbine based industries, such as power generation and industrial burners. The modeling and results can be and will be employed in current and future hydrocarbon rocket engine designs (improving combustion efficiency, ignition, stability, etc.).

A1.04: Electrified Aircraft Propulsion (SBIR)

Lead Center: GRC

Participating Center(s): AFRC, LaRC

Technology Area: 15.0.0 Aeronautics

Related Subtopic Pointer(s): T15.03 Z4.04 A2.01 A3.03 A1.07

Scope Description

Proposals are sought for the development of energy storage, propulsion airframe integration, power distribution, thermal, tools/modeling approaches, electric machines and electrical power conversion that will be required for aircraft which use turbo-electric, hybrid electric or all electric power generation as part of the propulsion system. A related STTR topic (T15.03) for electric aircraft propulsion energy storage is offered in parallel. Turbo-electric, hybrid electric, and all electric power generation, as well as distributed propulsive power, have been identified as candidate transformative aircraft configurations with reduced fuel consumption/energy use and emissions. However, components and management methods for power generation, distribution, and conversion are not currently available in the high power ranges with the necessary efficiency, power density, electrical stability and safety required for thin haul/short haul, or transport-class aircraft. Novel developments are sought in:

- Energy storage systems with specific energy >400 Whr/kg at the system level and cycle life >10,000 cycles. This subtopic seeks energy solutions in the Technology Readiness Level (TRL) 3-5 range, appropriate for near-term applications. Proposers working on lower TRL energy storage technologies with a research institution partner should consider proposing to the "Electrified Aircraft Propulsion Energy Storage" subtopic in the STTR solicitation.
- Additive manufacturing solutions for the seamless integration of thermal management technology within the Electrified Aircraft Propulsion (EAP) powertrain, airframe, thermal sources and sinks to minimize system mass and thermal impedance through a tight airframe integration scheme that potentially provides a multi-functional structure solution (load bearing and thermal transport).
- High voltage lightweight fault management devices with individual device rating of 600-3000 V DC, 200-1000 A.
- Design and analysis of airframe-integrated, high-performance distributed electric propulsion (DEP) inlet/fan systems and the resulting effect on: (1) distortion and swirl at the aerodynamic interface plane (AIP), (2) fan efficiency, stability and structural robustness, and (3) operation of adjacent flow paths for DEP inlet/fan concepts and/or boundary layer ingestion (BLI) aircraft.
- Lightweight electrical insulation materials/composites for high altitude, high voltage power transmission with dielectric breakdown strength (V/m) of the insulation minimally 2.5 times that of the operating electric field stress (V/m) at the conductor surface, high resistivity (1019 to 106 Ω×cm), low dialectic dissipation factor (tan δ), Insulation Class H (180˚ C) to Class C (>240 ˚C), moisture resistant, good mechanical properties and improved thermal conductivity, above 0.5 W/m*K.
- Additive manufacturing processes and advanced materials for future generation electric motor designs and windings which provide lower costs, compact designs (>25% volume reduction), lighter

weight (>30% reduction), advanced cooling/improved thermal conductivity, multi-materials and/or greatly improved material or component properties which significantly contribute toward improved electric machine performance. Maintaining electrical insulating and lifetime properties over repetitive thermal cycling, along with being resistant to corona effects, is of interest.

References:

Electrified Aircraft Propulsion (EAP) is called out as a key part of Thrust 4 in the Aeronautics Research Mission Directorate (ARMD) strategic plan: https://www.nasa.gov/aeroresearch/strategy

Overview of NASA's EAP Research for Large Subsonic Aircraft: https://ntrs.nasa.gov/search.jsp?R=20170006235

NASA X-57 Project: https://www.nasa.gov/aeroresearch/X-57/technical/index.html

Expected TRL or TRL range at completion of the project: 2 to 6

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Software, Research

Desired Deliverables Description

Deliverables vary considerably within the topic, but ideally proposals would identify a technology pull area (with a market size estimate), how the proposed idea addresses the needs of the technology pull area and then deliver a combination of analysis and prototypes that substantiate the idea's merit.

State of the Art and Critical Gaps:

The critical technical need is for lightweight, high-efficiency power distribution systems and energy storage that have flight-critical reliability. Typically, the weight needs to be reduced by a factor of 2-3 and efficiency needs to be improved. Higher efficiency reduces losses and makes thermal management more achievable in an aircraft. Another need for medium to large aircraft is the ability to operate at voltages above 600V. This capability results in reduced weight, however, is called out specifically because it impacts all of the power system components.

Technologies that address these gaps enable Electrified Aircraft Propulsion which enables new aircraft configurations and capabilities for the point-to-point on-demand mobility market and a new type of innovation for transport aircraft to reduce fuel consumption and emissions.

Relevance / Science Traceability:

Electrified Aircraft Propulsion (EAP) is an area of strong and growing interest in ARMD. There are emerging vehicle level efforts in Urban On-Demand Mobility, the X-57 electric airplane being built to demonstrate EAP advances applicable to thin and short haul aircraft markets and an ongoing technology development sub-project to enable EAP for single aisle aircraft. Additionally, NASA is formulating a MW-level EAP flight demo this year.

Key Outcomes NASA intends to achieve in this area are:

- Outcome for 2015-2025: markets will begin to open for electrified small aircraft.
- Outcome for 2025-2035: certified small aircraft fleets enabled by electrified aircraft propulsion will provide new mobility options. The decade may also see initial application of electrified aircraft propulsion on large aircraft.
- Outcome for >2035: The prevalence of small-aircraft fleets with electrified propulsion will provide improved economics, performance, safety, and environmental impact, while growth in fleet operations of large aircraft with cleaner, more efficient alternative propulsion systems that will substantially contribute to carbon reduction.

Projects working in the vehicle aspects of EAP include:

- Advanced Air Vehicles Program (AAVP) / Advanced Air Transport Technology (AATT)
- Integrated Aviation Systems Program (IASP)/ Flight Demonstrations & Capabilities (FDC) Project
- Advanced Air Vehicles Program (AAVP)/Revolutionary Vertical Lift Technology (RVLT) Project
- Transformative Aeronautics Concepts Program (TACP)/Convergent Aeronautics Solutions (CAS) Project

A1.05: Computational Tools and Methods (SBIR)

Lead Center: LaRC

Participating Center(s): ARC, GRC

Technology Area: 15.0.0 Aeronautics

Related Subtopic Pointer(s): A1.08 A1.01 S5.01

Scope Description

Computational Fluid Dynamics (CFD) plays an important role in the design and development of a vast array of aerospace vehicles, from commercial transports to space systems. With the ever-increasing computational power, usage of higher fidelity, fast CFD tools and processes will significantly improve the aerodynamic performance of airframe and propulsion systems, as well as greatly reduce non-recurring costs associated with ground-based and flight testing. Historically, the growth of CFD accuracy has allowed NASA and other organizations, including commercial companies, to reduce wind tunnel and single-engine component tests. Going forward, increased CFD fidelity for complete vehicle or engine configurations holds the promise of significantly reducing development costs by enabling certification by analysis. Confidence in fast, accurate CFD allows engineers to reach out of their existing design space and accelerate technology maturation schedules. NASA's CFD Vision 2030 Study (https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20140003093.pdf) highlighted the many shortcomings in the existing computational technologies used for conducting high-fidelity simulations and made specific recommendations for investments necessary to overcome these challenges.

One area of research is scale-resolving numerical simulations, which are playing an increasing role in CFD analysis of new and existing aerodynamic configurations at off-design conditions. It is well-known that traditional steady-state Reynolds Averaged Navier-Stokes (RANS) analysis performs poorly in separated boundary layers and shear layers. Time-accurate Wall-Modeled Large Eddy Simulation (WMLES) and hybrid RANS-LES have demonstrated increased accuracy for a subset of these flows where large scale fluctuations are computationally resolved while the near-wall small scale fluctuations are modeled. Since RANS can accurately compute attached flow regions, it is desirable from a computational cost perspective to initiate scale resolving simulations just upstream of the separated flow regions. However, unsteady disturbances must be added to kick-start scale resolving simulations but an accurate and robust approach to accomplish that is lacking. The goal of this solicitation is to overcome this deficiency. One approach is to insert synthetic turbulent eddies at the start of the scale-resolving flow domain to effectively “trip” the flow. Several methods have been reported in the literature to generate these turbulent fluctuations, but these are not general enough to apply to realistic aircraft configurations, do not evolve into resolved physical turbulent structures in a reasonable amount of time/space, or cause large acoustic fluctuations rendering them inapplicable to aero-acoustic analysis.

An ideal turbulence generator for embedded scale-resolving simulations targeting hybrid RANS-LES and wall-modeled LES would satisfy the following criteria:

- Easy to implement/apply to general aircraft/rockets configurations locally embedded within a larger CFD domain

- Use existing upstream RANS data (e.g., using the Spalart-Allmaras turbulence model), such as velocity profile and estimated Reynolds stresses, and little to nothing else in terms of user parameters
- Develop into realistic turbulence under 10-15 boundary layer thickness from the plane (or volume) where it is applied (based on first order statistics and two-point correlations)
- Require little to no change to an existing scale-resolving flow solver independent of grid paradigm (unstructured, structured overset, or Cartesian)
- Properly handle the inner region of hybrid RANS-LES and WMLES simulations leading to fast skin friction recovery within 10-15 boundary layer thickness
- Create negligible acoustic fluctuations (i.e., smaller than magnitude of attached wall-bounded turbulence)

What is being solicited is a “plug and play” software module that could be easily inserted in an independent CFD solver (e.g., a NASA code) to provide necessary input for scale resolving simulations. The awardee will demonstrate the software tool for carefully selected relevant test cases, before delivering it to NASA.

References

https://www.nasa.gov/aeroresearch/programs/aavp

https://www.nasa.gov/aeroresearch/programs/tacp

Expected TRL or TRL range at completion of the project: 3 to 6

Desired Deliverables of Phase II

Analysis, Software, Research

Desired Deliverables Description

The deliverable will be a software tool that could be used in conjunction with computational fluid dynamic solvers to perform scale resolving simulations that are relevant to NASA missions, particularly the Aeronautics Research Mission Directorate (ARMD) where this capability is needed for flow control applications, aircraft maximum lift prediction and certification by analysis. The awardee will demonstrate the developed computational tool on relevant aerodynamic configurations before delivering it to NASA.

State of the Art and Critical Gaps

NASA's CFD Vision 2030 Study identified several impediments in computational technologies and this solicitation addresses one of those related to application of scale resolving simulations needed for expanding the scope of application of CFD across the aircraft flight envelope, particularly in the prediction of maximum lift.

Relevance / Science Traceability

Various programs and projects of NASA missions use computational fluid dynamics for advanced aircraft concepts, launch vehicle design and planetary entry vehicles. The developed technology will enable design decisions by ARMD and Human Exploration and Operations Mission Directorate (HEOMD).

A1.06: Vertical Lift Technology and Urban Air Mobility (SBIR)

Lead Center: LaRC

Participating Center(s): AFRC, ARC, GRC

Technology Area: 15.0.0 Aeronautics

Related Subtopic Pointer(s): T15.03 A1.02 A1.09

Scope Title

Vertical Takeoff and Landing (VTOL) Urban Air Mobility (UAM) Ride Quality

Scope Description

Urban air mobility (UAM) is a concept for air transportation around metropolitan areas consisting of passenger-carrying operations. An emerging UAM market will require a high density of vertical takeoff and landing (VTOL) operations for on-demand, affordable, quiet and fast transportation in a scalable and conveniently-accessible "vertiport" network. UAM is envisioned to provide increased mobility within a given metropolitan area by traveling faster, and using shorter and more direct routing as compared to ground vehicles.

The expanding UAM vehicle industry has generated a significant level of enthusiasm among aviation designers and manufacturers, resulting in numerous vehicle configurations. The majority of the prototype UAM vehicles have more than 4 rotors or propellers, have electric propulsion, carry 2-6 passengers, fly more like a helicopter (vertical take-off and landing) than a fixed-wing aircraft and will fly relatively close to the ground and near buildings. There are many unknowns as to how the industry will mature but technical barriers may be secondary to the challenge of attracting passengers to fly in these new aircraft that are unconventional in appearance and operations.

A critical challenge for UAM market growth is to gain public acceptance that UAM VTOL aircraft are: 1) as safe, or safer than, commercial air travel and automotive transportation, and 2) as comfortable as conventional modes of transportation.

The solicitation will address likely obstacles to passenger acceptance of UAM vehicles. Passenger acceptance concerns include feeling safe, vehicle motion, noise and vibration, availability and access, passenger well-being, concern for the environment and others. Some of these concerns are highlighted in Ref. 1, and in a recent study funded by NASA (Ref. 2) below.

Phase I of the SBIR should review these passenger acceptance concerns and propose mitigation strategies.

Phase II of the SBIR should include development and demonstration of strategies for improving the passenger experience for VTOL UAM vehicles.

References

1. Adelstein, Bernard D.: Air Vehicle Factors Affecting Occupant Health, Comfort, and Productivity. Vertical Flight Society 6th Annual Electric VTOL Symposium 2019, January 29-31, 2019. Mesa, AZ.
2. Edwards, T.: eVTOL Passenger Experience Final Report. NASA Contractor Report HQ-E-DAA-TN70962, June 26, 2019.

Expected TRL or TRL range at completion of the project: 2 to 4

Desired Deliverables of Phase II

Prototype, Analysis, Research

Desired Deliverables Description

Strategies that address the safety and comfort expectations of UAM vehicle passengers.

State of the Art and Critical Gaps

There are approximately 150 UAM vehicle concepts in varying stages of development. The immediate focus of the vehicle developers is overcoming obstacles on the path to certification. The public has experience flying in large transport aircraft and ground transportation (cars, trains, buses) and are calibrated to the comfort levels (motion, noise, vibration, air conditioning, heating, lighting, etc.) associated with these modes of transportation. Multirotor UAM vehicles will fly more like a helicopter and as a consequence, will likely have more or different motion, vibration and noise transmitted into the cabin. For UAM aircraft, research is needed that 1) addresses the safety and comfort expectations of the passengers and crew, and 2) provides vehicle design strategies for improving passenger comfort.

Relevance / Science Traceability

This subtopic is relevant to the Aeronautics Research Mission Directorate (ARMD) Revolutionary Vertical Lift Technology (RVLT) Project under the Advanced Air Vehicle Program. The goal of the RVLT Project is to develop and validate tools, technologies and concepts to overcome key barriers for vertical lift vehicles. The scope encompasses technologies that address noise, speed, mobility, payload, efficiency, environment and safety for both conventional and non-conventional vertical lift configurations. This subtopic directly aligns with the mission, goals and scope in addressing safety of non-conventional vertical lift configurations.

A1.07: Propulsion Efficiency - Turbomachinery Technology for High Power Density Turbine-Engines (SBIR)

Lead Center: GRC

Participating Center(s): AFRC

Technology Area: 15.0.0 Aeronautics

Related Subtopic Pointer(s): A1.04 T15.03

Scope Description

NASA is looking for improvement in aeropropulsive power density and efficiency in support of its Strategic Thrust in the area of Ultra-Efficient Subsonic Transports. Focus is on small core turbofan engines for next-generation and future large commercial transport aircraft, conventional as well as electrified. The subtopic is closely aligned with NASA Aeronautics programs in the areas of Compact Gas Turbine (CGT) and Electrified Aircraft Propulsion (EAP), and will augment the corresponding Advanced Air Transport Technology (AATT) Project's Technical Challenges. Technical Challenges are targeted technology development areas. Main areas of interest include: Improved efficiency of small core engines, integrated thermal management, innovative cycles, use of artificial intelligence (AI) for turbomachinery components design and optimization, and efficient turbomachinery for EAP, including large electric power extraction in serial-hybrid electrified aircraft and efficient turbine-engines for power generation. The improvements will help airlines to reduce costs by reduced fuel burn. Future electrified airplanes that rely on turbine engines as their energy sources will also be able to maximize their advantages over conventional propulsion.

The detailed areas solicited and the corresponding specific technologies sought include:

1. <u>Small-core engines efficiency improvements:</u>
    a. Desensitizing performance to losses due to tip leakage, secondary flows, seals, purge flows and cooling air
    b. Compact transition ducts
    c. Active and passive flow control for improved airfoil performance and reduce tip clearance losses
    d. Innovative turbine shrouding to circumvent tip clearances loss generation
2. <u>Turbofan thermal management:</u>
    a. Compact thermal management systems using multi-functional structures and additive manufacturing

b. Integrated thermal management of turbofan-electric components for more-electric and hybrid-electric aircraft

c. Turbine high effectiveness cooling and loss reduction

d. Innovative aviation-weight compact heat exchangers for cooling the cooling air and associated heat recovery or rejection

3. Optimized integrated combustor – turbine systems:

    a. Integration concepts of combustor and turbine for improved overall and component performance

4. Innovative methods for turbomachinery design and aerothermal analysis

    a. Automating design of turbomachinery components using AI

    b. Automated turbomachinery computational fluid dynamics (CFD) grid generation using AI

    c. CFD models for turbomachinery unsteady flows including transition and separation for accurate loss prediction

    d. Components performance maps generation using Artificial Intelligence (AI) and Machine Learning (ML)

    e. Use of additive manufacturing to enable designs and improvements not possible with conventional manufacturing processes

    f. Remote non-contact dynamic temperature mapping in the presence of significant radiative background. Surface temperature mapping tools including efficient image processing algorithms are sought that will be compatible with silicon carbide based components with or without low thermal expansion oxide environmental barrier coating

    g. Capability of fast full-wheel, unsteady, multi-stage, CFD for compressor and turbine components for aerothermal analysis

5. Innovative engine cycles as improvements alternatives to conventional engines

    a. Closed cycles for thermal management and primary propulsion (e.g., supercritical CO2 Brayton cycles, organic fluid Rankine cycles, etc.)

    b. Turbofan waste heat recovery and utilization

6. Efficient and light-weight turbomachinery for EAP and More Electric Aircraft

    a. Turbomachinery for high power extraction from turbofans. The desire is to enable larger than 20% of low pressure spool power at altitude cruise to be extracted as shaft power. The power is to electric generator(s) to provide power to electric motor-driven propulsors (example: STARC-ABL concept). Design of turbomachinery components and optimization of extraction from low- and high-pressure spools is sought.

    b. Efficiency improvements of small turboshaft engines powering turbo-generators/range-extenders used in regional EAP aircraft concepts. Small turboshafts suffer from low efficiency, and design of high effectiveness aviation-weight improvements are sought. Ideas to consider include recuperation using light-weight heat exchangers and concepts employing multifunctional and additive manufacturing approaches.

References

Links:

https://www.nasa.gov/aeroresearch/strategy

https://www.nasa.gov/aeroresearch

Summary:

NASA Strategic Plan 2018:

- Strategic Goal 3: Address National Challenges and Catalyze Economic Growth
    - Strategic Objective 3.2: Transform Aviation Through Revolutionary Technology Research, Development and Transfer

Aeronautics Research Mission Directorate (ARMD) New Strategic Thrust 3: Ultra Efficient Subsonic Transports - Thrust description: Realize revolutionary improvements in economics and environmental performance for subsonic transports with opportunities to transition to alternative propulsion and energy

Expected TRL or TRL range at completion of the project: 1 to 4

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Software, Research

Desired Deliverables Description

The objective of this subtopic solicitation is to develop technologies that contribute to increasing the power density of future turbofan engines. The deliverables of Phase I will be feasibility assessment of innovative ideas in the form of results of numerical studies, software tools, results of experiments, or tests of demonstration prototypes. Projects showing successful feasibility may be selected for further development under Phase II.

The scope of turbomachinery includes the rotating machinery in the high and low pressure spools, transition ducts, purge and bleed flows, casing and hub. It also includes turbomachinery aspects of EAP concepts where a turbine engine is the power source. The latter includes hybrid-electric turbofan power extraction and efficiency improvements of small turbine engine powering turbogenerator/ range-extenders. This topic address only aerothermal aspects of turbomachinery. Materials, controls and other areas are not included in this subtopic and may be solicited under separate subtopics.

This solicitation's desire is to focus on the turbofan engine core, but unique novel ideas relevant to the whole engine are also sought.

State of the Art and Critical Gaps

System and technology studies have indicated that advanced gas turbine propulsion will remain critical for next-generation and future subsonic transports.

The main interest of this solicitation is in turbofan engines. Turbofans will be relevant for next-generation and future conventionally powered aircraft. They will also be relevant as power sources of future electrified airplanes.

Impressive advancements were made in turbofan technologies that increased their efficiency and performance. Most recent upcoming near term technologies being incorporated in engines as the GE9X and Rolls Royce SuperFan intend to include overall pressure-ratio (OPR) of 60, large diameter fans with low blade count and low fan pressure-ratio, bypass ratio of order 11, advanced booster designs, highly 3D airfoil designs, high compressor pressure ratio in the range of 27, application of CMC (Carbon Matrix Composites) materials in hot sections and more. Despite these advances, there is potential for additional improvements; they are possible and needed for future aircraft architecture and concepts.

In the turbine, the very high cycle temperatures demanded by advanced engine cycles place a premium on the cooling technologies required to ensure adequate life of the turbine component. New capabilities as well as challenges are provided with expected increased use of ceramic matrix composites (CMC). Presently, engines are overcooled because of uncertainty in hot section flow uniformity caused by hot streaks. Reduced cooling flow rates and/or increased cycle temperatures enabled by these technologies have a dramatic impact on the engine performance.

In the compression system, advanced concepts and technologies are required to increase stage loading and widen operating range. Interrelated to the turbine, the cooling flow presently result in high penalty caused by the typical 20% bleed air ratio; the goal is to reduce it to 5%. OPR may be increased to the order of 100. As result the overall thermal efficiency can be increased by 10-15%. Aerothermal improvements not only will improve performance, but also will lead to reduced weight and increase the core specific power.

Engines are currently designed in a time-consuming iterative manner taking several months for a complete system. AI and ML approaches are expected to speed up the process and lead to optimized designs maximizing the efficiency and power density and take it down to a matter of hours and days.

NASA and industry are actively working on electrified aircraft concepts. Many of these concepts employ turbine-engines as power sources. The impact on the turbomachinery requirement and design needs to be addressed, which, in turn, will impact the viability of the EAP concepts.

Finally, innovative methods for engine waste heat recovery and re-utilization will increase the effective engine efficiency. And alternatives to the conventional open Brayton cycle may also lead to revolutionary propulsion system, or at least to improvements of existing systems.

Relevance / Science Traceability

The solicited topics are directly relevant to NASA' Aeronautics project goals in the area of high power density cores - to lead to realizing revolutionary improvements in economics and environmental performance for subsonic transports with opportunities to transition to alternative propulsion and energy.

A1.08: Aeronautics Ground Test and Measurement Technologies (SBIR)

Lead Center: LaRC

Participating Center(s): ARC, GRC

Technology Area: 15.0.0 Aeronautics

Related Subtopic Pointer(s): A1.05 A1.09 A2.01 Z7.06

NASA's aeroscience ground test facilities include wind tunnels, air-breathing engine test facilities and simulation and loads laboratories. They play an integral role in the design, development, evaluation and analysis of advanced aerospace technologies and vehicles. These facilities provide critical data and fundamental insight required to understand complex phenomena and support the advancement of computational tools for modeling and simulation. The primary objective of the Aeronautics Ground Test and Measurements Technologies subtopic is to develop innovative tools and technologies for application in NASA's aeroscience ground test facilities that can revolutionize testing and measurement capabilities and improve utilization and efficiency. Tools and technologies that can be applied in NASA's portfolio of large-scale ground test facilities are of primary interest. For this solicitation, NASA seeks proposals for innovative research and development in the following areas:

Non-Intrusive Temperature Measurements of Super-Cooled Water Droplets and Ice Crystals

Non-intrusive ice and super-cooled water particle temperature measurement techniques are sought for NASA's Icing Test Facilities, the Propulsion Systems Laboratory and the Icing Research Tunnel.

Accurate temperature measurements of individual ice particles and super-cooled water droplets within an icing cloud in NASA icing test facilities is a key capability to enable technologies for the advancement of engine and airframe icing simulation tools. For engine icing facilities, this is important for characterizing the particle cloud entering the engine being tested and understanding the temperature history of the liquid droplets when they transition to ice crystals. For airframe icing, this is important for understanding the thermodynamic state of super-cooled large water droplets at the test section location. Proper validation of experimental simulations and computational models of ice accretion processes requires that the test facility be able to continuously measure and monitor the icing cloud particle/water droplet temperature at multiple locations simultaneously and non-intrusively.

Cryogenic Shear Measurements

Shear stress measurements are needed to validate computational tools that ultimately will be used to support the certification of aerospace vehicles by analysis. Shear stress is an important parameter for characterizing the interaction between a fluid and a surface over which it is moving. Quantitative measurements of shear stress provide information about the surface conditions on a model and help determine the location where features such as flow separation occur. Currently, shear stress is measured at discrete locations using sensors and probes; however, global (2D) measurements are also needed to help determine measurement locations for these sensors a priori and to provide Computational Fluid Dynamics (CFD) code validation data. Robust systems are sought to enable measurements on simple and complex geometries and configurations at both room temperature and cryogenic conditions (down to 80 Kelvin).

Wind Tunnel Characterization

Wind tunnel tests required to enable the CFD2030 Vision and support Certification by Analysis will need to have boundary conditions in the wind tunnel properly measured and documented. NASA is seeking non-intrusive measurement systems that can be installed permanently within NASA's larger facilities to document the test section inflow and/or outflow conditions. Specific flow parameters of interest include pressure, velocity, temperature, and density. Target facilities include the 11-Foot Wind Tunnel at NASA Ames Research Center, the 9x15 Low-Speed Wind Tunnel at NASA Glenn Research Center and the 14x22 Subsonic Tunnel at NASA Langley Research Center. These facilities feature large test sections with considerable optical access and are highly utilized. Another target facility is the Langley 8-foot High Temperature Tunnel (HTT), a combustion-heated, high-enthalpy supersonic wind tunnel having water vapor and water droplets in the free-stream flow. For this facility, desired measurements include gas temperature, velocity, water vapor concentration, as well as droplet size and the concentration and distributions thereof.

References

https://www.nasa.gov/aeroresearch/programs/aavp/aetc/ground-facilities

https://ntrs.nasa.gov/search.jsp?R=20140003093

A1.09: Inflight Icing Hazard Mitigation Technology (SBIR)

Lead Center: GRC

Participating Center(s): None

Technology Area: 15.0.0 Aeronautics

Related Subtopic Pointer(s): A1.08 A2.02 A1.06

Scope Title
Sensing and Mitigation of Icing Conditions

Scope Description

All-weather sensing and mitigation is a future challenge for electric vehicles, both electric vertical take-off and landing (eVTOL) operating in the urban air mobility (UAM) mission and unmanned aerial systems (UAS) in current and future mission profiles. The primary focus is on icing but other weather hazards including wind, reduced visibility, lightning and degradation of Global Positioning System (GPS) may also be addressed. Characterize the conditions which create ice accretions on a UAS and/or eVTOL (either a class or a specific aircraft) across the anticipated operational envelope, and analyze the ice shapes using simulation tools and ground test methods. Map performance degradation to atmospheric conditions obtained from flight test and/or atmospheric simulations. In-situ characterization of icing conditions using existing or new instruments or techniques must address the weight and power constraints expected for a class or specific vehicle. Ground-based remote sensing of icing conditions must be suitable for various vertiport sites, based on commercial instruments and/or data services.

References

1. Avery, A., and Jacob, J., "Evaluation of Low Altitude Icing Conditions for Small Unmanned Aircraft," 9th AIAA Atmospheric and Space Environments Conference, Denver, CO, June, 2017.

2. Thorpe, R., McCrink, M., and Gregory, J., "Measurement of Unsteady Gusts in an Urban Wind Field using a UAV-based Anemometer," AIAA Applied Aerodynamics Conference, Atlanta, GA, June, 2018.

3. Yan, S., Opazo, T., Palacios, J., Langelaan, J., and Germain, L., "Experimental Evaluation of Multi-rotor UAV Operation under Icing Conditions," American Helicopter Society 74th Annual Forum, Phoenix, AZ, May, 2018.

4. Sehgal, A., and Ernst, R., "MQ-8 Fire Scout Icing Solution Challenges," American Helicopter Society 72nd Annual Forum, West Palm Beach, FL, May, 2016.

5. Johnson, W., Silva, C., and Solis, E., "Concept Vehicles for VTOL Air Taxi Operations," American Helicopter Society Technical Conference on Aeromechanics Design for Transformative Vertical Flight, San Francisco, CA, January, 2018.

Expected TRL or TRL range at completion of the project: 3 to 5.

Desired Deliverables of Phase II

Prototype, Analysis

Desired Deliverables Description

Deliverables may include some or all of the following: design or prototype of a multi-sensor suite for weather hazard identification, characterization of expected icing conditions along with associated performance degradation, and/or novel algorithms for identification of weather hazards.

State of the Art and Critical Gaps

All-weather operations are important for vertical lift air vehicles, which have missions that require operating in weather at altitude. Formation of ice over lifting surfaces can affect aerodynamic performance.

Detection and avoidance of icing is a key technology for acceptance and certification, for both manned and unmanned vehicles. Unplanned icing incidents have already occurred involving unmanned aerial systems undertaking current missions. Icing detection requires a broad database of icing encounters for validation. This requires a significant campaign of testing in icing wind tunnels and in flight.

Atmospheric characterization is another key part of detection and avoidance. A vehicle must not only detect that it is in icing but also quantify the severity of the icing and any decision that must be made in a timely manner. Remote sensing methods, whether from a terminal area sensor or from a forward-looking sensor on the vehicle, are not currently capable of meeting these requirements. Current aviation weather research mostly involves either ground-level or cruise altitudes, since this is where current commercial aviation operation takes place. However, Unmanned Aerial Vehicles (UAVs) and eVTOLs may operate at low altitudes (within a few hundred feet altitude), where complex meteorological events can occur that are not well represented in prior weather research.

Relevance / Science Traceability

All-weather sensing and mitigation is a particular challenge for electric vehicles, both eVTOL operating in the UAM mission and UAVs operating in current and future mission profiles. Mitigation through detection and avoidance is especially critical for systems which already have stringent power and weight requirements.

A1.10: Hypersonic/High Speed Technology - Seals and Thermal Barriers (SBIR)

Lead Center: GRC

Participating Center(s): LaRC

Technology Area: 15.0.0 Aeronautics

Related Subtopic Pointer(s): H5.02 Z7.03

Scope Title

Development of High Temperature, Wear-Resistant Coatings for Seals and Thermal Barriers

Scope Description

Future high speed vehicles will require high temperature, dynamic seals and thermal barriers around movable surfaces to minimize the ingestion of hot gases through sealed interfaces and protect underlying temperature-sensitive structures. Locations include around the edges and along the hinge lines of movable control surfaces (e.g., flaps, rudders), panels, and doors. The seals must operate in high heat flux, oxidizing environments and restrict the flow of hot gases at temperatures on the order of 2000° F. They must be flexible enough to accommodate distorted sealing surfaces while remaining in contact with them to create an effective seal. In some locations, they may also have to limit applied loads against sealing surfaces that are fragile or covered with delicate protective coatings. The seals must also be sufficiently durable to meet required life goals. They must resist damage as they are rubbed over rough, distorted sealing surfaces without incurring excessive increases in leakage due to wear. In some locations the seals may have to seal against rough thermal protection system (TPS) materials without sticking to their surfaces. Previous testing has shown that coatings on flexible fabrics can potentially improve seal durability. The objective of this opportunity is to identify and/or develop high temperature, wear-resistant coatings for seals and thermal barriers and evaluate their durability under representative operating conditions.

References

https://www.nasa.gov/aeroresearch/programs/aavp/ht

Expected TRL or TRL range at completion of the project: 1 to 5

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Research

Desired Deliverables Description

Deliverables include development, production, demonstration and evaluation of high temperature, wear-resistant coatings for seals and thermal barriers with key demonstrations/evaluations of their durability under representative operating conditions.

State of the Art and Critical Gaps

State-of-the-art seals and thermal barriers are often fabricated out of flexible, high-temperature ceramic fibers and fabrics to help minimize seal compression loads and to allow them to accommodate variable gap geometries and distorted sealing surfaces. However, these materials can become damaged when they are rubbed against adjacent sealing surfaces, especially in dynamic applications. This can lead to higher leak rates and increases in temperature near critical components thereby requiring the seals to be replaced, often after a limited number of missions.

Relevance / Science Traceability

This subtopic relates to the Hypersonics project within Aeronautics Research Mission Directorate (ARMD). Materials development is a long lead-time research area, and engaging innovation across a wider community through SBIR provides time to develop technologies that can be enabling for future hypersonic vehicles.

Scope Title

Development of High Temperature Elastomer for Use in Seal Applications at 700+°F

Scope Description

Future high-speed vehicles will require high temperature, low leakage seals to minimize the ingestion of hot gases through sealed interfaces and protect underlying temperature-sensitive structures (mostly static interfaces). The objective of this opportunity is to identify and/or develop a high temperature elastomer that can be formed (e.g., molded, extruded) into various seal geometries for use at temperatures of 700°F or greater. Upon successful identification/development of the elastomer, test specimens will be fabricated and evaluated under representative operating conditions.

References

https://www.nasa.gov/aeroresearch/programs/aavp/ht

Expected TRL or TRL range at completion of the project: 1 to 5

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Research

Desired Deliverables Description

Deliverables include development, production, demonstration and evaluation of a high temperature elastomer that can be formed (e.g., molded, extruded) into various seal geometries for use at temperatures of 700°F or greater with key demonstrations/evaluations of sealing capability under representative operating conditions.

State of the Art and Critical Gaps

Low leakage seals such as O-rings are often made of elastomers because these materials exhibit little plastic flow and rapid, nearly complete recovery from an extending or compressing force. However, even the most heat-resistant elastomers have maximum continuous use temperature limits of about 600°F. Current heat-resistant elastomers have maximum continuous use temperature limits of about 600°F at which point they begin to break down and cease to function as an effective seal.

Relevance / Science Traceability

This subtopic relates to the Hypersonics project within ARMD. Materials development is a long lead-time research area, and engaging innovation across a wider community through SBIR provides time to develop technologies that can be enabling for future hypersonic vehicles.

**<u>Note</u>: This subtopic solicits proposals in high temperature sealing needs which require, dynamic, static and/or barrier needs. Proposers working on hot structures should consider proposing to the H5.02 - Hot Structure Technology for Aerospace Vehicles subtopic in the Human Exploration and Operations Mission Directorate.

T15.03: Electrified Aircraft Propulsion Energy Storage (STTR)

Lead Center: GRC

Participating Center(s): AFRC, LaRC

Technology Area: 15.0.0 Aeronautics

Related Subtopic Pointer(s): A1.04 A1.06 A1.07

Scope Description

Proposals are sought for the development of enabling rechargeable batteries (or other types of energy storage) for Electrified Aircraft Propulsion (EAP).

Two paths to improved battery performance are sought:

1. Innovative thermal, structural, and electrical integration that reduce the mass fraction added when scaling from a battery cell to an integrated battery
2. Battery chemistry improvements that substantially enhance usable energy density, cycle life, life cycle cost, and safety

Batteries and other energy storage systems with some combination of some or all of the following performance levels at the integrated battery pack level are sought:

- Specific energy >400Whr/kg at the system level
- Cycle life >10,000 cycles
- Prime flight quality and safety
- Cost effective enough to close electric air services at a profit

Battery pack level energy density means the amount of usable energy after derating for depth of discharge, cycle life, C rate limits, thermal constraints, and any other applicable limit to energy that can be used during the mission divided by the mass of the battery package (including the structure, safety devices, battery management system, and thermal management parts that are mounted to the battery). This will typically require cell level energy densities in the range to 600-800 W-hr/kg along with an innovative combination of those cells into a battery system. Alternate electrical energy storage approaches will also be considered.

All-electric conventional and vertical takeoff research vehicles that can carry one or two people have been demonstrated. In order to achieve commercial viability, improvements in batteries are required for the aircraft to have sufficient range, safety, and operational economics for regular service. Markets needs span Urban Air Mobility (UAM), thin/short haul aviation, and commercial air transport vehicles which use electrified aircraft propulsion. Hybrid electric and all electric power generation as well as distributed propulsive power have been identified as candidate transformative aircraft configurations with reduced fuel consumption/energy use and emissions.

References

Electrified Aircraft Propulsion (EAP) is called out as a key part of Thrust 4 in the ARMD strategic plan: https://www.nasa.gov/aeroresearch/strategy

NASA Urban Air Mobility (UAM): https://www.nasa.gov/aero/taking-air-travel-to-the-streets-or-just-above-them

NASA X-57 Project: https://www.nasa.gov/aeroresearch/X-57/technical/index.html

Expected TRL or TRL range at completion of the project: 2 to 6

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Research

Desired Deliverables Description

Deliverables most likely will include prototypes of energy storage units along with research and analysis addressing safety and cost considerations. In some cases test data for safety may be a deliverable. Ideally, proposals would identify a technology pull area (with a market size estimate), how the proposed idea addresses the needs of the technology pull area, and then deliver a combination of analysis and prototypes that substantiate the idea's merit.

Please consider SBIR subtopic A1.04 - Electrified Aircraft Propulsion if you are considering energy storage technologies appropriate for near term applications that will have a higher TRL (3-5) at completion.

State of the Art and Critical Gaps

Specific Energy: Need approximately a factor of 2 improvement. Current assessment of battery specific energy requirements for all-electric operations are in the 300-400 Wh/kg at the installed/pack level (Installed means after derating for depth of discharge limit, cycle life, battery management, packaging, and thermal environment). This assumes the ability to quickly recharge between flights. Current state of the art (SOA) is about ≈ 160-170 Wh/kg (pack level). Li-ion batteries are nearing practical maximums so new chemistry(s) or energy storage types are likely required to meet all-electric UAM mission needs, solid state appears to be the most promising. For reference, automotive needs will likely be more than met with 300-500 Wh/kg (cell level), but, with regards to NASA goals, all electric helicopters and regional passenger aircraft will likely need 600Wh/kg and 500-700Wh/kg (cell level) respectively. Note that approximately 30-40% Wh/kg is lost when cells are integrated into packs and installed; justify any improvements you expect.

Cycle Life: Need a substantial improvement. Current SOA is 1500-3000 cycles which lasts about 3 months for UAM. For reference, automotive needs 500-1000 cycles for 10 year lifespans.

Cost: Aviation is probably less sensitive to cost than automotive if the overall operations and vehicle concept can close profitably.

Prime Flight Quality: New feature that needs to be demonstrated. The expected reliability of an aviation system is probably a few orders of magnitude higher than an automotive application and safety considerations are a more significant driver – including time needed to get passengers out of danger. Justify how your concept may address these goals.

Relevance / Science Traceability

Electrified Aircraft Propulsion (EAP) is an area of strong and growing interest in ARMD. Energy Storage is an enabling technology for the UAM and Thin Haul segments of the effort. There are emerging vehicle level efforts in Urban On-Demand Mobility, the X-57 electric airplane being built to demonstrate EAP advances applicable to thin and short haul aircraft markets, and an ongoing technology development subproject to enable EAP for single aisle aircraft. Additionally, NASA is formulating a megawatt-level EAP flight demo this year.

EAP is called out as a key part of Thrust 4 in the ARMD strategic plan.

Key Outcomes NASA intends to achieve in this area are:

- Outcome for 2015-2025: Markets will begin to open for electrified small aircraft.
- Outcome for 2025-2035: Certified small aircraft fleets enabled by electrified aircraft propulsion will provide new mobility options. The decade may also see initial application of electrified aircraft propulsion on large aircraft.
- Outcome for >2035: The prevalence of small-aircraft fleets with electrified propulsion will provide improved economics, performance, safety, and environmental impact, while growth in fleet operations of large aircraft with cleaner, more efficient alternative propulsion systems will substantially contribute to carbon reduction.

Projects working in the vehicle aspects of EAP include: Advanced Air Vehicles Program (AAVP)/Advanced Air Transport Technology (AATT) Projects, Integrated Aviation Systems Program (IASP)/ Flight Demonstrations & Capabilities (FDC) Project, AAVP/Revolutionary Vertical Lift Technology (RVLT) Project, and Transformative Aeronautics Concepts Program (TACP)/Convergent Aeronautics Solutions (CAS) Projects.

T15.04: Integration of Airframe with Distributed Electric Propulsion (DEP) System (STTR)

Lead Center: AFRC

Participating Center(s): ARC, GRC

Technology Area: 15.0.0 Aeronautics

Related Subtopic Pointer(s):

Scope Title
Develop Highly-Integrated Air Vehicle Technologies Using both Distributed Electric Propulsion (DEP) System and Airframe

Scope Description

NASA/Aeronautics Research Mission Directorate (ARMD) laid out Strategic Implementation Plan for aeronautical research aimed at the next 25 years and beyond. The documentation includes a set of Strategic Thrusts that are research areas which NASA will invest and guide. It encompasses a broad range of technologies to meet future needs of the aviation community, the nation, and the world for safe, efficient, flexible, and environmentally sustainable air transportation. Furthermore, the convergence of various technologies will also enable highly integrated electric air vehicles to be operated in domestic or international air space. In response to Strategic Thrust #1 (Safe, Efficient Growth in Global Operations), #3 (Ultra-Efficient Commercial Vehicles) and #4 (Transition to Low-Carbon Propulsion), a new subtopic titled “Integration of Airframe with Distributed Electric Propulsion (DEP) System” is proposed in all areas related to the subject.

References

ARMD/Advanced Air Transport Technology (AATT) Project:
https://www.nasa.gov/aeroresearch/programs/aavp/aatt

ARMD/Revolutionary Vertical Lift Technology (RVLT) Project:
https://www.nasa.gov/aeroresearch/programs/aavp/rvlt

ARMD/Convergent Aeronautics Solutions (CAS) Project:
https://www.nasa.gov/aeroresearch/programs/tacp/cas

ARMD/Transformational Tools and Technologies (TTT) Project:
https://www.nasa.gov/aeroresearch/programs/tacp/ttt

ARMD/University Innovation (UI) Project: https://www.nasa.gov/aeroresearch/programs/tacp/ui

ARMD Strategic Implementation Plan: https://www.nasa.gov/aeroresearch/strategy

ARMD Urban Air Mobility Grand Challenge: https://www.nasa.gov/uamgc

Expected TRL or TRL range at completion of the project: 2 to 6

Desired Deliverables of Phase II

Prototype, Analysis, Software, Hardware, Research

Desired Deliverables Description

Integration of Distributed Electric Propulsion (DEP) system into an aircraft involves multidisciplinary design, analysis, and optimization (MDAO) of several disciplines in aircraft technologies. These disciplines include aerodynamics, propulsion, structures, acoustics, and/or control in traditional aeronautics related subjects. The use of light-weight high-power electric components (e.g. motors, controllers, etc.) in propulsion system are enabling new electric propulsion aircraft for fixed wing and Vertical Take-Off and Landing (VTOL) applications. Addressing ARMD's Strategic Thrust#1 (Safe, Efficient Growth in Global Operations), #3 (Ultra-Efficient Commercial Vehicles) and #4 (Transition to Low-Carbon Propulsion), innovative approaches in designing and analyzing highly integrated DEP aircraft are needed to reduce the energy use, noise, emissions, and safety concerns. In support of these three Strategic Thrusts, the following integration research areas for DEP aircraft are to be considered under this solicitation.

1. Configure and analyze DEP-enabled highly-integrated multidisciplinary aircraft features or vehicle configuration.
2. Develop MDAO tools and methods to assess DEP-enabled highly-integrated multidisciplinary aircraft features or vehicle configuration.
3. Develop tools and methods to assess safety issues associated with DEP-enabled highly-integrated multidisciplinary aircraft features or vehicle configuration.

Expected outcome (TRL 2-3) of Phase I awards, but not limited to:

- Highly integrated multidisciplinary aircraft features with DEP system for fixed wing or VTOL application.
- Highly integrated DEP-enabled fixed wing or VTOL aircraft definition and system level assessment.
- Initial development of analytical/computational/experimental/simulation tools and methods in assessing highly integrated multidisciplinary aircraft features or vehicle configuration with DEP system.

Expected outcome (TRL 4-6) of Phase II awards, but not limited to:

- Detailed feasibility study and demonstration of the subscale hardware of highly integrated multidisciplinary aircraft features or vehicle configuration with DEP system.
- Refinement of tools and methods in assessing highly integrated multidisciplinary aircraft features or vehicle configuration with DEP system.
- Experimental (e.g., wind tunnel) results or simulation capability that assess the validity of the highly integrated multidisciplinary aircraft features or vehicle configuration with DEP system.

State of the Art and Critical Gaps

Design and analysis (analytical, experimental, computational, and/or system analysis) addressing highly-integrated DEP aircraft technology are critically needed.

Traditional/conventional aircraft design and development have been approached from individual discipline topics such as aerodynamics, propulsion, structure, etc. In order to improve the performance of an aircraft, multidisciplinary solutions including MDAO approach are encouraged.

Relevance / Science Traceability

The proposed subtopic supports ARMD's Strategic Thrust#1 (Safe, Efficient Growth in Global Operations), #3 (Ultra-Efficient Commercial Vehicles), #4 (Transition to Low-Carbon Propulsion), and ARMD Strategic Implementation Plan 2017. Specifically, the following ARMD programs and projects are highly relevant.

NASA/ARMD/Advanced Air Vehicles Program (AAVP):

- Advanced Air Transport Technology (AATT) project

- Revolutionary Vertical Lift Technology (RVLT) project

NASA/ARMD/Transformative Aeronautics Concepts Program (TACP):

- Convergent Aeronautics Solutions (CAS) project
- Transformational Tools and Technologies (TTT) project
- University Innovation (UI) project

Focus Area 19: Integrated Flight Systems

Lead MD: ARMD

Participating MD(s): None

This focus area includes technologies that contribute to the Integrated Aviation Systems Program's (IASP) objectives to demonstrate integrated concepts and technologies to a maturity level sufficient to reduce risk of implementation for stakeholders in the aviation community through the rigorous execution of highly complex flight tests and related experiments.

A2.01: Flight Test and Measurement Technologies (SBIR)

Lead Center: AFRC

Participating Center(s): ARC, GRC, LaRC

Technology Area: 15.0.0 Aeronautics

Related Subtopic Pointer(s): A2.02 A1.04 T13.01 Z8.10 A3.03 A1.08 A3.01

Scope Description

NASA continues to use flight research as a critical element in the maturation of technology. This includes developing test techniques that improve the control of in-flight test conditions, expand measurement and analysis methodologies and improve test data acquisition and management with sensors and systems that have fast response, low volume, minimal intrusion and high accuracy and reliability. By using state-of-the-art flight test techniques along with novel measurement and data acquisition technologies, NASA and the aerospace industry will be able to conduct flight research more effectively and also meet the challenges presented by NASA and industry’s cutting edge research and development programs.

NASA's Flight Demonstrations and Capabilities Project supports a variety of flight regimes and vehicle types ranging from low speed, sub-sonic applications and electric propulsion, through transonic and high-speed flight regimes. Therefore, this solicitation can cover a wide range of flight conditions and vehicles. NASA also requires improved measurement and analysis techniques for acquisition of real-time, in-flight data used to determine aerodynamic, structural, flight control and propulsion system performance characteristics. These data will be used to provide information necessary to safely expand the flight and test envelopes of aerospace vehicles and components. This requirement includes the development of sensors for both in-situ and remote sensing to enhance the monitoring of test aircraft safety and atmospheric conditions during flight testing. This subtopic supports innovative flight platform development for use in hypersonic flight testing, science missions and related subsystems development.

Flight test and measurement technologies proposals may significantly enhance the capabilities of major government and industry flight test facilities. Proposals may address innovative methods and technologies to reduce costs and extend the health, maintainability, communication and test techniques of flight research support facilities.

Areas of interest emphasizing flight test and measurement technologies include:

- High efficiency digital telemetry techniques and/or systems to enable high data rate and high volume telemetry for flight test. This includes Air-to-Air and Air-to-Ground communication.
- Architecture and tools for high integrity data capture and fusion.
- Real-time integration of multiple data sources from on-board, off-board, satellite and ground-based measurement equipment.
- Advanced in-situ/onboard sensing and/or integrated secured remote services for use in real-time decision-making.
- Prognostic and intelligent health monitoring for hybrid and/or all-electric propulsion systems using an adaptive embedded control system.
- Methods for accurately estimating and significantly extending the life of electric aircraft propulsion energy source (e.g., batteries, fuel cells, etc.).
- Test techniques, including optical-based measurement methods that capture data in various spectra, for conducting quantitative in-flight boundary layer flow visualization, Schlieren photography, near and far-field sonic boom determination, and atmospheric modeling as well as measurements of global surface pressure and shock wave propagation.
- Measurement technologies for in-flight steady and unsteady aerodynamics, juncture flow measurements, propulsion airframe integration, structural dynamics, stability and control and propulsion system performance.
- Improved rugged wideband fiber optic sweeping laser system design for optical frequency domain reflectometry containing no moving parts, to be operated onboard NASA's wide range of aircraft. Improved development of polarization insensitive fiber measurements using optical frequency domain reflectometry.
- Wireless sensors, sensing technologies and telecommunication methods that can be used for flight test instrumentation applications for manned and unmanned aircraft. Emphasis should be on developing a variety of specialized low profile sensors that are capable of participating in a synchronized, high data rate and high data volume diverse wireless sensor measurement network with a capability to deliver time-stamped data to a central node. This area of technologies also includes wireless (non-intrusion) power transferring techniques and/or wirelessly powering remote sensors.
- Innovative measurement methods that utilize intelligent sensors for autonomous remote sensing in support of advanced flight testing.
- Fast imaging spectrometry that captures all dimensions (spatial/spectral/temporal) and can be used on unmanned aerial systems (UAS) platforms.
- Innovative new flight platforms, airframes and the associated subsystems development for use in all areas of flight tests and missions, e.g., X-planes testing, hypersonic testing, science missions, etc.

The emphasis of this subtopic is on flight test and flight test facility needs.

The technologies developed for this subtopic directly address the technical challenges in the Aeronautics Research Mission Directorate (ARMD) Integrated Aviation Systems Program (IASP), the Electrified Powertrain Flight Demonstration (EPFD) and Flight Demonstrations and Capabilities (FDC) projects. The FDC conducts complex flight research demonstration to support multiple ARMD programs. FDC is seeking to enhance flight research and test capabilities necessary to address and achieve the ARMD Strategic plan. They could also support Advanced Air Vehicle Program (AAVP) Projects: Commercial Supersonic Technology (CST), and AAVP - Aeronautic Evaluation & Test.

References

https://sbir.nasa.gov/

https://www.nasa.gov/mission_pages/lowboom/index.html

https://www.nasa.gov/centers/armstrong/news/FactSheets/FS-109.html

https://www.nasa.gov/centers/armstrong/research/X-56/index.html

https://www.nasa.gov/centers/armstrong/news/FactSheets/FS-108-AFRC.html

https://www.nasa.gov/centers/armstrong/features/shock_and_awesome.html

https://technology-afrc.ndc.nasa.gov/featurestory/fiber-optic-sensing

Expected TRL or TRL range at completion of the project: 1 to 6

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Software, Research

Desired Deliverables Description

For a Phase I effort, at least a report is desired that describes the effort's successes, failures and the proposed path ahead.

For a Phase II effort, the small business should show a maturation of the idea or technology that allows for a presentation of detailed influential analysis or a thorough demonstration at least, and most ideally a delivery of a prototype that includes beta-style or better hardware or software.

State of the Art and Critical Gaps

Current atmospheric flight systems cover a large range of uses from point-to-point drones, to high performance small aircraft, to large transports, to general aviation. In all areas, advancements can be possible if insights can be gained, studied and used to create new technologies. New insights will require an evolution of current testing and measurement techniques as well as novel forms and implementations. Known gaps include: Wireless instrumentation for flight, advanced telemetry technique, intelligent internal state monitoring for air and space vehicles, techniques for studying sonic booms, advanced techniques for capturing all dimensions of system operation and vehicle health (spatial/spectral/temporal) and extreme environment high-speed large area distributive sensing techniques. Along with these comes secure telemetry of data to ensure informed operation of the flight system.

Relevance / Science Traceability

The technologies developed for this subtopic directly address the technical challenges in ARMD's IASP and FDC projects. FDC conducts complex flight research demonstrations to support different ARMD programs. FDC is seeking to enhance flight research and test capabilities necessary to address and achieve ARMD Strategic plan. Also, they could support IASP Electrified Powertrain Flight Demonstration Project, Advanced Air Vehicle Projects (AAVP) - Commercial Supersonic Technology (CST), and AAVP - Aeronautic Evaluation & Test.

A2.02: Unmanned Aircraft Systems (UAS) Technologies (SBIR)

Lead Center: AFRC

Participating Center(s): ARC, GRC, LaRC

Technology Area: 4.0.0 Robotics, Telerobotics and Autonomous Systems

Related Subtopic Pointer(s): H9.03 T5.04 T8.06 T4.01 S1.08 A3.03 A3.04 A2.01 A1.09 Z8.02 A3.01 A3.02

Scope Title
Enabling Autonomy

Scope Description

Unmanned Aircraft Systems (UAS) offer significant advantages over manned aircraft for applications which are dangerous to humans, long in duration, requiring fast response and high degree of precision. Some examples include remote sensing, disaster response, delivery of goods, industrial inspection and agricultural support. Additionally, UAS may eventually be capable of safely transporting passengers, which can increase operational flexibility. The addition of autonomy to UAS enables more capability and promises greater economic and operational advantages. Some of these advantages include a higher degree of resilience to off-nominal conditions, the ability to adapt to dynamic situations and less reliance on humans during operations.

There are many barriers that are restricting greater use and application of autonomy in UAS. These barriers include, but are not limited to, the lack of methods, architectures and tools that enable:

- The verification, validation and certification of complex and/or nondeterministic systems
- Sensing, perception, cognition and decision-making
- Cost-effective, resilient and self-organizing communications
- Improved survivability in degraded or off-nominal conditions

NASA and the aviation industry are involved in research that would greatly benefit from breakthroughs in UAS capabilities that could eventually enable the new Urban Air Mobility market. A few of the areas of research and missions are listed below.

- Remote sensing missions utilizing one or more UAS would benefit from autonomous planning algorithms that can coordinate and execute a mission with minimal human oversight
- Detect and avoid algorithms, sensor fusion techniques, robust trajectory planners and contingency management systems that can enable Urban Air Mobility (UAM) and higher levels of UAS integration into the national airspace

This solicitation is intended to break through these and other barriers with innovative and high-risk research.

The Integrated Aviation Systems Program's work on UAS technology for the FY 2020 NASA SBIR solicitation is focused on tackling these barriers to enable greater use of UAS in NASA research, in civil aviation use and ultimately in the emerging UAM market. The following four research areas are the primary focus of this solicitation, but other closely related areas will also be considered for award. The primary research areas are:

- Verification, Validation and Certification - New methods of verification, validation and certification need to be developed which enable application of complex systems to be certified for use in the National Airspace System (NAS). Proposed research could include novel hardware and/or software architectures that enable alternate or expedite traditional verification and validation requirements.
- Sensing, Perception, Cognition and Decision Making - Technologies need to be developed that provide the ability of UAS to detect and extract internal and external information of the vehicle, transform the raw data into information that can be understood by machines or humans, and recognize patterns and make decisions based on the data and patterns.
- Cost-effective, Resilient and Self-organizing Communications - Methods that ensure reliable, trusted-source communications with increasingly complex and interconnected systems are needed to minimize the impact of infrastructure outages (e.g. Global Positioning System (GPS) or ground station) and that are resilient against both internal and external cyber-physical attacks. Several key areas of interest are Resilient Position Navigation and Timing (RPNT) for GPS denied/degraded environments,

mesh/self-organizing networks, and quantum communication technologies, in particular, quantum repeaters and quantum key distribution methods.

- Improved survivability in degraded or off-nominal conditions - Vehicle health monitoring techniques and contingency management algorithms that will mitigate risk to people and assets on the ground or in the air.

It is important to note that some technologies such as quantum communications can be utilized in many areas and it is recommended that the scope of such proposals be tailored to unmanned aircraft.

References

1) https://www.hq.nasa.gov/office/aero/pdf/armd-strategic-implementation-plan.pdf
2) https://www.nasa.gov/sites/default/files/atoms/files/nac_tie_aug2018_tfong_tagged.pdf

Expected TRL or TRL range at completion of the project: 3 to 6

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Software, Research

Desired Deliverables Description

Phase I deliverables should include, but are not limited to:

- A final report clearly stating the technology challenge addressed, the state of the technology before the work was begun, the state of technology after the work was completed, the innovations that were made during the work period, the remaining barriers in the technology challenge, a plan to overcome the remaining barriers and a plan to infuse the technology developments into UAS application.
- A technology demonstration in a simulation environment which clearly shows the benefits of the technology developed.
- A written plan to continue the technology development and/or to infuse the technology into the UAS market. This may be part of the final report.

Phase II deliverables should include, but are not limited to:

- A final report clearly stating the technology challenge addressed, the state of the technology before the work was begun, the state of technology after the work was completed, the innovations that were made during the work period, the remaining barriers in the technology challenge, a plan to overcome the remaining barriers, and a plan to infuse the technology developments into UAS application.
- A technology demonstration in a relevant flight environment which clearly shows the benefits of the technology developed.
- There should be evidence of infusing the technology into the UAS market or a clear written plan for near term infusion of the technology into the UAS market. This may be part of the final report.

State of the Art and Critical Gaps

Current autonomous systems have limited capabilities, poor perception of the environment, require human oversight and need special clearances to fly in the NAS. Future autonomous systems with higher degrees of autonomy will be able to freely fly in the NAS but will require certifiable software that ensure a high degree of safety assurance. Additionally, advanced sensors and more sophisticated algorithms that can plan around other UAS/UAM vehicles and obstacles will be needed. Therefore, the technology that will be required to advance the state of the art are as follows:

1. A certification process for complex non-deterministic algorithms
2. Sensors (LIDAR, GPS, etc.) and sensor fusion algorithms
3. Decision making and cooperative planning algorithms
4. Secure and robust communications

Relevance / Science Traceability

This subtopic is relevant to NASA ARMD's Strategic Thrust 5 and Strategic Thrust 6.

- https://www.nasa.gov/aeroresearch/programs/tacp
- https://www.nasa.gov/aeroresearch/programs/aosp
- https://www.nasa.gov/aeroresearch/programs/iasp

Focus Area 20: Airspace Operations and Safety

Lead MD: ARMD

Participating MD(s): None

This focus area includes technologies addressing both the Airspace Operations and Safety Program (AOSP), and NASA's ARMD Strategic Thrusts 1, 5, and 6. AOSP is targeting system-wide operational benefits of high impact for NextGen and beyond, both in the areas of airspace operations and safety management. The SBIR Airspace Operations and Safety Topic is focused on research and technology development for enabling a modernized air transportation system that will achieve much greater capacity and operational efficiency while maintaining or improving safety and other performance measures. This will include the integration of new types of vehicles such as unmanned vehicles, advanced subsonic aircraft, supersonic or commercial space vehicles; new types of business models or operations (i.e., urban air mobility); and new architectures or services for enabling these operations within the NAS.

A3.01: Advanced Air Traffic Management System Concepts (SBIR)

Lead Center: ARC

Participating Center(s): LaRC

Technology Area: 15.0.0 Aeronautics

Related Subtopic Pointer(s): A2.02 A3.02 A3.03 A3.04 A2.01

Scope Description

This subtopic addresses contributions towards Air Traffic Management (ATM) systems and concepts with potential application in the near-future National Airspace System (2025-2030). The subtopic seeks proposals that can apply novel and innovative technologies and concepts towards addressing established ATM challenges of improving efficiency, capacity, and throughput while minimizing negative environmental impact, and maintaining or improving safety and/or which can accelerate the implementation of NASA technologies in the current and future National Airspace System (NAS).

The NASA technologies that are being researched and developed for the future NAS include, but are not limited to; Integrated Arrival, Departure, and Surface (IADS) capabilities, routing and rerouting around weather from ground-based and cockpit-based systems, tools enabling Trajectory-Based Operations (TBO), and capabilities that can be integrated with a fully-realized Unmanned Aircraft Systems Traffic Management (UTM) system for a wide range of commercial and public use.

Technologies, concepts, models, algorithms, architectures and tools are sought in this solicitation to bridge the gap from NASA’s Research and Development (R&D) to operational implementation, and should address such nearer-term ATM challenges as:

- Safe, end-to-end TBO
- Enabling and integrating existing independent systems and domains, and increasingly diverse and unconventional operations (gradually enabling the future integration of large unmanned vehicles, unconventional commercial airline business models, space traffic management, subsonic and supersonic vehicles)
- Applying elements of the service-based architecture concept being pioneered in the UTM domain

References

https://www.nasa.gov/aeroresearch/programs/aosp

Expected TRL or TRL range at completion of the project: 1 to 4

Desired Deliverables of Phase II

Prototype, Analysis, Software, Research

Desired Deliverables Description

Technologies that can advance safe and efficient growth in global operations (ARMD Thrust 1 Goal) which can be incorporated into existing and future NASA concepts.

State of the Art and Critical Gaps

State of the Art: NASA has been researching advanced air transportation concepts and technologies to improve commercial operations in the National Airspace System.

Critical Gaps: Significant challenges remain in integrating air transportation technologies across different domains and operators (e.g., airport surface and terminal area; airport authority and air navigation service providers; etc.) providing comprehensive, strategic scheduling and traffic management technologies, enabling concepts that will allow for increased demand and complexity of operations.

Relevance / Science Traceability

Airspace Operations and Safety Program (AOSP) within Aeronautics Research Mission Directorate (ARMD).

Successful technologies in this subtopic have helped to advance the air traffic management/airspace operations objectives of the Program, and enable successful technology transfer to external stakeholders (including the Federal Aviation Administration and the air transportation industry).

A3.02: Increasing Autonomy in the National Airspace System (NAS) (SBIR)

Lead Center: ARC

Participating Center(s): LaRC

Technology Area: 15.0.0 Aeronautics

Related Subtopic Pointer(s): S5.03 A2.02 A3.01 A3.03 A3.04

Scope Description

NASA's future concepts for air transportation will significantly expand the capabilities of airspace and vehicle management and are anticipated to increasingly rely on autonomy and/or artificial intelligence to ensure safe and equitable operations. Such future concepts propose a seamless, integrated, flexible and robust set of systems that are anticipated to include:

- Traditional as well as novel vehicle types: Unmanned Aircraft Systems (UAS), Urban Air Mobility (UAM), supersonic vehicles and space transportation vehicles
- All airspace domains and operations: airport, metroplex, en route, regional/national traffic flow management, integration of multiple domains, on-demand aircraft and operations, and non-towered airports, vertiports, spaceports, ramps and airline operations centers
- All mission types: commercial passenger, cargo transport, emergency response, surveillance, security, etc.

Further, the future concepts accommodate changes to a diverse range of environmental and operational conditions while maintaining expected safety levels.

This subtopic focuses on the future air transportation system (beyond 2025) including a widespread service-based architecture, as demonstrated within the NASA Unmanned Aircraft Systems Traffic Management (UTM) model, as appropriate.

This subtopic seeks proposals that will apply novel and innovative techniques, methods and approaches, to developing tools and/or technologies that will enable the successful transition to, or be an integral component of, the eventual realization of an autonomously operating airspace system in all airspace domains, from one in which human operators and decision-makers play a significant role.

Research and Development (R&D) challenges related to either transition or end-state autonomous airspace include:

- Transition of largely human-centric systems to human-autonomy teaming systems
- Autonomy/autonomous technologies and concepts for trajectory management and efficient/safe traffic flows
- Weather and environment-integrated flight planning, rerouting, and execution
- Fleet, crew and operator management to reduce the total cost of operations
- Graceful, manageable degradation in off-nominal conditions

This subtopic is also particularly interested in proposals focused on the application of advanced data science, and non-traditional data or information sources, towards Air Traffic Management (ATM) problems while incorporating meaningful ATM domain knowledge for more sophisticated results.

References

https://www.nasa.gov/aeroresearch/programs/aosp

Expected TRL or TRL range at completion of the project: 1 to 4

Desired Deliverables of Phase II

Prototype, Analysis, Software, Research

Desired Deliverables Description

Technologies that can advance safe and efficient growth in global operations (ARMD Thrust 1 Goal) as well as developing autonomy applications for aviation (as under ARMD Thrust 6).

State of the Art and Critical Gaps

State of the Art: NASA has been researching advanced air transportation concepts and technologies to improve commercial operations in the National Airspace System. Autonomy is the focus of increased ARMD interest as evidenced in Thrust 6, Assured Autonomy for Aviation Transformation. Airspace Operations and Safety Program (AOSP) research is increasingly applying autonomy technologies and capabilities towards air transportation challenges. These may be more limited solutions to targeted problems.

Critical Gaps: Data sciences and autonomy/artificial intelligence technologies continue to be growing areas that have great potential to benefit the development of a more autonomous air transportation system, which is expected to be needed to accommodate the increasing demand and diversity of air transportation missions and operations.

Relevance / Science Traceability

Airspace Operations and Safety Program (AOSP).

Successful technologies in this subtopic have helped to advance the air traffic management/airspace operations objectives of the Program. The technologies also introduce new autonomy/artificial intelligence/data science methods and approaches to air transportation problems for current and near-future application, and show where such approaches are/are not appropriate to advance airspace operations.

A3.03: Future Aviation Systems Safety (SBIR)

Lead Center: ARC

Participating Center(s): LaRC

Technology Area: 15.0.0 Aeronautics

Related Subtopic Pointer(s): H9.03 A2.02 A3.01 A3.02 A1.02 A1.04 A2.01 A3.04

Scope Description

Public benefits derived from continued growth in the transport of passengers and cargo are dependent on the improvement of the intrinsic safety attributes of the Nation’s and the world’s current and future air transportation system. Recent developments to address increasing demand are leading to greater system complexity, including airspace systems with tightly coupled air and ground functions as well as widely distributed and integrated aircraft systems. Current methods of ensuring that designs meet desired safety levels will likely not scale to these levels of complexity (Aeronautics R&D Plan, p. 30). The Airspace Operations and Safety Program (AOSP) is addressing this challenge with a major area of focus on In-Time System-wide Safety Assurance (ISSA). A proactive approach to managing system safety requires (1) the ability to monitor the system continuously and to extract and fuse information from diverse data sources to identify emergent anomalous behaviors after new technologies, procedures, and training are introduced; and (2) the ability to reliably predict probabilities of the occurrence of hazardous events and of their safety risks.

Understanding and predicting system-wide safety concerns of the airspace system and the vehicles flying in it, as envisioned in future aviation systems is paramount. Such systems would include the emergent effects of increased use of automation and autonomy to enhance system capabilities, efficiency and performance beyond current, human-based systems, through health monitoring of system-wide functions that are integrated across distributed ground, air, and space systems. Emerging highly automated and even autonomous operations, such as those envisioned for unmanned aircraft systems (UAS) and urban air mobility (UAM) will play a major role in future airspace systems. In particular, operating beyond the operator’s visual line-of-sight (BVLOS) and near or over populated areas are topics of concern. Safety-critical risks include (1) flight outside of approved airspace, (2) unsafe proximity to people/property, (3) critical system failure (including loss of command and control (C2) link, loss or degraded GPS, loss of power, and engine failure); (4) loss-of-control (i.e., outside the envelope or flight control system failure).

Tools are being sought for use in creating prototypes of ISSA capabilities. The ultimate vision for ISSA is the delivery of a progression of capabilities that accelerate the detection, prognosis and resolution of system-wide threats.

Proposals under this subtopic are sought, but are not limited to, development and/or demonstration in the following areas (with an emphasis on safety applications):

- Data collection architecture, data exchange model and data collection mechanism (for example via UTM TCL-4).
- Data mining tools and techniques to detect and identify anomalies and precursors to safety threats system-wide.
- Tools and techniques to assess and predict safety margins system-wide to assure airspace safety.
- Prognostic decision support tools and techniques capable of supporting real-time safety assurance.
- Verification and validation (V&V) tools and techniques for assuring the safety of air traffic applications during certification and throughout their lifecycles, and techniques for supporting the in-time monitoring of safety requirements during operation.
- Products to address technologies, simulation capabilities and procedures for reducing flight risk in areas of attitude and energy aircraft state awareness.
- Decision support tools and automation that will reduce safety risks on the airport surface for normal operations and during severe weather events.
- Alerting strategies/protocols/techniques that consider operational context, as well as operator state, traits and intent.
- Methodologies and tools for integrated prevention, mitigation and recovery plans with information uncertainty and system dynamics in a UAS and in a trajectory-based operations (TBO) environment.
- Strategies for optimal human-machine coordination for real-time hazard mitigation.
- Methods and technologies enabling transition from a dedicated pilot-in-command or operator for each aircraft (as required per current regulations) to single operators safely and efficiently managing multiple unmanned and UAM aircraft in civil operations.
- Measurement methods and metrics for human-machine team performance and mitigation resolution.
- System-level performance models and metrics that include interdependencies and relationships among human and machine system elements.

References

https://www.nasa.gov/aeroresearch/programs/aosp

https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/aero-rdplan-2010.pdf

Expected TRL or TRL range at completion of the project: 1 to 3

Desired Deliverables of Phase II

Prototype, Analysis, Software, Research

Desired Deliverables Description

Technologies that can advance the goals of safe air transportation operations which can be incorporated into existing and future NASA concepts.

State of the Art and Critical Gaps

State of the Art: Recent developments to address increasing air transportation demand are leading to greater system complexity, including airspace systems with tightly coupled air and ground functions as well as widely distributed and integrated aircraft systems. Current methods of ensuring that designs meet desired safety levels will likely not scale to these levels of complexity (Aeronautics R&D Plan, p. 30). AOSP is addressing this challenge with a major area of focus on ISSA.

Critical Gaps: A proactive approach to managing system safety requires (1) the ability to monitor the system continuously and to extract and fuse information from diverse data sources to identify emergent anomalous behaviors after new technologies, procedures, and training are introduced; and (2) the ability to reliably predict probabilities of the occurrence of hazardous events and of their safety risks. Also, with the addition of UAM concepts, and increasing development of UTM, the safety research needs to expand to include these various missions and vehicles.

Relevance / Science Traceability

Successful technologies in this subtopic will advance the safety of the air transportation system. The AOSP safety effort focuses on pro-actively managing safety through continuous monitoring and extracting relevant information from diverse data sources and identifying anomalous behaviors to help predict hazardous events and evaluate safety risk. This subtopic contributes technologies towards those objectives.

A3.04: Non-Traditional Airspace Operations (SBIR)

Lead Center: ARC

Participating Center(s): LaRC

Technology Area: 15.0.0 Aeronautics

Related Subtopic Pointer(s): A2.02 A3.01 A3.02 A3.03

Scope Description

In addition to pioneering air traffic management research and development in conventional, commercial and traditional airspace environments, NASA is exploring airspace operations incorporating unmanned vehicles and novel operations occurring in all airspaces (controlled and uncontrolled), with a goal to safely and efficiently integrate with existing operations and mission types. NASA's research to enable unmanned vehicles to be safely and fully integrated into existing airspace structures (or lack thereof) has already demonstrated the potential benefits and capabilities of a service-based architecture (such as developed for the Unmanned Aircraft Systems Traffic Management [UTM] Research and Development [R&D] evaluations), and has led to new procedures, equipage and operating requirements and policy recommendations, to enable widespread, harmonized, equitable execution of diverse unmanned missions.

This subtopic welcomes proposals continuing to support and develop the UTM concept which seeks technologies to enable safe, heterogeneous (manned/unmanned) operations including, but not limited to, the following:

- To demonstrate the scalability of the UTM concept to potentially 10M+ users/operators
- To enable low size, weight, and power sense-and-avoid technologies
- The development of UTM-focused track and locate functions
- Autonomous and safe Unmanned Aircraft Systems (UAS) operations for the last and first 50 feet under diverse weather conditions

This subtopic also welcomes proposals supporting the Urban Air Mobility (UAM) concept, which seeks technologies including, but not limited to, the following:

- Service-based architecture designs that enable dense urban mobility operations and/or increasingly complex operations at ultra-high altitudes
- Dynamic route planning that considers changing environmental conditions, vehicle performance and endurance, airspace congestion and traffic avoidance
- Dynamic scheduling for on-demand access to constrained resources and interaction between vehicles with starkly different performance and control characteristics
- Integration of emergent users with legacy users, large commercial transport, including pass-through to and from ultra-high altitudes and interactions around major airports
- Operational concepts for future vehicle and missions, including vehicle performance, vehicle fleet and network management, market need and growth potential for future operations and airspace integration
- Identification of potential certification approaches for new vehicles operations (such as electric vertical take-off-and landing)

References

https://www.nasa.gov/aeroresearch/programs/aosp

https://www.aviationsystemsdivision.arc.nasa.gov/publications/index.shtml

https://www.aviationsystemsdivision.arc.nasa.gov/index.shtml

https://www.nasa.gov/aeroresearch/strategy

Expected TRL or TRL range at completion of the project: 1 to 4

Desired Deliverables of Phase II

Prototype, Analysis, Software, Research

Desired Deliverables Description

Technologies that can advance safe and efficient growth in global operations (ARMD Thrust 1 Goal) as well as developing autonomy applications for aviation (as under ARMD Thrust 6), that are specifically applicable to UTM and/or UAM operations.

State of the Art and Critical Gaps

Current state of the art: The proposed research and development area previously resided as a subset of existing subtopic (A3.02) Autonomy of the National Airspace System (NAS). This has made this subtopic too unwieldy in trying to capture both fundamental research supporting increasing autonomy in the NAS as well as technologies that can support or expand existing efforts in unmanned vehicles research, in particular UAS Traffic Management (UTM) and Urban Air Mobility (UAM) areas.

The state-of-the-art also covers the initial stages of UTM and UAM technology development.

Critical gaps: As identified in the Scope description, technologies are needed to expand from NASA-developed prototype testing conditions to technologies that would enable broader system capabilities, and achieve increased system robustness, scalability and agility to meet various mission needs.

Relevance / Science Traceability

Airspace Operations and Safety Program (AOSP)

Air Traffic Management eXploration (ATM-X) Project

Unmanned Aircraft Systems Traffic Management (UTM) Project

Successful technologies in this subtopic will help NASA pioneer UTM and UAM concepts and technologies. The technologies also incorporate new autonomy/artificial intelligence/data science methods and approaches to air transportation problems for current and near-future application.

Focus Area 21: Small Spacecraft Technologies

Lead MD: STMD

Participating MD(s): None

Small spacecraft can accomplish commercial, science and exploration missions in unique and more affordable ways than can large conventional spacecraft. Small spacecraft are typically defined as those weighing 180 kg or less, and often designed for “containerized” deployment – e.g. CubeSats. NASA seeks small spacecraft technical innovations to rival the capabilities of their larger more expensive counterparts, while also striving to make them cheaper and quicker to build, easier to launch and operate. Previously limited to low Earth orbit, NASA also seeks improvements for their long-term use in cislunar space for lunar exploration, as lunar communications and navigation infrastructure, and to explore Mars and other deep space destinations. For deep space missions, improvements are needed in: long-range high-bandwidth radios packaged for small spacecraft; creation of and use of novel navigation devices and navigation references for use well beyond Earth; improved power and thermal management technologies; and subsystems tolerant of radiation environment in deep space. Propulsion technologies are sought for Trans Lunar Injection (TLI), lunar orbit insertion and maintenance, including transfer stages that host small spacecraft, return-to-Earth and Earth entry and descent mechanisms. Cooperatively operating ensembles and large swarms of small spacecraft require technical innovations that reduce small spacecraft delivery time and operations costs while increasing production, availability and reliability. Commercially available “stock” optics are needed in place of expensive, long-lead custom designs. Advancements are needed in reliable low-cost manufacturability, including modular and wirelessly interconnected subsystems, advancements in systems engineering, verification and test. Intelligent autonomous operations algorithms, spatial sensors and processors needed to interoperate in groups and to operate at long distances to relieve human-in-the-loop operations. NASA’s Small Spacecraft Technology Program will consider promising SBIR technologies for spaceflight demonstration missions and seeks partnerships to accelerate spaceflight testing and commercial infusion. Some of the features that are desirable for small spacecraft technologies across all system areas are the following:

- Simple design.
- High reliability.
- Tolerant of extreme thermal and/or radiation environments.
- Low cost or short time to develop.
- Low cost to procure flight hardware when technology is mature.
- Small system volume or low mass.
- Low power consumption in operation.
- Suitable for rideshare launch opportunities or storage in habitable volumes (minimum hazards).
- Able to be stored in space for several years prior to use.
- High performance relative to existing system technology.

The following references discuss some of NASA's small spacecraft technology activities:

- www.nasa.gov/smallsats https://www.nasa.gov/smallsat-institute

Another useful reference is the Small Spacecraft Technology State of the Art Report at:

- http://www.nasa.gov/sites/default/files/atoms/files/small_spacecraft_technology_state_of_the_art_2015_tagged.pdf

Z8.02: Communications and Navigation for Distributed Small Spacecraft Beyond LEO (SBIR)

Lead Center: GRC

Participating Center(s): ARC, GSFC, JPL, LaRC

Technology Area: 5.0.0 Communication and Navigation

Related Subtopic Pointer(s): H9.07 H9.05 S3.04 S4.04 T4.03 H9.03 S3.08 H9.01 A2.02 T5.04

Scope Title

Distributed Spacecraft Mission Communications

Scope Description

Develop enabling technologies for beyond Low Earth Orbit (LEO) communications, relative and/or absolute position knowledge, and control of small spacecraft. Space communications and position knowledge and control are enabling capabilities required by spacecraft to conduct NASA Lunar and deep-space distributed spacecraft science missions. Innovations in communications and navigation technologies for distributed small spacecraft are essential to fulfill the envisioned science missions within the decadal surveys and contribute to the success of human exploration missions. To construct the lunar communications architecture, it is appropriate to consider a hybrid approach of large and small satellite assets. Primary applications include data relay from lunar surface to surface, data relay to earth, and navigational aids to surface and orbiting users. Distributing these capabilities across multiple smallsats may be necessary because of limited Size, Weight and Power (SWaP), but also to enhance coverage. Technologies for specific lunar architecture are especially needed, but considerations of extension to the Martian domain are also solicited.

References

1) [1] International Communication System Interoperability Standard (ICSIS), found at: https://www.internationaldeepspacestandards.com
2) [2] Interagency Operations Advisory Group (IOAG): https://www.ioag.org/.
3) [3] Space Communication Architecture Working Group (SCAWG) (2006) NASA Space Communication and Navigation Architecture Recommendations for 2005-2030: https://www.nas.nasa.gov/assets/pdf/techreports/2006/nas-06-014.pdf
4) [4] NASA Delay/Disruption Tolerant Networking (DTN): http://www.nasa.gov/content/dtn
5) [5] “Delay-tolerant networking: an approach to interplanetary internet." IEEE Communications Magazine 41, no. 6 (2003): 128-136.
6) [6] National Telecommunications and Information Administration Frequency Allocation Chart: https://www.ntia.doc.gov/files/ntia/publications/january_2016_spectrum_wall_chart.pdf
7) [7] National Telecommunications and Information Administration Tables of Frequency Allocations: https://www.ntia.doc.gov/legacy/osmhome/alloctbl/alloctbl.html
8) [8] NASA Spectrum Policy and Guidance for Small Satellite Missions: http://www.nasa.gov/directorates/heo/scan/spectrum/policy_and_guidance.html
9) [9] NASA Space Communications and Navigation networks: https://www.nasa.gov/directorates/heo/scan/services/networks/index.html

10) [10] NASA Optical Communications: https://www.nasa.gov/directorates/heo/scan/opticalcommunications/overview

Expected TRL or TRL range at completion of the project: 3 to 5

Desired Deliverables of Phase II

Prototype hardware and/or software.

Desired Deliverables Description

Phase I - Identify and explore options for the Distributed Spacecraft Mission (DSM) configuration control, conduct trade analysis and simulations, define operating concepts, and provide justification for proposed multiple access techniques, frequency bands of operation, command and data handling and networking solutions. Also identify, evaluate and develop design for integrated communications payload(s) and one or more constituent technologies that enable distributed spacecraft operations in the relevant space environment beyond LEO. Integrated communications system solutions and constituent component deliverables should offer potential advantages over the state of the art, demonstrate technical feasibility, and show a path towards a hardware/software infusion into practice. Bench-level or lab-environment level demonstrations or simulations are desirable. The Phase I proposal should outline a path that shows how the technology can be developed into space-qualifiable and commercially available small spacecraft communications payloads through Phase II efforts and beyond.

State of the Art and Critical Gaps

Communications among spacecraft in the DSM configuration and between the DSM configuration and the Earth become more challenging beyond LEO distances. Collaborative configurations of widely distributed (10s to 100s km apart) small spacecraft (180 kg or less) will operate far into the near-Earth region of space and beyond into deep space, further stressing the already limited communications capabilities of small spacecraft. Alternative operational approaches with associated enabling hardware and/or software will be needed with the following:

- DSM configuration control – distributed operations of the DSM configuration and of individual small spacecraft alternatives need to provide: science data time and location stamping; temporary data storage; distributed network control and data planes; networking protocols; and any other considerations associated with control of the configuration. Control needs to allow a swarm to fly with the precision approaching that of one large instrument, and/or produce relative position data that allows for compensation of measurements over time.
- Uplinks (Earth-to-space) and Downlinks (space-to-Earth) – alternatives for coordinated command and control of the DSM configuration and individual small spacecraft from Earth as well as return of science and telemetry data to Earth.
- Integrated communications payload– hardware and software designs for the common and unique capabilities of each small spacecraft in the DSM configuration.
- Small Spacecraft Antennas – development of antennas optimized for either inter-satellite or uplink/downlink communications are sought across a broad range of technologies including but not limited to deployable parabolic or planar arrays, active electronically steered arrays, novel antenna steering/positioning subsystems, and others suitable for use in high data rate transmission among small spacecraft over large distances. Operations compatible with NASA’s space communications infrastructure [9] and Government exclusive or Government/non-Government shared frequency spectrum allocations is required. [6, 7, 8].

- Compatibility and interoperability with lunar communications and navigation architecture plans [1, 2, and 3]. Application of the emerging lunar standards includes frequency allocations per link functionality, modulation, coding, and networking protocol standards.

Relevance / Science Traceability

Several missions are being planned to conduct investigations/observations in the cis-lunar region and beyond. All of these missions will benefit from improved communications and navigation capabilities. For example, follow-on missions to the current Mars Cube One mission.

Scope Title

Distributed Spacecraft Mission Position Knowledge and Control

Scope Description

The navigation portion of this subtopic solicits methods for determining and maintaining spacecraft position within a configuration of small spacecraft. In addition, timing distribution solutions for the smallsats may be important. Distributed Spacecraft Mission (DSM) navigation solutions may be addressed via hardware or software solutions, or a combination.

References

[1] International Communication System Interoperability Standard (ICSIS), found at https://www.internationaldeepspacestandards.com

[2] Interagency Operations Advisory Group (IOAG): https://www.ioag.org/.

[3] Space Communication Architecture Working Group (SCAWG) (2006) NASA Space Communication and Navigation Architecture Recommendations for 2005-2030. https://www.nas.nasa.gov/assets/pdf/techreports/2006/nas-06-014.pdf

[4] About NASA Delay/Disruption Tolerant Networking (DTN): http://www.nasa.gov/content/dtn

[5] “Delay-tolerant networking: an approach to interplanetary internet." IEEE Communications Magazine 41, no. 6 (2003): 128-136.

[6] National Telecommunications and Information Administration - United States Frequency Allocation Chart: https://www.ntia.doc.gov/files/ntia/publications/january_2016_spectrum_wall_chart.pdf

[7] National Telecommunications and Information Administration - Tables of Frequency Allocations: https://www.ntia.doc.gov/legacy/osmhome/alloctbl/alloctbl.html

[8] NASA Spectrum Policy and Guidance for Small Satellite Missions: http://www.nasa.gov/directorates/heo/scan/spectrum/policy_and_guidance.html

[9] NASA Space Communications and Navigation networks: https://www.nasa.gov/directorates/heo/scan/services/networks/index.html

[10] NASA Optical Communications Overview: https://www.nasa.gov/directorates/heo/scan/opticalcommunications/overview

Expected TRL or TRL range at completion of the project: 3 to 5

Desired Deliverables of Phase II

Prototype hardware and/or software.

Desired Deliverables Description

Phase I - Identify and explore options for the DSM configuration control, conduct trade analysis and simulations, define operating concepts, and provide justification for proposed multiple access techniques, frequency bands of operation, command and data handling and networking solutions. Also identify, evaluate and develop design for integrated communications payload(s) and one or more constituent technologies that enable distributed spacecraft operations in the relevant space environment beyond LEO. Integrated communications system solutions and constituent component deliverables should offer potential advantages over the state of the art, demonstrate technical feasibility, and show a path towards a hardware/software infusion into practice. Bench-level or lab-environment level demonstrations or simulations are desirable. The Phase I proposal should outline a path that shows how the technology can be developed into space-qualifiable and commercially available small spacecraft communications payloads through Phase II efforts and beyond.

State of the Art and Critical Gaps

Science measurements of DSMs are based on temporal and spatially distributed measurements where position knowledge and control are fundamental to the science interpretation. Current space navigation technologies are not adequate when relative or absolute position knowledge of multiple spacecraft are involved. Global navigation satellite services like the U.S. global positioning satellites (GPS) provide very limited services beyond GEO (Geocentric) distances and no practical services in deep space. Autonomous navigation capabilities are fundamental to DSMs to ensure known topography of the configuration at the time of data acquisition. Control of the distributed configuration requires robust absolute and relative position knowledge of each spacecraft within the configuration and the ability to control spacecraft position and movement according to mission needs.

- Optical navigation - Solutions are sought for visual based systems that leverage advances in optical sensors (i.e., cameras, star trackers) to observe and track a target spacecraft and perform pose and relative position estimation. In particular, low SWaP absolute attitude determination using star tackers, etc. to achieve sub-arcsecond accuracy. JPL's ASTERIA 6U CubeSat demonstrated pointing stability of 0.5 arcseconds (0.1 m^{o}) RMS over 20 minutes using guide stars *might* represent the state-of-the-art. Opportunities for innovation include methods that do not require the execution of satellite maneuvers are/or the design of external satellite features that enhance observability. Innovations may be appropriate for only certain regimes, such as near, medium, or far range; however, this context should be described. Solutions for various mission operations concepts are of interest.
- Long-term, high accuracy attitude determination; in particular, low SWaP absolute attitude determination using star trackers, etc. to achieve sub-arcsecond accuracy.
- Other novel navigation methods - Stellar navigation aids, such as navigation via quasars, X-rays and pulsars, may provide enabling capabilities in deep space. Surface-based navigation aids, such as systems detecting radio beacons or landmarks, are invited.
- Methods for autonomous position control are also of interest. Technologies that accomplish autonomous relative orbit control among the spacecraft are invited. Control may be accomplished as part of an integrated system that includes one or more of the measurement techniques described above. Of particular interest are autonomous control solutions that do not require operator commanding for individual spacecraft. That is, control solutions should accept as input swarm-level constraints and parameters, and provide control for individual spacecraft. Opportunities for innovation include the application of optimization techniques that are feasible for small satellite platforms and do not assume particular orbit eccentricities. NOTE: Small spacecraft *propulsion* technologies are not included in this subtopic.

Relevance / Science Traceability

Space communications and position knowledge and control are enabling capabilities required by spacecraft to conduct all NASA missions. The concept of Distributed Spacecraft Missions (DSM) involves the use of multiple spacecraft to achieve one or more science mission goals.

Several missions are being planned to conduct investigations/observations in the cis-lunar region and beyond. All of these missions will benefit from improved communications and navigation capabilities.

Z8.06: DragSails for Spacecraft Deorbit (SBIR)

Lead Center: MSFC

Participating Center(s): ARC

Technology Area: 2.0.0 In-Space Propulsion Technologies

Related Subtopic Pointer(s): Z7.03 Z7.04

Scope Description

DragSails are a generic family of drag devices that can:

- Provide coarse, non-propulsive de-orbit capability which can aid in the disposal of end-of-life spacecraft through burnup upon reentry.
- Provide an accurate means of de-orbiting by modulating the ballistic coefficient to guide the system to a desired point at the Von Karman altitude for precision reentry targeting.

Small, lightweight, deployable membranes have been tested and deployed in Earth for both solar sail and drag sail applications. NASA's 10 square meter NanoSail-D2 solar sail and The University of Surrey's InflateSail drag sail are two examples. These systems demonstrated the technical viability of developing a deployable drag device to accelerate the deorbit of satellites to comply with end-of-life regulations and to mitigate the growth of orbital debris. Given the underlining technology similarities between solar sail and drag sail systems there are opportunities for adaptation or cross-use of some system elements. Further, there is also opportunity for cross-use into other fields such as PowerSails, thin-film surface power generation, and thin-film thermal control systems.

In terms of controlled, targeted de-orbit, the NASA Exo-Brake development effort has yielded promising though nascent results with the development of controllable tension structures. Tension structures don't have the 'beam buckling' issue associated with the more common drag sails at the higher dynamic pressures at atmospheric entry interface. This approach, while not as applicable to larger disposal efforts, can allow for more targeted reentry with potential additional uses in inexpensive Entry, Descent, and Landing (EDL) test-beds or sample return concepts.

Developing systems to actively provide a de-orbit disposal, or targeted de-orbit/re-entry capability, is the next logical step toward such systems becoming widely available for spacecraft manufacturers, NASA and other government agencies as an alternative to conventional propulsion systems. Specific technology development areas of interest include:

- Restowable concepts which can deploy, operate, then re-stow multiple times. This may include new boom and materials concepts, but must include a restowable/redeployable deployment architecture capable of meeting the de-orbit requirements below.
- Phase I proof of concept and preliminary design efforts that will lead to, or can be integrated into, environmental qualification and/or flight demonstration prototypes in a Phase II effort are of interest.
- Desired system-level capabilities include the de-orbit of CubeSats (3U to 12U or larger) and small spacecraft in the 50kg - 200kg mass range (frontal areas on the order of 2000 to 2700 cubic cm) from altitudes between approximately 700km and 2,000km in 25 years or less. Spacecraft flying below 700km will generally meet the 25-year-or-less requirement without augmentation.

References

Alhorn, Dean, Joseph Casas, Elwood Agasid, Charles Adams, Greg Laue, Christopher Kitts, and Sue O'Brien. "Nanosail-d: The small satellite that could!" (2011), Utah State University Small Satellite Conference, https://digitalcommons.usu.edu/smallsat/2011/all2011/37/

Andrew Viquerat, Mark Schenk, Vaios Lappas, and Berry Sanders. "Functional and Qualification Testing of the InflateSail Technology Demonstrator", 2nd AIAA Spacecraft Structures Conference, AIAA SciTech Forum, (AIAA 2015-1627), https://doi.org/10.2514/6.2015-1627

Expected TRL or TRL range at completion of the project: 3 to 6

Desired Deliverables of Phase II

Prototype, Analysis, and Hardware

Desired Deliverables Description

Ideal Phase II deliverable would be DragSail subsystems tested in a relevant environment

State of the Art and Critical Gaps

State of the Art is currently being defined by the solar sail propulsion community whose interest is deploying similar large-area, lightweight sails to reflect photons and derive thrust. Technologies which support solar sail development are inherently similar to those that would be required to develop and implement DragSails. Thin-film membranes capable of being stored in a folded state for several years or decades, lightweight deployable and potentially retractable booms, and combinations thereof that can survive in Earth orbit environment (UV, atomic oxygen, ionizing radiation, etc.) that can deploy, augment a spacecraft's aerodynamic drag, and restow are of interest. Flight control systems for DragSails have yet to be demonstrated or tested and will be essential for DragSail systems that provide deorbit independently of other, proven, deorbit systems.

Relevance / Science Traceability

Any spacecraft in Earth orbit must demonstrate how it will be either de-orbited or moved to an orbit that poses no risk to other spacecraft within a set period after its useful life. Therefore, any spacecraft launched by government, universities or industry are potential customers for a DragSail deorbit system. Further, the concepts developed as a part of the DragSail are applicable to large area solar sails, power sails, thin-film surface power, and the like.

Z8.08: Technologies to Enable Cost & Schedule Reductions for Ultra-Stable Normal Incidence Mirrors for CubeSats (SBIR)

Lead Center: ARC

Participating Center(s): GSFC, JPL

Technology Area: 8.0.0 Science Instruments, Observatories & Sensor Systems

Related Subtopic Pointer(s): S2.02 S2.04

Scope Description

Relatively inexpensive small spacecraft offer several advantages over larger, more expensive spacecraft: small spacecraft can perform inspection and repair of larger spacecraft; several can be deployed for more frequent revisit rates over Earth's surface or planetary objects; and multiple craft can achieve affordable mission reliability through redundancy. To date, the utility of small spacecraft in missions involving remote sensing (in any spectral band) has been constrained by their low budget and compact size: optical sensitivity is limited in proportion to the diameter of a telescope's aperture and magnification is limited by the effective focal length.

The cost to produce one-of-a-kind optical assemblies is disproportionate and the production times too long to incorporate into the tight budgets and schedules typical of small spacecraft missions.

The objective of this subtopic is to receive proposals that articulate a demonstrable ability to manufacture, test and control ultra-low-cost optical systems that can meet the reference mission performance requirements (including infrastructure issues) within a time frame and budget compatible with a small spacecraft development cycle. For the purposes of this subtopic, small spacecraft are defined as CubeSats of 12U volume. Proposals are sought that will specify telescope figures of merit for a potential small spacecraft mission (e.g. Earth resource management, maritime traffic monitoring, observations for agricultural industry, lunar exploration precursors, manned spacecraft inspection, NEO asteroid detection, or other reference mission to be specified by proposer) and will include discussion of current state-of-the-art for telescope optical parameters (sensitivity, resolution and magnification within a spectral band), production cost and schedule significantly improved by the proposed telescope design. Detector electronics are not specifically sought for this subtopic.

References

None

Expected TRL or TRL range at completion of the project: 3 to 6

Desired Deliverables of Phase II

Prototype

Desired Deliverables Description

Prototype telescope appropriate for inclusion in a 12U CubeSat with up to 8U available for optics. A CubeSat class precision optical system would include an aperture of up to approximately 0.2m diameter. For Phase I, deliverables should include a design reference mission relevant to the telescope design, with key performance parameters identified. Identification of key relevant subcomponents of a telescope system require a prototype demonstration for fabrication, test or control technology required for a successful Phase II delivery of a prototype. Ideally Phase I includes a reviewed preliminary design and manufacturing plan which demonstrates production feasibility, appropriate material behavior, process controls, optical performance, and mounting/deploying issues especially with considerations to small spacecraft should be resolved and demonstrated. While final manufacturing and assembly will be conducted in Phase II, the preliminary design should address how optical, mechanical (static and dynamic) and thermal designs and performance analysis will be done to show compliance with proposed performance measures, survival of the launch environment and performance in the space environment (Earth orbiting or deep space).

In Phase II the project could complete environmental qualification testing of the telescope including measuring optical figure before and after vibration testing, acoustic testing, and thermal cycling. It would also demonstrate that the telescope maintains optical figure in a reference thermal environment including thermal gradients.

A successful mission oriented Phase II would yield a credible plan to deliver (in phase III) flight hardware within the allocated budget for a fully assembled and tested telescope assembly which can be integrated into the potential mission; and, demonstrate an understanding of how the engineering specifications of their system meets the performance requirements and operational constraints of the mission (including mechanical and thermal stability analysis). Cost and schedule goals and optical performance goals are listed under State of the Art and Critical Gaps.

State of the Art and Critical Gaps

Technical Challenges: To accomplish NASA CubeSat-class missions, a low-cost telescope with ultra-stable, normal incidence mirrors with low mass-to-collecting area ratios, should be delivered on short schedules. After performance, the most important metric for an advanced optical system is affordability. Long telescope fabrication times add significant program cost. Current normal incidence space telescopes in the 0.2- 0.5m aperture class have lead times of 12-18 months and cost $1 million to $5 million. This research effort seeks a schedule compression and cost reduction for precision optical components by 10 times, to 4-6 months and $100K-$500K for a 0.2 m aperture class telescope.

Specific metrics are defined for each wavelength application region:

For UV/Optical:

- Wavefront Figure < 5 nm RMS.
- Wavefront Stability < 1 nm / 10 min
- First Mode Frequency >500 Hz.
- Actuator Resolution < 1 nm RMS.

For EUV:

- Slope < 0.1 micro-radian.

Also needed is ability to fully characterize surface errors and predict optical performance.

Relevance / Science Traceability

A new class of low-cost, optically stable, wide spectral range telescopes designed specifically for small spacecraft have application in a variety of exploration, commercial and science missions. Existing missions can be accomplished in novel and more affordable ways with small spacecraft, and new missions will be enabled by high-performance telescopes in small spacecraft. A few examples include: Earth resource management, maritime traffic monitoring, observations for agricultural industry from Low Earth Orbit; lunar exploration precursors and manned spacecraft inspection in cislunar space; and near Earth object detection or exoplanet transit detection in deep space.

Z8.09: Small Launcher Lunar Transfer Stage Development (SBIR)

Lead Center: MSFC

Participating Center(s): AFRC, GRC

Technology Area: 2.0.0 In-Space Propulsion Technologies

Related Subtopic Pointer(s): Z10.01 T6.05 Z2.01 S3.08 S3.04 Z8.10

Scope Description

NASA desires to explore the lunar environment using small spacecraft. The lunar environment in this case includes: the lunar surface with specific interest in the south pole, low lunar and frozen lunar orbits, as well as cislunar space including Earth-moon LaGrange points and the lunar Near Rectilinear Halo Orbit (NRHOs) intended for Gateway. To allow CubeSats and small spacecraft, defined as total mass less than 180 kg fueled, to exploit these locations, NASA is interested in the development of a low cost cis-lunar transfer stage to guide and propel small spacecraft on Trans Lunar Injection (TLI) trajectories that will enable the spacecraft to enter the above referenced lunar locations or orbits, either with on board propulsion capability or via the transfer stage itself.

Transfer stage architectures and designs shall be compatible with U.S. small launch vehicles that are currently flying or will be launching in the next year. Proposals should identify one or more relevant small launch vehicles and shall describe how their designs fit within the constraints of those vehicles. Transfer stage designs shall contain all requisite systems for navigation, propulsion, and communication in order to complete the lunar mission. Any and all propulsion chemistries and methods may be considered, including electric propulsion, as long as the design closes within the reference mission constraints. Transfer stages shall also include method(s) to deploy smallsat payloads once on a TLI trajectory or upon arrival in lunar orbit.

This subtopic is targeting transfer stages for launch vehicles that have a capability range similar to that sought by the NASA Venture Class Launch Services. Rideshare applications that involve medium or heavy lift launch vehicles (e.g. Falcon 9, Atlas V) or deployment via the International Space Station (ISS) airlock are not part of this topic.

Design reference mission:

- Launch on a small launch vehicle (ground or air launch)
- Payload (deployable spacecraft) mass: at least 25 kg
- Provide sufficient delta V and guidance to enter into TLI after separation from small launch vehicle. An example mission is the CAPSTONE / NRHO Pathfinder 12U (25 kg) CubeSat that requires a Trans Lunar Injection orbit with a C3 of -0.6 km2/s2.
- (Optional) provide sufficient delta V and guidance to place a 25 to 50 kg spacecraft directly into lunar NHRO orbit
- Deploy spacecraft from transfer stage
- Safe and dispose of transfer stage

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https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20160010585.pdf

https://www.rocketlabusa.com/photon/

https://www.rocket.com/space/space-power-propulsion/bipropellant-space-propulsion

https://www.rocket.com/sites/default/files/documents/CubeSat%20Mod%20Prop-2sided.pdf

Expected TRL or TRL range at completion of the project

Proposed technologies should mature to TRL 4 to 6 by the end of Phase II effort.

Desired Deliverables of Phase II

Prototype Hardware and Software

Experimental data

Mission design and analysis data

Desired Deliverables Description

A Phase I effort should include a Preliminary Design Review (PDR) level design for a flight-like system and a near-Completion Design Review (CDR) level design for the prototype system. The feasibility of key elements in the system design should be evident through fabrication or testing demonstrations. The phase 1 report should include a mapping of key performance parameters (mass, power, cost, etc.) from the prototype to the flight design, along with potential opportunities for technology demonstration and commercialization. It is highly desired that the Phase II deliverable include demonstration test data for the prototype system along with detailed metrics (mass, power, cost, etc.) which are traceable to a flight design for the reference mission. Efforts leading to Phase II delivery of integrated prototype systems that could either be ground tested or flight-testing as part of a post-Phase II effort are of particular interest.

State of the Art and Critical Gaps

Many cubesat/small sat propulsion units are designed for low delta-V maneuvers such as orbit maintenance, station keeping, or reaction control. Larger delta-V systems are employed for larger satellites and science/exploration missions, but are often costly and integrated as part of the satellite design. Systems typically range from cold-gas to bi-propellant storables with electric systems also viable for very small systems. Aerojet Rocketdyne and Moog are prominent suppliers of SOA thrusters including commonly used variants of the R-4D engine. Rocket Labs has recently introduced an upgraded version of their kick-stage using a monopropellant system to support LEO operations for small sat payloads. While many of the right component technologies are reasonably mature, no integrated system capability has been developed and implemented specifically as a low cost solution for trans-lunar or cis-lunar mission designs.

Relevance / Science Traceability

This subtopic extends the capabilities of the Flight Opportunities Program and Launch Services Program by seeding potential providers to establish lunar/cis-lunar transfer capabilities.

Many technologies appropriate for this topic area are also relevant to NASA's lunar exploration goals. Small stages developed in this topic area would also be potential flight test beds for cryogenic management systems, wireless avionics, or advance guidance systems and sensors.

Z8.10: Wireless Communication for Avionics and Sensors for Space Applications (SBIR)

Lead Center: ARC

Participating Center(s): GRC, JPL, LaRC, MSFC

Technology Area: 5.0.0 Communication and Navigation

Related Subtopic Pointer(s): S3.08 Z4.04 T13.01 S5.05 H6.22 T6.05 A2.01 Z8.09

Subtopic Description

This subtopic solicits proposals to develop enabling concepts, components, and subsystems based on innovative avionics architectures for small spacecraft. Of interest are wireless systems that demonstrate reliable data transfer across avionics components, subsystems, and interfaces to simplify system integration, reconfiguration, and testing. Solutions that enable new avionic architectures and provide capabilities that expand mission performance while decreasing the Size, Weight, and Power (SWaP) consumption and cost of the resulting spacecraft are highly desirable. The goal of this effort is to mature wireless avionics technology that facilitates the reuse of components, subsystems and software across multiple spacecraft and missions while reducing production and operating costs.

Modularity is defined as utilizing a set of standardized parts or independent units to form a full avionics system and flexibility allows adapting modular components across different configurations, missions, and design stages. For example, wireless subnets improve modularity by eliminating the physical data connections from each component, simplifying physical integration. The scope is intended to range from simple wireless sensors to complete avionics systems including software incorporating functions compatible with common spacecraft components. This means being able to integrate a given component or entire subsystem into flight hardware and software using object-oriented frameworks allowing components or functions to be added to a new or existing spacecraft design without requiring significant changes to the other non-related components or subsystems.

This subtopic also solicits proposals to develop techniques, components, and systems that reduce or eliminate the dependency on wires, connectors, and penetrations for sensing and for the transmission of data and power across avionics subsystems, interfaces, and structures. Of interest are techniques that enable new applications through the use of innovative methods such as the use of flexible materials and additive manufacturing. The use of additive manufacturing and 3D printing to embed avionics components such as antennas, sensors, transmission lines and interface functions into a spacecraft structure during the design and manufacturing process can increase efficiency while maintaining structural integrity. Similarly, the use of thin and flexible materials to construct passive wireless sensors enables sensing systems for structures such as parachutes and inflatable spacecraft without breaching the pressure interface. Systems that are applicable to small spacecraft (typically 6U/12U/24U CubeSats including ESPA-class), but scalable to large vehicles can result in a significant reduction of risk for more complex and longer duration missions. Near-term missions include: cislunar, lunar orbiting, lunar landed, exploration precursor; Low Earth Orbit (LEO) “swarms” for Earth science and heliophysics; disaggregated cooperative ensembles and sustained infrastructure for human exploration. New applications might include manned spacecraft inspection, repair, communications support and related areas. Proposals that provide reliable performance in extreme environments and that show a path to a flight demonstration are preferable.

The subtopic solicits developments in wireless avionics and wireless sensing for small spacecraft and may include technologies that:

1. Improve the reliability and applicability of wireless avionics for small spacecraft with significant improvements in subsystem size, mass, volume, particularly if the technology can simplify the spacecraft fabrication, test and integration process.
2. Allow innovative architectures for wireless avionics featuring plug-and-play software supporting modular subsystems that can be easily incorporated into specific small satellite missions.
3. Improve fault detection aboard spacecraft using wireless sensor systems to augment current wired sensors and which include the capability of adding sensors to address Developmental and Flight Instrumentation use.
4. Use additive manufacturing techniques for embedding sensors and other avionics components into a spacecraft to reduce or eliminate large and heavy cables and connectors or that enable data transfer inside and across rotating mechanisms and pressure interfaces or into remote locations where it is difficult or unfeasible to run cables or where cables are at risk of failure.
5. Use additive manufacturing of wireless components such as antennas, sensors and processing elements into materials and structures that enable in-situ structural health management, contributing to the development of smart structures and materials.
6. Include sensors and actuators that can be distributed among cooperative spacecraft to enable automated inspection of space assets or resource detection at the surface of the moon, Mars or other celestial bodies.

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PWST Workshops – https://attend.ieee.org/wisee-2019/program/workshops/

Expected TRL or TRL range at completion of the project

TRL 1 to 2 concepts for science instruments and sensory systems for vehicles and observatories

TRL 3 to 6 for embedded sensor systems and modular avionics technology development and prototype demonstration

Desired Deliverables of Phase II

Prototype Hardware and Software, Demonstrations

Desired Deliverables Description

Possible deliverables include bench-top hardware systems that demonstrate reliable wireless inter-connectivity of two or more modules with a host flight CPU, or payload/DFI processor, inside a Cubesat or Small Satellite form-factor bus. This system need not be flight-ready, but it should be in a path to a flight demonstration that would serve as technology maturation and risk reduction activity for larger NASA missions such as Lunar Gateway, and other Artemis projects.

Specific Deliverables Include:

- Methods of improving reliability of wireless avionics technology
- Redundancy methods to broaden mission applicability
- Improvements in tolerance to extreme environments including radiation
- Novel avionics architecture definition and demonstration
- Software support for redundant modular avionics
- Plug and Play methods for handling dynamic changes to avionics configuration
- Fault detection and recovery for wireless avionics
- Improvements in spacecraft production
- Improvements in spacecraft Integration and Test
- Technologies that use additive manufacturing technology for embedded avionics systems that reduce cables, connectors, and penetrations and show a path to a full solution.
- Sensors and sensor systems based on current technology needs to develop point solutions that are applicable to NASA missions in near to mid-range time frames

State of the Art and Critical Gaps

Development of small satellites missions benefits from a growing number of users worldwide, resulting in a large pool of COTS components available for specific missions, depending on the type and class of mission. A variety of C&DH (Command and Data Handling) developments for CubeSats have resulted from in-house development, from new companies that specialize in CubeSat avionics, and from established companies who provide spacecraft avionics for the space industry in general. Presently there are a number of commercial vendors who offer highly integrated systems that contain the on-board computer, memory, electrical power system and the ability to support a variety of input & output for the CubeSat class of small spacecraft. Wireless networks have been incorporated as crew support networks aboard ISS, freeing the astronauts from cables.

Wireless sensor networks have been flown as demonstrations aboard CubeSats. Dynamic self-configuring wireless networks have been evaluated in the lab. The AIAA has defined the Space Plug-and-Play (SPA) standard and flight demonstrations are planned.

The maturation of additive manufacturing and 3D printing technology are making embedded wireless sensors and avionics a possibility. Embedding transmission lines, antennas, connectors, and sensors onto a spacecraft structure turns that structure into a multi-functional system that reduces or eliminates bulky cables and connectors. Embedded passive wireless sensors can greatly increase sensing and telemetry capabilities, including providing low-cost techniques for vehicle health management for future missions. Moreover, flexible embedded passive sensors created with conductive and functional fabrics are enabling new opportunities for sensing in surfaces and systems where sensing has been traditionally absent such as parachutes and inflatable structures

Relevance / Science Traceability

NASA and other space agencies are exploring the application of SmallSats for deep space missions. The availability of modular wireless data connectivity alleviates complexity in testing and integration of systems. Modular components allow easier reconfiguration and late additions to any design. This is a benefit conferred to any spacecraft of any size, with the larger systems benefiting from savings in mass due to a larger reduction in cable harnesses and connectors.

Focus Area 22: Low Earth Orbit Platform Utilization and Microgravity Research

Lead MD: HEOMD

Participating MD(s): None

The Human Exploration and Operations Mission Directorate (HEOMD) provides mission critical space exploration services to both NASA customers and to other partners within the U.S. and throughout the world: operating the International Space Station (ISS); ensuring safe and reliable access to space; maintaining secure and dependable communications between platforms across the solar system; and ensuring the health and safety of astronauts. Additionally, the HEOMD is chartered with the development of the core transportation elements, key systems, and enabling technologies required for beyond-Low Earth Orbit (LEO) human exploration that will provide the foundation for the next half-century of American leadership in space exploration. In this topic area, NASA is seeking technologies that address how to improve and lower costs related to use of flight assets; maximize the utilization of the ISS for in-situ research; and utilize the ISS as a platform for in-space commercial science and technology opportunities.

NASA seeks to accomplish these objectives by achieving following goals:

- Investing in the near- and mid-term development of highly-desirable system and technologies that provide innovative ways to leverage existing ISS facilities for scientific payloads
- Increasing investments in research to prepare for extended duration missions in near Earth space and beyond
- Enabling U.S. commercial spaceflight opportunities and technology development to support the commercialization of low Earth orbit (LEO)

Through the potential projects spurred by this topic, NASA hopes to incorporate SBIR-developed technologies into current and future systems to contribute to the expansion of humanity across the solar system while providing continued cost-effective ISS operations and utilization for its customers, with a high standard of safety, reliability, and affordability.

References:

- Space Station Research &Technology: https://www.nasa.gov/mission_pages/station/research/experiments/explorer
- Center for the Advancement of Science in Space: https://www.iss-casis.org/
-

H8.01: Utilization of the International Space Station (ISS) to Foster Commercial Development of Low-Earth Orbit (LEO) (SBIR)

Lead Center: JSC

Participating Center(s): ARC, GRC, JPL, KSC, LaRC, MSFC

Technology Area: 6.0.0 Human Health, Life Support and Habitation Systems

Related Subtopic Pointer(s): Z3.03 Z4.04

Scope Description

This subtopic seeks proposals that could aid in achieving NASA's newly-stated objective of leveraging International Space Station (ISS) capabilities to stimulate demand and catalyze markets leading to a broad commercial demand for Low Earth Orbit (LEO). The ISS SBIR program has particular interest in technologies and flight projects that could lead to valuable terrestrial applications due to development in microgravity, which can aid in fostering an economy in LEO. Use of the ISS will facilitate validation and enable development of the minimal viable product required to attract significant capital and lead to growth of new and emerging commercial markets in the following areas: in-space manufacturing, regenerative medicine, bioengineering and advanced materials production. Additionally, leveraging existing ISS facilities for new research and commercial product development which could improve, enhance and/or augment investigations being conducted, or planned to be conducted, on ISS is a high priority.

References

- Space Station Research & Technology at: https://www.nasa.gov/mission_pages/station/research/experiments/explorer
- Center for the Advancement of Science In Space, Inc. at: https://www.issnationallab.org/
- LEO Economy: https://cms.nasa.gov/leo-economy/low-earth-orbit-economy

Expected TRL or TRL range at completion of the project: 3 to 7

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Software, Research

Desired Deliverables Description

Desired deliverables at the end of Phase II would be engineering development units and/or software packages for NASA-sponsored testing that could be turned into proof-of-concept systems suitable for flight demonstrations.

State of the Art and Critical Gaps

The ISS is being used to stimulate both the supply and demand of commercial marketplace as NASA supports the development of the LEO space economy.

Relevance / Science Traceability

This subtopic is in direct support of NASA's recent policy to enable commercial and marketing activities to take place aboard the ISS. The ISS capabilities will be used to further stimulate the demand for commercial products development.

Focus Area 23: Digital Transformation for Aerospace

Lead MD: STTR

Participating MD(s): None

Digital Transformation is the strategic transformation of an organization's processes and capabilities, driven and enabled by rapidly advancing and converging digital technologies, to dramatically enhance the organization's performance and efficiency. These advancing digital technologies include cloud computing, data analytics, artificial intelligence, blockchain, mobile access, Internet of Things (IoT), agile software development and processes, social media, and others. Their convergence is producing major transformations across industries - media and entertainment, retail, advertising, software, publishing, health care, travel, transportation, etc. Through digital transformation, organizations seek to gain or retain their competitive edge by becoming more aware of and responsive to both customer and employee interests, more agile in testing and implementing new approaches, and more innovative and prescient in pioneering the next wave of products and services. Central to the success digital transformation is the pervasive (and often transparent) gathering of data about everything that impacts success--the organization's processes, activities, competencies, products and services, customers, partners, industry, and so on. Organizations can mine this massive, complex, and often unstructured data to develop accurate insights into how to improve organizational performance and efficiency. An organization may also use this data to train machine learning algorithms to automate processes, provide recommendations, or enhance customer experiences. The digital technologies listed above are essential to generate, collect, transform, mine, analyze, and utilize this data across the enterprise. NASA is undertaking a digital transformation journey to enhance mission success and impact. NASA intends to leverage digital transformation to:

- Boost innovation and creation of new knowledge.
- Reduce cost and increase the effectiveness and efficiency of processes for everything from human resources to science and engineering.
- Reduce the time to develop and mature new technologies.
- Facilitate efficient design and development of advanced aerospace vehicles.
- Ensure that increasingly complex missions are both cost-efficient and safe.
- Achieve data-driven insights and decisions.
- Increase autonomy in aerospace vehicles and ground facilities.
- Engage an enthusiastic and talented workforce.
- Maintain worldwide leadership in aerospace.

Through this focus area, NASA is seeking to help explore and develop technologies that may be critical to the Agency's successful digital transformation. Specific innovations being sought in this solicitation are:

- Blockchain for aerospace applications, including its use in distributed space missions and in model-based systems engineering.
- Intelligent digital assistants that reduce the cognitive workload of NASA personnel, from scientists and engineers to business and administrative staff.

Details about these applications of digital transformation technologies are in the respective subtopic descriptions.

T11.03: Distributed Digital Ledger for Aerospace Applications (STTR)

Lead Center: MSFC

Participating Center(s): ARC, GSFC, LaRC

Technology Area: 11.0.0 Modeling, Simulation, Information Technology and Processing

Related Subtopic Pointer(s): T11.04 H6.04 S5.04 S5.05

Scope Description

A Blockchain is a decentralized, online record keeping system, or ledger, maintained by a network of computers that verify and record transactions using established cryptographic techniques. A Blockchain is a data structure that makes it possible to create a consistent, digital ledger of data and share it among a network of independent parties. Blockchain distributed ledger technology may become a key enabler of digital transformation, enabling peer to peer transactions without requiring intermediaries or pre-established trust. Blockchain was originally developed to support digital currency transactions. Now, application of Blockchain is being explored for other financial services, software security, Internet of Things, parts tracking (supply chain), asset management, smart contracts, identify verification, and much more.

NASA is seeking innovative solutions involving Blockchain that would greatly enhance operational efficiency by providing a single, immutable "source of truth", viewable by all authorized parties, and usable by automated reporting and verification systems, for the following two NASA-specific challenges.

Model Based System Engineering (MBSE): A significant challenge in MBSE is knowing that the system model being used is the current (or needed) version, since various aspects evolve through the system development and operations lifecycle. Further, because systems are becoming increasingly complex, tracking the vast number of changes that occur needs to be automated and efficient. Blockchain solutions may enable a single, real-time source of truth for system models, to eliminate several sources of error and inefficiency in MBSE.

Distributed space mission management: To accomplish complex space mission and Earth observation objectives, constellations of distributed satellites are often the most cost-effective approach. These constellations share key consolidated resources such as ground stations, a space network, communication networks, onboard processes, etc. A blockchain solution to managing distributed space missions should enable collaboration in a partially trusted environment and increase responsiveness, reliability, and availability of spacecraft and ground resources. The management functions enhance flexibility (e.g., reduce overhead for components to join and leave constellations), and enhance automation (e.g., automate resource outage alerts, facilitate localized replanning, enable a constellation level model-based diagnostics). To accomplish this, proposed solutions must overcome the slow transaction rate, large file sizes, and concurrency issues of some blockchain implementations.

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Expected TRL or TRL range at completion of the project: 3 to 5

Desired Deliverables of Phase II

Prototype, Analysis, Research

Desired Deliverables Description

The desired deliverable is a prototype system that demonstrates a scalable, Blockchain-based solution to one of the NASA challenges described.

State of the Art and Critical Gaps

Almost all successful Blockchain solutions to date are for ledgers for digital currency transactions. Use of Blockchain is being explored in a broad range of areas, but there are no known scalable solutions for the NASA challenges described. Here, scalable means that the solution works efficiently and securely for a large number of transactions and users in a relevant, distributed digital environment.

Relevance / Science Traceability

Blockchain solutions can benefit all NASA Mission Directorates and functional organizations. NASA activities could be dramatically more efficient and lower risk through Blockchain support of more automated creation, execution, and completion verification of important agreements, such as international, supply chain, or data use.

T11.04: Digital Assistants for Science and Engineering (STTR)

Lead Center: LaRC

Participating Center(s): ARC

Technology Area: 11.0.0 Modeling, Simulation, Information Technology and Processing

Related Subtopic Pointer(s): S5.04 S5.03 T11.03 T4.04 Z3.04 Z4.05 H6.04

Scope Description

NASA is seeking innovative solutions that combine modern digital technologies (e.g., natural language processing, speech recognition, machine vision, machine learning and artificial intelligence, and virtual reality and augmented reality) to create digital assistants. These digital assistants can range in capability from low-level cognitive tasks (e.g., information search, information categorization and mapping, information surveys, semantic comparisons), to expert systems, to autonomous ideation. NASA is interested in digital assistants that reduce the cognitive workload of its engineers and scientists so that they can concentrate their talents on innovation and discovery. Digital assistant solutions can target tasks characterized as research, engineering, operations, data management and analysis (of science data, ground and flight test data, or simulation data), business or administrative. Examples of potential digital assistants include:

- A digital assistant that uses the semantic, numeric, and graphical content of engineering artifacts (e.g., requirements, design, verification) to automate traces among the artifacts and to assess completeness and consistency of traced content. For example, the digital agent can use semantic comparison to determine whether the full scope of a requirement may be verified based on the description(s) of the test case(s) traced from it. Similarly, the digital assistant can identify from design artifacts any functional, performance, or non-functional attributes of the design that do not trace back to requirements. Currently, this work is performed by project system engineers, quality assurance personnel, and major milestone review teams.
- A digital assistant that can identify current or past work related to an idea by providing a list of related government documents, academic publications, and/or popular publications. This is useful in characterizing the state-of-the-art when proposing or reviewing an idea for government funding. Currently, engineers and scientists accomplish this by executing multiple searches using different combinations of keywords from the idea text, each on a variety of search engines and databases; then the engineers read dozens of documents and returns to establish relevance. This example looks for digital assistive technologies to reduce this workload substantially.
- A digital assistant that can highlight lessons learned, suggest reusable assets, highlight past solutions or suggest collaborators based on the content that the engineer or scientist is currently working on. This example encourages digital solutions that can parse textual and/or graphical information from an in-progress work product and search Agency knowledge bases, project repositories, asset repositories, and other in-progress work products to identify relevantly similar information or assets. The digital assistant can then notify the engineer of the relevant information and/or its author (potential collaborator).
- A digital assistant that can recommend an action in real-time to operators of a facility, vehicle, or other physical asset. Such a system could work from a corpus of system information such as design artifacts, operator manuals, maintenance manuals, and operating procedures to correctly identify the current state of a system given sensor data, telemetry, component outputs, or other real-time data. The digital assistant can then use the same information to autonomously recommend a remedial action to the operator when it detects a failure, to warn the operator when their actions will result in a hazard or loss of a mission objective, or to suggest a course of action to the operator that will achieve a new mission objective given by the operator.
- A digital assistant that can create one or more component or system designs from a concept of operations, a set of high-level requirements, or a performance specification. Such an agent may combine reinforcement learning techniques, generative-adversarial networks, and simulations to autonomously ideate solutions.
- An expert system that uses a series of questions to generate an initial system model (e.g. using Systems Modeling Language [SysML]), plans, estimates, and other systems engineering artifacts.
- Question and Answer (Q&A) Bots: A digital agent that can answer commonly asked questions on "how-to" for scientists and engineers (e.g., what resources [grounds facilities, labs, media services, IT] are available; where to get site licenses for software packages; who to contact for assistance on a

topic; answers for general business procedures such as procurement, travel, time and attendance, etc.)

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Expected TRL or TRL range at completion of the project: 3 to 5

Desired Deliverables of Phase II

Prototype, Hardware, Software

Desired Deliverables Description

Phase II would conclude with a demonstration (prototype) or a deployable digital assistant with quantifiable reduction in time or cost of an activity typically performed by NASA scientists, engineers, or operators.

State of the Art and Critical Gaps

Digitally assistive technologies currently permeate the consumer market with products like the Amazon Echo, Apple devices with Siri, Google devices with Google Assistant, and Microsoft devices with Cortana. Though Apple, Google, and Microsoft are also moving their assistive technologies into the enterprise space, these developments are largely focused on reducing information technology costs. Some cities and college campuses have also acted as early adopters of smart city or smart campus technologies that include digital assistants. However, application of these assistive technologies to engineering and science has largely been limited to university research. Moreover, most assistive technologies exercise no more cognition than a Q&A bot or executing simple commands. The emergence of improved natural language processing brings the possibility of digital assistants that can perform low-level cognitive tasks. This subtopic aims not only to bring commercially available assistive technologies to the engineering environment, but elevate their cognitive capabilities so that engineers and scientists can spend more time innovating and less time on low-level cognitive work that is laborious or repetitive.

Relevance / Science Traceability

This subtopic is related to technology investments in the NASA Technology Roadmap, Technical Area 11 Modeling, Simulation, Information Technology, and Processing under sections 11.1.2.6 Cognitive Computer, 11.4.1.4 Onboard Data Capture and Triage Methodologies, and 11.4.1.5 Real-time Data Triage and Data Reduction Methodologies. This subtopic is seeking similar improvements in computer cognition, but more generally applied to the activities performed by engineers and scientists and made more easily accessible through technologies like speech recognition.

Focus Area 24: Dust Mitigation

Lead MD: STMD

Participating MD(s): HEOMD

A number of space exploration missions to planetary bodies have noted significant deleterious effects due to fine particulates. This fine dust can foul mechanisms, alter thermal properties, and obscure optical systems. It can abrade textiles and scratch surfaces. With near term goals to return to the Moon, lunar dust is of particular concern. It has the potential to negatively affect every lunar architecture system. The goal of this focus area is to develop dust mitigation technologies that can be incorporated into space exploration systems.

All planetary exploration missions require a proactive strategy to lessen the effects of dust. Dust mitigation approaches include active and passive technologies and informed engineering design. Much of the dust can be mitigated through operational constraints and architecture consideration early on in the system design lifecycle. However, passive and active technologies and novel engineering design are also needed to form a complete dust mitigation strategy. Proposed research may focus on development of new technologies, but there is particular interest in technologies that are approaching readiness for space environment testing.

Exploration systems require dust mitigation technologies within the following capability areas:

- Optical Systems – Viewports, camera lenses, solar panels, space suit visors, mass spectrometers, other sensitive optical instruments;
- Thermal Surfaces – Thermal radiators, thermal painted surfaces, thermal connections;
- Fabrics – Space suit fabrics, soft wall habitats, mechanism covers;
- Mechanisms – Linear actuators, bearings, rotary joints, hinges, quick disconnects, valves, linkages;
- Seals and Soft Goods – Space suit interfaces, hatches, connectors, hoses; and,
- Gaseous Filtration – Atmosphere revitalization and ISRU processes.

Specific dust mitigation innovations being sought in this solicitation will be outlined in the subtopic descriptions.

H3.03: Lunar Dust Management Technology for Spacecraft Atmospheres and Spacesuits (SBIR)

Lead Center: GRC

Participating Center(s): JSC, MSFC

Technology Area: 6.0.0 Human Health, Life Support and Habitation Systems

Related Subtopic Pointer(s): Z13.02 Z13.01

Scope Description

Upon their return to Earth one of the Apollo astronauts commented that “dust is probably one of our greatest inhibitors to a nominal operation on the Moon.” Advances in spacecraft atmospheric quality management are sought to address the intrusion and containment of lunar dust in pressurized volumes and compartments in spacecraft systems. This will require the development of particle filtration and separation techniques, barrier techniques and monitoring instruments. For space suits, the challenge is to prevent dust intrusion, while at the same time providing the capability to mate and de-mate connectors and suit components as well as enabling venting to the environment for certain components. This will require the development of specialized dust covers for a variety of connections.

Specifics Regarding Areas of Interest in Spacecraft Atmospheric Quality Management are the Following:

Particle Filtration and Separation Techniques

Techniques and methods are sought leading to compact, low power, autonomous, regenerable bulk particulate matter separation and collection techniques suitable for general spacecraft cabin air purification and removal of planetary lunar dust in main cabin quarters and airlock compartments. The particulate matter removal techniques and methods must accommodate high volumetric flow rates up to 11.3 m^3/minute and minimized pressure drop (typically <125 Pa). The filter and separation system needs to meet both the requirements for internally generated particulate matter, such as derived from materials, ECLSS and other processes, and biological matter and debris generated by the crew, and lunar dust intrusion. Permissible levels of suspended particulate matter total dust must be maintained to <3 mg/m^3, and the respirable fraction of the total dust to <2.5 µm in aerodynamic diameter to <1 mg/m^3, as per the standards in the NASA-STD-3001 Vol 2, Rev. B. More specifically lunar dust needs to be maintained to a time-weighted average of 0.3 mg/m^3 for particles < 10 µm during intermittent daily exposure periods that may persist up to 30 days in duration for the Gateway or Habitat, and an average of 1.6 mg/m^3 for particles < 10 µm for a 7 day exposure period on the lander . Filtration performance should be at minimum 99.97 % collection efficiency for particles 0.3 micron in diameter and larger (or HEPA efficiency standard). The filter and separation system needs to also provide microbial and fungal control as outlined in the NASA-STD-3001 Vol 2, Rev. B requirements.

Barrier Techniques

Specialized particulate matter management systems specifically designed to collect and remove lunar dust from airlocks or suit preparation compartments or areas that provide a > 99.5% effective barrier to lunar dust transfer between different volumes or compartments are also of interest. The barrier technique can include filtration, separation and mitigation techniques used within these smaller pressurized compartments and/or techniques that prevent the transport or transfer of lunar dust between compartments or to main cabin areas.

Monitoring Instruments

Instruments, or instrument technology, that measure particulate matter concentrations and particle sizes to verify compliance with particulate matter cleanliness levels (stated above) are desired. In addition, the instrument will need to monitor lunar dust intrusion in airlocks and into main cabin areas. Real-time measurement instruments must be compact and low power, requiring minimal maintenance and be able to maintain calibration for years. The instrument also needs to be compatible with the microgravity, reduced gravity and reduced pressure environments (26.2 kPa < pressure ≤ 103 kPa) in the cabin and airlocks of the transit and lander vehicles. The different environmental parameters may necessitate different modes of operation within one instrument (preferred to minimize payload and operational resources) or it may require different sensor types. Particle sensors that are capable of distinguishing between different material types (lunar vs generic dust) when measuring particulate matter concentration and particle sizes will be highly desirable.

Specifics Regarding Areas of Interest in Spacesuit Components are the Following:

Garment Protection:

A lunar space suit requires a dedicated Environmental Protection Garment (EPG) to protect the pressure garment and crewmember from the extreme lunar surface conditions. The extreme conditions include but are not limited to:

1. Extreme cold scenarios
2. Extreme hot scenarios
3. Highly abrasive lunar regolith

Not only does the EPG have to protect against the conditions above, but it must also not inhibit the space suit mobility. It would be beneficial if space suit solutions provide protection for the crewmember in the highly abrasive lunar regolith environment along with accommodating the extreme cold and hot conditions.

Venting Portable Life Support System (PLSS) Covers:

There are several spacesuit components that require access to the environment for gas flow, both in nominal and off-nominal operations. These components require specialized covers that prevent dust intrusion while at the same time allowing for sufficient gas flow. These components are:

1. PLSS Shell Vent Ports

The PLSS shell has two ports to allow the evaporated water from the spacesuit water membrane evaporator (SWME) and its backup the Mini Membrane Evaporator (Mini-ME) to escape. The operation of these components is dependent on a low back pressure and each of the vent ports must have a flow through area of at least 7 in^2 to maintain the appropriate pressure for evaporation within the PLSS shell. The vents need to accommodate a water vapor mass flow of at least 2.6 lb/hr. The total area available for the vent ports is approximately 10 by 2.5 inches on either side.

2. PLSS Rapid Cycle Amine (RCA) System Vent Quick Disconnect

The RCA system for water vapor and CO_2 removal requires vacuum access for the desorption of these constituents. This is accomplished via a Quick Disconnect (QD) on the PLSS backplate. For efficient desorption, the pressure in the vacuum access line needs to decrease quickly and allow the flow of 0.65 L of ullage gas to the environment. The ullage gas can be assumed to be 100 % O_2 at 2.15 psi. Without a specialized cover, this gas dissipates within about 2 seconds. After the ullage gas has dissipated, the desorbed gas consists of CO_2 and H_2O with a mass flow of 325 to 360 g/min depending on the bed loading and metabolic rate of the crew member. Between 210 to 230 g/min of that flow is CO_2. The rapid decompression of the vacuum line is essential for efficient operation of the RCA, as is the following diffusion of desorbed gas away from the absorber beds, both of which must not be impeded by the specialized dust cover.

3. Suit Purge Valve (SPV) and Low Flow Purge Valve (LFPV)

The SPV is located on top of the Display and Control Unit and is used during nitrogen purge operations in the airlock. The LFPV is used during off-nominal operations to ensure sufficient CO_2 washout in the helmet and to provide some gas flow through the pressure garment. While similar in design, both valves require different flow rates. The SPV requires 3.15-3.38 lb/hr and the LFPV requires 1.55-1.69 lb/hr of O_2 flow rate at 3.5 psi. Both valves are exposed on the outside of the spacesuit to enable crew member access and thus need specialized covers in order to tolerate large amounts of dust exposure.

4. Positive and Negative Pressure Relief Valves (PPRV and NPRV)

The PPRV and NPRV are located on the hard upper torso (HUT) and exposed to vacuum and dust. The full open flow rate requirement for the PPRV is 7.49 lb/hr of dry O_2 at 70°F with suit internal pressure of 10.1 psia and vacuum as the external reference. The requirement for the NPRV is 60.4 lb/hr of dry air at 70°F, with the airlock pressure at 4.15 psia and a suit pressure at 3.65 psia. Specialized covers are needed in order to tolerate dust exposure.

Non-Venting Portable Life Support (PLSS) Covers:

Two other connectors are on the exterior of the suit that do not need vacuum access and are nominally covered during an Extravehicular Activity (EVA). However, they need to be accessed at the conclusion of an EVA at which point they may be covered in dust. Specialized covers for these connectors are needed to both protect the connectors from dust intrusion during the EVA as well as during the removal of the covers. The connectors are as follows:

1. An 85-pin receptacle that serves as the battery charge connector and is located on the bottom corner of the PLSS.
2. The Spacesuit Common Connector (SCC) contains high pressure oxygen lines, water lines, an electrical connector as well as mechanical mounting features. The SCC is located on the front of the spacesuit and is integrated with the Display and Control Unit (DCU). The connector is flat and has a surface area of approximately 2.5 by 4 inches.

References

NASA-STD-3001 Vol 2, Rev. B.

Lunar Sourcebook, *edited by Grant H. Heiken, David T. Vaniman, Bevan M. French, 1991, Cambridge University Press*

Agui, Juan, R. Vijayakumar, and Jay Perry. "Particulate Filtration Design Considerations for Crewed Spacecraft Life Support Systems." 46th International Conference on Environmental Systems, 2016.

Apollo 17 Technical Crew Debrief, Page 20-12, NASA Manned Spacecraft Center, January 4, 1973, MSC-07631

Expected TRL or TRL range at completion of the project: 3 to 4

Desired Deliverables of Phase II

Prototype, Analysis, Hardware

Desired Deliverables Description

Phase I Deliverables - Reports demonstrating proof of concept, test data from proof of concept studies, concepts and designs for Phase II. Phase I tasks should answer critical questions focused on reducing development risk prior to entering Phase II.

Phase II Deliverables - Delivery of technologically mature hardware, including components, subsystems or treatments that demonstrate performance over the range of expected suit and spacecraft conditions. Hardware should be evaluated through parametric testing prior to shipment. Reports should include design drawings, safety evaluation, test data and analysis. Robustness must be demonstrated with long term operation and with periods of intermittent dormancy. System should incorporate safety margins and design features to provide safe operation upon delivery to a NASA facility.

State of the Art and Critical Gaps

The state of the art in spacecraft filtration are HEPA filters used on the ISS, known as Bacterial Filter Elements (BFE).

There are currently no viable airborne particle sensors for pressurized volumes on the ISS or slated for future missions. Commercial sensors are only compatible with standard conditions (1 atmosphere) and terrestrial gravity levels. Also there are no commercial particle sensors that can discriminate between material types or particle shapes that may be used to distinguish between lunar dust and generic cabin dust.

Relevance / Science Traceability

Lunar and Martian human surface missions (Artemis/lander/spacecraft) will be required to address and provide methods of controlling the intrusion of lunar dust into pressurized volumes.

The Life Support Systems (LSS) Project, under the Advanced Exploration Systems Program, Human Exploration and Operations Mission Directorate (HEOMD), is the expected customer for spacecraft cabin dust management technologies. The LSS Project would be in position to sponsor Phase III and technology infusion.

For Exploration EVA System Development, the xEMU Project is the expected customer.

Z13.01: Active and Passive Dust Mitigation Surfaces (SBIR)

Lead Center: KSC

Participating Center(s): JSC, LaRC

Technology Area: 7.0.0 Human Exploration Destination Systems

Related Subtopic Pointer(s): Z12.01 T5.03 Z2.01 Z5.05 H3.03 Z7.04 H5.01 S3.06 Z1.05

Subtopic description

NASA seeks new technologies that can be used to remove dust from surfaces that may have accumulated as a result of interactions of systems or subsystems exposed to dusty surfaces either directly or indirectly as a result of missions to the moon, Mars and/or small bodies (like asteroids, comets, and Near-Earth Objects). Unique materials and technologies that reduce or mitigate lunar dust adhesion will be critical to support long duration missions and eventual sustained presence on the lunar surface. This call in particular seeks new technologies for the prevention and accumulation of dust on surfaces which could cause deleterious effects in lunar environments. Such technology could be implemented onto various surfaces such as solar panels, thermal radiators, space suit outer layers, helmets, visors, boots, displays, control panels, viewports, batteries are examples of solid flat transparent or non-transparent surfaces depending on the dust-loading requirements for each subsystem. More complex mechanisms such as hatches, hatch seals, hatch mechanisms, hinges, quick disconnects, etc. that require dust mitigation technologies are covered by subtopic "Dust Tolerant Mechanisms.

Scope Title

Active Dust Mitigation Surfaces

Scope Description

Proposals are sought that use unique methods that may require power, gases, mechanisms, vibrations or other means necessary to keep vital surfaces clean under space conditions. Self-cleaning surfaces are highly desired which require minimal effort by astronauts. Proposers are expected to show an in-depth understanding of the current state-of-the-art (SOA) and quantitatively describe improvements over relevant SOA technologies that substantiate investment in the new technology. Proposers must also quantitatively explain the operational benefit of the new technology from the perspective of improving or enabling mission potential. Some examples of active dust mitigation technologies include but are not limited to:

- Brushing – a self-cleaning brush to mechanically remove dust from surfaces. The brush can be mechanically operated using power or temperature activated such as shape memory alloys
- Electrostatic Removal – methods to use DC electric fields to remove dust from surfaces either internal to the surface (embedded) or external using a removed high voltage source
- Liquid removal – a jet of liquid is applied to the surface which traps particles and removes them from the surface
- Vacuum – methods to remove particles from surfaces using suction of gases
- Jets - high-velocity gas jet which blows dust particles from surfaces.
- Spinning surfaces – surface rotates in a manner which does not allow collection of dust on it
- Vibrational surfaces – vibrating surface bounces the particles off of a surface
- Electrodynamic Removal – the surface contains embedded electrodes with varying high voltage signals applied to lift and transport dust off of the surface.

Proposals are highly sought in which the active dust mitigation strategy could be *combined* with the SOA of passive dust mitigation technologies. For example passive dust mitigation strategies include:

- Electrostatic Discharge (ESD) coatings and films– statically dissipative coatings are less likely to accumulate charge and hence dust in dry environments
- Superhydrophobic coatings – materials with a very high contact angle can lower the adhesion of water-based contaminants not allowing the capillary forces to take hold.
- EVA and robotic compatible dust proof electrical, fluid, and gas connectors
- Dust proof bearings and mechanical spacesuit connectors
- Dust tolerant or resistant hatches
- Docking systems - including suit port docking systems and pressurized rover and habitat docking systems
- Lotus leaf coating – microscopic nanostructures used to limit the Van der Waals force of adhesion
- Peel away coating – removable coatings from surfaces

Strong proposals are those which identify the active dust removal strategy in coordination with other dust prevention and removal methods as listed above.

Scope Title

Passive Dust Mitigation Surfaces

Scope Description

This call seeks unique research proposals focused on passive approaches, i.e., those that do not require external stimulus, that will minimize the potential impact Lunar dust will have on future exploration missions. These approaches may include novel materials and surfaces as well as technologies that require no external input (a self-activating system). Novel materials may include high performance plastics, metals, ceramics, etc. Surfaces may be homogeneous or heterogeneous, and rough or smooth with topography imparted by any number of approaches including but not limited to: lithography, embossing, roll-to-roll processing etc. Both the material and surface modification approach must be demonstrated to be scalable and exhibit a dramatic reduction (>90% relative to a reference material surface such as an aerospace aluminum alloy or polymeric film surface such as Kapton or Teflon) in particulate adhesion for micro-particles, specifically those described as Lunar dust simulant, with diameters < 50 micrometers.

References

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Wohl, C.; Belcher, M.; Ghose, S.; Hopkins, J.; Connell, J., Topographical modification of materials for mitigation of lunar dust adhesion. In 40th Lunar and Planetary Science Conference, The Woodlands, TX United States, 2009.

Gaier, J. R.; Meador, M. A.; Rogers, K. J.; Sheehy, B. H. Abrasion of Candidate Spacesuit Fabrics by Simulated Lunar Dust. National Aeronautics and Space Administration, 2009, TM-215800.

Expected TRL or TRL range at completion of the project: 3 to 6

Desired Deliverables of Phase II

Research, Analysis, Prototype, Hardware

Desired Deliverables Description

At the end of the Phase I research period, it is expected that a material or technology will be identified and initial characterization results collected. Initial characterization should indicate whether further development of the technology would be scalable and exhibit a dramatic reduction (>90% relative to full dust loading of a reference material surface such as an aerospace aluminum alloy or polymeric film surface such as Kapton or Teflon) in particulate adhesion for microparticles, specifically those described as Lunar dust simulant, with diameters < 50 micrometers. At the end of Phase II, it is expected that promising technologies will have been demonstrated through relevant environmental test conditions. The materials or technology should be demonstrated to be scalable to quantities sufficient for application beyond laboratory research requirements, i.e., at kilogram or greater quantities for materials or a similar measure for a passive technology. Cost analysis for scaling to mission-requirements level, as will be elucidated through the course of this research, will also be required.

If a Phase II is awarded, then further development of the technology shall be required, including a prototype delivered to NASA at the end of the two-year project with a goal of achieving TRL 6. A prototype of the new technology must be provided which shows the feasibility of the dust removal method. The technology must be demonstrated in a laboratory environment removing and/or keeping dust from adhering to a surface. The mass, power, volume and potential costs associated with the implementation of this technology must be addressed.

State of the Art and Critical Gaps

Active Dust Mitigation Technologies

All new technologies for Active Dust Mitigation must include a full knowledge base of the SOA and proposals that advance the current SOA are encouraged. For example, NASA has developed the Electrodynamic Dust Shield or EDS which lifts and transports dust off of surfaces with embedded electrodes within a dielectric. A brief but not complete introduction to the technology can be found in the references above.

The EDS can be incorporated into a variety of configurations addressing many of NASA's needs. However, there are several potential improvements and technologies that can further the development of the EDS technology are also highly sought within this call. Some potential advances include:

- Miniaturized high voltage 3-phase power supply – The current SOA for the EDS power supply is approximately 10 cm X 5 cm X 3 cm. It is highly desired to have smaller power supplies both in size and power to drive the EDS waveform for a variety of applications.
- High dielectric breakdown strength for both glues/epoxies as well as the coating material – The efficiency of dust removal for the EDS is limited to amount of voltage that can be applied to the electrodes. The electrical breakdown occurs across the 2-D surface because of the dielectric strength limitation of the adhering material as well as the coating material.
- Flexible transparent surfaces with high current capabilities – The optically transparent version of the EDS uses Indium Tin Oxide as the main conductive medium for its electrode. Although the EDS is not a high current DC device, the displacement current (I dV/dt) can be quite high. Transparent electrode materials are sought that can replace ITO as the conductive medium that have higher current capabilities and lower overall resistivities. Another shortcoming of ITO is its range of flexibility. Many ITO coatings cannot be bent past a certain degree and are not compatible with numerous folds and bends.
- The EDS technology also works on fabrics. However high voltage flexible wires than can be used as threads are unavailable. The electrodes would need to be low profile and sufficient to withstand up to +10 kV DC before breakdown. A unique feature of the EDS on fabrics is that it needs to be a multilayer system as most space fabrics are. One layer would have to support electrical grounding to protect the astronaut but intermediate layers would have withstand high voltage breakdown. The top layer would house the HV wire system comprised of the EDS requirements.
- Electrical attachment – most EDS systems have issues with the electrical connections between the HVPS and the electrodes. Any possibility of arcing and/or sparking as a result of slight differences between the wiring from one material configuration to another is exacerbated when powered with EDS waveforms. Proposals are highly sought that address this key issue for attaching HV wires to electrodes embedded in an EDS circuit. EDS circuit electrodes are made using a variety of the materials such as: copper (wires or vapor deposited), ITO, silver paint wires, carbon nanotube (CNT) and graphene to name a few. Likewise these and other electrodes are usually resting on or embedded into a substrate such as glass, Polyimide (Kapton), clothing fibers, PET, PTFE, nylon, acrylic, Lucite and other surfaces.
- Minimizing electromagnetic interference (EMI) - Most EDS designs can generate electrical noise that would be disadvantageous for it to be incorporated into a system. Methods to reduce electrical noise and EMI would be highly sought.

- Safety - with all EDS systems, the use of high voltage requires safety measures for the astronaut and the equipment. Methods to improve the safety and reliability of the EDS in the case of arcing is highly sought.
- Smart EDS technology - as with all dust mitigation technologies, methods to included adaptive techniques are highly sought. The system should be able to check its environment to see if dust clearing is necessary, and if it is, apply power to the system until the cleanliness requirements are met for reliability and power minimization.

Other active systems also require maturation. Critical gaps in these areas include:

- Effective and scratch resistant brushing techniques. Apollo astronauts used brushes that are largely ineffective for large surface areas and tended to scratch sensitive equipment, such as astronaut visors.
- Gaseous removal of dust on the lunar surface may contaminate other sensitive equipment. A better approach to gaseous or fluidized removal of dust is needed.
- Simple mechanical or vibrational dust mitigation implementations are required. As particles move, they also become highly electrostatically charged, further causing dust adhesion.

<u>Passive Dust Mitigation Technologies</u>

Although a myriad of materials and technologies exist for mitigation of surface contamination for a variety of terrestrial applications, requirements for mitigation of lunar dust adhesion indicate diminished efficacy of many materials. As an example, silicones are used ubiquitously to reduce adhesive interactions and can be effective for contamination prevention across a range of contaminants. These relatively soft materials though would exhibit deleterious properties in a traditional manifestation arising from particulate embedding due to the sharp edges and hardness of the lunar dust. Likewise, hard traditional ceramic materials have been shown to be beneficial for terrestrial applications. Triboelectrification, however, of an insulating material would increase adhesion interactions with lunar dust. Beyond these specific lunar dust properties, magnetic interactions, chemical activity, and the velocity of the Lunar dust, especially at the lunar terminator, all contribute to adhesion and therefore must be addressed for a material to be expected to perform well in this environment.

Relevance / Science Traceability

Adhesion of granular materials and the technologies that address mitigation through this subtopic will advance the state of knowledge of this difficult research subject. The interplay between the surface’s energy, chemistry, mechanical properties and the particle’s surface is a fascinating but not well understood science. This call will not only extend exploration missions on the lunar surface, they will enable exploration missions that would not have be possible. For example every mechanical seal was compromised on the Apollo missions in the course three days due to the exposure to the dust. Research that elucidates this complex behavior toward lunar dust adhesion could be vital for realization of a sustained lunar presence and although our understanding of the lunar environments has continued to improve, materials and technologies that arise from this research will expound our survival on dusty surfaces in space.

Ideally, a universal lunar simulant will be identified by NASA and should be used for performance verification of developed technologies. If no universal simulant is identified, then the specific properties of the utilized particulate material should be identified and related to known properties of lunar dust.

Z13.02: Dust Tolerant Mechanisms (SBIR)

Lead Center: KSC

Participating Center(s): GRC, JSC, LaRC

Technology Area: 7.0.0 Human Exploration Destination Systems

Related Subtopic Pointer(s): Z7.04 Z5.05 H3.03 H5.01

Scope Title

Dust Tolerant Joints

Scope Description

A return to the Moon to extend human presence, pursue scientific activities, use the Moon to prepare for future human missions to Mars and expand Earth's economic sphere, will require investment in developing new technologies and capabilities to achieve affordable and sustainable human exploration. From the operational experience gained and lessons learned during the Apollo missions, conducting long-term operations in the lunar environment will be a particular challenge, given the difficulties presented by the unique physical properties and other characteristics of lunar regolith, including dust. The Apollo missions and other lunar exploration have identified significant lunar dust-related problems that will challenge future mission success. Comprised of regolith particles ranging in size from tens of nanometers to microns, lunar dust is a manifestation of the complex interaction of the lunar soil with multiple mechanical, electrical and gravitational effects.

Mechanical systems will need to operate on the dusty surface of the moon for months to years. These systems will be exposed to the harsh regolith dust and will have little to no maintenance. This scope seeks technologies that will protect from or tolerate dust intrusion in the following areas:

- Rotary joints (steering, suspension, hinges, bearings, etc.)
- Linear joints (latches, shafts, restraint systems, landing gear, etc.)
- Static joints (quick disconnects, covers, airlocks, sample tools, etc.)

Successful solutions will enable operation in a lunar environment for 10 to 100 months with limited or no maintenance.

References

Dust mitigation gap assessment report - The International Space Exploration Coordination Group (ISECG) - https://www.globalspaceexploration.org/wordpress/docs/Dust%20Mitigation%20Gap%20Assessment%20Report.pdf

https://www.globalspaceexploration.org/wordpress/docs/Dust%20Mitigation%20Gap%20Assessment%20Report.pdf

Expected TRL or TRL range at completion of the project: 2 to 6

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Software, Research

Desired Deliverables Description

Research should be conducted to demonstrate technical feasibility during Phase I and show a path toward Phase II demonstration with delivery of a demonstration package for NASA testing in operational test environments at the completion of the Phase II contract.

Phase I Deliverables - Research, identify and evaluate candidate technologies or concepts for dust tolerant mechanisms. Simulations or lab-level demonstrations are desirable. Deliverables must include a report to documenting findings.

Phase II Deliverables - Emphasis should be placed on developing, prototyping and demonstrating the technology under simulated operational conditions (regolith, thermal, vacuum). Deliverables shall include a report outlining the path showing how the technology could be matured and applied to mission-worthy systems, functional and performance test results and other associated documentation. Deliverable of a functional prototype is expected at the completion of the Phase II contract. The technology concept at the end of Phase II should be at a TRL of 6 or higher.

State of the Art and Critical Gaps

Previous solutions used in the Apollo program did not address the current need of long term usage. Terrestrial solutions often employ materials or methods that are incompatible with the lunar environment.

Critical Gaps:

- Rotary joints
  - Seals: Rotary joints are very common for actuation in dusty environments because of the widespread availability of rotary seals. Most of these seals however use elastomers that would off-gas and become brittle in a lunar environment. Solutions are needed that employ materials or non-traditional techniques that can operate in the lunar environment for an extended period of time (months to years).
  - Bearings: Regolith getting past the protective seals of rotary joints bearings is a common failure point. Bearings designs that are highly dust tolerant may be needed to reduce the risk of failures due to dust intrusion.
- Linear joints
  - Seals: Linear joints are less common in dusty environments because of the challenge of sealing the sliding joints. Similar to rotary seals, linear joint seals are often made from elastomers and would need to be modified to operate in a lunar environment. Solutions are needed that employ materials or non-traditional techniques that can operate in the lunar environment for an extended period of time (months to years).
  - Bearings: Regolith getting past the protective seals of linear joints bearings is a common failure point. Bearings designs that are highly dust tolerant may be needed to reduce the risk of failures due to dust intrusion.
- Static joints
  - Operations on the lunar surface will include assembly, construction, and Extra-Vehicular Activity (EVA) tasks. These tasks will involve the mating/demating of various structural, electrical, and fluid connections. Dust on the surface of these joints will impede their proper function and lead to failures. Solutions are needed to protect these joints from dust contamination (e.g. power connection/termination related technologies that are impervious to environmental dust and enable robotic deployment, such as robotically-enabled high voltage connectors and/or near-field wireless power transfer in the 1-10kW range).

Relevance / Science Traceability

Dust will be one of the biggest challenges for operation on the lunar surface for the Artemis program.

“I think dust is probably one of our greatest inhibitors to a nominal operation on the Moon. I think we can overcome other physiological, physical or mechanical problems except dust.” Gene Cernan, Apollo 17 Technical Debrief.

Appendices

Appendix A: Technology Readiness Level (TRL) Descriptions

The Technology Readiness Level (TRL) describes the stage of maturity in the development process from observation of basic principles through final product operation. The exit criteria for each level documents that principles, concepts, applications or performance have been satisfactorily demonstrated in the appropriate environment required for that level. A relevant environment is a subset of the operational environment that is expected to have a dominant impact on operational performance. Thus, reduced-gravity may be only one of the operational environments in which the technology must be demonstrated or validated in order to advance to the next TRL.

TRL	Definition	Hardware Description	Software Description	Exit Criteria
1	Basic principles observed and reported.	Scientific knowledge generated underpinning hardware technology concepts/applications.	Scientific knowledge generated underpinning basic properties of software architecture and mathematical formulation.	Peer reviewed publication of research underlying the proposed concept/application.
2	Technology concept and/or application formulated.	Invention begins, practical application is identified but is speculative, no experimental proof or detailed analysis is available to support the conjecture.	Practical application is identified but is speculative, no experimental proof or detailed analysis is available to support the conjecture. Basic properties of algorithms, representations and concepts defined. Basic principles coded. Experiments performed with synthetic data.	Documented description of the application/concept that addresses feasibility and benefit.
3	Analytical and experimental critical function and/or characteristic proof of concept.	Analytical studies place the technology in an appropriate context and laboratory demonstrations, modeling and simulation validate analytical prediction.	Development of limited functionality to validate critical properties and predictions using non-integrated software components.	Documented analytical/experimental results validating predictions of key parameters.
4	Component and/or breadboard validation in laboratory environment.	A low fidelity system/component breadboard is built and operated to demonstrate basic functionality and critical test environments, and associated performance predictions are defined relative to the final operating environment.	Key, functionally critical, software components are integrated, and functionally validated, to establish interoperability and begin architecture development. Relevant Environments defined and performance in this environment predicted.	Documented test performance demonstrating agreement with analytical predictions. Documented definition of relevant environment.
5	Component and/or breadboard	A medium fidelity system/component brassboard is built and	End-to-end software elements implemented and interfaced with existing	Documented test performance demonstrating

	validation in relevant environment.	operated to demonstrate overall performance in a simulated operational environment with realistic support elements that demonstrates overall performance in critical areas. Performance predictions are made for subsequent development phases.	systems/simulations conforming to target environment. End-to-end software system, tested in relevant environment, meeting predicted performance. Operational environment performance predicted. Prototype implementations developed.	agreement with analytical predictions. Documented definition of scaling requirements.
6	System/sub-system model or prototype demonstration in a relevant environment.	A high fidelity system/component prototype that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate operations under critical environmental conditions.	Prototype implementations of the software demonstrated on full-scale realistic problems. Partially integrate with existing hardware/software systems. Limited documentation available. Engineering feasibility fully demonstrated.	Documented test performance demonstrating agreement with analytical predictions.
7	System prototype demonstration in an operational environment.	A high fidelity engineering unit that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate performance in the actual operational environment and platform (ground, airborne, or space).	Prototype software exists having all key functionality available for demonstration and test. Well integrated with operational hardware/software systems demonstrating operational feasibility. Most software bugs removed. Limited documentation available.	Documented test performance demonstrating agreement with analytical predictions.
8	Actual system completed and "flight qualified" through test and demonstration.	The final product in its final configuration is successfully demonstrated through test and analysis for its intended operational environment and platform (ground, airborne, or space).	All software has been thoroughly debugged and fully integrated with all operational hardware and software systems. All user documentation, training documentation, and maintenance documentation completed. All functionality successfully demonstrated in simulated operational scenarios. Verification and Validation (V&V) completed.	Documented test performance verifying analytical predictions.
9	Actual system flight proven through successful mission operations.	The final product is successfully operated in an actual mission.	All software has been thoroughly debugged and fully integrated with all operational hardware/software systems. All documentation has been completed. Sustaining software engineering support is in place. System has been successfully operated in the operational environment.	Documented mission operational results.

Definitions

Proof of Concept: Analytical and experimental demonstration of hardware/software concepts that may or may not be incorporated into subsequent development and/or operational units.

Breadboard: A low fidelity unit that demonstrates function only, without respect to form or fit in the case of hardware, or platform in the case of software. It often uses commercial and/or ad hoc components and is not intended to provide definitive information regarding operational performance.

Brassboard: A medium fidelity functional unit that typically tries to make use of as much operational hardware/software as possible and begins to address scaling issues associated with the operational system. It does not have the engineering pedigree in all aspects, but is structured to be able to operate in simulated operational environments in order to assess performance of critical functions.

Proto-type Unit: The proto-type unit demonstrates form, fit, and function at a scale deemed to be representative of the final product operating in its operational environment. A subscale test article provides fidelity sufficient to permit validation of analytical models capable of predicting the behavior of full-scale systems in an operational environment

Engineering Unit: A high fidelity unit that demonstrates critical aspects of the engineering processes involved in the development of the operational unit. Engineering test units are intended to closely resemble the final product (hardware/software) to the maximum extent possible and are built and tested so as to establish confidence that the design will function in the expected environments. In some cases, the engineering unit will become the final product, assuming proper traceability has been exercised over the components and hardware handling.

Mission Configuration: The final architecture/system design of the product that will be used in the operational environment. If the product is a subsystem/component, then it is embedded in the actual system in the actual configuration used in operation.

Laboratory Environment: An environment that does not address in any manner the environment to be encountered by the system, subsystem, or component (hardware or software) during its intended operation. Tests in a laboratory environment are solely for the purpose of demonstrating the underlying principles of technical performance (functions), without respect to the impact of environment.

Relevant Environment: Not all systems, subsystems, and/or components need to be operated in the operational environment in order to satisfactorily address performance margin requirements. Consequently, the relevant environment is the specific subset of the operational environment that is required to demonstrate critical "at risk" aspects of the final product performance in an operational environment. It is an environment that focuses specifically on "stressing" the technology advance in question.

Operational Environment: The environment in which the final product will be operated. In the case of space flight hardware/software, it is space. In the case of ground-based or airborne systems that are not directed toward space flight, it will be the environments defined by the scope of operations. For software, the environment will be defined by the operational platform.

Appendix B: SBIR/STTR and the Space Technology Roadmaps

NASA's technology development activities expand the frontiers of knowledge and capabilities in aeronautics, science, and space, creating opportunities, markets, and products for U.S. industry and academia. The 2015 NASA Technology Roadmaps are a set of documents that consider a wide range of needed technology candidates and development pathways for the next 20 years (2015-2035). The roadmaps focused on applied research and development activities. Technologies that support NASA's missions may also support science and exploration missions conducted by the commercial space industry and other government agencies. In addition, NASA technology development results in applications for the general population including devices that improve health, medicine, transportation, public safety, and consumer goods.

The 2020 NASA Technology Taxonomy is an evolution of the technology roadmaps. The 2020 NASA Technology Taxonomy provides a structure for articulating the technology development disciplines needed to enable future space missions and support commercial air travel. The 2020 revision is comprised of 17 distinct technical discipline based Taxonomies (TX) that provide a breakdown structure for each technology area. The taxonomy uses a three-level hierarchy for grouping and organizing technology types. Level 1 represents the technology area, which is the title of that area (e.g. TX01: Propulsion Systems). Level 2 is a list of the subareas (e.g. TX01.1 Chemical Space Propulsion). Level 3 categorizes the types of technologies within the subareas (e.g. TX1.1.1 Integrated Systems and Ancillary Technologies). The taxonomy is a foundational element of NASA's technology management process. NASA's mission directorates reference the taxonomy to solicit proposals and to inform decisions on NASA's technology policy, prioritization, and strategic investments.

Subtopics in this solicitation still reference the Space Technology Roadmap Technology Areas (TAs) within the subtopic descriptions. They are cross-referenced to the new Technology Taxonomy in the table below. Details on the 2015 NASA Technology Roadmaps remain accessible here: (https://www.nasa.gov/offices/oct/home/roadmaps/index.html), and information on the new 2020 NASA Technology Taxonomy can be found at: (https://www.nasa.gov/sites/default/files/atoms/files/2020_nasa_technology_taxonomy_lowres.pdf).

The research and technology subtopics for the SBIR Program are identified annually by Mission Directorates and Center Programs. The Directorates identify high priority research and technology needs for respective programs and projects. Research and technology subtopics for the STTR Program are aligned with needs associated with the research interest and core competencies across NASA Centers and aligned with the Space Technology Roadmaps. Both programs support a broad range of technologies defined by a list of subtopics that vary in content within each annual solicitation.

The table on the following pages relates the current SBIR/STTR subtopics to Technology Areas/Technology Taxonomy.

TA #	TA Mapping Level 1	TA Mapping Level 2	Subtopic #	Subtopic Title	2020 Technology Taxonomy
TA01	1.0.0 - Launch Propulsion Systems	1.3.0 - Air Breathing Propulsion Systems	A1.03	Low Emissions/Clean Power - Environmentally Responsible Propulsion	TX01 - Propulsion Systems
TA02	2.0.0 - In-Space Propulsion Technologies	2.1.0 - Chemical Propulsion	Z9.01	Small Launcher Lunar Transfer Stage Development	
		2.2.0 - Non-Chemical Propulsion	Z8.06	DragSails for Spacecraft Deorbit	
			Z10.03	Nuclear Thermal Propulsion	
			Z10.04	Manufacturing Processes Enabling Lower-Cost, In-Space Electric Propulsion Thrusters	
		2.4.0 - Supporting Technologies	T2.05	Advanced Concepts for Lunar and Martian Propellant Production, Storage, Transfer, and Usage	
			Z10.01	Cryogenic Fluid Management	
TA03	3.0.0 - Space Power and Energy Storage	3.1.0 - Power Generation	S3.02	Dynamic Power Conversion	TX03 - Aerospace Power and Energy Storage
			S3.01	Power Generation and Conversion	
			Z1.03	Kilowatt-Class Energy Conversion for Small Fission Reactors	
		3.2.0 - Energy Storage	S3.03	Energy Storage for Extreme Environments	
		3.3.0 - Power Management and Distribution	Z1.05	Lunar & Planetary Surface Power Management & Distribution	
			Z1.06	Radiation Tolerant High-Voltage, High-Power Electronics	
TA04	4.0.0 - Robotics, Telerobotics and Autonomous Systems	4.1.0 - Sensing & Perception	T4.01	Information Technologies for Intelligent and Adaptive Space Robotics	TX04 - Robotic Systems
			T13.01	Intelligent Sensor Systems	
		4.2.0 - Mobility	S4.04	Extreme Environments Technology	
			S3.05	Terrestrial Balloons and Planetary Aerial Vehicles	
			Z5.05	Lunar Rover Technologies for In-situ Resource Utilization and Exploration	
		4.3.0 - Manipulation	S4.02	Robotic Mobility, Manipulation and Sampling	
		4.5.0 - Autonomy	A2.02	Unmanned Aircraft Systems (UAS) Technologies	
			H10.02	Autonomous Operations Technologies for Ground and Launch Systems	
			S5.05	Fault Management Technologies	
			T4.03	Coordination and Control of Swarms of Space Vehicles	
			Z5.04	Technologies for Intra-Vehicular Activity Robotics	

		4.6.0 - Autonomous Rendezvous and Docking	Z3.05	Satellite Servicing Technologies	
		4.7.0 - RTA Systems Engineering	S4.05	Contamination Control and Planetary Protection	
TA05	5.0.0 - Communication and Navigation	5.1.0 - Optical Comm. And Navigation	H9.01	Long Range Optical Telecommunications	TX05 - Communications, Navigation, and Orbital Debris Tracking/ Characterization Systems
		5.2.0 - Radio Frequency Communications	T5.02	Electric Field Mapping and Prediction Methods within Spacecraft Enclosures	
			Z8.02	Communications and Navigation for Distributed Small Spacecraft Beyond LEO	
		5.3.0 - Internetworking	Z8.10	Wireless Communication for Avionics and Sensors for Space Applications	
		5.4.0 - Position, Navigation, and Timing	H9.03	Flight Dynamics and Navigation Technology	TX17 - Guidance, Navigation, and Control (GN&C)
			S3.04	Guidance, Navigation, and Control	
		5.5.0 - Integrated Technologies	H9.07	Cognitive Communication	TX05 - Communications, Navigation, and Orbital Debris Tracking/ Characterization Systems
		5.6.0 - Revolutionary Concepts	H9.05	Transformational Communications Technology	
			T5.04	Quantum Communications	
TA06	6.0.0 - Human Health, Life Support and Habitation Systems	6.1.0 - Environmental Control Life Support & Habitation Systems	H3.02	Microbial Monitoring for Spacecraft Cabins	TX06 - Human Health, Life Support, and Habitation Systems
			H3.03	Lunar Dust Management Technology for Spacecraft Atmospheres and Spacesuits	
			H3.01	Advancements in Carbon Dioxide Reduction: Critical Subsystems and Solid Carbon Repurposing	
			T6.06	Spacecraft Water Sustainability through Nanotechnology	
		6.2.0 - Extravehicular Activity Systems	H4.05	Liquid Cooling and Ventilation Garment Connector Upgrade and Glove Humidity Reduction	
			H4.01	Exploration Portable Life Support System Component Challenges	
		6.3.0 - Human Health and Performance	H12.01	Radioprotectors and Mitigators of Space Radiation-induced Health Risks	
			H8.01	Utilization of the International Space Station (ISS) to Foster Commercial Development of Low-Earth Orbit (LEO)	
			H12.05	Autonomous Medical Operations	
		6.5.0 - Radiation	T6.05	Testing of COTS Systems in Space Radiation Environments	
TA07		7.1.0 - In-Situ Resource Utilization	Z12.01	Extraction of Oxygen from Lunar Regolith	TX07 - Exploration Destination Systems

	7.0.0 - Human Exploration Destination Systems	7.2.0 - Sustainability & Supportability	T6.07	Space Exploration Plant Growth	
		7.3.0 - Advanced Human Mobility Systems	Z13.02	Dust Tolerant Mechanisms	
		7.6.0 - Cross-Cutting Systems	Z13.01	Active and Passive Dust Mitigation Surfaces	
TA08	8.0.0 - Science Instruments, Observatories & Sensor Systems	8.1.0 - Science Instruments	S1.10	Atomic Interferometry	TX08 - Sensors and Instruments
			S1.11	In Situ Instruments/Technologies and Plume Sampling Systems for Ocean Worlds Life Detection	
			S1.12	In Situ Instruments/Technologies for Heliophysics	
			S1.07	In Situ Instruments/Technologies for Lunar and Planetary Science	
			S1.06	Particles and Fields Sensors & Instrument Enabling Technologies	
			S2.02	Precision Deployable Optical Structures and Metrology	
			S2.01	Proximity Glare Suppression for Astronomical Direct Detection of Exoplanets	
			S1.04	Sensor and Detector Technologies for Visible, IR, Far-IR, and Submillimeter	
			S1.02	Technologies for Active Microwave Remote Sensing	
			S1.03	Technologies for Passive Microwave Remote Sensing	
			S2.05	Technology for the Precision Radial Velocity Measurement Technique	
			S2.04	X-Ray Mirror Systems Technology, Coating Technology for X-Ray-UV-OIR, and Free-Form Optics	
			T8.06	Quantum Sensing and Measurement	
			Z11.01	Nondestructive Evaluation (NDE) Sensors, Modeling, and Analysis	
			Z8.08	Technologies to Enable Cost & Schedule Reductions for Ultra-Stable Normal Incidence Mirrors for CubeSats	
		8.2.0 - Observations	S2.03	Advanced Optical Systems and Fabrication/Testing/Control Technologies for EUV/Optical and IR Telescope	
		8.3.0 - Sensor Systems	S1.09	Cryogenic Systems for Sensors and Detectors	
			S1.05	Detector Technologies for UV, X-Ray, Gamma-Ray Instruments	

			S1.01	Lidar Remote Sensing Technologies	
			S1.08	Suborbital Instruments and Sensor Systems for Earth Science Measurements	
			T8.04	Metamaterials and Metasurfaces Technology for Remote Sensing Applications	
TA09	9.0.0 - Entry, Descent and Landing Systems	9.1.0 - Aeroassist & Entry	Z7.05	3D Weaving Diagnostics	TX09 - Entry, Descent, and Landing
			Z7.06	Diagnostic Tools for High Enthalpy and High Temperature Materials Testing and Analysis	
			Z7.01	Entry Descent & Landing Sensors for Environment Characterization, Vehicle Performance, and Guidance, Navigation and Control	
		9.4.0 - Vehicle Systems Technology	Z7.03	Deployable Aerodynamic Decelerator Technology	
			Z7.04	Lander Systems Technologies	
TA11	11.0.0 - Modeling, Simulation, Information Technology and Processing	11.1.0 - Computing	H6.22	Deep Neural Net and Neuromorphic Processors for In-Space Autonomy and Cognition	TX11 - Software, Modeling, Simulation, and Information Processing
			S5.03	Accelerating NASA Science and Engineering through the Application of Artificial Intelligence	
			S3.08	Command, Data Handling, and Electronics	
			S5.01	Technologies for Large-Scale Numerical Simulation	
			Z6.01	High Performance Space Computing Technology	
		11.2.0 - Modeling	H6.04	Model Based Systems Engineering for Distributed Development	
			S5.04	Integrated Science Mission Modeling	
			S5.06	Space Weather R2O/O2R Technology Development	
		11.4.0 - Information Processing	T4.04	Autonomous Systems and Operations for the Lunar Orbital Platform-Gateway	
			T11.04	Digital Assistants for Science and Engineering	
			T11.03	Distributed Digital Ledger for Aerospace Applications	
TA12	12.0.0 - Materials, Structures, Mechanical Systems and Manufacturing	12.1.0 - Materials	T12.06	Extensible Modeling of Additive Manufacturing Processes	TX12 - Materials, Structures, Mechnical Systems, and Manufacturing
			T12.01	Thin-Ply Composite Technology and Applications	
		12.2.0 - Structures	H5.02	Hot Structure Technology for Aerospace Vehicles	

			H5.01	Lunar Surface Solar Array Structures	
			Z3.04	Autonomous Modular Assembly Technology for OSAM	
		12.4.0 - Manufacturing	T2.04	Advanced In-Space Propulsion	
			T12.05	Deposition and Curing of Thermoset Resin Mixtures for Thermal Protection	
			Z3.03	Development of Material Joining Technologies and Large-Scale Additive Manufacturing Processes for On-Orbit Manufacturing and Construction	
			Z4.04	Real Time Defect Detection, Identification and Correction in Wire-Feed Additive Manufacturing Processes	
TA13	13.0.0 - Ground and Launch Systems Processing	13.1.0 - Technologies to Optimize the Operational Life-Cycle	H10.01	Advanced Propulsion Systems Ground Test Technology	TX13 - Ground, Test, and Surface Systems
TA14	14.0.0 - Thermal Management Systems	14.2.0 - Thermal Control Systems	S3.06	Thermal Control Systems	TX14 - Thermal Management Systems
			Z2.01	Spacecraft Thermal Management	
TA15	15.0.0 - Aeronautics	15.1.0 - Safe, Efficient Growth in Global Aviation	A3.01	Advanced Air Traffic Management System Concepts	TX16 - Air Traffic Management and Range Tracking Systems
			A3.02	Increasing Autonomy in the National Airspace System (NAS)	
			A3.04	Non-Traditional Airspace Operations	
			A1.02	Quiet Performance - Aircraft Propulsion Noise	TA15 - Flight Vehicle Systems
			A1.09	Inflight Icing Hazard Mitigation Technology	
		15.2.0 - Innovation in Commercial Supersonic Aircraft	A1.01	Aeroelasticity and Aeroservoelastic Control	
		15.3.0 - Ultra-Efficient Commercial Vehicles	A1.05	Computational Tools and Methods	
			A1.06	Vertical Lift Technology and Urban Air Mobility	
			A1.08	Aeronautics Ground Test and Measurement Technologies	
			A1.07	Propulsion Efficiency - Turbomachinery Technology for High Power Density Turbine-Engines	
			T15.04	Integration of Airframe with Distributed Electric Propulsion (DEP) System	
		15.4.0 - Transition to Low-Carbon Propulsion	A1.04	Electrified Aircraft Propulsion	
			T15.03	Electrified Aircraft Propulsion Energy Storage	

		15.5.0 - Real-Time System-Wide Safety Assurance	A3.03	Future Aviation Systems Safety	TX16 - Air Traffic Management and Range Tracking Systems
		15.7.0 - Other	A2.01	Flight Test and Measurement Technologies	TX15 - Flight Vehicle Systems
			A1.10	Hypersonic/High Speed Technology - Seals and Thermal Barriers	