National Aeronautics and Space Administration

Small Business Innovation Research (SBIR)

Phase I

Fiscal Year 2025 Research Subtopics

Contents

Research Subtopics for SBIR

The SBIR subtopics are organized by NASA's Mission Directorates and thus identify subtopics where your research and development capabilities may be a good match. Appendix B contains a list of the subtopics as they align to the 2024 NASA Technology Taxonomy to help you identify subtopics based on technology areas.

In addition, there are some SBIR subtopics that may be closely aligned with the NASA STTR program. Consider both programs when planning to apply.

NASA uses the same subtopic numbering convention for the SBIR program each year:

For SBIR Subtopics:
A – Aeronautics Research Mission Directorate (ARMD)
H – Exploration Systems Development Mission Directorate (ESDMD) and Space Operations Mission Directorate (SOMD)
S – Science Mission Directorate (SMD)
Z – Space Technology Mission Directorate (STMD)

Think of the subtopic lead mission directorates and lead/participating centers as potential customers for your technical proposals. Multiple mission directorates and centers may have interests across the subtopics within a Technology Taxonomy area.

Guidance for Locating Subtopic Reference Materials

Each subtopic contains references that are intended to provide additional information about the technology need. Some of those references include technical articles that may be available through NASA's Technical Reports Server (NTRS) or through other technical journals or sources.
NTRS (https://ntrs.nasa.gov/) provides access to publicly available scientific and technical documents, images and videos created or funded by NASA.
While we work to only reference publicly available documents, if you find that referenced technical articles are behind a paywall, please contact your local library to request assistance in obtaining access.

Subtopic Pointers

Related subtopic pointers are identified in some subtopic headers to assist you with identifying other subtopics that seek related technologies for different customers or applications. It is your responsibility to select which subtopic to propose.

Aeronautics Research Mission Directorate (ARMD)

Aeronautics Research Mission Directorate (ARMD) maintains and advances U.S global leadership in aviation through applications of new concepts and technologies pioneered by NASA and developed in partnership with U.S. Industry that lead to transformative improvements in mobility, efficiency, and safety.

A1.02: Quiet Performance - Airframe Noise (SBIR)

Related Subtopic Pointers: T15.04
Lead Center: LaRC
Participating Center(s): GRC

Subtopic Introduction:

Innovative methods and technologies are necessary for the design and development of efficient and environmentally acceptable aircraft. In particular, the impact of aircraft noise on communities around airports is the predominant factor limiting the growth of the nation's air transportation system. Reductions in aircraft noise could improve community acceptance, lower airline operating costs where noise quotas or fees are employed and increase the potential for global air traffic growth. In support of the Advanced Air Vehicles Program (AAVP), Integrated Aviation Systems Program (IASP), and Transformative Aeronautics Concepts Program (TACP), improvements in noise prediction and noise control are needed to reduce the noise impact of commercial aviation transports on communities near airports, including noise from vehicles that cruise at subsonic or supersonic speeds.

Scope Title: Airframe Noise Analysis and Characterization

Scope Description:

NASA is seeking fundamental and applied computational fluid dynamics techniques that can be used for aeroacoustic analysis and can be adapted for design purposes. Example computational techniques of interest include innovative source identification methods for airframe noise sources, such as noise generation mechanisms from the landing gear and high-lift systems. Other examples include spatio-temporal turbulence details related to flow-induced noise typical of separated flow regions, vortices, shear layers, or aerodynamic interactions between aircraft components. Source identification techniques can target computational and/or experimental methods and data. Novel instrumentation, facility concepts, or measurement techniques that enable improved source identification are also sought.

Expected TRL or TRL Range at completion of the Project: 2 to 5

Primary Technology Taxonomy:

- Level 1: TX 15 Flight Vehicle Systems
- Level 2: TX 15.1 Aerosciences

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Concepts, technologies, and tools are sought that enable rapid assessment of the noise impact of novel engine/airframe configurations and/or aid in the development and optimization of noise control approaches for component noise sources that enable new aircraft configurations. Example Phase I deliverables include laboratory or computational demonstrations of limited scope that establish proof of concept of novel noise source identification or measurement techniques. Example Phase II deliverables include system or subsystem demonstrations concurrent with the establishment of a realistic path to concept production or incorporation into an existing software or measurement product.

State of the Art and Critical Gaps:

Solutions are sought to aid in the characterization and understanding of noise generation mechanisms of complex aircraft configurations or engine/airframe integration. For example, efficient computational tools that enable rapid evaluation of the noise impact of different aircraft configurations or engine/airframe configurations at the design stage are lacking. Existing numerical methods to study complex engine/airframe configurations are complex and difficult to leverage at the aircraft design stage where configuration details may be unspecified. Improvements to numerical methods, measurement techniques, and analysis approaches for studying the noise aspects of advanced airframe configurations, including engine integration, would ease consideration of acoustics in the design stage.

Relevance / Science Traceability:

AAVP: The Advanced Air Transport Technology (AATT) and Commercial Supersonic Technology (CST) Projects would benefit from computational and measurement techniques to efficiently characterize the performance and noise impacts of novel airframe configurations and engine installations. In addition, novel aircraft and propulsor configurations such as the Truss-Braced Wing, small-core turbofan engines, and ultra-high-bypass ratio engines will introduce new noise challenges that must be addressed to enable their successful deployment.

TACP: The Transformational Tools and Technologies (TTT) Project would benefit from tool developments to enhance consideration of acoustics earlier in the aircraft design process.

References:

1. AAVP - Advanced Air Transport Technology (AATT) Project: https://www.nasa.gov/aeroresearch/programs/aavp/aatt
2. AAVP - Commercial Supersonic Technology (CST) Project: https://www.nasa.gov/aeroresearch/programs/aavp/cst
3. TACP - Transformational Tools and Technologies (TTT) Project: https://www.nasa.gov/aeroresearch/programs/tacp/ttt

Scope Title: Airframe Noise-Prediction Technologies

Scope Description:

Numerical methods are sought to predict aerodynamic noise sources associated with the airframe, including those due to conventional and novel airframe configurations such as the Truss-Braced Wing. Aerodynamic noise sources of interest include interactions between the propulsors and the airframe and integration effects associated with novel propulsion sources, such as open fans, ultra-high-bypass ratio fans, or small-core engines.
Improvements in system-level noise prediction methodologies are also sought for predicting the noise generated by general landing and takeoff operations (as opposed to certification conditions) of subsonic or supersonic commercial transports.

Expected TRL or TRL Range at completion of the Project: 2 to 5

Primary Technology Taxonomy:

- Level 1: TX 15 Flight Vehicle Systems
- Level 2: TX 15.1 Aerosciences

Desired Deliverables of Phase I and Phase II:

- Software
- Analysis
- Research

Desired Deliverables Description:

Numerical tools are sought that enable rapid assessment of the noise impact of novel airframe and engine-airframe configurations, and/or aid in the development and optimization of noise control approaches for component noise sources that enable new aircraft configurations. Example Phase I deliverables include applications of novel computational tools with limited scope that demonstrate the potential for success on a larger scope. Example Phase II deliverables include incorporation of novel computational tools into existing modeling toolchains with validation cases to document capabilities.

State of the Art and Critical Gaps:

Solutions are sought for noise problems associated with complex aircraft configurations or noise challenges due to engine/airframe integration. For example, efficient computational tools that enable rapid evaluations of the noise of aircraft configurations or engine/airframe configurations at the design stage are lacking. Existing numerical methods to study complex engine/airframe configurations are complex and difficult to leverage at the aircraft design stage where configuration details may be unspecified. Improvements to numerical methods and models for studying the noise aspects of advanced airframe configurations, including engine integration, would ease consideration of acoustics during the design stage, rather than leaving acoustics to the late design stage where noise control solutions are costly and less effective. Improved tools would also enable more rapid evaluation and development of innovative noise control approaches that may be needed for novel aircraft and propulsor configurations.

Relevance / Science Traceability:

AAVP: The Advanced Air Transport Technology (AATT) and Commercial Supersonic Technology (CST) Projects would benefit from noise prediction methods that improve understanding of the aircraft noise footprint at landing and takeoff. Configurations with novel engine placement, such as above the fuselage, can reduce the noise footprint, but methodologies are needed to efficiently model the performance and noise impacts of these novel engine installations. In addition, novel aircraft and propulsor configurations such as the Truss-Braced Wing, small-core turbofan engines, and ultra-high-bypass ratio engines will introduce new noise modeling challenges that must be addressed to enable their successful deployment.

TACP: The Transformational Tools and Technologies (TTT) Project would benefit from tool developments to enhance consideration of acoustics earlier in the aircraft design process.

References:

1. AAVP - Advanced Air Transport Technology (AATT) Project: https://www.nasa.gov/aeroresearch/programs/aavp/aatt

2. AAVP - Commercial Supersonic Technology (CST) Project: https://www.nasa.gov/aeroresearch/programs/aavp/cst
3. TACP - Transformational Tools and Technologies (TTT) Project: https://www.nasa.gov/aeroresearch/programs/tacp/ttt

Scope Title: Airframe Noise Reduction

Scope Description:

Active or passive concepts are sought to reduce broadband aeroacoustic noise sources for subsonic and supersonic transports. Technologies of interest include active or adaptive flow control, noise control for specific aircraft configurations, advanced materials for noise control, structural concepts that reduce or enable control of airframe noise sources, and control methodologies related to airframe-propulsion integration on a vehicle. Concepts of interest also include active or passive acoustic liners and porous surfaces to reduce airframe noise and/or noise due to propulsion-airframe interactions. However, applications of liners inside the engine nacelle are specifically excluded from this solicitation.

Expected TRL or TRL Range at completion of the Project: 2 to 5

Primary Technology Taxonomy:

- Level 1: TX 15 Flight Vehicle Systems
- Level 2: TX 15.1 Aerosciences

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

Concepts and technologies are sought that mitigate component noise issues associated with novel aircraft configurations, and/or aid in the development and optimization of noise control approaches for component noise sources that enable new aircraft configurations. Example Phase I deliverables include laboratory demonstrations that establish proof of concept of noise reduction technologies. Example Phase II deliverables include system or subsystem demonstrations concurrent with the establishment of a realistic path to concept production.

State of the Art and Critical Gaps:

Solutions are sought that incorporate advanced material systems or adaptive mechanisms that can modify their performance based on the noise state of the vehicle. This includes novel material systems that could be applied to component noise sources on the aircraft, such as shape memory alloy actuators, or active or adaptive systems. Some advanced material systems have been investigated for airframe noise control but are generally in their infancy, especially in terms of certifiability and robustness. Solutions are also sought for noise problems of complex aircraft configurations or noise challenges due to engine/airframe integration.

Relevance / Science Traceability:

AAVP: The Advanced Air Transport Technology (AATT) and Commercial Supersonic Technology (CST) Projects would benefit from noise reduction technologies that reduce the aircraft noise footprint at landing and takeoff.

Configurations with novel aircraft and propulsor configurations such as the Truss-Braced Wing, small-core turbofan engines, and ultra-high-bypass ratio engines will introduce new noise challenges that must be addressed to enable their successful deployment.

TACP: The Transformational Tools and Technologies (TTT) Project would benefit from the development and demonstration of simple material systems, such as advanced liner concepts with reduced drag or adaptive materials 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.

References:

1. AAVP - Advanced Air Transport Technology (AATT) Project: https://www.nasa.gov/aeroresearch/programs/aavp/aatt
2. AAVP - Commercial Supersonic Technology (CST) Project: https://www.nasa.gov/aeroresearch/programs/aavp/cst
3. TACP - Transformational Tools and Technologies (TTT) Project: https://www.nasa.gov/aeroresearch/programs/tacp/ttt

A1.03: Propulsion Efficiency - Propulsion Materials and Structures (SBIR)

Lead Center: GRC
Participating Center(s): N/A

Subtopic Introduction:

Materials and structures research and development (R&D) contributes to NASA's ability to achieve its long-term aeronautics goals, including the development of advanced propulsion systems. Proposals are sought for advanced materials and structures technologies that will be enabling for new propulsion systems for subsonic transport vehicles with high levels of thermal, transmission, and propulsive efficiency. Integrated computational and experimental approaches are needed that can reduce the time necessary for development, testing, and validation of new materials systems and components. Advanced high-pressure-ratio compact gas turbine engines will include components of sufficiently compact size that new approaches to processing and advanced manufacturing will be needed. Temperature capability, thermomechanical performance, environmental durability, reliability, and cost-effectiveness are important considerations. The increased use of various types of modeling (multiscale modeling, machine learning, etc.) to improve R&D effectiveness and enable more rapid and revolutionary materials design has been identified as critical. NASA recently sponsored a study to define a potential 25-year goal for integrated, multiscale modeling of materials and systems to accelerate the pace and reduce the expense of innovation in future aeronautical systems. Through a series of surveys, workshops, and validation exercises, this study identified critical cultural changes and gaps facing the multiscale modeling community. The results of this study were published in a NASA report, "Vision 2040: A Roadmap for Integrated, Multiscale Modeling and Simulation of Materials and Systems". Some of the critical gaps identified in this report are: (1) under-development of physics-based models that link length and time scales, (2) inability to conduct real-time characterization at appropriate length and time scales, (3) lack of optimization methods that bridge scales, (4) lack of models that compute input sensitivities and propagate uncertainties, and (5) lack of verification and validation methods and data.

Scope Title: Advanced Materials and Structures Technologies Enabling New Highly Efficient Propulsion Systems for Subsonic Transport Vehicles

Scope Description:

Materials and structures research and development (R&D) contributes to NASA's ability to achieve its long-term aeronautics goals, including the development of advanced propulsion systems. Proposals are sought for advanced materials and structures technologies that will be enabling for new propulsion systems for subsonic transport vehicles with high levels of thermal, transmission, and propulsive efficiency. Integrated computational and experimental approaches are needed that can reduce the time necessary for development, testing, and validation of new materials systems and components. Advanced high-pressure-ratio compact gas turbine engines will include components of sufficiently compact size that new approaches to processing and advanced manufacturing will be needed. Temperature capability, thermomechanical performance, environmental durability, reliability, and cost-effectiveness are important considerations.

The increased use of various types of modeling to improve R&D effectiveness and enable more rapid and revolutionary materials design has been identified as critical. NASA recently sponsored a study to define a potential 25-year goal for integrated, multiscale modeling of materials and systems to accelerate the pace and reduce the expense of innovation in future aeronautical systems. Through a series of surveys, workshops, and validation exercises, this study identified critical cultural changes and gaps facing the multiscale modeling community. The results of this study were published in a NASA report, "Vision 2040: A Roadmap for Integrated, Multiscale Modeling and Simulation of Materials and Systems" [Ref. 1]. Some of the critical gaps identified in this report are: (1) under-development of physics-based models that link length and time scales, (2) inability to conduct real-time characterization at appropriate length and time scales, (3) lack of optimization methods that bridge scales, (4) lack of models that compute input sensitivities and propagate uncertainties, and (5) lack of verification and validation methods and data.

Proposals emphasizing modeling (both physics-based and data driven) and materials informatics which shall address gaps in that 2040 vision are encouraged. The range of topics could include data management [Ref 2], data analytics, machine learning [Ref 3], linkage and integration across spatiotemporal scales [Ref 4], and high through-put experiments and characterization of materials over their lifecycle as well as model parameter estimation methodologies [Ref 5]. Proposals may address any material class associated with aeronautics propulsion for subsonic transport vehicles, multiscale modeling and measurements, multiscale optimization methods, and verification and validation of models and methods. However, approaches should rely on iterative, predictive methods that integrate experiments and simulations to describe the behavior and response of materials at various length and time scales.

Technology areas of interest this year include:

Modeling

- Rapid characterization and validation of physics-based and data driven constitutive models (both deformation and damage) utilizing high-throughput uniaxial and/or multiaxial experiments over a wide range of temperatures.
- Computational materials and multiscale modeling tools, including methods to predict properties, and/or durability of propulsion materials based upon chemistry and processing for conventional as well as functionally graded, nanostructured, multifunctional, and adaptive materials.
- Robust and efficient methods/tools to design and model advanced propulsion system materials and structures at all length scale, including approaches that are adaptable for a multiscale framework.

- Multiscale design tools that integrate novel materials, mechanism design, and structural subcomponent design into system level designs.

High-Temperature Materials

- Advancing technology for ceramic matrix composites (CMCs) and their environmental barrier coatings (EBCs) for gas turbine engine components operating at 1,482 °C (2,700 °F) or higher. Focus areas include increased thermomechanical durability, increased resistance to environmental interactions (especially CMAS attack), cost-effectiveness of processing and manufacturing, and improved approaches to component fabrication and integration. Computational tools and integrated experimental/computational methods are sought, including models/tools to predict degradation and failure mechanisms.
- Additive manufacturing and other advanced processing/manufacturing approaches for structural components or materials to enable improved engine efficiency through decreasing weight and/or improving component design, properties, and performance.

Digital Twin and Digital Thread [Ref 6]

- Integration toolsets that enable task automation of workflows associated with ICME (Integrated Computational Materials Engineering), material science and structural engineering, concurrent material and structural optimization, and model exploration/ characterization / validation.
- Integration of creating, training, and maintaining of AI/ML models and methods for establishing, enhancing and rapid utilizing of digital twin and/or thread for propulsion materials and structures.

Expected TRL or TRL Range at completion of the Project: 1 to 4

Primary Technology Taxonomy:

- Level 1: TX 12 Materials, Structures, Mechanical Systems, and Manufacturing
- Level 2: TX 12.1 Materials

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

NASA's intent is to select proposals that have the potential to move a critical technology beyond Phase II SBIR funding and transition it to Phase III, where NASA's Aeronautics programs, another Government agency, or a commercial entity in the aeronautics sector can fund further maturation as needed, leading to actual usage in an enhanced propulsion system. The Phase I outcome should establish the scientific, technical, and commercial feasibility of the proposed innovation in fulfillment of NASA needs. Phase I should demonstrate advancement of a specific technology, supported by analytical and experimental studies that are documented in a final report. Phase IIs could yield: (1) models supported with experimental data, (2) software related to a model that was developed, (3) a material system or subcomponent that has been demonstrated to have better properties/performance (ability to operate at a higher temperature, enhanced durability, carry more current, etc.), and (4) modeling tools for incorporation in software, etc. that can be infused into a NASA project or lead to commercialization of the technology. Consequently, Phase II efforts are strengthened when they include a partnership with a potential end-user of the technology. Phase I award recipients must be thinking about commercialization and which organizations will be able to use the technology following a Phase II effort. It is necessary to take that into account, rather than just focusing on developing technology without putting a strong effort into developing a commercial partner or setting the effort up for continued funding by teaming with an organization post-Phase II.

State of the Art and Critical Gaps:

This subtopic would support R&D on advanced materials and structures technologies that will be enabling for new propulsion systems for subsonic transport vehicles with high levels of thermal, transmission, and propulsive efficiency. The needs are specified in the scope description. One of the major NASA Glenn Research Center core competencies is Materials and Structures for Extreme Environments. This subtopic supports that type of research—enabling materials and structures research that allows more efficient propulsion systems. In general, integrated computational and experimental (ICE) approaches are needed that can reduce the time necessary for development, testing, and validation of new materials systems and components. The increased use of various types of modeling to improve R&D effectiveness and enable more rapid and revolutionary materials design has been identified as critical. NASA recently conducted a study that identified critical cultural changes and gaps facing the multiscale modeling community. Advanced high-pressure-ratio compact gas turbine engines will include components of sufficiently compact size such that new approaches to processing and advanced manufacturing will be needed. Improvements in temperature capability, thermomechanical performance, environmental durability, reliability, and cost-effectiveness are important considerations.

Relevance / Science Traceability:

Aeronautics Research Mission Directorate (ARMD) projects that could support each of the specified areas of interest are listed below, along with advocates for the technologies. The technologies would lead to improved propulsion efficiencies for subsonic transport vehicles.

- Computational materials and multiscale modeling tools, including methods to predict properties, and/or durability of propulsion materials based upon chemistry and processing for conventional as well as functionally graded, nanostructured, multifunctional, and adaptive materials. Transformational Tools and Technologies (TTT) Project.
- Robust and efficient methods/tools to design and model advanced propulsion system materials and structures at all scale levels, including approaches that are adaptable for a multiscale framework. TTT Project.
- Multiscale design tools that integrate novel materials, mechanism design, and structural subcomponent design into system level designs. TTT Project.
- Advancing technology for CMCs and their EBCs for gas turbine engine components operating at 1,482 °C (2,700 °F) or higher. TTT and Advanced Air Transport Technology (AATT) Projects.
- Understanding and abating CMAS attack of EBCs.
- Additive manufacturing and other advanced processing/manufacturing approaches for structural components or materials to enable improved engine efficiency through decreasing weight and/or improving component design, properties, and performance. TTT Project.

References:

1. Vision 2040: A Roadmap for Integrated, Multiscale Modeling and Simulation of Materials and Systems, NASA/CR-2018-219771, https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20180002010.pdf
2. Hearley, B. L. and Arnold S.M.: “NASA GRC ICME Schema for Materials Data Management: An Executive Summary”, NASA TM-20230018337
3. Stuckner, J., Harder, B., & Smith, T. M.; “Microstructure segmentation with deep learning encoders pre-trained on a large microscopy dataset”, *npj Computational Materials, 8*(1), 2022.

4. Hearley, B. L. and Arnold, S.M.; "Automation of the ICME Workflow Incorporating Material Digital Twins at Different Length Scales Within a Robust Information Management System", TMS 2025, 154th Annual Meeting & Exhibition, Las Vegas, NV, March 2025.
5. Saleeb, A.F., Gendy, A.S., and Wilt, T.E.; "Parameter Estimation Algorithms for Characterizing a Class of Isotropic and Anisotropic Viscoplastic Material Models", Mechanics of Time-Dependent Materials, Vol. 6, pp 323-362, 2002.
6. Arnold, Cribb, French, Ganguli, Goodman, Hatakeyama, Lorang, Matlik, Fischer, Schindel, Taylor and Wang; "Digital Thread: Definition, Value and Reference Model", An AIAA, AIA, and NAFEMS Position Paper, June 2023

A1.04: Novel Aircraft Configurations for Electrified Aircraft Propulsion (SBIR)

Related Subtopic Pointers: T15.04
Lead Center: GRC
Participating Center(s): N/A

Subtopic Introduction:

The purpose of this subtopic is to stimulate near-term U.S. entrepreneurship in zero-emission electric aircraft for 1,500 to 5,000 lbs. drones and piloted aircraft.

Configurations that will be considered are novel and enabled using electric propulsion. The scale of the prototype can be as small as needed to fit in the budget while demonstrating many or all of the functions and integrations expected in the full-scale aircraft. It should be supported by a design study showing that, at the size needed for 1,500 to 5,000 lbs. aircraft, the system will use less total energy than current aircraft.

Scope Title: Electric Aircraft for Zero Emission

Scope Description:

For the purposes of this solicitation, zero-emission shall consider the aircraft boundary. Recharging these aircraft on the ground should be compatible with existing infrastructure, chargers used by other industries, or identified potential future infrastructure.

The key performance metrics of the aircraft are the payload, range, speed, energy use per mile, and in-flight emissions per mile.

The outcome sought at the end of phase II is a small, flying prototype, zero-emission electric aircraft. It should be supported by a study showing how it is scalable to 1,500 to 5,000 lbs. aircraft applications. The engine should be able to produce both thrust and electric power. The ratio of the two outputs should align with the intended aircraft application.

Strong proposals will have several characteristics.

- One or more identified launch customers with letters of commitment.
- A focused effort to create an aircraft with a path to a Federal Aviation Administration (FAA) certification date of 2030 or earlier must be shown. It is understood that this part of the effort would be beyond Phase II.
- The payload, range, speed, energy use per mile, and in-flight emissions per mile should be matched to the expected launch customer.

- Proposals should support market introduction to the existing large unmanned aerial vehicle (UAV) or the emerging electric and electric aircraft markets. The topic seeks solutions applicable for UAV, aircraft, and electric vertical takeoff and landing (eVTOL) systems in the 1,500 to 5,000 lbs. class or larger electric aircraft with a near-term market entry on-ramp.
- A clear understanding of relevant FAA and/or military standards for engines and aviation electrical systems must be demonstrated.
- An operational concept should describe the expected operation of the zero-emission aircraft over a typical flight mission. What are the expected conditions and modes during the flight segments? What is the concept for recharge of the aircraft?
- Facilities to support development and testing in Phase I and Phase II.

Note: This subtopic is for electric propulsion aircraft designs and not hybrid-electric aircraft engines. See subtopic A1.09 Zero Emissions Technologies for Aircraft for electric aircraft engine-related proposals.

Expected TRL or TRL Range at completion of the Project: 1 to 3

Primary Technology Taxonomy:

- Level 1: TX 01 Propulsion Systems
- Level 2: TX 01.3 Aero Propulsion

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Phase I Deliverables:

1. Demonstrate a novel configuration, zero-emission electric aircraft for 1,500 to 5,000 lbs. drones and piloted aircraft through a design study showing that the system will use less total energy than current aircraft of that size. The engine should be able to produce both thrust and electric power. The ratio of the two outputs should align with the intended aircraft application.
2. Demonstrate that the design of the aircraft has a clear path to an FAA certification date of 2030 or earlier. It is understood that this part of the effort would be beyond Phase II.
3. One or more identified launch customers with letters of commitment. The payload, range, speed, energy use per mile, and in-flight emissions per mile should be matched to the expected launch customer.
4. A clear understanding of relevant FAA and/or military standards for engines and aviation electrical systems must be demonstrated.
5. An operational concept should describe the expected operation of the zero-emission aircraft over a typical flight mission. What are the expected conditions and modes during the flight segments? What is the concept for recharge of the aircraft?
6. Facilities to support development and testing in Phase I and Phase II.

Phase II Deliverables:

1. A small, flying prototype, zero-emission electric aircraft. It should be supported by the Phase I design study showing how it is scalable to 1,500 to 5,000 lbs. aircraft applications.

State of the Art and Critical Gaps:

Small electric aircraft are being created. This topic goes beyond what is available in industry because it focuses specifically on the aircraft configurations enabled by electrified aircraft propulsion (EAP).

Relevance / Science Traceability:

Zero-emissions technology is an emerging focus of the NASA ARMD. This topic allows us to engage small business in the activity with a potential path to further funding of ideas developed under this topic through the ARMD projects mentioned above.

EAP is an area of strong and growing interest in the ARMD. There are emerging-vehicle-level efforts in urban on-demand mobility and an ongoing technology development subproject to enable EAP for single-aisle aircraft. Additionally, NASA is executing the Electrified Powertrain Flight Demonstration (EPFD) project to enable a megawatt-class aircraft.

Key outcomes NASA intends to achieve in this area are:

- 2015 to 2025: Markets will begin to open for electrified small aircraft.
- 2025 to 2035: Certified small-aircraft fleets enabled by EAP will provide new mobility options. The decade may also see initial application of EAP on large aircraft.
- Post-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) Project.
- Integrated Aviation Systems Program (IASP)/Flight Demonstrations and Capabilities (FDC) Project.
- AAVP/Revolutionary Vertical Lift Technology (RVLT) Project.
- Transformative Aeronautics Concepts Program (TACP)/Convergent Aeronautics Solutions (CAS) Project.
- TACP/Transformational Tools and Technologies (TTT) Project.

References:

1. EAP is called out as a key part of Thrust 3 in the ARMD Strategic Implementation Plan: https://www.nasa.gov/wp-content/uploads/2021/04/sip-2023-final-508.pdf
2. Overview of NASA's EAP Research for Large Subsonic Aircraft: https://ntrs.nasa.gov/search.jsp?R=20170006235
3. NASA X-57 Project: https://www.nasa.gov/aeroresearch/X-57/technical/index.html
4. “High Efficiency Megawatt Motor Preliminary Design,” Jansen et al.: https://ntrs.nasa.gov/citations/20190029589

A1.06: Vertical Takeoff and Landing (VTOL) Vehicle Technologies - Vehicle Design Tool & Electric Powertrain Test Capability (SBIR)

Related Subtopic Pointers: T15.04
Lead Center: GRC
Participating Center(s): AFRC, ARC, LaRC

Subtopic Introduction:

The expanding Urban Air Mobility (UAM) vehicle industry has generated a significant level of enthusiasm among aviation designers and manufacturers, resulting in numerous vehicle configurations. The majority of the proposed UAM vehicles have more than four rotors or propellers, have electric propulsion, carry two to six passengers, fly more like a helicopter (vertical takeoff and landing) than a fixed-wing aircraft and will fly relatively close to the ground and near buildings. There are many technical challenges facing industry's development of safe, quiet, reliable, affordable, comfortable, and certifiable UAM vehicles and vehicle operations. This SBIR subtopic focuses on vehicle technologies associated with those challenges. The subtopic is also focused on the future generations of UAM vehicles and the technologies that would extend the VTOL aircraft use for other missions. Each year, the subtopic focuses on different technologies, areas, and/or applications for VTOL aircraft, such as propulsion, handling qualities, structures, acoustics, weather tolerance, cabin environment, and other key vehicle technologies. This year, the subtopic targets capability improvements in rotorcraft design tools and electric powertrain testing.

Scope Title: Technologies to Improve VTOL Vehicle Design Tools

Scope Description:

Rotorcraft Design Tool Airfoil Table Generator: Automated tool for preparing C81-formatted airfoil tables.

C81-format airfoil coefficient table files are used by rotorcraft prediction tools for keeping calculation resource cost manageable. These tables are sets of airfoil coefficients (lift, drag, moment) over +180/-180 degrees of angle of attack, and for a series of operating Mach numbers which cover the operating range of the rotor section. These C81 tables are usually generated by a combination of experimental and predicted values. Generating the C81 tables typically requires some engineering judgment and is somewhat complicated and tedious because of the limitations of legacy Fortran text files. For future aircraft, with novel operating conditions and novel rotor systems, the ability to generate C81 tables using predicted coefficients will be even more important. Airfoils may have sharp or blunt leading or trailing edges, have smoothly curved surfaces, and be made up of more than one enclosed shape element (as in a slotted flap or slat). Multiple flap positions may be defined and recorded as separate C81 tables or as augmented tables. Airfoils may operate from tens of thousands in chord Reynolds number to tens of millions, and Mach numbers may vary from nearly zero to greater than Mach 1. C81 tables will capture stall, post-stall, and reversed flow, but not hysteresis install and reattachment, as there is a single value of coefficient for each angle of attack-Mach pairing.

The desired solution can make use of multiple aerodynamic solvers for either speed of execution or because the solvers are better suited to different aspects of a problem (for instance, accurately capturing stall versus compressibility effects). For instance, the existing tool being used by NASA is capable of interfacing with Massachusetts Institute of Technology's xfoil or MSES, or NASA's Overflow and then assembling results into a single. Airfoil coordinates are typically specified as ordered coordinate pairs, and the tool should be able to take a variety of airfoil coordinate input formats, generate computational grids as necessary, launch the solver(s), manage failed cases, and read the results. The tool should be able to launch and manage multiple processes, on both a local and remote computational resource. The tool should be able to run via a graphical user interface or via command-line interface. An application programming interface mode of operation via Python is desirable.

The tool should also merge the predicted airfoil coefficients with those from other sources, as is often used to blend in NACA 0012 airfoil coefficients from a standard table for high angles of attack where solver accuracy is questionable and perhaps airfoil specifics are less important.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:

- Level 1: TX 11 Software, Modeling, Simulation, and Information Processing
- Level 2: TX 11.2 Modeling

Desired Deliverables of Phase I and Phase II:

- Analysis
- Research
- Prototype

Desired Deliverables Description:

Phase I of the SBIR should develop design concepts for specific technology advancements supported by analytical studies including modeling and simulation. Phase I effort should establish Phase II goals and should quantify projections of technology performance.

Phase II of the SBIR should further develop the technology designs and validate achievement of goals through additional analysis, modeling, simulation, and product demonstration.

State of the Art and Critical Gaps:

C81-format airfoil coefficient table files are used by rotorcraft prediction tools for keeping calculation resource cost manageable. For future aircraft, with novel operating conditions and novel rotor systems, the ability to generate C81 tables using predicted coefficients will be even more important to advance the vehicle design capability and vehicle performance.

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 project scope encompasses technologies that address noise, speed, mobility, payload, efficiency, environment, and safety for both conventional and nonconventional vertical lift configurations. This subtopic directly aligns with the mission, goals, and scope in addressing the Advanced Air Mobility mission objectives, and the Directorate Strategic Implementation Plan's Strategic Thrust 4: Safe, Quiet, and Affordable Vertical Lift Air Vehicles.

References:

1. Kallstrom, K., Shirazi, D., "Airfoil Table Generation and Validation for the VR-12 and SSC-A09 Airfoils and Quadrotor Performance Prediction," Vertical Flight Society Sixth Decennial

Aeromechanics Specialists' Conference, Santa Clara, CA, February 2024. https://rotorcraft.arc.nasa.gov/Publications/files/VFS_TVF_Kallstrom_Shirazi_VR12_SSCA09.pdf
2. Kallstrom, K., "Exploring Airfoil Table Generation using XFOIL and OVERFLOW," Presented at the VFS Aeromechanics for Advanced Vertical Flight Technical Meeting, San Jose, CA, Jan 25-27, 2022. https://rotorcraft.arc.nasa.gov/Publications/files/Kristin_Kallstrom_Final_Paper_18-Jan-2022.pdf

Scope Title: High Voltage eVTOL Powertrain Test Equipment

Scope Description:

NASA is developing electric-powered aircraft under both the Electrified Aircraft Propulsion Technologies (EAPT) and RVLT projects, where testbeds are being used to investigate system interactions and power quality (PQ) to feed associated standards for these classes of vehicles. NASA is also working with the Federal Aviation Administration (FAA) to provide pertinent data for drafting of the certification processes. As part of the testbed development, NASA needs electromagnetic interference (EMI) and performance qualification (PQ) test equipment for higher voltage / higher power applications, which does not currently exist. The objective of this SBIR subtopic scope is to develop EMI and PQ test equipment for eVTOL powertrain systems and ground testbeds. For RVLT applications, the requirements are to develop EMI equipment (power amplifiers, isolation transformers, ripple and surge injection units, etc.) and power equipment (power amplifiers, isolation transformers, fault injection units, dynamic load banks, and wide bandwidth emulators/power supplies) capable of testing systems/loads with operating voltages of at least 650 Vdc (1 kV preferred), 150 A (300 A preferred), with minimum bandwidths of direct current (DC) to 250 kHz (although may vary depending on application), and operating up to altitudes of 15,000 ft. The 250 kHz is of interest for investigation of EMI noise.

Expected TRL or TRL Range at completion of the Project: 4 to 6

Primary Technology Taxonomy:

- Level 1: TX 13 Ground, Test, and Surface Systems
- Level 2: TX 13.2 Test and Qualification

Desired Deliverables of Phase I and Phase II:

- Hardware
- Analysis

Desired Deliverables Description:

The desired deliverables for Phase I would be, at a minimum, detailed design and analysis of proposed equipment. An added benefit would be the build of breadboard units to validate the proposed approach.

The desired deliverables for Phase II would be prototype hardware validated through test.

State of the Art and Critical Gaps:

Aircraft (VTOL and small conventional takeoff and landing (CTOL)) companies are designing and building aircraft with electric propulsion systems. The power systems for these vehicles will be high voltage, kW to MW power systems. EMI and PQ test equipment for these higher voltage/higher power applications does not exist. With the advent of electrified aircraft efforts, this type of test equipment will be critical in evaluating safety and system interaction aspects for the myriad of designs being proposed for the urban air mobility market.

Relevance / Science Traceability:

This subtopic is relevant to the ARMD 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 project scope encompasses technologies that address noise, speed, mobility, payload, efficiency, environment, and safety for both conventional and nonconventional vertical lift configurations. This subtopic directly aligns with the mission, goals, and scope in addressing the Advanced Air Mobility mission objectives, and the Directorate Strategic Implementation Plan's Strategic Thrust 4: Safe, Quiet, and Affordable Vertical Lift Air Vehicles.

References:

1. Silva, C., Johnson, W. R., Solis, E., Patterson, M. D., and Antcliff, K. R., "VTOL Urban Air Mobility Concept Vehicles for Technology Development," 2018 Aviation Technology, Integration, and Operations Conference, American Institute of Aeronautics and Astronautics, 2018. [AIAA 2018-3847] https://rotorcraft.arc.nasa.gov/Publications/files/vtol-urban-air-2.pdf
2. Johnson, W., Silva, C., and Solis, E., "Concept Vehicles for VTOL Air Taxi Operations," AHS Specialists' Conference on Aeromechanics Design for Transformative Vertical Flight, San Francisco, CA, 2018. https://ntrs.nasa.gov/api/citations/20180003381/downloads/20180003381.pdf
3. Dever, T., Collazo, X, Hanlon, P.,Hunker, K., Sadey, D., Theman, C., Malone, B., "Impedance Measurements of Motor Drives and Supply in SPEED Testbed", AIAA/IEEE Electric Aircraft Technologies Symposium, 12-16 June 2023. Microsoft PowerPoint - 2023 EATS SPEED Impedance Measurement v2.pptx (nasa.gov)
4. Hanlon, P., Sadey, D., Theman, C., Hunker, K. Fain, H., Nawash, N., Thomas, G., Nowak, P., Collazo Fernandez, X., Rupp, T., Malone, B., Valco, M., "NASA Scaled Power Electrified Drivetrain", Preparation of Papers for AIAA Journals (nasa.gov)
5. Sadey, D., Hanlon, P., "NASA Advanced Reconfigurable Electrified Aircraft Laboratory (AREAL)", AIAA/IEEE Electric Aircraft Technologies Symposium, 12-16 June 2023 Microsoft PowerPoint - AIAA EATS Presentation 2023 AREAL (nasa.gov)

A1.08: Aeronautics Ground Test and Measurement Technologies: Diagnostic Systems for High-Speed Flows and Icing (SBIR)

Lead Center: LaRC
Participating Center(s): ARC, GRC

Subtopic Introduction:

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 that can be applied in NASA's aeroscience ground test facilities to revolutionize testing and measurement capabilities and improve utilization and efficiency. Of primary interest are technologies that can be applied to NASA's portfolio of large-scale ground test facilities.

Scope Title: Miniaturized Flow Diagnostics for High-Speed Flows

Scope Description:

Spatially resolved flow-field measurement diagnostics are sought for application in high-speed wind tunnel flows (transonic, supersonic, and hypersonic), in both combusting and noncombusting flows. Improved measurement capabilities are needed for velocity, temperature, density, and/or species concentrations in harsh wind-tunnel environments. Molecular-based diagnostics are appropriate for multiparameter measurement approaches. Additionally, particle seeded or unseeded flow velocity measurement approaches are also of interest. Measurement systems should be both reliable and robust and preferably able to be implemented in multiple wind-tunnel facilities and facility types, including blowdown tunnels, combustion-heated tunnels, shock tubes, shock tunnels, and arc jets. Linear or planar, spatially resolved measurement approaches are preferred for the particulate-based seeding approaches. Molecular approaches can be point based; however, linear and/or planar measurement domains are not discouraged. Ability to measure multiple parameters simultaneously is desirable. The ability to time-resolve unsteady flow fields so that frequency spectra of the measured phenomena can be obtained is a secondary benefit but not required.

The highest priority will be given to compact/miniaturized systems that could be installed inside a wind-tunnel test article and/or systems capable of measuring temperature, water vapor concentrations, and velocity at the nozzle exit of large hypersonic tunnels, such as the 8-ft High-Temperature Tunnel at NASA Langley Research Center (LaRC).

- For embeddable miniaturized measurement systems, external power, fiber optic, and/or data signal connections can be used. An estimate of the volumetric requirements of the measurement head should also be clearly stated, along with optical access requirements. Small planar windows are preferred over large curved optical access ports, which are ultimately defined by the test application. Measurement systems should be validated against accepted standards (thermocouples, calibration flames, etc.) to determine measurement accuracy and precision. Proposals should project anticipated accuracies and precisions of the proposed measurement system(s) based on prior cited or demonstrated work.
- Measurement diagnostics for the nozzle exit of large hypersonic tunnels will be used to quantify facility performance and to determine test-article inflow conditions. Such flow fields may contain water droplets; therefore, any diagnostic proposed for this environment must be insensitive to water droplets. Measurements of the nozzle-exit flow field are desired at high repetition rates (tens of kilohertz) and should be able to operate continuously or repeatedly for several minutes' duration to obtain an appropriate amount of data to improve statistical error and provide detailed information about the time-varying nature of these flow fields.

Expected TRL or TRL Range at completion of the Project: 4 to 7

Primary Technology Taxonomy:

- Level 1: TX 13 Ground, Test, and Surface Systems
- Level 2: TX 13.5 Surface Systems Technologies

Desired Deliverables of Phase I and Phase II:

- Hardware
- Prototype
- Research
- Analysis
- Software

Desired Deliverables Description:

- Phase I: Research shall include proof of concept of proposed idea. The proposer must provide the design for the comprehensive system that would be developed in Phase II, including detailed analysis of the expected performance (consideration for beam steering, spatial resolution, time response, accuracy, precision, etc.) A benchtop demonstration of the prototype in a company's lab is strongly encouraged.

- Phase II: Production and delivery of a turnkey system with sufficient documentation for NASA researchers to install and operate the measurement system in NASA's facilities. NASA may choose, at its discretion, to visit the contractor's site prior to hardware delivery to observe system setup and operation (including software). Any computer equipment or electronic systems included in the system must comply with the government's Section 889 certification requirements.

State of the Art and Critical Gaps:

There are very limited technologies for measuring gas velocity, temperature, and density simultaneously. The techniques that are available are sensitive to background scattered light and tend to be point based. A planar-based technique capable of simultaneously and accurately measuring gas velocity and state variables would be a large advance in the state of the art. Another challenge is employing these optical diagnostic techniques in NASA's large-scale wind tunnels, where there may be limited optical access or large distances from a viewing window to the test article in the tunnel. An alternative approach could be to implement miniaturized point, line, and/or planar techniques for acquiring near-surface velocity measurements that are small enough to be integrated into the test model or to be flown onboard aircraft for in-flight measurements. Single optical port access (or maximum of two optical access ports) for obtaining near-surface (boundary layer) and short-standoff (several feet) measurement capabilities would both be highly desirable.

There are also very limited technologies for measuring nozzle exit conditions in hypersonic facilities. Some systems exist, but there have been very limited applications. A technology that can measure nozzle exit conditions could also be used for engine inlet and outflow conditions. A promising technology was developed to study aircraft engine outflow plumes using Air Force SBIR project support. This included using an array of laser beams to perform absorption spectroscopy at the exit of a J-85 jet engine. Temperature and water vapor concentration was measured over an area of ~1 m × 1 m. A gap in this technology is that the gas velocity, a highly desirable parameter, was not measured. More consideration would be given to an approach that provides a full reconstruction of the velocity, temperature, and water content across the entire face of the 8-ft tunnel exit diameter. Another gap that is needed by the facility managers and customers at some of the larger combustion-heated hypersonic facilities at NASA is the ability to measure water vapor droplet size and concentration (water droplets are an undesirable consequence of combustion heating and can affect engine performance). The proposed instrument need not meet all of these requirements but should show a viable path towards the desired spatially resolved facility characterization detailed above.

Relevance / Science Traceability:

The target application of this technology is at NASA's large-scale test facilities: the National Transonic Facility (NTF) and Transonic Dynamics Tunnel (TDT) at Langley Research Center, the 8×6 Supersonic Wind Tunnel and the 10×10 Abe Silverstein Supersonic Wind Tunnel at Glenn Research Center, and the Unitary Plan Wind Tunnels at Ames Research Center. The technology could also be applied to measure in-flow and near-wall conditions in other types of facilities like shock tubes and shock tunnels as well as conventional aeronautical testing facilities. The ARMD/AETC-owned 8-ft High Temperature Tunnel at NASA Langley also benefits from this technology, particularly if designed to measure nozzle exit conditions. The technology also has other applications, such as to measure inflow or outflow for engines being tested at NASA Glenn.

References:

1. ARMD Strategic Implementation Plan: https://www.nasa.gov/wp-content/uploads/2021/04/sip-2023-final-508.pdf

Scope Title: Water Drop Temperature Measurements for Icing Wind Tunnel Facilities

Scope Description:

Current icing wind tunnel facilities have primarily been designed and calibrated for icing envelopes described in Title 14 CFR Part 25 Appendix C [Ref. 1]. The investigation following the American Eagle Flight 4184 accident identified that the probable cause of the accident was due to an encounter with icing conditions outside of the existing Appendix C envelopes. Specifically, it was identified that the drop distribution encountered contained significant water content in drops with large diameters. Compared with drops in more common icing clouds, these supercooled large drops (SLD) interact differently with aircraft, causing impingement further aft on the wing than would be expected with an encounter with the existing Appendix C envelopes. In response, Title 14 CFR Part 25 Appendix O [Ref. 2] was introduced in 2015, which expanded the icing certification requirements that aircraft manufacturers must consider when designing and certifying future aircraft. These envelopes are (1) freezing drizzle less than 40 μm mean volumetric diameter (MVD), (2) freezing drizzle greater than 40 μm MVD, (3) freezing rain less than 40μm MVD, and (4) freezing rain greater than 40 μm MVD.

Ground test facilities such as the Icing Research Tunnel (IRT) are looking to expand capabilities to simulate SLD conditions. One area of concern is centered around the temperature of the larger drops in the test section. Water drops are typically introduced into the flow via an atomizing spray bar system upstream of both the test section and convergent nozzle of the wind tunnel. The water is introduced into the flow at above freezing temperatures to prevent water freezeout in the spray bars. As the drops travel towards the test section, they begin to cool and ideally are supercooled to the air temperature of the tunnel in the residence time available between the spray bar and the test section. As the drop size increases, the ratio of surface area to the volume of the drop decreases, resulting in a need for a larger residence time for the drop to cool to the air temperature. As such, there is uncertainty in whether the water temperature of the cloud is equal to the air temperature. Additionally, if there is a temperature difference between the cloud and the air temperature, it is important to know how that difference varies with drop diameter. Therefore, it is desirable to be able to measure the water temperature as a function of drop diameter. Additionally, due to limitations in the IRT, it is desirable for a measurement capability to work on deionized water (i.e., no additives added to the water supply). NASA is seeking a measurement capability for the water temperature of individual large drops within the cloud of a flowing wind tunnel for test conditions achievable within the IRT.

Expected TRL or TRL Range at completion of the Project: 4 to 6

Primary Technology Taxonomy:

- Level 1: TX 13 Ground, Test, and Surface Systems
- Level 2: TX 13.2 Test and Qualification

Desired Deliverables of Phase I and Phase II:

- Research
- Prototype

- Hardware
- Analysis

Desired Deliverables Description:

Desired deliverables for Phase I would be detailed design and analysis of proposed hardware, preliminary concept demonstration, and a proposed path to system integration into the IRT facility. Demonstration of prototype capability to measure the temperature of a non-stationary water drop via bench top testing is encouraged.

Desired deliverables for Phase II would be prototype hardware that has been validated through test and traceable metrics for hardware calibration and characterization. The prototype system will be configured to operate on/through the window ports of the IRT facility or inside the IRT test section. Higher weighting will be given to approaches/systems that are able to measure water temperature of individual large drops, especially larger than 500 μm, to assess the potential variation of water temperature with drop diameter. The prototype hardware should be delivered ready to install and use in the IRT facility with set-up and operational instructions. NASA may choose, at its discretion, to visit the contractor's site prior to hardware delivery to observe system setup and operation (including software). Any computer equipment or electronic systems included in the system must comply with the government's Section 889 certification requirements.

State of the Art and Critical Gaps:

The NASA Glenn Icing Research Tunnel [Ref. 3] is a ground test facility for studying ice accretion on aircraft component surfaces across a range of drop diameters and concentrations. Water drops are introduced into the refrigerated flow using an array of over 500 spray nozzles. Water drops are cooled to temperatures ranging from 0 to -35 °C. Some techniques in the literature include using a temperature-sensitive luminescent additive in the water [Ref. 4], which is undesirable in the IRT due to restrictions on introducing additives into the water supply. Additionally, light scattering techniques have been used to measure the bulk water temperature of the cloud [Ref. 5], however, it is unclear if this method can measure the water temperature as a function of drop diameter. The goal of the proposed work would be to supply a nonintrusive particle drop temperature measurement system that can be mounted externally or internally in the IRT test section. Depending on the ultimate system design and configuration, measurement approaches that could ultimately be made into a compact format for use in smaller scale wind tunnel facilities, such as NASA's Adaptive Icing Tunnel that has a one foot by one foot test section, would be given more consideration [Ref. 6].

Relevance / Science Traceability:

NASA's ARMD has a significant interest in vehicles that are transformative including commercial supersonics, advanced air mobility, and sustainable aviation. While Title 14 CFR Part 25 Appendix O has an exemption for vehicles with a maximum take-off weight over 60,000 pounds, it has been noted that novel vehicles may be subject to a special condition, requiring compliance [Ref. 7]. Additionally, European Union Aviation Safety Agency (EASA) regulations provide no such exemption for certification in Europe. For the Appendix O regime, the state of the art of computational simulation tools and ground test facilities is likely not at a sufficient TRL to enable direct compliance. While flight testing remains a technical option for direct compliance, it may not be a commercially viable option due to cost. To enable market entry of these transformative vehicles, advancement in the TRL of ground-based test capabilities is likely required.

References:

1. Title 14 CFR Part 25 Appendix C, Code of Federal Regulations: https://www.ecfr.gov/current/title-14/chapter-I/subchapter-C/part-25/appendix-Appendix%20C%20to%20Part%2025

2. Title 14 CFR Part 25 Appendix O, Code of Federal Regulations: https://www.ecfr.gov/current/title-14/chapter-I/subchapter-C/part-25/appendix-Appendix%20O%20to%20Part%2025
3. NASA Glenn Research Center Icing Research Tunnel: https://www1.grc.nasa.gov/facilities/irt/
4. Tanaka, Mio, et al. "Time-resolved temperature distribution of icing process of supercooled water in microscopic scale." 6th AIAA atmospheric and space environments conference. 201: https://arc.aiaa.org/doi/pdf/10.2514/6.2014-2329
5. Saengkaew, S.; Godard, G.; and Grehan, G. "Global Rainbow Technique: Temperature Evolution Measurements of Super-Cold Droplets." 14th International Conference on Liquid Atomization and Spray Systems (ICLASS), Chicago, USA. 2018: https://www.rainbow-visions.com/wp-content/uploads/2020/03/ICLASS2018_No-227-Sawitree-Saengkaew_Revised2.pdf
6. NASA Glenn Research Center Adaptive Icing Tunnel (AIT): https://www1.grc.nasa.gov/aeronautics/icing/facilities/ait/
7. "Airplane and Engine Certification Requirements in Supercooled Large Drop, Mixed Phase, and Ice Crystal Icing Conditions," Rule by the Federal Aviation Administration on 11/04/2014, Federal Register: https://www.federalregister.gov/documents/2014/11/04/2014-25789/airplane-and-engine-certification-requirements-in-supercooled-large-drop-mixed-phase-and-ice-crystal

A1.09: Zero-Emissions Technologies for Aircraft (SBIR)

Related Subtopic Pointers: Z-GO.01
Lead Center: GRC
Participating Center(s): N/A

Subtopic Introduction:

The purpose of this subtopic is to stimulate near-term U.S. entrepreneurship in the zero-emission hybrid electric aircraft engines for drones and piloted aircraft weighing 1,500 to 5,000 pounds. We seek solutions that use liquid natural gas, hydrogen, or other atypical aircraft fuels. This subtopic does not seek Jet-A or sustainable aviation fuel solutions. The technologies proposed should have both a technical and business pathway for introduction into the air fleet.

Scope Title: Zero-Emission Hybrid Electric Aircraft Engine

Scope Description:

For the purposes of this solicitation, the zero-emission hybrid electric engine shall be defined as an engine that converts an atypical aviation fuel to a combination of thrust and electrical power. The input boundaries of the system are the fuel connection and the air inlet. The output boundaries are the electrical connection and the exit port or nozzle of the engine. The key performance metrics are the total output power (electrical + mechanical), the mass, the thrust, and the electrical parameters (power and voltage).

The outcome sought at the end of Phase II is a lab-tested small prototype zero-emission hybrid electric engine. It should be supported by a study showing how it can scale to 1,500 to 5,000 pounds for aircraft applications. The engine should be able to produce both thrust and electric power. The ratio of the two outputs should align with the intended aircraft application.

Strong proposals will have several characteristics:

- One or more identified launch customers with letters of commitment.
- Proposals should support market introduction to the existing large UAV or the emerging electric and hybrid electric aircraft markets. The topic seeks solutions applicable for UAV aircraft and electric

vertical takeoff and landing (eVTOL) systems in the 1,500- to 5,000-pound size class or larger hybrid electric aircraft with near-term market entry onramp.
- A clear understanding of relevant Federal Aviation Administration (FAA) and/or military standards for engines and aviation electrical systems must be demonstrated.
- A focused effort to develop a hybrid turbine with a path to FAA certification date by 2030 or earlier must be shown. It is understood that this part of the effort would be beyond Phase II.
- The thrust, fuel type, and electrical power and voltage charge should match to the expected launch customer.
- An operational concept that describes the expected operation of the hybrid turbine and aircraft over a typical flight mission and that includes the following: expected conditions and modes during the flight segments, expected modes/conditions during ground operations, expected modes/conditions during storage and transport.
- Facilities to support development and testing in Phase I and Phase II.

Note: This subtopic is for hybrid electric aircraft engines and not aircraft. See Subtopic A1.04 Novel Aircraft Configurations for electric propulsion for aircraft related proposals.

Expected TRL or TRL Range at completion of the Project: 2 to 4

Primary Technology Taxonomy:

- Level 1: TX 01 Propulsion Systems
- Level 2: TX 01.3 Aero Propulsion

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Phase I work should include: (1) details on how the specific technology and configuration of the technology in an aircraft concept leads to a benefit; (2) the plan to introduce the technology into a near-term market; (3) clear trade studies and analytical results to justify a Phase II investment; and (4) if possible, prototype hardware components or key parts for high-risk areas or areas of performance risk.

Phase II work should include: (1) final designs and supporting analysis, (2) analysis showing technology benefit to aircraft energy use or emissions, (3) technology to market plan and/or plan for Phase IIE or Phase III SBIR support, (4) hardware demonstrations of technology, (5) written test reports showing performance of hardware, and (6) comparison of analytical estimated performance and actual measured performance of technology or components.

State of the Art and Critical Gaps:

The current state of the art in aircraft does not have a path to zero emissions. Significant investments are being made to reach net zero through a combination of sustainable aviation fuels, engine, and airframe technology. This subtopic is positioned at the step beyond that of true zero emissions, which is well suited for government investments to incentivize innovation.

Relevance / Science Traceability:

Projects that could use this technology are Transformational Tools and Technologies (TTT), Advanced Air Transport Technology (AATT) Project, and Convergent Aeronautics Solutions (CAS). Zero-emissions technology is an emerging focus of the NASA Aeronautics Research Mission Directorate (ARMD). This topic allows us to engage small businesses in the activity with a potential path to further funding of ideas developed under this topic through the ARMD projects mentioned previously.

References:

1. NASA ARMD Strategic Implementation Plan 2023: https://www.nasa.gov/wp-content/uploads/2021/04/sip-2023-final-508.pdf
2. NASA Aeronautics Research Mission Directorate: https://www.nasa.gov/aeroresearch
3. NASA Aeronautics Sustainable Aviation: https://www.nasa.gov/aeroresearch/sustainable-aviation
4. NASA Electrified Aircraft Propulsion: https://www1.grc.nasa.gov/aeronautics/eap/
5. NASA Aims for Climate-Friendly Aviation: https://www.nasa.gov/aeronautics/nasa-aims-for-climate-friendly-aviation/
6. Subsonic Single Aft Engine (SUSAN) Aircraft: https://www1.grc.nasa.gov/aeronautics/eap/airplane-concepts/susan/
7. Subsonic Single Aft Engine (SUSAN) Transport Aircraft Concept and Trade Space Exploration. 2022 AIAA Science and Technology Forum and Exposition: https://arc.aiaa.org/doi/pdf/10.2514/6.2022-2179

A1.11: Health Management and Sensing Technologies for Sustainable Aviation Vehicles (SBIR)

Lead Center: GRC
Participating Center(s): AFRC, ARC, LaRC

Subtopic Introduction:

NASA is committed to supporting the U.S. climate goal of achieving net-zero greenhouse gas emissions from the aviation sector by 2050 and is leading federal agencies and industry to accelerate the development of sustainable aviation technologies. This includes enabling use of sustainable aviation fuels and deploying new vehicle designs and architectures. Hybrid Electric or All Electric vehicle concepts are in active development as are new Alternative Fuel/Hydrogen Vehicles. However, these aircraft concepts introduce new hardware systems along with new health management challenges. For example, fault detection and diagnostics of hybrid electric or all electric propulsion systems requires an understanding of the operation, performance, degradation, and failure mechanisms of electric machines, converters (inverters/rectifiers), and power cables along with the operation of these devices in increasingly complex flight environments. Introduction of new vehicle types and integrated vehicle systems (power, structure, avionic, and propulsion systems) requires increasingly intelligent vehicle systems with capability to detect, diagnose, and predict system degradation, faults, and failures in a resilient and trustworthy manner.

Furthermore, these intelligent vehicle systems must be capable of estimating vehicle capabilities as it degrades especially for new vehicles systems entering the airspace. Monitoring the system health state has an impact on system operating cost, performance, efficiency, and improved system safety. Predictive maintenance reduces maintenance cost and vehicle down-time through reduced unnecessary maintenance and improved vehicle availability and throughput. Development of approaches and techniques for integrating diagnostic, and prognostic information into maintenance and fault management strategies for sustainable aviation vehicles (i.e., predictive and condition-based maintenance). These are critical features that would allow new sustainable aviation vehicles to have more rapid introduction into the airspace.

This subtopic is not seeking proposals in the following areas:

- Battery health management technologies
- Electrical fault management systems and protective devices (such as circuit breakers).

Scope Title: Health Management and Sensing Technologies for Electric/Hybrid Sustainable Designs

Scope Description:

This scope seeks health management technologies for electric/hybrid aircraft designs. The technologies should be able to operate as needed in a high electric noise flight environment and provide actionable information for higher level diagnostics and prognostics. New electric/hybrid vehicles and their propulsion systems can be more economic, smarter, and safer by enabling increased health management capabilities. Areas of interest include:

- Health management technologies for the sensing, diagnosis, and prognosis of degradation and faults in flight quality electrical hardware and systems. The technology could be focused on electrical systems such as:
    - Electric machines (motors/generators) including the health of bearings, lubrication and cooling, windings, rotor, insulation, etc.
    - Converters (inverters/rectifiers) including the health of electronic components, cooling system, etc.
    - High voltage wire and cables, including short or open circuits and insulation breakdown.
    - Overall power quality including degradation/faults leading to voltage ripple, power instabilities, etc.
    - Thermal management system health.
- System-level approaches that leverage measurement data collected across sustainable aviation systems including electromechanically coupled subsystems to infer overall system health. This includes distributed or coupled architectures comprised of electrical systems, motor driven propulsors, energy storage devices, gearboxes, mechanical drives, and fuel burning engines.

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:

- Level 1: TX 10 Autonomous Systems
- Level 2: TX 10.1 Situational and Self Awareness

Desired Deliverables of Phase I and Phase II:

- Prototype
- 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 applications.
- A technology demonstration that clearly shows the benefits of the technology developed.
- A written plan to continue the technology development and/or to infuse the technology. This may be part of the final report.
- Resulting products can include hardware, software, demonstrations, reports, products, components, and integrated systems.

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, and a plan to infuse the technology developments into applications.
- A technology demonstration in an appropriate environment which clearly shows the benefits and viability of the technology developed.
- There should be evidence of efforts taken to infuse the technology into applications or a clear written plan for near term infusion of the technology. This may be part of the final report.
- Resulting products can include hardware, software, demonstrations, components, and integrated systems.

State of the Art and Critical Gaps:

The technical need is for system health management in the evolving field of sustainable aviation. For electrified aircraft propulsion (EAP) and vehicles, many conventional subsystems remain in EAP architectures – e.g., gas turbines, rotating drives, gearboxes, propellers/fans, etc. but new challenges in sensing, diagnosis, and prognosis must be addressed:

- Architectures are more coupled and integrated in nature.
- Boundary between propulsion system and vehicle not as clearly defined.
- Might require means of partitioning the health management problem by subsystem.
- Data compression and feature extraction techniques for high-frequency electrical system measurements will be necessary.
- Electrical systems may not exhibit graceful degradation / failure making timely diagnostics and prognostics more challenging.

Technologies that address these gaps enable sustainable aircraft, which in-turn 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:

EAP is an area of particularly strong and growing interest in the Aeronautics Research Mission Directorate (ARMD). There are emerging-vehicle-level efforts in urban on-demand mobility and an ongoing technology development subproject to enable EAP for single-aisle aircraft. Additionally, NASA started the Electrified Powertrain Flight Demonstration (EPFD) project to enable a megawatt-class aircraft.

Key outcomes NASA intends to achieve in this area are:

- Outcome for 2015 to 2025: Markets will begin to open for electrified small aircraft.
- Outcome for 2025 to 2035: Certified small-aircraft fleets enabled by EAP will provide new mobility options. The decade may also see initial application of EAP 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.

References:

1. D. Simon, "Health Management Considerations for Electrified Aircraft Propulsion Systems", SAE E32 Aerospace Propulsion Health Management Committee Meeting March 29-31, 2022. https://ntrs.nasa.gov/api/citations/20220004260/downloads/EAP_HealthMangementConsideration_DSimon_v2.pdf
2. EAP is called out as a key part of Thrust 3 in the ARMD Strategic Implementation Plan: https://www.nasa.gov/directorates/armd/armd-strategic-implementation-plan/
3. Overview of NASA's EAP Research for Large Subsonic Aircraft: https://ntrs.nasa.gov/search.jsp?R=20170006235
4. NASA X-57 Project: https://www.nasa.gov/aeroresearch/X-57/technical/index.html
5. "High Efficiency Megawatt Motor Preliminary Design," Jansen et al. https://ntrs.nasa.gov/citations/20190029589
6. L. Tang, A. Saxena, and K. Younsi, "Prognostics And Health Management For Electrified Aircraft Propulsion: State Of The Art And Challenges", Proceedings of ASME Turbo Expo 2024 Turbomachinery Technical Conference and Exposition, June 2024, London, GT2024-122290 https://doi.org/10.1115/GT2024-122290
7. C. Teubert, A. A. Pohya, and G. Gorospe, "An Analysis of Barriers Preventing the Widespread Adoption of Predictive and Prescriptive Maintenance in Aviation", April, 2023, NASA/TM–20230000841 https://ntrs.nasa.gov/citations/20230000841

Scope Title: Health Management and Sensing Technologies for Sustainable Aviation Fuel Systems

Scope Description:

This scope seeks health management technologies alternate fuel aircraft and new sustainable aircraft designs. The technologies should be able to provide actionable information for higher level diagnostics. Alternate fuel vehicles and their propulsion systems can be more economic, smarter, and safer by enabling increased health management capabilities. However, changing the fuel, e.g., the adoption of cryogenic hydrogen, can have massive impact on vehicle operations and health. Areas of interest include:

- Health management technologies for the sensing, diagnosis, and prognosis of degradation and faults in sustainable aviation fuel systems such as hydrogen vehicles that include cryogenic systems. The use of such fuels introduces their own health management challenges beyond that of conventional fuel systems.
- System-level approaches that leverage measurement data collected across sustainable aviation systems including alternate fuel vehicle subsystem and component information correlating multiple aspects of overall system health including structural degradation, fuel tank integrity, and fuel safety.

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:

- Level 1: TX 10 Autonomous Systems
- Level 2: TX 10.1 Situational and Self Awareness

Desired Deliverables of Phase I and Phase II:

- Research
- Prototype
- Hardware
- Software

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 applications.
- A technology demonstration that clearly shows the benefits of the technology developed.
- A written plan to continue the technology development and/or to infuse the technology. This may be part of the final report.
- Resulting products can include hardware, software, demonstrations, reports, products, components, and integrated systems.

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, and a plan to infuse the technology developments into applications.
- A technology demonstration in an appropriate environment which clearly shows the benefits and viability of the technology developed.
- There should be evidence of efforts taken to infuse the technology into applications or a clear written plan for near term infusion of the technology. This may be part of the final report.
- Resulting products can include hardware, software, demonstrations, components, and integrated systems.

State of the Art and Critical Gaps:

The technical need is for system health management in the evolving field of sustainable aviation. For alternate fuel vehicles such as those using hydrogen, especially cryogenic hydrogen, safety considerations presently constrain the acceptable airframe/tank/passenger layout. The is a need for better leak and fire detection methods for hydrogen applicable wherever hydrogen could accumulate. Further, there is potential for structural degradation of multiple system components using cryogenic hydrogen: seals, insulation, material embrittlement, and thermal expansion characteristics. Sensing, diagnosis, and prognosis of faults and degradation of these systems is required.

Technologies that address these gaps enable sustainable aircraft, which in-turn 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:

Hydrogen powered aircraft are a vital component of European plans for sustainable aviation and are increasingly being investigated in NASA programs such as Convergent Aeronautics Solutions. NASA has a focus on increasing the presence of sustainable vehicles in the airspace the coming decades including the introduction of hydrogen powered systems. There is a driving need to reduce costs, enhance the sustainability of aviation, as well as expand the production and use of sustainable aviation fuel to meet 100% of U.S. demand by 2050. Sustainable aviation is also part of the Advancing NASA's Climate Strategy and alternate fuels such as cryogenic hydrogen can be a component of such a sustainable aviation future, but significant technical challenges remain on a component as well as system level. The ability to detect, diagnose, and prognose the health state of new forms of alternate fuel vehicles is a notable aspect of their safe introduction to the market and commercial acceptance.

References:

1. NASA’s Meeting on Cryogenic Fuel Systems for Aircraft, NASA Glenn Research Center, Sept. 2022.
2. C. Snyder, "NASA Meeting on Cryogenic Fuel Systems for Aircraft, Overview of Previous Workshops and Studies”, September 2022, https://ntrs.nasa.gov/api/citations/20220014107/downloads/NASA-CryoFuels_Workshops-studies_2022-09_CSnyder_final-STI.pdf
3. NASA Funded Center for High-Efficiency Electrical Technologies for Aircraft (CHEETA), https://cheeta.illinois.edu/research
4. J. Moder, M. L. Meyer, W. L. Johnson, “NASA Liquid Hydrogen Aircraft Opportunities and Technologies”, presented at the Cryogenic Engineering Conference and International Cryogenic Materials Conference, Honolulu, HI, July 2023, https://ntrs.nasa.gov/api/citations/20230009800/downloads/CEC%20NASA%20aircraft%20overview_v2-c.pdf
5. J. Cavolowsky and I. Jakupca, “NASA Hydrogen and Fuel Cell Perspectives”, 2022 H2-Aero Symposium & Workshop, March 29, 2022, https://ntrs.nasa.gov/api/citations/20220005022/downloads/NASA%20Hydrogen%20and%20Fuel%20Cell%20Perspectives%20-%2020220329.pdf
6. V. Lvovich, D. Perkins, T. Lavelle, P. Hanlon, H. Hasseeb, et.al., "Commercially-viable Hydrogen Aircraft for Reduction of Greenhouse Emissions", 26th ISABE Conference, Toulouse, FR, 2024, https://ntrs.nasa.gov/api/citations/20240008370/downloads/ISABE2024%20September%202024.pdf
7. C. Teubert, A. A. Pohya, and G. Gorospe, “An Analysis of Barriers Preventing the Widespread Adoption of Predictive and Prescriptive Maintenance in Aviation”, April, 2023, NASA/TM–20230000841 https://ntrs.nasa.gov/citations/20230000841

Scope Title: Health Management and Sensing Tools for Sustainable Aviation Vehicles

Scope Description:

This scope seeks health management and sensing tools applicable for both electric/hybrid or alternate fuel aircraft and new sustainable aircraft designs. The technologies should be able to operate as needed in a high electromagnetic effects flight environment, provide actionable information for higher level diagnostics. New electric/hybrid and alternate fuel vehicles and their propulsion systems can be more economic, smarter, and safer by enabling increased health management capabilities. Areas of interest include:

- Structural sensing, diagnosis, and prognosis for sustainable vehicles whose design may notably differ compared to conventional vehicle systems requiring new approaches and techniques to identify faults and degradation. This includes both electric and alternative fuel vehicles.
- Advanced sensing technologies such as embedded additive manufactured sensors into sustainable vehicle components that offer light weight minimally intrusive sensing solutions.
- System-level approaches that leverage measurement data collected across sustainable aviation systems.
- The use of data analytics and artificial intelligence to provide a more complete system level view of sustainable vehicle health.
- Health management and intelligent maintenance technologies and approaches for sustainable aviation vehicles.

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:

- Level 1: TX 10 Autonomous Systems
- Level 2: TX 10.1 Situational and Self Awareness

Desired Deliverables of Phase I and Phase II:

- Research
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Phase I deliverables should include, but are not limited to:

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State of the Art and Critical Gaps:

The technical need is for system health management in the evolving field of sustainable aviation. For electrified aircraft propulsion (EAP) and vehicles, many conventional subsystems remain in EAP architectures – e.g., gas turbines, rotating drives, gearboxes, propellers/fans, etc. but new challenges in sensing, diagnosis, and prognosis must be addressed:

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Technologies that address these gaps enable sustainable aircraft, which in-turn 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:

EAP is an area of particularly strong and growing interest in the Aeronautics Research Mission Directorate (ARMD). There are emerging vehicle level efforts in urban on demand mobility and an ongoing technology development subproject to enable EAP for single-aisle aircraft. Additionally, NASA started the Electrified Powertrain Flight Demonstration (EPFD) project to enable a megawatt-class aircraft.

Key outcomes NASA intends to achieve in this area are:

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- 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.

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1. D. Simon, "Health Management Considerations for Electrified Aircraft Propulsion Systems", SAE E32 Aerospace Propulsion Health Management Committee Meeting March 29-31, 2022. https://ntrs.nasa.gov/api/citations/20220004260/downloads/EAP_HealthMangementConsideration_DSimon_v2.pdf
2. EAP is called out as a key part of Thrust 3 in the ARMD Strategic Implementation Plan: https://www.nasa.gov/directorates/armd/armd-strategic-implementation-plan/
3. Overview of NASA's EAP Research for Large Subsonic Aircraft: https://ntrs.nasa.gov/search.jsp?R=20170006235
4. NASA X-57 Project: https://www.nasa.gov/aeroresearch/X-57/technical/index.html
5. "High Efficiency Megawatt Motor Preliminary Design," Jansen et al. https://ntrs.nasa.gov/citations/20190029589
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7. C. Teubert, A. A. Pohya, and G. Gorospe, "An Analysis of Barriers Preventing the Widespread Adoption of Predictive and Prescriptive Maintenance in Aviation", April, 2023, NASA/TM–20230000841
8. https://ntrs.nasa.gov/citations/20230000841
9. NASA's Meeting on Cryogenic Fuel Systems for Aircraft, NASA Glenn Research Center, Sept. 2022.
10. C. Snyder, "NASA Meeting on Cryogenic Fuel Systems for Aircraft, Overview of Previous Workshops and Studies", September 2022, https://ntrs.nasa.gov/api/citations/20220014107/downloads/NASA-CryoFuels_Workshops-studies_2022-09_CSnyder_final-STI.pdf
11. NASA Funded Center for High Efficiency Electrical Technologies for Aircraft (CHEETA), https://cheeta.illinois.edu/research
12. J. Moder, M. L. Meyer, W. L. Johnson, "NASA Liquid Hydrogen Aircraft Opportunities and Technologies", presented at the Cryogenic Engineering Conference and International Cryogenic Materials Conference, Honolulu, HI, July 2023, https://ntrs.nasa.gov/api/citations/20230009800/downloads/CEC%20NASA%20aircraft%20overview_v2-c.pdf
13. J. Cavolowsky and I. Jakupca, "NASA Hydrogen and Fuel Cell Perspectives", 2022 H2-Aero Symposium & Workshop, March 29, 2022, https://ntrs.nasa.gov/api/citations/20220005022/downloads/NASA%20Hydrogen%20and%20Fuel%20Cell%20Perspectives%20-%2020220329.pdf
14. V. Lvovich, D. Perkins, T. Lavelle, P. Hanlon, H. Hasseeb, et.al., "Commerically-viable Hydrogen Aircraft for Reducton of Greenhouse Emissions", 26th ISABE Conference, Toulouse, FR, 2024 https://ntrs.nasa.gov/api/citations/20240008370/downloads/ISABE2024%20September%202024.pdf

A2.01: Flight Test and Measurement Technologies (SBIR)

Related Subtopic Pointers: H9.03, Z-ENABLE.05, T15.04
Lead Center: AFRC
Participating Center(s): ARC, GRC, GSFC, LaRC

Subtopic Introduction:

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 meet the challenges presented by NASA's and industry's cutting-edge research and development programs.

Scope Title: Flight Test and Measurement Technologies

Scope Description:

The role of UAV (Uncrewed Aerial Vehicles) in human endeavors is expanding rapidly. Besides imaging, small UAVs can play a vital role in scientific explorations in challenging environments. Evolving small UAV architectures to meet NASA needs and unique applications have the potential to spur the domestic small UAV market to new heights. NASA invites small businesses to provide out-of-the box solutions to further advance the small UAV platform architecture by incorporating novel solutions in operational elegance, power management, and effective data processing and dissemination. This solicitation involves small businesses in proposing technological advancements for small UAV architectures, focusing on reducing size, weight, power consumption, and cost, as well as improving form, fit, and functionality to aid NASA applications.

NASA's Flight Demonstrations and Capabilities (FDC) Project supports a variety of flight regimes and vehicle types, ranging from low-speed, subsonic applications and electric propulsion through transonic and high-speed flight regimes. Therefore, this subtopic covers 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.

Flight test and measurement technology 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 to directly enhance flight test and measurement.

For this year's solicitation, areas of interest emphasizing flight test and measurement technologies will be focusing on digital data processing, telemetry, and optical sensing. An extra emphasis is placed on current state-of-the-art in UAV technologies to further develop and/or adapt and test new sensor suites for supporting the NASA Aeronautics Research Mission Directorate (ARMD) mission and beyond. Areas of interest include:

- Advanced UAV-based navigation in urban and extreme environmental settings, aid in future vertiport management, assess environmental safety including hazardous weather conditions due to wind, snow, wildfire.
- Novel sensor architectures with limited range but increased precision or resolution in performance for UAV applications involving altimeters, ranging, terrain slope, rock/debris locations, thermal locations, landing beacon navigation, landers for extreme environments.
- Development of UAVs with low size, weight, power consumption and cost (SWaP-C), including autopilot with multiple integrated components.
- High-efficiency digital telemetry techniques and/or systems to enable high data-rate and high-volume telemetry for flight test, including air-to-air and air-to-ground communications.
- Improved processing technologies that can perform low-latency, near real-time telemetry processing that can utilize open-source operating system.
- Real-time integration of multiple data sources from onboard, off-board, satellite, and ground-based measurement equipment, including recording of data bus/avionics architectures.
- 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/shear and shock wave propagation.
- Improved ruggedized, single-longitudinal mode, wide bandwidth wavelength-sweeping laser system design for in-situ flight structural health monitoring to be operated in aircraft, specifically for optical frequency domain reflectometry (OFDR) technology utilized in NASA’s Fiber Optic Sensing System (FOSS).

The emphasis here is for technology, preferably both flight hardware prototype(s) and software package(s), to be developed for flight test and flight test facility needs.

The technologies developed for this subtopic directly address the technical challenges in the ARMD Integrated Aviation Systems Program (IASP) and FDC (Flight Demonstration and Capabilities) projects. The FDC Project conducts complex flight research demonstrations to support multiple ARMD programs. FDC is seeking to enhance flight research and test capabilities necessary to address and achieve the ARMD strategic plan. Technologies for this subtopic could also support Advanced Air Vehicle Program (AAVP) projects, including Commercial Supersonic Technology (CST), Revolutionary Vertical Lift Technology (RVLT), and the Hypersonics Technology Project (HTP), as well as the Aerosciences Evaluation and Test Capabilities (AETC) Portfolio Office.

For technologies focused on ground testing or operations, please consider submitting to subtopic A1.08 (Aeronautics Ground Test and Measurement Technologies), as ground testing technologies will be considered out of scope for the A2.01 subtopic.

For technologies with space-only applications, please consider submitting to a related subtopic in the Space Technology Mission Directorate (STMD), as space-only technologies will be considered out of scope for the A2.01 subtopic.

Proposals that focus solely on flight vehicle development rather than focusing on technologies applicable to flight test and measurement will also be considered out of scope for the A2.01 subtopic.

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:

- Level 1: TX 08 Sensors and Instruments
- Level 2: TX 08.1 Remote Sensing Instruments/Sensors

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

For a Phase I effort, the small business is expected to generate a mid-term report showing progress of the work. A summary report is expected at the end of Phase I that describes the research effort's successes, failures, and the proposed path ahead.

For a Phase II effort, the small business should show a maturation of the technology that allows for the presentation of a thorough demonstration. Most ideally, the small business would deliver a prototype that includes beta-style or better hardware and/or software that is suitable to work in ground testing and can be proven, via relevant environment testing, to work in a flight environment. This relevant environment testing would satisfy NASA's technical readiness level (TRL) expectations at the end of Phase II.

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 advanced telemetry techniques; intelligent internal state monitoring for air and space vehicles; techniques for studying sonic booms, including novel photography techniques; 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 the need for secure telemetry of data to ensure informed operation of the flight system.

For low-SWaP-C UAV development, current state of the art can be developing communication payload equipment for high altitude endurance aircraft that support high bandwidth direct-to-device communication (5G) for disaster response, as well as sensor suites for integrated sensors that provide airborne position, navigation, and timing solutions to increase precision and accuracy of aircraft location for a GPS-denied geographic region.

For single longitudinal mode continuously tunable laser systems, current state of the art can either utilize an external cavity setup that involves a mechanically swept-tuned laser that is susceptible to vibration, or an electronically tunable laser that will mode-hop at low bandwidth range (for a couple of nanometers of tuning range). A desirable laser is an electrically tuned laser that can sustain 10 nanometers of tuning range while maintaining single mode throughout the sweeping range.

Relevance / Science Traceability:

The technologies developed for this subtopic directly address the technical and capability challenges in ARMD's FDC Project. FDC conducts complex flight research demonstrations to support various ARMD programs. FDC is seeking to enhance flight research and test capabilities necessary to address and achieve ARMD's strategic plan. Also, the technologies could support the IASP and Electrified Powertrain Flight Demonstration (EPFD) projects, as well as the CST and RVLT projects, as well as the AETC Portfolio Office. Potential hardware from this solicitation will provide improved measurement capabilities that can be implemented in flight experiments.

References:

1. NASA Advanced Air Mobility missions: https://www.nasa.gov/centers-and-facilities/armstrong/building-the-infrastructure-for-advanced-air-mobility/
2. NASA Advanced Capabilities for Emergency Response Operations (ACERO): https://www.nasa.gov/centers-and-facilities/ames/acero-and-wildland-fires/
3. NASA's Quesst mission to reduce the loudness of a sonic boom and gather data on human responses to supersonic flight overhead: https://www.nasa.gov/X59
4. NASA Armstrong Fact Sheet: Fiber Optic Sensing System: https://www.nasa.gov/centers/armstrong/news/FactSheets/FS-110-AFRC.html
5. Schlieren Images Reveal Supersonic Shock Waves: https://www.nasa.gov/centers/armstrong/features/supersonic-shockwave-interaction.html
6. NASA's Commercial Supersonic Technology (CST) Project: https://www.nasa.gov/aeroresearch/programs/aavp/cst
7. NASA's Revolutionary Vertical Lift Technology (RVLT) Project: https://www.nasa.gov/aeroresearch/programs/aavp/rvlt
8. NASA's Aerosciences Evaluation and Test Capabilities (AETC) Portfolio Office: https://www.nasa.gov/aetc

Scope Title: Small UAV Compatible Sensor Development and Payload Integration for Aeronautics Applications

Scope Description:

This scope seeks proposals that leverage the current state-of-the-art in UAV technologies to further develop and/or adapt and test new sensor suites and associated interface architectures that will lead to the emergence of advanced data gathering sensor platforms for supporting NASA ARMD missions and beyond. Proposals should clearly describe how the development of its technologies and products will benefit domestic UAV market for public as well private enterprises and serve the national security and community needs. Of specific interest are proposals that plan to develop valuable terrestrial applications which could lead to the establishment of commercial markets and provide a path for future NASA missions. The range of topics of interest are as follows. Proposals that advance UAV based navigation in urban and extreme environmental settings, aid in future vertiport management, assess environmental safety including hazardous weather conditions due to wind, snow, wildfire etc., support weather tolerant operations and provide tools for sense and avoid operations. Also sought are proposals that demonstrate novel sensor architectures with limited range but increased precision or resolution in performance for applications involving altimeters, ranging, terrain slope, rock/debris locations, thermal locations, landing beacon navigation, landers for extreme environments.

The UAV can be the sensor platform, serving as the landing vehicle simulator or terrain following vehicle or can carry and release at altitude a landing vehicle which then flies a landing sequence. The proposals can demonstrate sensors and algorithms for terrain relative guidance with extended applications in lunar and planetary surfaces. Sensors of interest include obstruction (i.e., mountains, hills, walls, inclines) ranging, precise altitude (within 0.5 m) without GPS, terrain slope (positive or negative). Also, the proposals could promote the next generation of instrument systems and avionics tools to support high priority applications such as navigation through indoor surveillance, search and rescue, disaster zones etc. Technologies incorporating instrument suites such as visual inertial odometry (VIO) for navigation through dynamic GPS to complex GPS denied environments are encouraged. Tools enabling advanced capabilities for emergency response operations such as airspace management are desired with the goal of resolving conflicts through situational awareness-based communication and information sharing schemes. Also, UAV platform infrastructure that incorporates commercial visible and infrared multispectral stereo imaging for monitoring airborne hazards will enable reconstructing 3D distribution of plumes associated with wildfire, volcanic eruptions, and various other disaster environments to support efficient and expedited decision-making processes. Airborne position, navigation, and timing solutions to increase the precision, reliability, and accuracy of localization for a GPS-denied geographic region to support disaster response operations are desired. Onboard software subsystems for inflight detection and characterization of signatures of interest, relaying data to investigators, and ability for re-targeting of operations are highly encouraged. Also of interest are proposals that will collect and disseminate data and images from forward disaster zones using novel RF techniques for real time visualization and evaluation and assist in effective logistics management. Solutions must have well-defined and transparent data-processing algorithms and workflows and should provide data products that conforms to international data and metadata standards and formats to enable them to plug-and-play with various system configurations.

Finally, development of UAVs with low size, less weight, low power consumption and cost (SWAP-C) including concepts utilizing autopilot with multiple integrated components are highly encouraged. Examples include low-SWaP-C communication payload equipment for high altitude longer endurance aircraft (e.g., high-altitude pseudo-satellite/HAPS) that supports high bandwidth direct-to-device communication (e.g., 5G/6G) to establish communication networks in non-connected environments for disaster response (e.g., wildland fire) and the need for improved detect and avoid systems. Addressing challenges regarding low SWAP-C computing to process imagery/video/radar/lidar for GN&C inputs to ensure high-quality, low latency products is highly encouraged.

Expected TRL or TRL Range at completion of the Project: 2 to 4

Primary Technology Taxonomy:

- Level 1: TX 08 Sensors and Instruments
- Level 2: TX 08.1 Remote Sensing Instruments/Sensors

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

The Phase 1 will result in an architecture design and CONOPS describing UAV compatible sensor module and integrated operational interfaces for data collection and dissemination suitable for fieldable prototype implementation in the Phase 2 effort and beyond. The technology business case and perceived market impact is also required. Desired deliverables at the end of Phase II are a final report discussing design details, concept of operations, integration and test results of prototype unit integrated on a suitable UAV platform and updated commercialization plan.

State of the Art and Critical Gaps:

The United States is steadily losing the small UAV market to foreign competition regarding sensing, imaging and surveillance applications. The proposed SBIR opportunity is intended for recapturing the UAV related market by developing advanced and versatile UAV platform sensor infrastructure and interface technologies through stimulating innovation in transformation, adaptability, ruggedization, safety, accessibility, and cost advantages. The overall goal of this subtopic is to advance strategic vison and research objectives of NASA's ARMD missions and beyond.

Relevance / Science Traceability:

The proposed project aligns with AAM, UAM, SWS, ACERO, CAS and various other ARMD project goals for building suitable low SWAP-C UAV infrastructures as well as advancing ARMD mission goals for disaster management and response framework including events such as wildfires, hurricanes. tornadoes, and volcanic eruptions.

NASA's AAM mission goal: "NASA's vision for Advanced Air Mobility (AAM) Mission is to help emerging aviation markets to safely develop an air transportation system that moves people and cargo between places previously not served or underserved by aviation – local, regional, intraregional, urban – using revolutionary new aircraft that are only just now becoming possible. AAM includes NASA's work on Urban Air Mobility and will provide substantial benefit to U.S. industry and the public.

NASA's UAM (Urban Air Mobility) vision: "NASA is leading the nation to quickly open a new era in air travel called Urban Air Mobility, or UAM. Our vision of UAM is that of a safe and efficient air transportation system where everything from small package delivery drones to passenger-carrying air taxis is operating above populated areas".

NASA ACERO Vision: "ACERO is collaborating with other government agencies, the science community, and commercial industries to develop a concept of operations for the future of wildland fire management". "ACERO builds on previous NASA Aeronautics research including Scalable Traffic Management for Emergency Response Operations project and the Unmanned Aircraft System Traffic Management project."

NASA System-Wide Safety (SWS): "SWS has two primary goals:

- Explore, discover, and understand how safety could be affected by the growing complexity of advanced aviation systems.
- Develop and demonstrate the research tools, innovative technologies and operational methods that will proactively mitigate potential risks to maintain the aviation industry's unparalleled safety record.

References:

1. https://www.nasa.gov/aam
2. Building the Infrastructure for Advanced Air Mobility | NASA
3. Capabilities and Facilities | NASA
4. Bander Alzahrani, et. al., "UAV assistance paradigm: State-of-the-art in applications and challenges," Journal of Network and Computer Applications, Vol. 166, 15 September 2020.
5. Advanced Capabilities for Emergency Response Operations | NASA
6. Airspace Operations and Safety Program | NASA

A2.02: Enabling Aircraft Autonomy (SBIR)

Related Subtopic Pointers: A3.02, T15.04
Lead Center: AFRC
Participating Center(s): ARC, GRC, LaRC

Subtopic Introduction:

The increased use of automation on aircraft offers significant advantages over traditional manned aircraft for applications that are dangerous to humans, long in duration, and/or require a fast response and high degree of precision. Some examples include remote sensing, wildfire and disaster response, delivery of goods, industrial inspection, and agricultural support. Advanced autonomous functions in aircraft can enable greater capabilities and promise 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 air vehicles. These barriers include, but are not limited to, the lack of methods, architectures, and tools that enable:

- Cognition and multi-objective decision-making.
- Cost-effective, resilient, and self-organizing communications.
- Prognostics, survivability, and fault tolerance.
- Verification and validation technology and certification approaches.

Other barriers affect the ability to rapidly research, test and iterate on the autonomy tools that would address the above. These barriers range from hardware barriers such as the need for NDAA (National Defense Authorization Act) compliant computers to software barriers such as the need for flight control architectures that can adapt to multiple aircraft configurations.

NASA and the aviation industry are involved in research that would greatly benefit from breakthroughs in autonomous capabilities that could eventually enable the Advanced Air Mobility (AAM) Mission. Consider these three examples:

1. Remote missions utilizing one or more unmanned aircraft systems (UAS) have a need for autonomous planning algorithms that can coordinate and execute a mission with minimal human oversight.
2. Efforts to enable AAM and to integrate UAS into the National Airspace System (NAS) have a need for detect-and-avoid algorithms, sensor fusion techniques, robust trajectory planners, and contingency management systems.
3. Autonomous contingency management systems have a need for fault detection, diagnostics, and prognostics capabilities.

This subtopic is intended to address these needs with innovative and high-risk research, enabling greater use of autonomy in NASA research, civil aviation, and ultimately the emerging AAM market.

The scopes in this subtopic will target applications of autonomy in air vehicles that will address one or more of the barriers described above.

Scope Title: Autonomy for Rapid Research

Scope Description:

NASA's Convergent Aeronautics Solutions (CAS) Streamlined Workflow for Innovative Flight Test (SWIFT) project is looking for autonomy technologies to aid in its research goals. SWIFT aims to develop a modular and scalable flight research architecture and views autonomy as an important part of this effort. The technologies developed for this scope would help facilitate autonomy research for NASA's Aeronautics Research Mission Directorate (ARMD).

The following technologies are of interest to the CAS SWIFT project. Any submission to this scope must address one of these areas.

- Machine Learning (ML) based approaches for flight controls
- NDAA (National Defense Authorization Act) compliant flight computers configurable for various autonomy algorithms and technologies.

SWIFT is looking for tools that would aid in the rapid design and testing of flight platforms with varying levels of autonomy. An ML based approach would be valuable in attaining this goal. These ML approaches should be able to provide stable control laws for various aircraft configurations without making changes to the overall control architecture. For example, a small UAS could be reconfigured with different pods and stores. An ML based flight controller would be able to tune gains inflight to ensure stable flight. Other use cases for ML that would aid aerospace autonomy systems are also of interest. These include machine learning-based prognostics or computer vision systems that could be used in a variety of autonomy-enabled aircraft.

SWIFT is also looking for NDAA compliant flight computers that can be used as research flight computers. These computers should be able to work with current workflows, such as being able to run Simulink auto-code. The desire is for an NDAA compliant flight computer that can be interfaced with the main flight computer, and also any additional research hardware or software. Specifically, SWIFT is looking for NDAA compliant computers that can handle cutting edge technology, such as computer vision and neural networks, that require hardware acceleration like Field Programmable Gate Arrays (FPGAs). For example, the flight computer could contain a FPGA that can be used to offload computationally intensive tasks such as machine learning or be reconfigured to use with a computer vision system.

Delivery of prototypes is expected by the end of Phase II. Prototype deliverables such as toolboxes, integrated hardware prototypes, training databases, or development/testing environments would allow for better possible infusion of the proposed technology into current and future NASA programs and projects.

It is important to note that any proposals for UAS aircraft development will not be considered.

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:

- Level 1: TX 10 Autonomous Systems
- Level 2: TX 10.X Other Autonomous Systems

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis

- Prototype
- Hardware
- Software

Desired Deliverables Description:

Phase I deliverables should include, but are not limited to:

• A written plan to continue the technology development and/or to infuse the technology (i.e., sensors and algorithms). This may be included in the final report.

• 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, and a plan to overcome the remaining barriers.

• A technology demonstration in a simulation environment that clearly shows the benefits of the technology developed.

Phase II deliverables should include, but are not limited to:

• A usable/workable prototype of the technology (or software program), such as toolboxes, integrated hardware prototypes, training databases, or development/testing environments.

• A technology demonstration in a relevant flight environment that clearly shows the benefits of the technology developed.

• 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, and a plan to overcome the remaining barriers.

• There should be evidence of infusing the technology or a clear written plan for near-term infusion of the technology. This may be part of the final report.

State of the Art and Critical Gaps:

Relevant to this subtopic and scope, there are current technology gaps in the tools needed for rapid research and development of autonomous systems. The scope addresses the need for adaptable flight controls that would allow new configurations of flight platforms to get to flight and the need for NDAA research flight computers that are modular and can be configured for various configurations of autonomous systems.

Relevance / Science Traceability:

This subtopic is particularly relevant to the NASA Aeronautics Research Mission Directorate (ARMD) Strategic Thrust 6 (Assured Autonomy for Aviation Transformation)

- Transformative Aeronautics Concepts Program (TACP): https://www.nasa.gov/aeroresearch/programs/tacp
- Airspace Operations and Safety Program (AOSP): https://www.nasa.gov/aeroresearch/programs/aosp
- Integrated Aviation Systems Program (IASP)**:** https://www.nasa.gov/aeroresearch/programs/iasp

References:

1. Convergent Aeronautics Solutions Project https://www.nasa.gov/directorates/armd/tacp/cas/
2. Strategic Implementation Plan for NASA's ARMD: https://www.nasa.gov/directorates/armd/armd-strategic-implementation-plan/
3. Autonomous Systems: NASA Capability Overview (2018 presentation by Terry Fong, Senior Scientist): https://www.nasa.gov/sites/default/files/atoms/files/nac_tie_aug2018_tfong_tagged.pdf
4. UAS Integration in the NAS Project (concluded Sept 2020): https://www.nasa.gov/directorates/armd/past-armd-projects/uas-in-the-nas/#:~:text=The%20Unmanned%20Aircraft%20Systems%20(UAS,tests%20in%20a%20relevant%20environment.
5. NASA Explores "Smart" Data for Autonomous World: https://www.nasa.gov/aeroresearch/nasa-explores-smart-data-for-autonomous-world
6. Autonomous Systems Research at NASA's Armstrong Flight Research Center: https://www.nasa.gov/feature/autonomous-systems

A2.04: Aviation Cybersecurity (SBIR)

Lead Center: GRC
Participating Center(s): AFRC, ARC, LaRC

Subtopic Introduction:

The Federal Aviation Administration (FAA) has determined that its airworthiness regulations are inadequate and inappropriate to address the cybersecurity vulnerabilities caused by increased equipment, systems, and network information interconnectivity.

Airplane equipment, systems, and their networks are at risk and require information security protection. Considered separately and in relation to one another, these varied systems must be protected from intentional unauthorized electronic interactions that may result in adverse effects on the safety of the airplane and the airspace. FAA expects mitigation would occur through applicant's installation of single or multilayered protection mechanisms or process controls to maintain and ensure functional integrity. The FAA has proposed Advisory Circular (AC) 20-XXX, "Aircraft Systems Information Security/Protection (ASISP)." This AC would provide guidance on acceptable means, but not the only means, of assuring compliance to airworthiness regulations.

The focus of this subtopic is on onboard-multicast-network systems monitoring, in-time anomaly detection, local reporting of real-time operations, remote reporting to operations centers, and quick response mitigation to protect fleet safety. New flight systems are increasingly incorporating more commercial standards, such as ethernet style systems, wireless LANs, ARINC629, ARINC664, CANbus, internet protocols, etc. Aircraft, drones, and advanced air mobility vehicles will essentially become onboard data processing systems directly connected to the world.

Modern flight systems are difficult to monitor due to their complexity, multiple vendors, and intricate architectures. However, this challenge is disappearing with the use of high-performance computing power and standardized protocols. The retrofitting of current systems is complicated and impractical. As a result, unprotected network busses and Operational Technology (OT) systems will continue. New technologies are needed for run time assurance, attestation of software loads, and detection of cybersecurity attacks and unintended performance changes within a system. New technologies are also needed for in-time reporting and secure logging of events to an operations center for near real-time analysis.

Scope Title: On-Board-Multicast-Network Systems Monitoring and Anomaly Detection with Reporting

Scope Description:

This scope seeks technologies for on-board-multicast-network systems monitoring and anomaly detection, with reporting locally to support real-time operations and remotely to operations centers for fleet protection and prediction. Examples of systems monitored include: ethernet style systems, wireless LANs, ARINC629, ARINC 664, CANbus, and Internet Protocols. Aircraft have become increasingly like on board data systems and need to be protected as such. Desired solutions include:

- Technologies for monitoring, in-time detecting, and in-time reporting cybersecurity safety risks for assessment, via a formal reporting system, to an in-time cybersecurity vulnerability mitigation system.
- Aircraft Systems Information Security/Protection (ASISP) to detect and identify anomalies, safety risk precursors, and safety margins.
- In-time reporting to a centralized formal cybersecurity system for immediate remediation to restore sufficient network or application services to support mission essential functions.

Expected TRL or TRL Range at completion of the Project: 4 to 5

Primary Technology Taxonomy:

- Level 1: TX 10 Autonomous Systems
- Level 2: TX 10.4 Engineering and Integrity

Desired Deliverables of Phase I and Phase II:

- Prototype
- Software
- Hardware

Desired Deliverables Description:

A system that can detect cyber events and provide information to the safety and security infrastructure is desired.

Phase I: An architecture, prototype passive detection system that includes logging and draft cybersecurity messaging for reporting.

Phase II: Refined prototype passive detection system that includes logging, validation of performance, and refined formal short message format for standardization.

State of the Art and Critical Gaps:

Current work focuses on monitoring serial data busses and data bus traffic anomalies. Current approaches are reactive, and inadequate to protect the more connected systems of the future, thus impacting the potential safety of these operations. It is necessary to apply the resources and capabilities of the Operational Technology (OT) and Information Technology (IT) world to secure new flight systems. To ensure future aviation systems are safe from cybersecurity attacks, anomalies must be detected and mitigated in near real time. This will allow insight for operators to view attacks as they work through systems and provide the ability to interrupt and mitigate attacks.

Relevance / Science Traceability:

To support ARMD's In-Time System-Wide Safety Assurance (ISSA) strategic thrust, monitoring and prediction systems can operate at different levels—individually, in combination, or system wide—and any of these configurations may perform one or more of these functions:

- Monitor: detect anomalies or deviations from normal operations.
- Localize: validate software and determine attack target.
- Predict: provide analysis to forecast the probability of events.
- Report: onboard and off board, and logging.
- Correct: where possible, mitigate incidents without loss of operational capabilities, and prioritize corrective actions for onboard operators/systems.

Given the developing Advanced Air Mobility (AAM) and traditional aviation systems, a number of possible analytical approaches may be possible, either individually or in combinations. These include:

- Digital Twin: analytical combinations on board and off board models digitally signed.
- Attestation: provable by observation methodologies.
- Traffic monitoring: monitoring of aviation bus data, network data or other data flows.
- Multidisciplinary design analysis optimization.
- Artificial Intelligence and Machine Learning: adapting defenses as engagement changes and reporting to fleet management.

References:

1. Equipment, Systems, and Network Information Security Protection, Federal Register, August 21, 2024. https://public-inspection.federalregister.gov/2024-17916.pdf
2. Aviation Cyber Security: https://www.iata.org/en/programs/security/cyber-security/
3. Aviation Cybersecurity: https://www.icao.int/aviationcybersecurity/Pages/default.aspx
4. Cybersecurity Overview: https://www.easa.europa.eu/en/domains/cyber-security/overview
5. An Autonomous Intrusion Detection System for Ethernet-Based Avionics Communication Bus. Proceedings of the 7th International Conference on Engineering and Emerging Technologies (ICEET), October 2021. https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=9659587

Scope Title: Methods to Monitor-Assess-Mitigate Cybersecurity Vulnerabilities in Near Real Time

Scope Description:

In alignment with ARMD's Strategic Thrust 5, In-Time System-Wide Safety Assurance (ISSA), the Airspace Operations and Safety Program's (AOSP) System Wide Safety (SWS) Project is developing an In-Time Aviation Safety Management System (IASMS), a scalable and distributed system approach to address aviation safety needs. IASMS services, functions, and capabilities (SFCs) are structured to monitor-assess-mitigate operational safety risks. SFCs are envisioned to include increasingly automated and autonomous functionality to adapt and scale to the increasing complexity of aviation operations, necessitating new approaches to assure autonomous functionality. Due to the digital transformation of the airspace system and nature of the IASMS, an area of high interest is developing methods for monitoring, detecting, assessing, and mitigating cybersecurity vulnerabilities and attacks in near real time. Innovative approaches and methods are sought that monitor-assess-mitigate cybersecurity vulnerabilities in near real time. Proposals that lack a technology/function that can be integrated into the concept of IASMS will be rejected.

Proposals are sought for technologies that can be integrated into IASMS to effectively monitor, detect, assess, and mitigate potential cybersecurity or cyber-physical attacks that could adversely affect the performance of aviation operational systems:

1. Cost-effective cybersecurity safety-data-messaging architecture, data exchange methodology, and data collection mechanisms for aviation.
2. Simulation capabilities to mitigate fleet-wide cyber-attacks, investigate cybersecurity safety risks to the aviation system, and recommend cybersecurity safety margins and airspace attacks.

Expected TRL or TRL Range at completion of the Project: 2 to 4

Primary Technology Taxonomy:

- Level 1: TX 16 Air Traffic Management and Range Tracking Systems
- Level 2: TX 16.1 Safe All Vehicle Access

Desired Deliverables of Phase I and Phase II:

- Analysis
- Prototype
- Software

Desired Deliverables Description:

Desired deliverables include cybersecurity vulnerability detection technologies that can advance the goals of safe air transportation operations and be incorporated into existing and future NASA concepts. In particular, new technologies are sought that address AOSP SWS project efforts to develop an IASMS.

- Desired deliverables for Phase I include multiple concepts/approaches, tradeoffs analyses, and proof-of-concept demonstrations.
- Desired deliverables for Phase II include functional prototypes, integration of prototypes into existing and future NASA concepts, and demonstration of prototypes in a realistic environment.

Capabilities include:

- Cost-effective cybersecurity safety-data-messaging architecture, data exchange methodology, and data collection mechanisms for aviation.
- Simulation capabilities to mitigate fleet-wide cyber-attacks; investigate cybersecurity safety risks to the aviation system; and recommend cybersecurity safety margins and airspace attacks.

State of the Art and Critical Gaps:

The NAS is critical infrastructure, with billions of dollars of commerce, national defense, and emergency response operations daily. The Cybersecurity and Infrastructure Security Agency (CISA) and Community Emergency Response Team (CERT) perform functions for the internet. The FAA, the Aviation Cyber Initiative, airlines, and others are starting to coordinate cybersecurity for aviation; however, none are focused on creating a comprehensive cybersecurity response system for the NAS. With no coordinated or dedicated reporting system, the NAS must detect, report and repair cyber events.

Relevance / Science Traceability:

Aviation safety: As the NAS becomes more complex with newer and more connected systems, in-time safety management needs tools and capabilities to protect against intentional acts that are being delivered to the NAS by a computer.

References:

1. Equipment, Systems, and Network Information Security Protection: https://public-inspection.federalregister.gov/2024-17916.pdf
2. Aviation Cybersecurity: https://www.iata.org/en/programs/security/cyber-security/
3. Aviation Cybersecurity: https://www.icao.int/aviationcybersecurity/Pages/default.aspx
4. Cybersecurity Overview: https://www.easa.europa.eu/en/domains/cyber-security/overview
5. An Autonomous Intrusion Detection System for Ethernet-Based Avionics Communication Bus: https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=9659587

A3.02: Advanced Air Traffic Management for Nontraditional Airspace Missions (SBIR)

Related Subtopic Pointers: A2.02, A3.05
Lead Center: ARC
Participating Center(s): LaRC

Subtopic Introduction:

NASA's ARMD has made significant contributions to enable widespread use of small, unmanned aircraft systems (sUAS) by developing air traffic management capabilities for low-altitude unmanned vehicle operations, referred to as "UAS Traffic Management" (UTM). This work is being adapted to safely and efficiently integrate larger Advanced Air Mobility (AAM) vehicles and operations with existing operations and mission types. NASA is exploring airspace operations that will support "nontraditional" aviation missions, specifically (1) AAM applications for commerce and mobility and (2) wildfire response applications for public safety and environmental stewardship. NASA's research to enable such missions to be safely and fully integrated into the airspace leverages capabilities of a service-based architecture inspired by that developed for UTM. This has led to new procedures, equipage, operating requirements, and policy recommendations to enable widespread, harmonized, and equitable execution of diverse missions. These missions range from urban air taxi to local cargo delivery and public-good missions, such as emergency response operations. Innovation is needed to spur the development of effective new air traffic management concepts, tools, and technologies that will support the advent and scalability of AAM and wildfire response operations. Although NASA also sponsors research pertaining to traditional, longer-haul air transportation missions involving the movement of people and goods over hundreds or thousands of miles, the current subtopic's application to nontraditional airspace missions is highly relevant to NASA's aeronautics research mission, its nontraditional stakeholders (e.g., third-party service suppliers, public safety and government entities, nontraditional operators, etc.) and the public at large.

Scope Title: Nontraditional Aviation Operations for Advanced Air Mobility (AAM)

Scope Description:

This scope is focused on AAM airspace operations only and is not accepting proposals specific to other nontraditional aviation missions. In addition, proposals that focus only on cyber-resiliency solutions without proposing specific AAM services will be rejected.

This subtopic seeks proposals with application to AAM including:

- Service-based architecture designs that enable greater scalability of AAM operations.
- Tools and methods to bridge the gap between current-day operations and future AAM operations by facilitating teaming and collaboration between human operators and the autonomous agents/technologies needed for AAM operations to scale (i.e., human-autonomy teaming). Objectives include:
    - Improve the effectiveness or efficiency with which human operators work with increasingly autonomous airspace systems.
    - Leverage the benefits of human operator expertise and participation in the airspace system.
    - Address challenges associated with integrating new technologies in the airspace environment that involve human participation/decision making.
- Dynamic route planning that considers changing environmental conditions, vehicle performance and endurance, and 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 AAM operations with legacy operations in low-altitude airspace and around major airports.
- Operational concepts for fleet and network management, market need, and growth potential for future operations, and airspace integration.
- Identification of potential certification approaches for new vehicle operations (such as electric vertical takeoff and landing).

Future service-based architectures also require resiliency to cyberattacks to ensure safe and robust operations that maintain expected levels of safety and security. Therefore, proposals should incorporate cyber-resiliency methods, tools, or capabilities, or address cyber-resiliency as part of the proposed effort. However, proposals focused exclusively on cybersecurity will be rejected.

Expected TRL or TRL Range at completion of the Project: 1 to 4

Primary Technology Taxonomy:

- Level 1: TX 16 Air Traffic Management and Range Tracking Systems
- Level 2: TX 16.3 Traffic Management Concepts

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Software

Desired Deliverables Description:

NASA's intent is to select proposals that have the potential to move a critical technology or concept beyond Phase II SBIR funding and transition it to Phase III, where a NASA aeronautics program, another government agency, or a commercial entity in the aeronautics sector can fund further maturation as needed, leading to actual usage in future airspace operations.

The Phase I outcome should establish the scientific, technical, and commercial feasibility of the proposed innovation in fulfillment of NASA objectives and broader aviation community needs. Phase I should demonstrate advancement of a specific technology or technique, supported by analytical and/or experimental studies that are documented in a final report.

Phase II efforts should yield:

1. Models supported with experimental data,
2. Software related to a model that was developed,
3. A material system or prototype tool, or
4. Modeling tools for incorporation in software, etc. that can be infused into a NASA project or that lead to commercialization of the technology.

Consequently, Phase II efforts are strengthened when they include a partnership with a potential end-user of the technology.

Phase I award recipients must be thinking about commercialization and which organizations will be able to use the technology following a Phase II effort. It is necessary to take that into account, rather than just focusing on developing technology without putting a strong effort into developing a commercial partner or setting the effort up for continued funding by teaming with an organization post-Phase II.

State of the Art and Critical Gaps:

Current state of the art: NASA has been researching advanced air transportation concepts and technologies to improve the viability and scalability of AAM operations in the National Airspace System (NAS).

Critical gaps: Significant challenges remain to fully develop the AAM airspace concept of operations, including:

- Integrating air transportation technologies across different domains and operators.
- Facilitating productive human-autonomy teaming.
- Providing comprehensive, strategic scheduling and traffic management technologies.
- Enabling concepts that will allow for scaling demand and complexity of operations.

This subtopic is focused on airspace operations for the AAM concept only. Proposals must have clear application to AAM airspace operations. Proposals that focus on AAM vehicle capabilities or onboard vehicle technologies or systems will be rejected. Proposals that are specific to other nontraditional aviation missions (e.g., space traffic management, autonomous operation of conventional aircraft, traffic management for small UAS [e.g., UTM], and ultra–high altitude operations) without clear application to AAM will be rejected.

Relevance / Science Traceability:

- Airspace Operations and Safety Program (AOSP)
- Air Mobility Pathfinders (AMP) Project
- Air Traffic Management-eXploration (ATM-X) Project
- Successful technologies in this subtopic will help NASA pioneer AAM concepts and technologies and scale them up to meet the needs of everyday travelers. The technologies may also leverage new autonomy/artificial intelligence/data science methods and approaches.

References:

1. Airspace Operations and Safety Program (AOSP): https://www.nasa.gov/aeroresearch/programs/aosp

2. NASA Aeronautics Research Mission Directorate (ARMD) Strategic Implementation Plan: https://www.nasa.gov/directorates/armd/armd-strategic-implementation-plan/

Scope Title: Nontraditional Aviation Operations for Wildfire Response

Scope Description:

In the United States, wildfires are becoming increasingly severe and costly in terms of acreage burned, property damaged, and most importantly, lives lost. Wildfire frequency and intensity is escalating, inducing budgetary, personnel, and equipment challenges. Furthermore, California and other western states have been facing persistent drought conditions and much hotter temperatures, which are fueling wildfire intensity and duration. These alarming trends have made it urgent to better predict, mitigate, and manage wildland fires.

NASA's history of contributions to wildfire and other disaster management efforts includes remote sensing, instrumentation, mapping, data fusion, and prediction. More recently, NASA ARMD has been investigating capabilities to help manage wildfire suppression and mitigation efforts through technologies for coordination of airspace operations for wildfire management.

NASA ARMD has recently made a significant contribution to enable widespread use of small, unmanned aircraft systems (sUAS) by developing air traffic management capabilities for low-altitude unmanned vehicle operations, called UAS Traffic Management (UTM). This work is being adapted to safely and efficiently integrate larger vehicles and operations with existing operations and mission types. NASA recognizes the value these capabilities could provide when applied to the aerial wildfire management domain.

Current applications of aviation to wildfire management include deployment of smoke jumpers to a fire; transport of firefighters, equipment, and supplies; fire retardant or water drop; reconnaissance of fire locations and fire behavior; and supervision of air tactical operations.

Current challenges of aerial wildfire management include the following:

- Existing airspace management techniques are manual and cannot accommodate new aircraft types suitable for wildfire response operations (e.g., unmanned aircraft).
- Aerial firefighting is limited to acceptable visual conditions (no night operations).
- Monitoring and remote-sensing missions are intermittent, flown outside of active firefighting or available periodically from satellite assets.
- There is a lack of reliable, resilient, and secure data communications for quick information dissemination to support effective decision making.

NASA is seeking technologies to:

- Provide strategic planning capabilities to collect, process, and disseminate information that enables persistent monitoring of wildland fire conditions (e.g., satellites, conventional aircraft, and UAS).
- Provide strategic planning and tracking capabilities to enable the most effective use of ground crews, ground equipment, and aircraft during operations (e.g., both at a single incident and across multiple incidents).
- Provide strategic planning capabilities that support multi-mission planning to support efficient mission assignments to support concurrent operations (e.g., air attack and search and rescue).
- Provide an extension to the UTM network that considers the unique needs and characteristics of wildfire disaster situations (e.g., non-connected environments) and the response to combat them.
- Increase the throughput of available communications, reduce the latency of data transfer, provide interoperability with existing communication solutions, and provide a reliable network for the use of UAS, other aviation assets, and emergency responders on the ground.

- Provide a mobile position, navigation, and timing solution to support automated operations (e.g., automated precision water drops) in Global Positioning System (GPS) degraded environments (e.g., mountainous canyons).
- Provide wildland fire prediction, airspace coordination, and resource tracking for a common operating picture for situational awareness that supports various stakeholders in the incident command structure (e.g., incident commander, air tactical group supervisor, aircraft dispatch, UAS pilot, etc.).
- Ensure the highest safety and efficiency of operations.

Proposers wanting to focus on services or technologies to coordinate airborne operations across a wildfire area should submit their proposal to the current subtopic scope.

Proposals focused on the following will be rejected for this subtopic:

- Technologies that help autonomous or piloted flight in areas with degraded visibility.
- Technologies that enable single-pilot multi-ship operations.
- Technologies that support unmanned logistic operations such as moving supplies to a different area.
- Technologies that support wildfire suppression and management missions.

Expected TRL or TRL Range at completion of the Project: 1 to 5

Primary Technology Taxonomy:

- Level 1: TX 16 Air Traffic Management and Range Tracking Systems
- Level 2: TX 16.3 Traffic Management Concepts

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Software

Desired Deliverables Description:

NASA's intent is to select proposals that have the potential to move a critical technology or concept beyond Phase II SBIR funding and transition it to Phase III, where a NASA aeronautics program, another government agency, or a commercial entity in the aeronautics sector can fund further maturation as needed, leading to actual usage in future airspace operations.

The Phase I outcome should establish the scientific, technical, and commercial feasibility of the proposed innovation in fulfillment of NASA objectives and broader aviation community needs. Phase I should demonstrate advancement of a specific technology or technique, supported by analytical and/or experimental studies that are documented in a final report.

Phase II efforts should yield:

1. Models supported with experimental data,
2. Software related to a model that was developed,
3. A material system or prototype tool, or
4. Modeling tools for incorporation in software, etc. that can be infused into a NASA project or that lead to commercialization of the technology.

Consequently, Phase II efforts are strengthened when they include a partnership with a potential end-user of the technology.

Phase I award recipients must be thinking about commercialization and which organizations will be able to use the technology following a Phase II effort. It is necessary to take that into account, rather than just focusing on developing technology without putting a strong effort into developing a commercial partner or setting the effort up for continued funding by teaming with an organization post-Phase II.

State of the Art and Critical Gaps:

The current state of the art for coordination of aerial firefighting is a manual process that must be coordinated across multiple entities, often bringing multiple aerial assets to the wildfire fighting environment. Advanced tools and techniques are required to address the following gaps:

- Existing airspace management process is very manual and slow.
- Awareness of aircraft operations is conducted by visual monitoring and radio communication.
- Unmanned systems are not easily integrated into aerial fire suppression operations.
- Operations are limited by visibility and no operations are conducted at night, when fires often die back.
- Surveillance images are captured and disseminated only every 4 hours.
- Intermittent communication can delay effective response.
- Conditions can rapidly change, requiring timely information for effective decision making.
- Decision makers for emergency response are overloaded with data.
- Information requirements differ for various roles within the disaster response.
- Tools and data are often spread across numerous applications.

Relevance / Science Traceability:

Due to climate change, wildfires are becoming increasingly more frequent and severe. Fire seasons are longer, lasting 6 to 8 months; in some cases, fire season is year-round. The 2020 fire season was the worst in recorded history, burning over 4 million acres of land, destroying more than 8,500 structures, and killing more than 30 people. The economic impact of these fires is in the hundreds of billions of dollars and results in lasting societal impact. The annual cost of fire suppression has soared from roughly $425 million per year in 1999 to $1.6 billion in 2019.

On June 30, 2021, President Biden and Vice President Harris met with governors from western states, Cabinet officials, and private-sector partners to discuss specific actions the public and private sectors are each taking to strengthen prevention, preparedness, mitigation, and response efforts to protect communities across our country from wildfires and their devastating impacts. The President directed several actions, in close coordination with state and local governments and the private sector, to ensure the federal government can most effectively protect public safety and deliver assistance to our people in times of urgent need.

References:

1. Airspace Operations and Safety Program (AOSP): https://www.nasa.gov/aeroresearch/programs/aosp
2. NASA Aeronautics Research Mission Directorate (ARMD) Strategic Implementation Plan: https://www.nasa.gov/directorates/armd/armd-strategic-implementation-plan/

A3.03: Future Aviation Systems Safety (SBIR)

Lead Center: ARC
Participating Center(s): LaRC

Subtopic Introduction:

The Airspace Operations and Safety Program's (AOSP) System Wide Safety Project is developing an In-Time Aviation Safety Management System (IASMS), a scalable and distributed system approach to address aviation safety needs. IASMS services, functions, and capabilities (SFCs) are structured to "Monitor-Assess-Mitigate" operational safety risks. SFCs are envisioned to include increasingly automated and autonomous functionality to adapt and scale to increasing complexity of aviation operations, requiring new approaches to assure autonomous functionality. Proposals focused on monitoring, assessing, and mitigating operational safety risks, and those focused on assurance of autonomy for operational systems will be considered for award.

Proposals are sought whose technologies can be integrated into IASMS, such as those listed below; proposals that cannot be integrated into IASMS will be rejected.

IASMS Services, Functions and Capabilities:

- Address safety-critical risks identified in beyond-visual-line-of-sight operations in small and large UAS.
- Research and development of In-time System-wide Safety Assurance objectives.
- Supporting safety prognostic decision-support tools, automation, techniques, strategies, and protocols.
- Develop, apply, and assure IASMS SFCs to emergency response missions using aerospace vehicle operations. Operations may include wildfire fighting, hurricane disaster relief and recovery, search and rescue, medical courier, and security operations.

Assurance of Autonomy for Operational Systems:

- Assurance of highly automated and increasingly autonomous systems that support safety-critical functions.

Scope Title: Research and Development of In-Time Aviation Safety Management System (IASMS) Services, Functions, and Capabilities

Scope Description:

Proposals are sought whose technologies can be integrated into IASMS:

- Address safety-critical risks identified in beyond-visual-line-of-sight operations in small and large UAS, such as:
  - Flight outside of approved airspace.
  - Unsafe proximity to people/property.
  - Critical system failure (including loss of command-and-control link, loss or degraded GPS, loss of power, and engine failure).
  - Loss-of-control (i.e., outside envelope or flight control system failure).
- R&D of In-time System-wide Safety Assurance objectives:
  - Detect and identify system-wide safety anomalies (including previously unknown safety issues), precursors, and margins to safety.
  - Develop safety-data-focused architecture, data exchange model, and data collection mechanisms.

    - Enable simulations to investigate flight risks.
- Supporting safety prognostic decision-support tools, automation, techniques, strategies, and protocols:
    - Support real-time safety assurance (including in-time monitoring of safety requirements).
    - Consider operational context as well as operator state, traits, and intent.
    - Integrated prevention, mitigation, and recovery plans with information uncertainty and system dynamics in small and large UAS and trajectory-based operations environment.
    - Enable transition from a dedicated pilot in command or operator for each aircraft (as required per current regulations) to m:N operations.
    - Enable efficient management of multiple unmanned and Advanced Air Mobility (AAM) aircraft in civil operations.
- Develop, apply, and assure IASMS services, functions, and/or capabilities for emergency response missions using aerospace vehicle operations. Operations may include hurricane disaster relief and recovery, search and rescue, medical courier, and security operations.
    - Services, Functions, and Capabilities (SFCs) should address one or more hazards highlighted in previous sections or identified through hazard analysis. Proposers are encouraged to leverage prior NASA work in this area.

Expected TRL or TRL Range at completion of the Project: 1 to 3

Primary Technology Taxonomy:

- Level 1: TX 16 Air Traffic Management and Range Tracking Systems
- Level 2: TX 16.1 Safe All Vehicle Access

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Software

Desired Deliverables Description:

Technologies that can advance the goals of safe air transportation operations that can be incorporated into existing and future NASA concepts. In particular, new technologies are sought that address AOSP SWS Project efforts to develop an IASMS.

- Desired deliverables for Phase I include development of multiple concepts/approaches, tradeoffs analyses, and proof-of-concept demonstrations.
- Desired deliverables for Phase II include development of functional prototypes, integration of prototypes into existing and future NASA concepts, and demonstration of the prototype in a realistic environment.

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. AOSP is addressing this challenge with a major area of focus on In-Time System-Wide Safety Assurance (ISSA)/IASMS.

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 Urban Air Mobility (UAM)/AAM concepts and increasing development of UAS Traffic Management (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 proactively managing safety through continuous monitoring, extracting relevant information from diverse data sources, and identifying anomalous behaviors to help predict hazardous events and evaluate safety risk. This subtopic contributes technologies toward those objectives.

References:

1. AOSP: https://www.nasa.gov/aeroresearch/programs/aosp

Scope Title: Research and Development of Verification and Validation (V&V) Technologies for Assurance of Autonomy for Operational Systems

Scope Description:

New methodologies for verification and validation of IASMS services, functions, and capabilities (SFCs) are needed to ensure safe operations in the National Airspace System (NAS). Proposals are sought whose technologies can be integrated into IASMS:

- Assurance of highly automated and increasingly autonomous systems that support safety-critical functions. Focus includes:
    - Identification and development of new technologies that enable increasingly autonomous air safety services. Technology should be accompanied by examples of services it enables.
    - Overcome limitations of current V&V capabilities with respect to new increasingly autonomous systems (i.e., new testing techniques for deploying ML-enabled systems).
    - Determination of where current certification standards (such as DO-178C) fail to address assurance needs for these technologies or fail to consider V&V results associated with new technologies.
    - Development of use-cases demonstrating novel certification approaches (i.e., overarching properties or safety cases) that enable certification of increasingly autonomous systems.
    - Development of use cases demonstrating assurance of cyber-physical-human systems that accommodate shifting roles and responsibilities between humans and automation.

Expected TRL or TRL Range at completion of the Project: 1 to 3

Primary Technology Taxonomy:

- Level 1: TX 16 Air Traffic Management and Range Tracking Systems
- Level 2: TX 16.1 Safe All Vehicle Access

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Software

Desired Deliverables Description:

Technologies that can advance the goals of safe air transportation operations that can be incorporated into existing and future NASA concepts. In particular, new technologies are sought that address AOSP SWS Project efforts to develop an IASMS.

- Desired deliverables for Phase I include development of multiple concepts/approaches, tradeoffs analyses, and proof-of-concept demonstrations.
- Desired deliverables for Phase II include development of functional prototypes, integration of prototypes into existing and future NASA concepts, and demonstration of the prototype in a realistic environment.

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. AOSP is addressing this challenge with a major area of focus on ISSA/IASMS.

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/AAM 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 proactively managing safety through continuous monitoring, extracting relevant information from diverse data sources, and identifying anomalous behaviors to help predict hazardous events and evaluate safety risk. This subtopic contributes technologies toward those objectives.

References:

1. AOSP: https://www.nasa.gov/aeroresearch/programs/aosp

A3.05: Advanced Air Mobility (AAM) Integration (SBIR)

Related Subtopic Pointers: A3.02, T15.04
Lead Center: HQ
Participating Center(s): LaRC

Subtopic Introduction:

Advanced Air Mobility (AAM) is a concept for safe, sustainable, affordable, and accessible aviation for transformational local and intraregional missions. AAM includes many potential mission types (e.g., passenger transport, aerial work, and cargo transport) that may be accomplished with many different aircraft types (e.g., manned and unmanned, conventional, short, and/or vertical takeoff and landing, all-electric and hybrid-electric, etc.) and is envisioned to bring aviation into people's daily lives. Although passenger-carrying urban air mobility (UAM) is an AAM mission with much investment, other AAM missions, including (but not limited to) thin-haul/regional air mobility (RAM), low-altitude operations (e.g., infrastructure inspection or search missions), and medical transport, are also of interest. Responses to this subtopic are not limited to strictly any single AAM mission but are focused on aspects that would integrate across aspects of the ecosystem and wouldn't be better located in air traffic management or vehicle subtopics.

Scope Title: Scope 1 - Determining Rain Precipitation Rates for Incorporation Into Decision Making

Scope Description:

The goal of this scope is four-fold: 1) to develop methods to efficiently determine the rates of rainfall; 2) provide that information to AAM operators; 3) inform future versions of the American Society for Testing and Materials (ASTM) standard "F3673-23 Performance for Weather Information Reports, Data Interfaces, and Weather Information Providers (WIPS)" around impactful rain precipitation rates and; 4) utilize the data to broaden the weather data available to non-aviation customers and thus increase the market base for hyperlocal and microweather data.

Microweather, or hyperlocal weather, is weather over a small community or geographical area generally considered to be less than a kilometer, or the approximate size of a city block. Being able to determine the actual weather conditions for these areas, nowcasting these conditions and forecasting future conditions is critical for safe AAM operations, passenger comfort, and the economic viability of AAM missions. Some elements of actual and nowcasting/forecasting weather are also of interest to non-aviation customers, such as developing notifications of safety-of-life phenomena e.g., tornados, icing on roads, and potential flooding. To be able to predict where and when flooding will occur is dependent upon local geography, knowing where it is raining and the rain rate. National Weather Service data indicates that on average, 127 people die in the U.S. each year in flash floods (Ref. 1). For AAM, operations could still be possible in a light rain, but greater rain rates could negatively impact the power required to complete a mission and many sUAS are not designed to withstand moisture or water. Various rain intensities could also impact the sensing capabilities of autonomous vehicles including ground vehicles.

Efforts within this scope of this subtopic would include proposals planning to achieve all four scope goals. Efficient systems would provide hyperlocal information and be cost effective while providing the data/information needed by the end user whether that is a sUAS operator, an eVTOL air-taxi operator or city emergency management personnel. Assessing types of sensors and their capabilities would provide a foundation for ASTM standard tier recommendations in future versions of the F3673-23 standard, and support efficient weather system design criteria and designs. Identifying or creating plans to initiate partnerships/consumer relationships across several different types of customers would provide insight into potential customer needs, support weather system design criteria/decisions, and increase the market potential of an eventual product.

Expected TRL or TRL Range at completion of the Project: 4 to 7

Primary Technology Taxonomy:

- Level 1: TX 08 Sensors and Instruments
- Level 2: TX 08.X Other Sensors and Instruments

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Phase I deliverables of this scope would include an assessment of the state-of-the-art of existing and proposed observational data sources, and the current and future challenges that need to be addressed to enable proposed and envisioned future operations. Phase I would also begin to design a potential system architecture that would leverage existing and new data sources, especially citizen scientists, for information to provide rainfall rate observations that can be utilized for AAM operations and to improve public safety. Lastly, Phase I should be used to identify users of the data produced by this architecture, including AAM operators, city emergency operators, and the ASTM standard working group.

Phase II deliverables of this scope would be to refine this system architecture and build an initial instantiation to demonstrate the feasibility and the ability to provide new, relevant and beneficial information, advance the ASTM standard and leverage its commercialization opportunities.

State of the Art and Critical Gaps:

The current state of art to derive rain rates is to utilize rain gauges, optical or impact sensors, and weather radars. Satellite data are less direct and less accurate than either gauges or radar, but have the advantage of complete coverage over oceans, mountainous regions, and sparsely populated areas where other sources of rainfall data are not available. However, satellites do not provide hyperlocal spatial resolutions. The data collected by these systems is limited by the numbers needed for hyperlocal measurements, curvature of the earth, and being able to access the data in real or “in-time.” Lastly, the current ASTM standard does not include tiers or thresholds for measuring rainfall rates.

Relevance / Science Traceability:

This effort has greater applicability to the AAM ecosystem or potentially as a supporting capability to NASA science climate research by providing planetary boundary layer observational data that isn't currently available.

References:

1. https://www.weather.gov/shv/awarenessweek_severe_flashflood#:~:text=The%20national%2030%2Dyear%20average,flood%20fatalities%20are%20vehicle%2Drelated

2. https://www.weatherlink.com/

Scope Title: Scope 2 - Weather Information Systems for Vertiports

Scope Description:

AAM-focused Weather information systems will be critical for resilient and scalable AAM operations. It is also a near term need as multiple AAM operators have announced that they will begin operations in 2025. Weather systems for places where AAM operations will land will be different than current airport/heliport weather information systems due to several factors. These include the AAM aircraft being lighter, potentially being fully automated, having multiple different configurations, operating primarily in the turbulent boundary layer and operating in environments that are more likely to be noise intolerant. The systems will also be different because the 3rd Party Weather Providers (3PWPs) will be qualified instead of the sensors being certified, and operational densities are envisioned to be greater and occur at lower altitudes where the atmosphere is more turbulent and less monitored. There is however, still investment risk in current development of these weather information systems as there are still a number of unknowns. These unknowns include: the qualification process for 3PWP is still being determined, the applicable Advisory Circular(s) and standards are maturing, and the roles and responsibilities across AAM are still being determined. For vertiport weather information systems there are two emerging likely business models each with their own pros and cons. One model could be the vertiport operator engages with a qualified 3PWP to provide services. The other model could be the vertiport operator goes through the qualification process to become a 3PWP and provides weather information. This effort is intended to be applicable to either business model and potential other ones including a regional airport authority engaging the services of a 3PWP or becoming a qualified 3PWP themselves.

Expected TRL or TRL Range at completion of the Project: 2 to 6

Primary Technology Taxonomy:

- Level 1: TX 11 Software, Modeling, Simulation, and Information Processing
- Level 2: TX 11.5 Mission Architecture, Systems Analysis and Concept Development

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Within Phase I the effort for this scope would:

1. Develop requirements for a vertiport/airport AAM weather information system in partnership with several likely stakeholders e.g., air-taxi/eVTOL operator(s), vertiport/heliport operator(s) and/or regional/municipal airport authorities.
2. Architect an AAM weather information system design process that can be utilized to design airport/vertiport/heliport weather information systems tailored to a specific location, likely mission, typical weather that is reliable and cost effective and meets the ASTM standard (ASTM standard F3673-23 Performance for Weather Information Reports, Data Interfaces, and Weather Information Providers (WIPS)).

3. Develop a phased schedule to build the design process.
4. Identify potential partners/locations to build the designed system(s)

Within Phase II, the effort would:

1. Build the architected design process developed in Phase I.
2. Design and cost an AAM weather information system for a vertiport, regional airport, or heliport that meets the requirements determined above ideally with one of the requirement developers or potential partners identified.

State of the Art and Critical Gaps:

Currently, aviation weather information systems are federal government or airport/vertiport operator provided; these systems are certified and expensive and they are located at areas with greater traffic density. Consequently, many regional airports and heliports rely on a windsock and national weather products that have a course resolution covering large geographic areas e.g., NOAA's High-Resolution Rapid Refresh (HRRR) has 3 km resolution. One of the challenges is many AAM operations have not yet commenced. There are only two vertiports in the U.S. built to conform to the now cancelled Advisory Circular for tiltwing operations and ASTM's standard F3673-23 was released in early 2024. So, there aren't actual operations, a mature performance-based standard, or an FAA vertiport advisory circular to support weather information system requirements development. Additionally, the roles for all the stakeholders are still being developed, and the various business models are still very much in flux.

Relevance / Science Traceability:

This effort has greater applicability to the AAM ecosystem or potentially as a supporting capability to NASA science climate research by providing planetary boundary layer observational data that isn't currently available.

References:

1. Advanced Air Mobility Vertiport Considerations: A List and Overview: https://ntrs.nasa.gov/api/citations/20220006982/downloads/Vertiport%20Considerations%20AIAA%20Presentation%20Final%20(submission%20version)%206_13.pdf
2. Vertiport Automation Software Architecture and Requirements: https://ntrs.nasa.gov/api/citations/20210019083/downloads/20210019083_MJohnson_VASArchReq_manuscript_final.pdf

Exploration Systems Development Mission Directorate (ESDMD) and Space Operations Mission Directorate (SOMD)

The Exploration Systems Development Mission Directorate (ESDMD) defines and manages systems development for programs critical to NASA's Artemis program and planning for NASA's Moon to Mars exploration approach. ESDMD manages the human exploration system development for lunar orbital, lunar surface, and Mars exploration. The Space Operations Mission Directorate (SOMD) maintains a continuous human presence in space for the benefit of people on Earth. The programs within the directorate are the heart of NASA's space exploration efforts, enabling Artemis, commercial space, science, and other agency missions through communication, launch services, research capabilities, and crew support.

H3.13: Oxygen Compatible Habitation Solutions for Exploration Environments (SBIR)

Lead Center: MSFC
Participating Center(s): ARC, GRC, JSC, KSC, LaRC

Subtopic Introduction:

Exploration missions requiring high frequency Extravehicular Activity (EVA) benefit from a cabin environment at lower than Earth-ambient pressure. This reduces the time required for the crew to prebreathe to reduce decompression sickness (DCS) risk. However, it also requires the cabin to have increased oxygen concentration to prevent hypoxia. The targeted nominal environment for exploration missions is 8.2 psia cabin pressure and >33.7 volume% oxygen (balance nitrogen). Due to limitations in control systems, the oxygen concentration in exploration vehicles may go as high as 38 vol%. This introduces the new challenge of increased flammability risk. This is particularly challenging for lunar surface missions where partial gravity further exacerbates the risk. There are very few known materials that are non-flammable at 38% oxygen, necessitating new materials or approaches for habitation applications in crewed spacecraft. Plastic storage bags produce molten "drips" that can ignite other materials. Foams used on the International Space Station (ISS) have only been tested to 30% O2 and burned beyond the limit of 6 inches in testing (C rating). Other materials used for life support and habitation systems have similar challenges. New materials capable of passing NASA-STD-6001B Test 1 Upward Flame Propagation are therefore needed for exploration missions.

Scope Title: Oxygen Compatible Materials

Scope Description:

This scope targets the formulation, development, fabrication, and/or production of materials that pass NASA-STD-6001B Test 1 Upward Flame Propagation[1] at 38 vol% O2. Materials for use in habitation systems including upholstery fabrics, crew restraints (e.g., seatbelts), acoustic barriers, and insulation are highly desirable. Materials used in logistics such as non-flammable/non-molten alternatives to plastic storage bags, bungees, straps, restraints, trash containment, food packaging and storage materials, and labels are also highly desirable. Foams that meet the flammability requirements are also of high interest for applications including acoustic barriers, insulation, packaging, bedding, and cushions. Of lower priority, but still of interest, includes materials used in crew comfort and exercise clothing, sleeping bags, sewing threads, zippers, seam enclosures, cargo transfer bags, and other surface habitation, logistics, and crew materials.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:

- Level 1: TX 06 Human Health, Life Support, and Habitation Systems
- Level 2: TX 06.1 Environmental Control & Life Support Systems (ECLSS) and Habitation Systems

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware

Desired Deliverables Description:

Phase I Deliverable: Test data showing flammability and operational performance in the targeted application(s) of one or more materials.

Phase II Deliverable: Material samples of a size commensurate with the targeted application(s) in multiples to enable independent testing at NASA.

State of the Art and Critical Gaps:

There are currently very few materials that are not extremely flammable in 38% oxygen, which significantly increases the risk to the crew. This is a critical gap for the majority of surface habitation applications and for insulation and acoustic barriers for life support systems. NASA Space Technology Mission Directorate (STMD) Civil Space Shortfall[3] Integrated Ranking (2024) lists 1520: Fire Safety for Habitation as 10th overall and 1518: Logistics Tracking, Clothing, and Trash Management for Habitation as 87th.

Relevance / Science Traceability:

Most Artemis missions beyond Artemis V will require oxygen compatible materials. Availability of these new materials is likely to impact the Human Landing Systems, Pressurized Rover, and surface habitation.

References:

1. "Flammability, Offgassing, and Compatibility Requirements and Test Procedures," NASA-STD-6001B w/Change 2. April 21, 2021.
2. MAPTIS Database: HT-Afmaflex(TM), Solimide AC-550. https://maptis.nasa.gov/Home, Accessed 8/26/2024.
3. "Civil Space Shortfall Ranking," July 2024. https://www.nasa.gov/spacetechpriorities/. Accessed 8/26/2024.

Scope Title: Alternative Approaches to Habitation and Logistic Challenges in High Oxygen Environments

Scope Description:

Exploration missions with high-frequency EVA target crewed habitats at 8.2 psia and 33.7% oxygen. Under these conditions, most known materials are highly flammable[2] and introduce considerable risk to crew safety. This subtopic targets alternative approaches to solutions that traditionally rely on materials that will be flammable at up to 38% oxygen. Notably, this is not a call for new materials, but rather a call for new techniques that do not rely on flammable materials. Examples of applications where alternative approaches could be employed include food packaging (alternatives to flammable/melting plastic bags), trash containment, tape, labels, clothing dryers and/or hampers, and restraints (e.g., bungees, straps, Velcro, etc.). Offerors are encouraged to consider these and any other applications where flammable materials are currently used in crewed spacecraft.

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:

- Level 1: TX 06 Human Health, Life Support, and Habitation Systems
- Level 2: TX 06.1 Environmental Control & Life Support Systems (ECLSS) and Habitation Systems

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware
- Analysis

Desired Deliverables Description:

Phase I Deliverable: Analysis and/or demonstration of technical solution to replace current approach that uses a flammable material.

Phase II Deliverable: Brassboard hardware demonstration of a technical solution that performs the targeted application and corresponding flammability.

State of the Art and Critical Gaps:

There are currently very few materials that are not extremely flammable in 38% oxygen, which significantly increases the risk to the crew. This is a critical gap for the majority of surface habitation applications and for insulation and acoustic barriers for life support systems. NASA Space Technology Mission Directorate (STMD) Civil Space Shortfall[1] Integrated Ranking (2024) lists 1520: Fire Safety for Habitation as 10th overall and1518: Logistics Tracking, Clothing, and Trash Management for Habitation as 87th.

Relevance / Science Traceability:

Most Artemis missions beyond Artemis V will require oxygen compatible materials. Availability of these new materials is likely to impact the Human Landing Systems, Pressurized Rover, and surface habitation.

References:

1. "Civil Space Shortfall Ranking," July 2024. https://www.nasa.gov/spacetechpriorities/. Accessed 8/26/2024.
2. "Flammability, Offgassing, and Compatibility Requirements and Test Procedures," NASA-STD-6001B w/Change 2. April 21, 2021.

H3.14: Nanobubble Facilitated Hydrogen Peroxide Production In Space (SBIR)

Lead Center: JSC
Participating Center(s): ARC, MSFC

Subtopic Introduction:

Environmental Control and Life Support Systems (ECLSS) currently rely on hazardous chemicals and other consumables, launched from the ground, for disinfection of surfaces and wastewater stabilization. Launch logistics would be simplified if disinfecting and stabilizing chemicals could be made on location, in the spacecraft, without the need of chemical reagents. NASA's Small Business Innovation Research (SBIR) program previously sponsored development efforts to manufacture hydrogen peroxide (H_2O_2) using electrochemical methods. Feasibility of the process was demonstrated, but the service life of the membrane electrode assemblies was short lived. New research has shown that the addition of nanobubbles into process water improves oxygen solubility limitations, increases reaction rates, lowers system voltage requirements, and has the potential to dramatically increase the lifetime of, and/or eliminate the need for, membranes when used to generate H_2O_2 using electrochemical processes. The goal of this subtopic is to develop an effective and long-lasting method of producing H_2O_2 in a spacecraft environment.

Scope Title: Nanobubble Facilitated H2O2 Production In Space

Scope Description:

The scope of this subtopic focuses on developing compact and effective methods of producing hydrogen peroxide in a spacecraft environment and demonstrating service life that meets NASA's exploration needs. Compact systems using electrochemical approaches for H_2O_2 manufacture have been developed and demonstrated, but the early demonstration systems could not operate for extended durations of time, mainly due to membrane degradation. Recent publications report that the adding nanobubbles into process water can increase the rate of H_2O_2 generation and increase the service life of the membrane-based electrode assemblies. Application of nanobubble technology is therefore considered a viable pathway toward advancing the development of reagentless disinfection technology and for the in situ generation of H_2O_2. In addition, as an emerging field nanobubble technology has the potential to enhance a host of biological, chemical, and physical processes relevant to both space and terrestrial applications. Currently, NASA is seeking ways to produce H_2O_2 in a spacecraft environment for the purposes of disinfection, cleaning, and wastewater stabilization.

Expected TRL or TRL Range at completion of the Project: 2 to 3

Primary Technology Taxonomy:

- Level 1: TX 06 Human Health, Life Support, and Habitation Systems
- Level 2: TX 06.1 Environmental Control & Life Support Systems (ECLSS) and Habitation Systems

Desired Deliverables of Phase I and Phase II:

- Research
- Prototype

Desired Deliverables Description:

Desired Phase I deliverable is a technology demonstration system with a membrane electrode assembly with at least 100 cm2 effective surface area. This demonstration system should produce >10 l/day of an H_2O_2 solution (>100 mg/l) with an energy consumption of < 5kW-hr/day. The Phase I deliverable should be capable of operating continuously >500 hours with a degradation of performance of <10%.

Desired Phase II deliverable is an engineering technology demonstrator with a membrane electrode assembly with at least 100 cm2 effective surface area. This demonstration system should produce >10 l/day of an H_2O_2 solution (>100 mg/l) with an energy consumption of < 4kW-hr/day. The Phase II deliverable should be capable of operating continuously >2500 hours with a degradation of performance of <10%.

State of the Art and Critical Gaps:

There is no flight qualified method to produce H_2O_2 in a spacecraft environment. On-board manufacture of H_2O_2 would simplify launch logistics and reduce the amount of toxic reagents on board the spacecraft at any given time. Best available technology demonstrators are compact and capable of generating H_2O_2, but service life is too short for human exploration. If successful, this technology could fill technology gaps for on-board production of disinfectants. Specifically, gaps include Exploration Systems Development Mission Directorate (ESDMD) Gap numbers 303 Dormancy Recovery for Habitat Water Storage, Distribution, and Reclamation and related Child Gaps; 867 Water Recovery Mitigation for Dormant Periods; 984 Robust Advanced Water Recovery Systems; and 1005 Disinfection Solutions To Meet Potable Water Microbial Specifications During Nominal and Uncrewed Operations. This technology solicitation also addresses similar identified shortfalls under Space Technology Mission Directorate (STMD): 1516 Water and Dormancy Management for Habitation Systems, 1525 Food and Nutrition for Mars and Sustained Lunar, 1515 Water and Dormancy Management for Habitation; 1523 Earth Independent Human Operations within Habitat, and gaps associated with Systems Capability Leadership Team (SCLT) Clothing and Cleaning Logistics: 998 In Situ Integrated Disinfection Generation Compatible with Life Support and 1147 Mitigation of Microbial Growth for Planetary Protection.

Relevance / Science Traceability:

Exploration Systems Mission Directorate can use this technology for ECLSS related to the Artemis missions (e.g., Orion, Gateway, Human Lander Systems, and Rovers).

Benefits:

- Multiple spacecraft applications (e.g., wet wipes for disinfecting surfaces, urine pre-treatment and wastewater stabilization, flush and/or "pickling" solutions for wetted systems during dormancy, and reduction of bioburden for planetary protection).
- No byproducts as disinfectant naturally decomposes to water and oxygen.
- Water and ambient air from habitat are only inputs.
- Reduces system hazards.
- Reduces and/or eliminate consumable upmass (e.g., supply and storage of chemicals, premoistened disinfecting wipes, etc.).

References:

1. Magdaleno, A., Cerrón-Calle, G., dos Santos, A., Lanza, M., Apul, O.G., Garcia-Segura, S. 2024. Unlocking the Potential of Nanobubbles: Achieving Exceptional Gas Efficiency in Electrogeneration of Hydrogen Peroxide. Small. 20: 2470021.

2. Perry, S.C., Pangotra, D., Vieira, L. et al. 2019. Electrochemical Synthesis of Hydrogen Peroxide from Water and Oxygen. Nat Rev Chem 3, 442–458. https://doi.org/10.1038/s41570-019-0110-6.
3. Yu, F., Zhou, M., Zhou, L., et al., 2014. A Novel Electro-Fenton Process with H2O2 Generation in a Rotating Disk Reactor for Organic Pollutant Degradation. Environ. Sci. Technol. Lett. 1 (7), 320–324.

H4.09: Long-Duration Exploration Portable Life Support System (PLSS) Capabilities (SBIR)

Lead Center: JSC
Participating Center(s): N/A

Subtopic Introduction:

To enable astronauts to work efficiently on the surface of the Moon or on Mars, a new spacesuit is needed capable of extended periods of use in the harshest environment NASA has yet faced. The focus of long-duration Portable Life Support System (PLSS) capabilities is carbon dioxide (CO_2)/water (H_2O) removal and heat rejection technologies that do not vent to atmosphere and do not require a strong vacuum to operate, as a strong vacuum is not present, and excess venting will lead to a consumables and logistics hindrance to the mission. Innovation is needed in all of the following focus areas, though submissions should focus on one gap at a time:

1. Non-venting and continuous CO_2 & H_2O sequestration:
    - Adsorbents- current adsorbents require frequent regeneration during extravehicular activity (EVA). New adsorbents might be found to reduce or eliminate the need for regeneration during the EVA.
    - Ionic Liquids-Uptake capacities are high for the targeted compounds, but the rate is low, leading to insufficient performance on the PLSS scale.
    - Supporting instrumentation for pressure swing/temperature swing.
    - Additive manufacturing for amine scrubbers - current amine scrubbers use metal foams to mitigate the thermal effects in the swinging beds. These foams are random and difficult to fill, leading to voids and unused space. A highly ordered structure that is 3D printed could eliminate these dead spaces.
    - Boost Compressors - the current state-of-the-art (SOA) swinging beds rely on a partial pressure gradient between the adsorbing cycle and desorbing cycle that requires access to strong vacuum that won't be available on the Martian surface. A boost compressor could be used to artificially induce the partial pressure gradient needed for operation.
2. Gravity independent condensing heat exchanger:
    - The condensing heat exchanger must operate in reduced gravity and microgravity.
    - Traditional hygroscopic coating are toxic and fragile.
    - Newer, long lasting and more robust solutions are required to prevent the failures such as seen on the current Extravehicular Mobility Unit (EMU).
3. Non-venting heat rejection for Mars atmosphere - the current heat rejection is water evaporation/sublimation which requires a consumable that cannot afford to be lost and has a large mass penalty for launch:
    - Phase change materials
    - Lightweight radiators
    - Heat pumps
4. Trace Contamination Control:
    - Regenerable TCC
    - Combined TCC and CO2 removal

These areas are consistent with the shortfalls identified by STMD earlier this year:

- 1529: EVA and Intravehicular (IVA) suit system capabilities for Mars missions
- 1609: Surface-based lunar logistics management for sustained lunar evolution
- 1528: Spacesuit Physiology
- 672: Long-life thermal control for surface suites capable of extreme access
- 1517: Metabolic waste management for habitation

Scope Title: Long-Duration Exploration Portable Life Support System (PLSS) Capabilities

Scope Description:

Innovative designs for PLSS are sought to enable future long-duration missions to the Moon and Mars in one or more of the following areas:

1. Non-Venting continuous CO_2/H_2O sequestration.

For long-duration Exploration PLSSs supporting both long-term lunar and Mars operations, the desire to save the water and CO_2 released from the human operator during an extravehicular activity (EVA) increases with the EVA count and mission duration as water and oxygen are both consumables that need to be conserved and regenerated and are not readily available from the environment. Non-venting carbon dioxide (CO_2)/water (H_2O) sequestration would seek to mount within the PLSS, sequester CO_2/H_2O from the ventilation loop of the suit, which is closed and circulated by a fan keeping the outlet CO_2/H_2O levels low for subsequent return of the gas to the suit volume. Upon completion of the EVA, the recovered water and CO_2 could be regenerated by some mechanism to provide it to the vehicle Environmental Control and Life Support System (ECLSS) for subsequent processing. The current State of the Art CO_2 system vents to atmosphere, and will not work without a hard vacuum, and so is unsuitable for the Martian surface, so by funding non-venting innovation, the technology will become more viable for the long term NASA mission of Mars.

Key parameters include:

- CO_2 uptake rates: 2.5 g/min at 1600 BTU/hr and 3.2 g/min at 2000 BTU/hr with outlet gas concentration <2.5 mmHg
- H_2O uptake rates: 2 g/min at 1600 BTU/hr to 2.4 g/min at 2000 BTU/hr (this is limited by the usage of a liquid cooling and ventilation garment in the suit volume) with outlet gas concentration below 50% RH and <45 ºF dew point
- Overall volume constraints with any valve/manifold: W (<10 in.) x H (<8 in.) x D (<5 in.)
- Overall mass constraints: <12 lbm with goal of <6 lbm
- Flow rate through system: 6 acfm (170 lpm)
- Allowable pressure drop: <2 in.-H_2O at 4.3 psia, 6 acfm, 60 ºF
- Operating pressure range: 3.5 to 23.5 psia
- Gas inlet temperature range: 50 to 90 ºF
- Working fluids: air or 100% oxygen
- g-field operations: 1g, 1/6g, 3/8g, microgravity (ug)
- Electrical interface: 28 VDC
- Power during non-regeneration usage: <25W

2. Condensing Heat Exchanger (CHX) With Gravitational Field (g-Field) Independent Slurper:

For long-duration Exploration PLSSs supporting both long-term lunar and Mars operations, the benefit to save the water released from the human operator during an EVA increases with the EVA count and mission duration as water is not readily available from the environment. Almost regardless of the selected CO_2 scrubbing option, sequestration, or semi-open loop, a CHX could be used upstream of the CO_2 scrubber to recover the water vapor.

Upon completion of the EVA, the recovered water could be removed from the capture reservoir for processing by the vehicle water reclamation system. The current state of the art CHXs require fragile hydrophilic surface coatings. Key objectives for this CHX approach include: no coatings* required on the internal surfaces for water handling, operation in varied g-field including microgravity, and passive operation without requirement for sweep gas or differential pressure gradients.

*NOTE: Coatings tend to spall and cause system reliability issues over time.

Key parameters include:

- H_2O uptake rates: 2 g/min at 1600 BTU/hr to 2.4 g/min at 2000 BTU/hr (this is limited by the usage of a liquid cooling and ventilation garment in the suit volume) with outlet gas concentration below 50% RH and <45 ºF dew point
- Overall volume constraints with any valve/manifold: W (<10 in.) x H (<8 in.) x D (<5 in.)
- Overall mass constraints: <2 lbm
- Flow rate through system: 6 acfm (170 lpm)
- Allowable pressure drop: <0.75 in.-H_2O at 4.3 psia, 6 acfm, 60 ºF
- Operating pressure range: 3.5 to 23.5 psia
- Gas inlet temperature range: 50 to 90 ºF
- Working fluids: air or 100% oxygen
- g-field operations: 1g, 1/6g, 3/8g, ug

3. Non-Venting Heat Rejection for Mars Atmosphere:

For long-duration Exploration PLSSs supporting both long-term lunar and Mars operations, the desire to minimize or eliminate the water used for evaporative cooling of the spacesuit during an EVA increases with the EVA count and mission duration as water is not readily available from the environment. The state of the art with respect to spacesuit cooling technologies for the past 60 years has been sublimation of feedwater to vacuum with more recent developments using evaporation across a membrane of feedwater to a reduced pressure environment such as vacuum. In both cases, water usage on the order of 5-10+ lbm of feedwater is experienced per EVA to enable the elimination of waste heat from the crewmember, avionics, and environmental inleakage. In order to be more efficient with usage of a limited resource during spacesuit activities, the suit would greatly benefit from being able to reject heat using means that do not result in such significant water usage, such as radiators or phase changing materials.

Peak Heat Rejection: 500 W metabolic waste heat, 100 W avionics waste heat, 100 W in leakage from the environment

Interface to transport loop that removes heat from the system (crewmember and avionics):

- Working fluid: water
- Nominal flow rate: 200 +20/-30 pph
- Allowable pressure drop: <1 psid
- Outlet temperature: <50 °F (10 °C)
- EVA duration: 8 hr
- Nominal heat rejection: 460 W
- Ambient pressure: vacuum to 9 Torr (CO_2)
- Ambient sink: varied
- Volume/form factors: The rear surface of the PLSS is approximately W (23 in.) x H (30 in.) x D (7 in.)
    - The internal volume that could be available if replacing the evaporator:
- Mass limitation: <15 lbm
- Additional consideration given the implementation will relate to fall impact loads should the solution be mounted to the PLSS and subject to contact with objects during a fall during an EVA in 1/6g or 3/8g

4. Trace Contaminant Control:

For all EVA suits, the buildup and control of trace contaminants is of vital importance for crew safety. The crew's metabolic activity as well as the suit's materials produce toxic gasses which have to be controlled for the duration of suited operations, including but not limited to light oxygenates, siloxanes, cyclical aromatics, ammonia, and other volatile hydrocarbons. Currently these are controlled by non-regenerable activated carbon beds. The greater the EVA duration and frequency, the faster these compounds build up, so that for long duration exploration PLSS applications where frequent EVAs are expected, the need for TCC is greater than for Low Earth Orbit (LEO) or even short term lunar missions where EVAs are expected to be more infrequent. The current state of the art would require frequent resupply which will not be possible for Mars missions. Therefore, in particular interest in long term missions are regenerable TCC which does not require constant resupply, or integration of the TCC and CO2 removal capabilities to simplify the design and remove redundant adsorbent beds.

Key parameters include:

- Ability to remove key gasses identified in NASA JSC-20584
- Flow rate through system: 6 acfm (170 lpm)
- Operating pressure range: 3.5 to 23.5 psia
- Gas inlet temperature range: 50 to 90 ºF
- Working fluids: air or 100% oxygen
- g-field operations: 1g, 1/6g, 3/8g, ug

Expected TRL or TRL Range at completion of the Project: 2 to 4

Primary Technology Taxonomy:

- Level 1: TX 06 Human Health, Life Support, and Habitation Systems
- Level 2: TX 06.2 Extravehicular Activity Systems

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

Phase I:

- Objective: Feasibility assessment for given technology.
- Deliverables: Interim and final reports.

Phase II:

- Objective: Prototype that can be integrated into the Exploration Extravehicular Mobility Unit (xEMU) Design, Verification, and Test (DVT) unit enabling both component and integrated system testing.
- Deliverables: Interim and final reports along with prototype hardware.

State of the Art and Critical Gaps:

The state-of-the-art PLSS components exist in the current Extravehicular Mobility Unit (EMU) that is in operation on the International Space Station. Gaps exist for spacesuit components to operate on the lunar surface for extended duration and for operation on Mars, already identified by STMD in the document https://www.nasa.gov/spacetechpriorities/ as gaps 672, 1517, 1528, 1529, and 1609. The gaps will be defined in the PLSS Roadmap to be released to the public at a workshop planned for FY 2024.

Relevance / Science Traceability:

This technology is planned for future lunar and Mars missions where long-duration stays are required. This work can be traced to the Exploration Systems Development Mission Directorate (ESDMD) and Space Operations Mission Directorate (SOMD). The targeted suit configuration for this subtopic takes innovation beyond the xEMU that was designed, integrated, and tested in-house by the EC5/Crew and Thermal Systems Division at the Johnson Space Center.

References:

The PLSS Roadmap was published in a conference paper titled, "NASA Extravehicular Activity Technology Roadmaps for Exploration" at the International Conference on Environmental Systems in July 2024. It may be obtained at the following link:

1. https://ttu-ir.tdl.org/items/cdfa8c84-7f99-443f-98b4-f287234e86e8

The following link will provide access to peer-reviewed papers published at the International Conference on Environmental Systems for technologies developed for the xEMU PLSS prototype in related areas such as the Rapid Cycle Amine CO_2 Removal and the Spacesuit Water Membrane Evaporator for heat rejection:

1. https://ttu-ir.tdl.org/collections/ef7ac1dd-cfc8-4fb0-9bd9-81e30264df7f

Other pertinent references:

1. https://www.nasa.gov/extravehicular-activity-and-human-surface-mobility/
2. https://www.nasa.gov/wp-content/uploads/2024/06/jsc-20584-smacs-rev-c-final.pdf?emrc=17fbbc

H4.11: Advanced Materials for Durable Spacesuits for the Moon and Mars (SBIR)

Lead Center: JSC
Participating Center(s): N/A

Subtopic Introduction:

Next generation spacesuits will need to be more reliable and durable in extreme environments to enable sustained human exploration on the Moon and Mars. The current state-of-the-art spacesuit components are capable of operation in microgravity and are not suitable for long-duration operation on the Moon or Mars. Even advanced suits under development now are expected to meet the needs of initial missions to the Moon but will not be durable enough for sustaining missions to the Mars. This solicitation maps to Space Technology Mission Directorate (STMD) Shortfall 1529 – EVA (extravehicular activity) and IVA (intravehicular activity) Suit System Capabilities for Mars Missions.

This solicitation seeks advanced material development for hard structural (hard upper torso (HUT), brief, etc.) and mobility (joints, bearings, disconnects, etc.) components of the spacesuit Pressure Garment Subsystem (PGS). A Technology Development Roadmap has been developed for the PGS identifying the risks, gaps, and a technology plan that will facilitate the focus of technology development where the risks and gaps exist. Challenges and gaps remain for many components of the spacesuit as it relates to providing durability and maintainability of components in extreme environments like the Moon or Mars for extended periods of time.

These materials will be developed for both structural spacesuit components, such as the HUT, brief, or disconnects, as well as mobility spacesuit components, such as bearings. These materials need to meet requirements for cycle life even when exposed to the abrasiveness of the lunar or Martian dust, the extreme temperature ranges in which the spacesuit will need to operate, exposure of the spacesuit components to radiation, and many other possible contaminants on the surface of the Moon and in the Mars atmosphere.

With solutions from this subtopic, the spacesuit components will be able to operate more reliably and be more durable so as to protect the astronaut for longer periods of time and allow them to operate the spacesuit in much harsher environments than experienced in the microgravity environment of the International Space Station. It will fundamentally enable Mars EVA by providing the necessary structural protection and mass reduction required to allow crew to conduct spacewalks safely and effectively.

Scope Title: Advanced Materials

Scope Description:

At a high level, this subtopic and scope is soliciting development of advanced material solutions for EVA suits on the Martian and lunar surface. It seeks to address deficits with previous developments as it relates to impact resistance (damage tolerance), strength, environmental resistance, mass, and feasibility for use in a spacesuit application. Specific components of concern include the HUT, hard brief, and mobility elements such as bearings, disconnects, and other hard mobility joints. For this development, there are several characteristics of concern:

- Operating range -170 °F to +170 °F, considerations for thermal cycling and CTE of composite materials.
- Impact resistance for structures: <0.5 LPM leakage after impact of 300J (Goal: 600J) at 4.3 psi.
- Tensile strength.
- Cycle life and structural rigidity of bearings.

Expected TRL or TRL Range at completion of the Project: 1 to 5

Primary Technology Taxonomy:

- Level 1: TX 06 Human Health, Life Support, and Habitation Systems
- Level 2: TX 06.2 Extravehicular Activity Systems

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype

Desired Deliverables Description:

Phase I Deliverables

- Analysis of candidate and/or proposed materials against requirements and validation of compatibility with spacesuit hardware and the relevant environments.
- Analysis of proposed material(s) to determine feasible optimizations within Phase I related to: composition, design, processing, and/or manufacturing.
- Prototype material coupons, sub-scale or full-scale PGS components in sufficient quantity for vendor testing against requirements and for delivery of appropriate quantity to NASA.
- Testing results and analysis.
- Final report.

Phase II Deliverables

- Analysis of Phase I material and results for opportunities for material optimization.
- Optimization of material properties with respect to requirements.
- Manufacturing and Non-Destructive Evaluation (NDE) plan for the material/component.
- Sub-scale or Full-scale PGS component prototype in sufficient quantity for NDE and destructive testing by vendor, and for delivery to NASA.
- Testing results and analysis.
- Final report.

State of the Art and Critical Gaps:

The current state of the art materials exist in the Extravehicular Mobility Unit (EMU) that is in operation on the International Space Station. This includes MXB7701/7781 epoxy/fiberglass prepreg for the EMU HUT and stainless steel bearings. At a lower TRL, current state of the art is also available for reference in the Exploration Extravehicular Mobility Unit (xEMU) government reference design advanced suit prototype. This suit has two options for hard structural materials (HUT, brief) - Aluminum 6061-T6, and a lightweight fiberglass composite (HexForce 6781HT/Patz PMT-F4A). Additionally, bearings and disconnects are constructed out of Titanium 6AL-4V. While these materials offer reduced mass for the Moon, they are still insufficient to enable EVAs on Mars due to the combination of mass and impact resistance of structures.

This proposal seeks developments for advanced material solutions that will offer improved impact and environmental resistance, at reduced mass, compared to the state of the art xEMU materials. Possible solutions for components may include 3d woven composites, fiber reinforced thermoplastics, or novel bearing and softgoods integration methods, but this list is not inclusive. Additive manufacturing (particularly in situ manufacturing) is within the scope of possible solutions.

Note: Generally, gaps exist for spacesuit components to operate on the lunar surface for extended duration and for operation on Mars. The gaps are defined in the PGS Roadmap released to the public in Summer of 2024 (see References).

Relevance / Science Traceability:

The scope has relevancy for not only spacesuits, but also pressurized rover, habitats, or any other mission elements that require high strength/toughness at reduced mass.

References:

1. NASA, SLS-SPEC-159 Revision 1, "Cross-Program Design Specification for Natural Environments (DSNE)" (Oct. 2021). https://ntrs.nasa.gov/api/citations/20210024522/downloads/SLS-SPEC-159%20Cross-Program%20Design%20Specification%20for%20Natural%20Environments%20(DSNE)%20REVISION%20I.pdf
2. The PGS roadmap. https://ttu-ir.tdl.org/collections/ef7ac1dd-cfc8-4fb0-9bd9-81e30264df7f
3. ICES-2018-220: Design and Validation Testing of Titanium Spacesuit Bearings. https://ttu-ir.tdl.org/items/30266fdd-0bca-496c-a460-46bccae4a353
4. ICES-2016-60: Development and Evaluation of Titanium Space Suit Bearings. https://ttu-ir.tdl.org/items/3b979127-ce7d-4ce2-abba-19da0a453a21
5. ICES-2017-242: Development and Wear Evaluation of Titanium Spacesuit Bearings. https://ttu-ir.tdl.org/items/7ad92d25-4882-427f-899c-2c8fe7650415
6. ICES-2023-286: Exploration Extra-Vehicular Mobility Unit (xEMU) Composite Hard Upper Torso (CHUT) Development. https://ttu-ir.tdl.org/items/89aff2c9-f2f2-4281-9952-29972c93503d
7. ICES-2022-258: NASA Advanced Space Suit xEMU Development Report -- Hard Upper Torso Assembly. https://ttu-ir.tdl.org/items/bbe48e6a-bb23-4966-8f40-9d34b166b2d0

H5.01: Modular, Multi-Use 50 kW Lunar Solar Array Structures (SBIR)

Related Subtopic Pointers: T12.01
Lead Center: LaRC
Participating Center(s): GRC

Subtopic Introduction:

This subtopic seeks structural and mechanical innovations for second-generation, modular 50-kW vertical solar arrays near the lunar south pole for powering anticipated increases in lunar base infrastructure in the late 2020s-2030s, including larger habitats and laboratories; multiple pressurized rovers; regenerative fuel cells; and construction, mining, and material processing equipment. Increasing the solar array unit size from first-generation 10 kW to second-generation 50 kW is a logical evolution as power demands are expected to grow over time, and it provides additional electrical power redundancy. This increase in size by 5 times while maximizing specific power (goal is >75 W/kg) needs structures and mechanisms innovations and development effort to ensure compact packaging, safe transportation in space and on the lunar surface, reliable deployment, stable operation while Sun tracking, and occasional retraction and relocation.

This subtopic requests proposals that also consider how these tall vertical solar arrays can be designed for secondary purposes other than generating power. An obvious example of multi-use capability is adding equipment to the solar array tip for communications, lighting, remote sensing, navigation, laser power beaming, or mirrors to reflect sunlight to other locations. Ideally, new equipment could also be easily added or replaced on the lunar surface as needed. Piggybacked equipment could conceivably also be distributed along the solar array length, perhaps to measure dust accumulation versus height. Modular design innovations could also possibly be developed to allow reuse or recycling of solar array components for other purposes.

Scope Title: Modular, Multi-Use 50 kW Lunar Solar Array Structures

Scope Description:

NASA intends to land near the lunar south pole (at south latitudes ranging from 84° to 90°) in 2026 in the Artemis III mission, evolving to a sustainable long-term presence in the 2030s. At exactly the lunar south pole (90° S), the Sun elevation angle varies between -1.5° and 1.5° during the year. At 84° S latitude, the elevation angle variation increases to between -7.5° and 7.5°. These persistently shallow Sun grazing angles result in the interior of many polar craters never receiving sunlight while some elevated peaks, 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. Extended illumination at elevated sites occurs because the Sun is visible below the horizon. For this reason, these elevated sites are valuable locations for human exploration and settlement since they avoid the 354-hr nights found elsewhere on the Moon while providing nearly continuous sunlight for site illumination, moderate temperatures, and solar power [Refs. 1-2].

Under a “Game Changing” project in NASA’s Space Technology Mission Directorate (STMD) named Vertical Solar Array Technology (VSAT), several firms are developing relocatable 10-kW vertical solar arrays for initial power generation near the lunar south pole [Refs. 3-4]. These 10-kW arrays can be retracted and moved as needed to support evolving requirements for South Pole human occupation. Their relatively small size (35 m^2 of deployed area) allows them to be used individually or in combination to power loads up to a few tens of kilowatts. However, because the Sun is always close to the horizon, using numerous small, interconnected arrays for electrical power loads >>10 kW can result in appreciable shadowing of one array onto another as well as increased positioning, leveling, cabling, and deployment challenges to locate multiple 10-kW units at optimally illuminated locations.

NASA recently released their prioritized list of technology shortfalls for civil space [Ref. 5], and the second-highest ranked shortfall out of 187 is “High Power Energy Generation on Moon and Mars Surfaces,” which specifically targets development of 50 kW lunar solar arrays, the subject of this subtopic. Therefore, there is a high level of programmatic pull from both the space community (ranked #1 by both small and large industry) and NASA HQ and Centers for the work solicited in this SBIR subtopic. Additionally, NASA’s Lunar Infrastructure Goal (LI-01-L) is to “Develop an incremental lunar power generation and distribution system that is evolvable to support continuous robotic/human operation and is capable of scaling to global power utilization and industrial power levels.” [Ref. 6, p. 69]

At the top level, there are two basic design approaches for 50 kW lunar solar arrays: monolithic or modular. Monolithic designs are a single mechanical unit, possibly just an enlarged version of an existing 10 kW design. Modular designs, on the other hand, contain several discrete identical or similar subsystems assembled by some means. One solution is to just combine five 10-kW designs to create a 50-kW design, but there are other possibilities. NASA’s intention is to study modular concepts that can increase fault tolerance and redundancy; simplify design, analysis, and testing; and potentially allow in-service replacement of faulty modules. Modular approaches for both assembly and repair would be valuable new capabilities.

Subtopic H5.01 has focused over the past three years on developing monolithic 50 kW designs, and in 2025 the focus changes to modular designs. It is unclear whether monolithic or modular designs are best for high-power vertical solar arrays, and this subtopic seeks to help provide a better understanding to the community. The ultimate preference of a monolithic or modular design will likely also depend on lunar support systems that are not fully developed or known yet such as specific mobility vehicles and robotic assistance capabilities.

In 2025, this subtopic seeks structural and mechanical innovations for second-generation, modular 50-kW vertical solar arrays near the lunar south pole for powering anticipated increases in lunar base infrastructure in the late 2020s-2030s, including larger habitats and laboratories; multiple pressurized rovers; regenerative fuel cells; and construction, mining, and material processing equipment. Increasing the solar array unit size from first-generation 10 kW to second-generation 50 kW is a logical evolution as power demands are expected to grow over time, and it provides additional electrical power redundancy. This increase in size by 5 times while maximizing specific power (goal is >75 W/kg) needs structures and mechanisms innovations and development effort to ensure compact packaging, safe transportation in space and on the lunar surface, reliable deployment, stable operation while Sun tracking, and occasional retraction and relocation. Small Business Innovation Research (SBIR) contracts can help flesh out technical requirements and new technical concepts and challenges for these larger 50 kW solar arrays based in part on VSAT results for smaller 10 kW arrays.

In 2025, this subtopic requests proposals that also consider how these tall vertical solar arrays can be designed for secondary purposes other than generating power. An obvious example of multi-use capability is adding equipment to the solar array tip for communications, lighting, remote sensing, navigation, laser power beaming, or mirrors to reflect sunlight to other locations. Ideally, new equipment could also be easily added or replaced on the lunar surface as needed. Piggybacked equipment could conceivably also be distributed along the solar array length, perhaps to measure dust accumulation versus height. Modular design innovations could also possibly be developed to allow reuse or recycling of solar array components for other purposes.

Solar array retraction will allow valuable solar array hardware to be relocated, repurposed, or refurbished and to minimize nearby rocket plume loads, blast ejecta damage, and dust accumulation. Also, innovations to raise the bottom of the solar cell area as high as 15 m (increased from 10 m in 2024) above the ground to reduce shadowing from local terrain and other structures are required [Ref. 7]. Transportation can use separate surface-mobility systems (i.e., not necessarily part of the solar array system), but design of array structures and mechanisms must accommodate loads likely to be encountered during transport along the lunar surface, as well as launch and landing loads. Novel changes or combinations of existing 10-kW array components to these larger 50-kW arrays, including those being developed under the VSAT project, are of special interest.

Design guidelines for these deployable/retractable solar arrays are:

- Deployed area: approximately 175 m2 per 50 kW unit, assuming state-of-the-art space solar cells.
- Single-axis Sun tracking about the vertical axis.
- Adjustable from 0 m to 15 m above the surface to reduce shadowing from terrain and other structures.
- Deployable, stable base for supporting tall vertical array on unprepared lunar surfaces.
- Base must accommodate a local 15° terrain slope with adjustable leveling to less than 0.5° of vertical.
- Retractable over a hardware temperature range of -60 °C to +60 °C for relocating, repurposing, or refurbishing.
- Number of deploy/retract cycles in service: >5; stretch goal >10.
- Lunar dust, radiation, and temperature resistant components.
- Specific mass >75 W/kg and specific packing volume >20 kW/m3, including all mechanical and electrical components.
- Factor of safety of 1.5 on all components.
- Lifetime: 10 years.

Suggested areas of innovation include:

- Novel packaging, deployment, retraction, and modularity concepts.
- Novel lightweight, compact components including booms, ribs, solar cell blankets, and mechanisms.
- Novel actuators for telescoping solar arrays such as gear/rack, piezoelectric, ratcheting, or rubber-wheel drive devices.
- Multi-purpose, external robotic actuators instead of traditional single-purpose actuators [Ref. 8, Appendix A].

- Mechanisms and seals with exceptionally high resistance to lunar dust.
- Analysis and testing of dust effects and dust mitigation methods.
- Load-limiting devices to avoid damage during deployment, retraction, and solar tracking.
- Methodology for stabilizing large vertical arrays such as compactly packageable support bases, using regolith as ballast mass, or novel guy wire and surface anchor systems.
- Optimized use of advanced lightweight materials, including composite materials with ultra-high modulus (>280 GPa) combined with low coefficient of thermal expansion (<0.1 parts per million per °C).
- Parametric analyses of deployable vertical solar array concepts from 10 kW to 100 kW.
- Validated modeling, analysis, and simulation techniques.
- Adaptable solar array concepts for multiple lunar surface use cases possibly including horizontal configurations for future low- and mid-latitude sites.
- Completely new concepts (e.g., thinned rigid panel or 3D-printed solar arrays, nonrotating "chimney" arrays, or lightweight reflectors to redirect sunlight onto solar arrays or into dark craters).
- Innovations for low-temperature survival. Temperature cycles down to 40 K may damage the solar array itself.
- Concepts of operation for fully autonomous deployment, retraction, operation, assembly, and repair.

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. Solar array concepts should be compatible with state-of-the-art solar cell technologies with documented performance and environmental degradation properties. Design, build, and test of scaled flight hardware or functioning laboratory models to validate proposed innovations are of high interest.

Expected TRL or TRL Range at completion of the Project: 4 to 5

Primary Technology Taxonomy:

- Level 1: TX 12 Materials, Structures, Mechanical Systems, and Manufacturing
- Level 2: TX 12.2 Structures

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

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 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 lunar surface power. 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 have motorized retraction capability either. The critical technology gap filled by this subtopic is a lightweight, vertically deployed, retractable 50-kW solar array for surface electrical power near the lunar south pole for diverse needs, including In Situ Resource Utilization (ISRU), lunar bases, dedicated power landers, and rechargeable rovers.

This subtopic contributes significantly to closing NASA's Capability Shortfall #1596 [Ref. 5]. The description reads, in part: "Existing solar array systems do not provide sufficient durability or scale to support full scale ISRU production in the Lunar Pole thermal, dust, and radiation environment. Current technology for deployment of towers and reflectors is not optimized to gather sunlight low on the horizon as at the Lunar poles. Mission architects must know what capability will be available to them to start full-scale ISRU production operations." The corresponding metric is "50 kWe class system for photovoltaic systems," which directly aligns with the objectives of this subtopic.

This subtopic also directly contributes to NASA's Lunar Infrastructure Goal (LI-01-L) from the March 2024 Moon to Mars (M2M) Architecture Definition Document, Rev A [Ref. 6, p. 69], which is to "Develop an incremental lunar power generation and distribution system that is evolvable to support continuous robotic/human operation and is capable of scaling to global power utilization and industrial power levels." It also aligns closely with Center strategies at both Langley Research Center (LaRC) for structures (Subtopic Lead) and Glenn Research Center (GRC) for power (Participating Subtopic Manager). Deployable solar array development requires both mechanical and electrical expertise.

Relevance / Science Traceability:

Robust, lightweight, redeployable solar arrays for lunar surface applications are a topic of great current interest to NASA for its return to the Moon. The subtopic extends the focus area from monolithic concepts to modular concepts along with refined design guidelines. Several infusion paths likely lead 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 about 10 kW of electrical power for first-generation capabilities and 50 kW for second-generation capabilities.

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H6.25: Trusted Autonomy in Space Systems (SBIR)

Related Subtopic Pointers: S17.03
Lead Center: ARC
Participating Center(s): JPL, JSC, MSFC

Subtopic Introduction:

This subtopic seeks to develop verification methods to prove autonomous systems are safe and mission effective. The non-deterministic behavior of autonomous system software, which usually embodies software for learning or reasoning, renders the traditional method of extensive testing inadequate. The problem is that the extremely large number of possible state values makes exhaustive testing of all possible combinations impossible. The large number of state variables is caused both by the variation in operating conditions external to the system as well as the decision branching software used by the planner and supervisory executive software. Formal methods are also equally unsuitable to verify the functionality of autonomous systems, albeit formal methods may help verify system components. The problem formal verification methods face is that it is very difficult to express robotic safety rules in the temporal logic language required by model checkers.

The ability to adapt to changing situations is at once the greatest strength and the greatest weakness of autonomous systems. Imagine the trepidation an office manager has when a subordinate is left in charge of the office while he is away on vacation. Although the office manager may be confident the subordinate can handle most events well, there is always the possibility an unforeseen development could cause the subordinate to make a bad decision, plunging the office into chaos. The concern for autonomous systems left in charge of space assets is no different. How can it be determined that autonomous systems can handle all situations? How do autonomous systems handle component failures? How can it be determined that autonomous systems are safe, and that the human operators can trust them? This subtopic seeks the development of methods to provide the means to trust autonomous systems.

Providing the means to trust autonomous systems is extremely challenging because the methods used to verify the operations of safety critical software do not scale to the large number of parameters and states embodied in autonomous system software, or to the changing environments in which they must operate. Generally, there are two ways to verify software: testing and formal methods. Testing is the most straightforward and easy to understand. It comes down to testing the autonomous software to see if it performs as desired in all conceivable modes and operating regimes. The weakness of this approach is that testing can never prove the absence of error. Autonomous systems have far too many variables to allow a systematic variation of all possible states, variable values, control parameters, and conditions. Formal methods are either mathematical proofs that a software will not fail, or require building of a model of the system in temporal logic to prove that all paths through the software do not show anomalous behavior. The problem is that building a model of the software is usually only possible for small systems of limited complexity. No autonomous real system has ever been verified by formal methods (completely) because the number of parameters to be varied causes the well-known state explosion problem. An additional problem is that the people who understand formal methods well enough to implement model-checking programs do not have an understanding of what is required to keep the autonomous system safe. Telling them what makes the system safe in words is not sufficient because the safety properties also need to be specified as temporal logic assertions that are not easy to formulate. The objective of this subtopic is to develop methods to prove autonomous system operation can be trusted that are as easy to implement as testing, and yet are as comprehensive as formal methods. If successful, this will have application to the autonomous and semi-autonomous systems being planned for space exploration. Additionally, there are many non-NASA commercial applications for this technology such as self-driving car software.

The primary difficulty with adaptive, autonomous software is that left unbounded, the control system may be nondeterministic. Nondeterminism is a problem for adaptive software because the actions are, by definition, not predictable. What is needed is the means to prove that the autonomous software is always bounded. That means that although the next command of an autonomous system cannot be precisely predicted, there will exist guarantees to bound the domain of the command. This bounding is necessary to improve system stability and ensure a harmful command is not generated. Although testing and simulation of the autonomous software may be part of the assurance case, it is important to recognize that testing cannot prove the absence of error.

This subtopic has three scopes:

- Certification of Autonomous System Software
- Verification of Distributed Autonomous Commanding Software
- Verification of Machine Learning

Scope Title: Certification of Autonomous Systems Software

Scope Description:

This scope seeks to develop methods that address how autonomous systems may be certified for operational use. In this context, certification means that a defined safety process has been followed to guarantee that the autonomous system meets the required criteria for safe operation. Although a relative wealth of information has been developed for the certification of commercial aviation software, there is a significant lack of recommended methods to certify space-based autonomous systems. This scope seeks to help close the certification gap in several ways.

First, a literature search should be conducted to determine the standards used to assure the operation of terrestrial autonomous software and hardware other than the means specified for commercial aviation by the Federal Aviation Administration (FAA). There are many other standards and guides for Earth-based autonomous systems that may be applicable to the certification of autonomous software for spacecraft automation. Such standards could relate to autonomous system interoperability and human system interaction. Second, metrics need to be developed that can objectively quantify the performance of autonomous systems used in spacecraft. The identification of suitable metrics will most likely be a fallout of the literature survey once all current methods have been assessed.

There is no certification authority for space system software approval like the FAA provides for commercial aviation software, but there are similar guidelines which state that the system must have met all performance requirements. Hence, the objective is to develop a certification method for application to space-based robots and other autonomous systems that will likely be suitable for proving mission readiness. One method might be the development of a safety case to provide a list of human-understandable assertions which much be true. Because the autonomous systems may operate far from earth, it is also desirable that there be software to effectively provide an indication of autonomous system certifiability during the mission. This means that the autonomous system certification method must be constantly testing for conditions that may lead to unsafe operation.

It is necessary to demonstrate that the certification approach is feasible in the context of controlling an automated or autonomous system. A demonstration using an autonomous robotic system is preferable. Robotic systems must not only have the means to detect internal system failures, but also the ability to detect when the system has failed to achieve the mission. Robust detection of these failures is required because detection alone is insufficient. Detection must be accomplished within a time short enough to allow a robust recovery from the failure. Although robotic systems may be able to communicate with ground or other space-based assets, such communication is likely insufficient to enable a robust response. Moreover, it is also imperative that once autonomous systems recognize a failure that they don't simply shut down, but rather have a fail-active response to maintain safety and achieve mission success. Techniques and methods to identify incomplete or corrupt sensor data and take mitigating actions are needed.

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:

- Level 1: TX 10 Autonomous Systems
- Level 2: TX 10.2 Reasoning and Acting

Desired Deliverables of Phase I and Phase II:

- Software

Desired Deliverables Description:

At the end of Phase I, a literature survey will be presented to document the many standards and guidelines used to certify or develop autonomous system software. The objective is to determine which ones provide valuable insight into certifying autonomous systems used in space applications such as the NASA Artemis Program. The final report will explain which guidelines and standards developed for autonomous systems on Earth seem to have concepts that can be extended to allow the certification of space autonomous systems such as automated docking systems, autonomous landing software, or autonomous abort software.

At the end of Phase II, it is expected that the first scope will provide methods to address how autonomous systems may be certified for operational use. A demonstration will be performed to demonstrate the feasibility of the certification approach in the context of controlling an automated or autonomous system.

State of the Art and Critical Gaps:

Currently, there is no certification method for autonomous systems to be used in NASA exploration systems. For commercial aviation software, the FAA is the certification authority established by congress that certifies (approves) flight software for commercial use. In contrast, there is no governmental authority that provides certification of autonomous software, or any other software for space applications. On the commercial aviation side, the FAA states that one way to gain certification (but not the only way) is to meet the software development processes specified in DO-178C, A New Standard for Software Safety Certification. The NASA space program needs a similar document from which some office within NASA might one day require autonomous systems to follow in order to gain NASA approval.

A reasonable question to ask is "Why not just use DO-178C?" The reason is that DO-178C is developed for commercial aviation software that is deterministic. It cannot be successfully applied to non-deterministic autonomous systems. For example, after over 50 years of operation, certification of autopilot software is still not certifiable under DO-178C because of its nondeterministic software. The FAA allows it to be used but will not say that it is certified for use. Nondeterministic software is at the heart of autonomous systems and the means to gain approval of that type of software is not just important for NASA exploration, but also has widespread application to autonomous software developed for unmanned aerial vehicles and autonomous cars.

This scope addresses shortfalls:

- 1542: Metrics and Processes for Establishing Trust and Certifying the Trustworthiness of Autonomous Systems
- 1438: Autonomy, Edge Computation, and Interoperable Networking for Small Spacecraft
- 512: Cooperative interfaces, aids, and standards

Relevance / Science Traceability:

Moon-2-Mars Program, Human Landing System Program, Artemis Program

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Scope Title: Verification of Distributed Autonomous Commanding Software

Scope Description:

There currently exists a variety of papers that describe plans for software and hardware to allow humans and robots to interact successfully. The robotic systems may include semi-autonomous rovers, equipment movers, loaders, fuel production robots, or equipment aboard spacecraft. Several issues confront how autonomous systems interact with not only humans, but with other automated systems. An autonomous vehicle designed to operate on the lunar surface may use its own planner and executive software to move to another location. At the same time, the autonomous vehicle might need to respond to control inputs from on-board crewmembers or crewmembers located in a spacecraft on the surface, a spacecraft in orbit, or even from a ground control station located on Earth. It is possible that another autonomous vehicle may also issue commands for collaborative operation. A problem is that there must be an established protocol to make sure at least one entity is in control of the vehicle, and at the same time enforce a command and control structure to establish the priority of user control.

This scope seeks the development of methods to verify methodologies for distributed commanding of autonomous vehicles and robotic equipment. The verification methods need to be cognizant of the operational environment because the allowable autonomous behavior in one environment may be different that another. The verification methods must have the means to account for operation latency when commanded from stations far away as well as when commanded locally by crew. The verification methods must be able to verify correct autonomous behavior is achieved even when multiple entities may be controlling the spacecraft at various times. The requires the verification method to give careful consideration to autonomous control architecture.

Expected TRL or TRL Range at completion of the Project: 2 to 5

Primary Technology Taxonomy:

- Level 1: TX 04 Robotics Systems
- Level 2: TX 04.4 Human-Robot Interaction

Desired Deliverables of Phase I and Phase II:

- Software
- Analysis

Desired Deliverables Description:

At the end of Phase I, the offeror will present a literature survey of autonomous commanding software used in terrestrial industrial settings. This survey should explain the verification rationale of established guidelines developed by relevant standards committees. Plans to demonstrate and test a new verification method to verify distributed commanding software will be presented. Formal verification methods based on model checking are discouraged, but some form of runtime monitoring or safety case generation may be acceptable.

At the end of Phase II, the offeror will provide a simulation that models the autonomous commanding software to demonstrate the suitability of the verification method in a realistic application environment. A reasonable simulation environment could be the autonomous control of a piloted crew surface vehicle that can either operate autonomously, be commanded by the on-board crew, commanded by an orbiting spacecraft, or commanded from an Earth-based control station. The verification method must establish the means to prove the control actions of the autonomous vehicle and the remote control stations can operate without force fights over control.

State of the Art and Critical Gaps:

The Human Landing System (HLS) providers currently have equipment that can be remotely controlled from Earth or controlled from the spacecraft they are installed, or perhaps another spacecraft. There currently exists no verification strategy capable of modelling and verifying a distributing commanding network of this complexity and having very significant latency for remote controllers. Similarly, Gateway has a requirement for command arbitration, but requires a robust verification method to ensure that proper command and control results.

This scope addresses shortfalls:

- 1543: Multi-Agent Robotic Coordination and Interoperability for Cooperative Task Planning and Performance
- 1625: Intelligent Multi-Agent Constellations for Cooperative Operations
- 1542: Metrics and Processes for Establishing Trust and Certifying the Trustworthiness of Autonomous Systems
- 1438: Autonomy, Edge Computation, and Interoperable Networking for Small Spacecraft

Relevance / Science Traceability:

Moon-2-Mars Program, Artemis Program, Human Landing System Program

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Scope Title: Verification of Machine Learning

Scope Description:

This scope aims to address the need to verify and validate machine learning algorithms that have been proposed for use in autonomous systems. The majority of machine learning algorithms today involve the use of convolutional neural networks. Although this approach has seen some recent successes, a significant problem is that a large data set is required to train the network (i.e., it takes a lot of input-response data to determine the weights of the network.) This can be a problem for autonomous systems because once trained, neural networks tend to be brittle in that they cannot adapt to conditions not included in the training data set.

This scope seeks the development methods to provide assurance of machine learning methods proposed for autonomous systems. Ways to verify the proper function of machine learning algorithms are desired that can provide robust operation of autonomous systems in the context of varied situations and incomplete/corrupted data. These approaches must allow the machine intelligence algorithm to sense, orient, decide, and act at the same speed and in the same manner as a human controller. In addition to neural networks, other model-based systems that adapt their model over time may also be considered. Again, in this case, a real-time verification method is needed because the model changes over time and cannot be verified ahead of time.

Expected TRL or TRL Range at completion of the Project: 2 to 6

Primary Technology Taxonomy:

- Level 1: TX 10 Autonomous Systems
- Level 2: TX 10.2 Reasoning and Acting

Desired Deliverables of Phase I and Phase II:

- Software
- Analysis

Desired Deliverables Description:

At the end of Phase I, the results of a literature survey will be presented of verification methods for machine learning that address the type of modelling used for the autonomous system, the learning method, the verification approach taken, and what methods might be good for machine learning in autonomous systems. A description of an approach or tool to verify machine learning will be presented.

At the end of Phase II, the proposed method to verify machine learning will be tested in simulation. The simulation must have the means to simulate learning in a changing environment with inclusion of process and measurement noise.

State of the Art and Critical Gaps:

The development of machine learning methods has received substantial attention in the last few decades. Machine learning attempts to learn the relationships between system inputs and outputs by identifying the coefficients of various models. The methods of least squares and Kalman filtering have been used to determine the values of a control derivative matrices. More recently, neural networks have been proposed to model relationships between large sensor inputs and system outputs for application in both vision and autonomous control. The advantage of multi-layer neural networks is that the weights of the network provide many degrees of modelling freedom. The problem with neural networks is that they require large data sets having many combinations of inputs and system responses to "learn" the system. A network that is trained using a particular data set may not work well when environmental or system changes.

It is hoped that this scope will provide assurance methods to provide real time verification of machine learning methods. As the environment or system changes, it is expected that the machine learning is going to need time to adapt as it acquires new inputs and outputs. A verification method is needed to determine when the learning process is complete and correct. Such methods do not currently exist. Methods for verification of machine learning will have application beyond NASA (e.g., self-driving cars, unmanned aircraft).

This scope addresses shortfalls:

- 1304: Robust, High-Progress-Rate, and Long-Distance Autonomous Surface Mobility
- 1542: Metrics and Processes for Establishing Trust and Certifying the Trustworthiness of Autonomous Systems
- 1532: Autonomous Planning, Scheduling, and Decision-Support to Enable Sustained Earth-Independent Missions
- 1438: Autonomy, Edge Computation, and Interoperable Networking for Small Spacecraft
- 1544: Resilient Agency: Adaptable Intelligence and Robust Online Learning for Long-Duration and Dynamic Missions

Relevance / Science Traceability:

Moon-2-Mars Program, Artemis Program, Human Landing System Program

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H8.01: In-Space Production Applications (InSPA) Flight Development and Demonstrations on ISS (SBIR)

Related Subtopic Pointers: T12.01
Lead Center: JSC
Participating Center(s): ARC, LaRC, MSFC

Subtopic Introduction
The NASA In-Space Production Applications (InSPA) portfolio invests in U.S. entities to develop, demonstrate, and master inspace production of goods and materials (including biomaterials) that target important terrestrial markets and lead to the creation of new markets and industries in space. InSPA is a collaboration between NASA and the International Space Station (ISS) National Laboratory to encourage use of the ISS and future low-Earth orbit (LEO) platforms that follow the ISS to advance NASA's objective to maintain and strengthen the United States' leadership of in-space manufacturing and production.

This subtopic supports the InSPA Project goals to: (1) Serve U.S. national interests by developing materials and technologies that strengthen industry leadership and improve national security; (2) provide benefits to humanity by developing products that significantly improve the quality of life on Earth; and (3) accelerate development of the space economy in LEO by stimulating demand for scalable and sustainable non-NASA utilization of future commercial LEO destinations.

Scope Title: Use of the ISS to Foster Commercialization of LEO Space

Scope Description
This subtopic seeks proposals that leverage the unique capabilities of the ISS to develop and test new technologies that will lead to in-space manufacturing of advanced materials and products for use on Earth. Proposals should clearly describe how development of its technologies and products will benefit from the space environment to produce advanced materials and products to a level of quality and performance superior to that which is possible on Earth. In addition, the value of the application, the market size, and the role space plays in developing a better product should be clearly presented. The intent is to transition the results of this subtopic into customer-scale, in-space manufacturing products to achieve U.S. Government objectives for developing the LEO economy.

Of specific interest are proposals that plan to develop valuable terrestrial applications that could lead to commercial markets in LEO. The emphasis is on producing goods or materials in space that are superior to what can be achieved on Earth and serve important national needs, benefit humanity, or lead to sustainable markets. Use of the ISS should facilitate validation of these applications and enable development of a product at reduced cost to attract significant capital and lead to growth of new and emerging LEO commercial markets in the following areas: advanced materials and biomanufacturing.

Proposals that can be implemented on the ISS within 2.5 years from first funds to first flight are highly encouraged to apply. Proposers with little or no flight experience are encouraged to contact the operator of the ISS National Laboratory—the Center for the Advancement of Science in Space (CASIS)—to discuss the practicalities of implementing their concept. Many first-time fliers have succeeded in flying their manufacturing or production prototypes on the ISS over the past 5 years. A high percentage of InSPA Small Business Innovation Research (SBIR) awards going back to 2016 have already flown at least once, and often more than once, on the ISS. In addition, proposed production strategies should be appropriate for the crewed vehicle and fit within the accommodations and constraints of the ISS National Laboratory.

For further information on InSPA goals and opportunities, please visit https://www.nasa.gov/international-space-station/space-station-research-and-technology/in-space-production-applications/

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy

- Level 1:TX 12 Materials, Structures, Mechanical Systems, and Manufacturing
- Level 2:TX 12.4 Manufacturing

Desired Deliverables of Phase I and Phase II

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description

For Phase I, as a minimum, development and test of a bench-top prototype and a written report detailing evidence of demonstrated prototype technology in the laboratory or in a relevant environment and stating the future path toward hardware demonstration in orbit. A preliminary assessment of the technology business case (cost and revenue forecast, market size, potential customers, etc.) is also required.
Desired deliverables at the end of Phase II would be a preliminary design and concept of operations, development, and test of an engineering development unit in a relevant environment (ground or space), and a report containing detailed science requirements, results of testing, and an updated business case analysis and/or application plan. Concepts that can achieve flight demonstration on a suborbital flight or on the ISS during Phase II are especially valuable.

State of the Art and Critical Gaps

The ISS is being used to stimulate both the supply and demand of the commercial LEO marketplace as NASA supports the development of the LEO space economy, while being aligned with the national goal to ensure the United States remains a world leader of in-space manufacturing and production of advanced materials.

This scope addresses gap #490 Additive Manufacturing for New and High Performance Materials found in the document: [https://www.nasa.gov/spacetechpriorities/.](https://www.nasa.gov/spacetechpriorities/)

Relevance / Science Traceability

This subtopic is in direct support of NASA's recent policy to enable commercial activities to take place aboard the ISS. The ISS capabilities will be used to further stimulate the demand for commercial products development and strengthen U.S. leadership in in-space manufacturing and production.

References

1. NASA LEO Economy Strategy:
   https://cms.nasa.gov/leo-economy/low-earth-orbit-economy and
   Solicitations: Where to Submit InSPA Proposals - NASA
2. Space Station Research & Technology at:
   Space Station Research Explorer on NASA.gov
3. Center for the Advancement of Science In Space, Inc. at:
   https://www.issnationallab.org and
   In-Space Production Applications (issnationallab.org).
   Both links are external.

H9.03: Flight Dynamics and Navigation Technologies (SBIR)

Related Subtopic Pointers: A2.01, S13.01, S16.03, Z-EXPAND.03, T5.06
Lead Center: GSFC
Participating Center(s): JPL, JSC, MSFC

Subtopic Introduction:

Future NASA missions require precision landing, rendezvous and proximity operations, non-cooperative object capture, formation flying, constellation design, and coordinated platform operations in Earth orbit, cislunar space, libration orbits, and deep space. These missions require a high degree of onboard autonomy that combines higher level mission planning with onboard state estimation and maneuver targeting/optimization. This subtopic seeks advancements in autonomous 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 operations.

The U.S. Space Surveillance Network currently tracks more than 45,000 Earth-orbiting objects larger than 10 cm, and the number of objects in orbit is steadily increasing, which causes an increasing threat to assets in the near-Earth environment. The NASA Conjunction Assessment Risk Analysis (CARA) program determines the risk posed by close approach events (conjunctions) between NASA satellites and other space objects as predicted by CARA operators at the Vandenberg Space Force Base using Department of Defense (DOD) and operator-provided trajectory information. CARA recommends risk mitigation strategies, including collision avoidance maneuvers, to spacecraft owner/operators for use to protect space assets and prevent the proliferation of space debris.

This subtopic addresses technology shortfall gaps from the July 2024 NASA Civil Space Shortfall Rankings Report (https://www.nasa.gov/spacetechpriorities/):

- Position, Navigation, and Timing (PNT) for In-Orbit and Surface Applications (ID 1557)
- Autonomous Guidance and Navigation for Deep Space Missions (ID 1531)
- Deep Space Autonomous Navigation (ID 1559)
- Space Situational Awareness (ID 1589)

Scope Title: Autonomous Onboard Spacecraft Navigation and Guidance

Scope Description:

Future human and robotic lunar, Mars, and small body missions require landing within a 50-m radius of the desired location to land near features of interest or other vehicles. Also, future exploration, on-orbit servicing alongside assembly and manufacturing, as well as Distributed Systems Missions (DSM) require rendezvous, precision formation flying, proximity operations, noncooperative object capture, and coordinated spacecraft navigation and guidance in Earth orbit, cislunar space, libration orbits, and deep space. Furthermore, the next generation of human spaceflight missions in cislunar space (e.g., Artemis, Human Landing Systems, and Gateway) will require complex trajectories, support of a variety of mission standard operating procedures, and detect a wide range of possible abort and contingency scenarios and execute verifiable operation procedures. These missions all require a high degree of autonomy, using onboard navigation/guidance algorithms alongside higher level planning and scheduling.

The subtopic seeks advancements in autonomous, onboard trajectory design, spacecraft navigation and guidance algorithms and software for application in Earth orbit, lunar, cislunar, libration, and deep space to reduce dependence on ground-based tracking, and orbit determination, including:

- Advanced, computationally efficient algorithms and software that can be run onboard a spacecraft for safe, precision landing on small bodies, planets, and moons, including real-time 3D terrain mapping, autonomous hazard detection and avoidance, and terrain relative navigation algorithms that leverage active lidar-based imaging, or methods with limited or no reliance on a priori maps.
- Computer vision techniques to support optical/terrain relative navigation and/or spacecraft rendezvous/proximity operations at unmapped bodies without a long survey/mapping phase and can operate in low and variable lighting conditions.
- Onboard relative and proximity navigation (relative position, velocity, and attitude, and/or pose), guidance algorithms and software, and onboard planning algorithms applying mission specific Guidance, Navigation and Control (GNC) methods which support cooperative and collaborative multi-spacecraft operations.
- Demonstration of utilization and integration of high-performance space computing-type assets to run complex navigation and guidance algorithms, such as Simultaneous Location and Mapping (SLAM), Terrain Relative Navigation (TRN), or in-flight convex optimization.
- Advancement of time estimation based on onboard clock and observable processing algorithms for supporting precision PNT for End User Spacecraft. Do not propose any hardware; refer to the related SBIR subtopic S203 Guidance, Navigation, and Control.
- Autonomous onboard mission design, applying mission specific trajectory design into planning and scheduling crewed and uncrewed missions.

    - For crewed missions, a loss-of-comm scenario in cislunar space could require potentially complex multi-burn transfer trajectory solutions to return to Earth without inputs from ground controllers. This includes onboard detection methods, trajectory optimization, and analytical or semi-analytical methods to seed optimization or guidance algorithms.

    - Uncrewed missions may require the autonomous computation of maneuvers to maintain or reconfigure a single spacecraft or distributed spacecraft system.

Proposals that leverage state-of-the-art capabilities already developed by NASA, or that can integrate with those packages, such as the core Flight System (cFS), AutoNav, Goddard Image Analysis and Navigation Tool (GIANT), or other available NASA hardware and software tools are highly 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.

Expected TRL or TRL Range at completion of the Project: 2 to 6

Primary Technology Taxonomy:

- Level 1: TX 17 Guidance, Navigation, and Control (GN&C)
- Level 2: TX 17.2 Navigation Technologies

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Software

Desired Deliverables Description:

Phase I research should demonstrate technical feasibility, determine expected system performance, and assess computational resource requirements, with preliminary software being delivered to NASA, as well as show a plan towards Phase II integration.

Phase II new technology development efforts shall deliver components at the TRL 5 to 6 level to NASA, with mature algorithms and software components with complete and preliminary integration and testing in an operational environment.

State of the Art and Critical Gaps:

Currently, navigation and guidance 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 necessary to reduce reliance on Earth for navigation solutions and maneuver planning. For example, spacecraft that arrive at a planetary surface may have limited ground inputs and no surface or orbiting navigational aids and may require rapid navigation updates to feed autonomous trajectory guidance updates and control. NASA currently has only limited navigational, trajectory, and attitude flight control technologies that permit fully autonomous approach, proximity operations, and landing without navigation support from Earth-based resources.

This subtopic addresses technology shortfall gaps from the July 2024 NASA Civil Space Shortfall Rankings Report (https://www.nasa.gov/spacetechpriorities/):

- Position, Navigation, and Timing (PNT) for In-Orbit and Surface Applications (ID 1557)
- Autonomous Guidance and Navigation for Deep Space Missions (ID 1531)
- Deep Space Autonomous Navigation (ID 1559)

Relevance / Science Traceability:

Relevant missions and projects include:

- Artemis (Lunar Gateway, Orion Multi-Purpose Crew Vehicle, HLS).
- Artemis On-Orbit Robotic Servicing, Assembly, and Manufacturing Applications.
- LunaNet.
- Autonomous Navigation, Guidance, and Control (autoNGC).

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 replanning and opportunistic science. It also aims to enable classes of missions that would otherwise not be possible due to round-trip communication time constraints.

References:

1. core Flight System (cFS): https://cfs.gsfc.nasa.gov/
2. LunaNet: https://esc.gsfc.nasa.gov/news/_LunaNetConcept
3. Goddard Image Analysis and Navigation Tool (GIANT): https://github.com/nasa/giant
4. Bhaskaran, S., "Autonomous Navigation for Deep Space Missions," Proceedings of the SpaceOps 2012 Conference, AIAA 20212-1267135, Stockholm, Sweden, June 11-15, 2012
5. autoNGC: https://ntrs.nasa.gov/api/citations/20240005228/downloads/autoNGC_SMD_Software_Workshop.pdf

Scope Title: Earth Orbit Conjunction Risk Analysis

Scope Description:

The NASA CARA program protects NASA assets from collision with other objects by submitting owner/operator trajectory information for the protected spacecraft, including predicted maneuvers, to the orbital safety analysts at Vandenberg Space Force Base in California. The trajectories are screened against the catalog of space objects, and information about predicted close approaches between NASA satellites and other space objects is sent back to CARA. CARA then determines the risk posed by those events and works with the spacecraft owner/operator to develop an appropriate mitigation strategy.

Note that this SBIR subtopic solicitation is a separate opportunity from the STTR subtopic solicitation (STTR CA subtopic ID T251). This opportunity focuses on proposals for Earth orbiting conjunction risk analysis applications. The STTR is focused on non-Earth orbit (lunar, cislunar, libration point, other planet orbits) conjunction risk analysis.

This subtopic seeks innovative technologies to improve the risk assessment process, including the following specific areas (see Reference 1 for the 2020 NASA Technology Taxonomy (TX) areas TX05.6.4, TX10.1.4, TX10.1.5, and TX10.1.6):

- Alternative risk assessment techniques and parameters. The Probability of Collision (Pc) is the standard metric for assessing collision likelihood. Its use has substantial advantages over the previous practice of using standoff distances. The Pc considers the uncertainties in the predicted state estimates at the time of closest approach (TCA), so it provides a probabilistic statement of risk. Several concerns with the use of the Pc, however, have been identified, including "diluted" probability (see Reference 2), "false confidence" (see Reference 3), and being "statistically biased" (see Reference 15). Special consideration will be directed to approaches that explicitly avoid extreme conservatism but instead enable taking prudent measures, at reasonable cost, to improve safety of flight, without imposing an undue burden on mission operations and the balancing required to improve safety while allowing largely unencumbered space mission operations.
- Innovative approaches to characterizing the uncertainties in the hard-body radius and object covariances (see Reference 4) that account for all the uncertainties in the inputs to the Pc calculation. The desired product is a range or Probability Density Function (PDF) of possible collision probabilities, or some other parameter that takes account of these uncertainties. Parameter uncertainties to consider include space weather, atmospheric density, solar

radiation pressure, object effective area, empirical covariance scale factors, etc. CARA does not perform orbit determination and cannot change the state estimation/propagation and uncertainty representation paradigm, so solutions that involve changes in orbit determination processes are not solicited.

• New or improved techniques or algorithms that use information available in a Conjunction Data Message (CDM) and historical information of a given space object to predict event severity in either a singular event or an ensemble risk assessment for contiguous close approaches for several events including those using artificial intelligence (AI) or machine learning (ML) are sought. Consideration should be given to the fact that sufficient truth data does not exist for collisions to train an AI system, so only solutions for decision-making, not for screening, are sought. Past NASA work in this can be found at https://www.nasa.gov/cara/cara-publications/#pub-i.

• New or improved techniques are sought to increase the speed of risk analysis of conjunction events that also retain the ability to screen the planned trajectory via the 19th Space Defense Squadron (19 SDS) process (see Space-Track.org). A semiautomatic approach for risk analysis could involve preliminary analysis on the severity levels of a given conjunction as a form of triage.

• Conjunction event visualizations are an effective method of improving understanding of conjunction geometry. To date, these visualizations have been set up manually when conjunctions of interest arise. It would be beneficial to be able to automatically produce an image showing the visualization of a close approach (state information in various coordinate/reference frames, covariance, variable hard-body radius information, approach angles, and other pertinent information using data from CDMs) when high-risk conjunctions are reported. These images would be accessible via a website platform and would have the ability to be packaged and sent out as an email summarizing the high-risk event in addition to providing user access to view current and a subset of historic high-risk events.

Expected TRL or TRL Range at completion of the Project: 2 to 5

Primary Technology Taxonomy:

- Level 1: TX 05 Communications, Navigation, and Orbital Debris Tracking and Characterization Systems
- Level 2: TX 05.6 Networking and Ground Based Orbital Debris Tracking and Management

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Software

Desired Deliverables Description:

Phase I research should demonstrate technical feasibility, with preliminary software being delivered to NASA, as well as show a plan toward Phase II integration.
Phase II new technology development efforts shall deliver components at the TRL 5 to 6 level to NASA, with mature algorithms and software components complete and preliminary integration and testing in a quasi-operational environment.

State of the Art and Critical Gaps:

The number of conjunction events is expected to continually increase with the increase of resident space objects from large constellations, the ability to track smaller objects, the increasing numbers of CubeSat/SmallSats, and the proliferation of space debris. Thus, CARA has identified the following challenges to which we are actively looking for solutions: efficient 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 risk evolution prediction, Machine Learning/Artificial Intelligence (ML/AI) applied to CA risk assessment parameters and/or event evolution. The decision space for collision avoidance relies on not only the quality of the data (state and covariance) but also the tools and techniques.

This subtopic addresses technology shortfall gaps from the July 2024 NASA Civil Space Shortfall Rankings Report (https://www.nasa.gov/spacetechpriorities/):

- Space Situational Awareness (ID 1589)

Relevance / Science Traceability:

This technology is relevant and needed for all missions operating in Earth orbit. The ability to perform conjunction risk assessment more accurately will improve space safety for all operations involving orbiting spacecraft.

References:

1. 2020 NASA Technology Taxonomy: https://www3.nasa.gov/sites/default/files/atoms/files/2020_nasa_technology_taxonomy_lowres.pdf
2. Alfano, Salvatore. "A numerical implementation of spherical object collision probability." The Journal of the Astronautical Sciences 53, no. 1 (2005): 103-109, https://link.springer.com/article/10.1007/BF03546397
3. Balch, Michael Scott, Martin, Ryan, and Ferson, Scott, "Satellite conjunction analysis and the false confidence theorem." Proceedings of the Royal Society A 475, no. 2227 (2019): 20180565, https://royalsocietypublishing.org/doi/10.1098/rspa.2018.0565
4. Frigm, Ryan C., Hejduk, Matthew D., Johnson, Lauren C., and Plakalovic, Dragan, "Total probability of collision as a metric for finite conjunction assessment and collision risk management." Proceedings of the Advanced Maui Optical and Space Surveillance Technologies Conference, Wailea, Maui, Hawaii. 2015, https://ntrs.nasa.gov/api/citations/20150018410/downloads/20150018410.pdf
5. NASA Conjunction Assessment Risk Analysis (CARA) Office website: https://www.nasa.gov/conjunction-assessment
6. 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
7. 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
8. Newman, Lauri K., et al., “NASA Conjunction Assessment Risk Analysis Updated Requirements Architecture,” AIAA/AAS Astrodynamics Specialist Conference, Portland, ME, AAS 19-668, (2019), https://ntrs.nasa.gov/api/citations/20190029214/downloads/20190029214.pdf
9. Office of the Chief Engineer, “NASA Procedural Requirements: NASA Spacecraft Conjunction Analysis and Collision Avoidance for Space Environment Protection,” NPR 8079.1, https://nodis3.gsfc.nasa.gov/displayDir.cfm?t=NPR&c=8079&s=1
10. NASA Spacecraft Conjunction Assessment and Collision Avoidance Best Practices Handbook: OCE_51.pdf (nasa.gov)
11. Consultative Committee for Space Data Systems (CCSDS) Recommended Standard for Conjunction Data Messages: https://public.ccsds.org/Pubs/508x0b1e2c2.pdf
12. S. Elkantassi and A.C. Davison, “Space Oddity? A Statistical Formulation of Conjunction Assessment”, Journal of Guidance, Control and Dynamics, Vol. 45, No. 12, December 2022, https://arc.aiaa.org/doi/pdf/10.2514/1.G006282
13. NASA's Space Sustainability Strategy, https://www.nasa.gov/spacesustainability/

H9.08: Lunar 3GPP Technologies (SBIR)

Lead Center: GRC
Participating Center(s): JSC

Subtopic Introduction:

NASA's Space Communications and Navigation (SCaN) program seeks innovative approaches to leverage terrestrial cellular technologies, standards, and architectures to establish and grow an adaptable and interoperable lunar communications infrastructure capable of supporting a wide range of future lunar mission users through lunar surface assets, as well as orbiting relay constellations. The lunar Third Generation Partnership Project (3GPP) subtopic focuses on any aspect of network development that may enhance capabilities for operating 3GPP networks in service of the Artemis program. This may include 3GPP compatible hardware that can operate in space and on the lunar surface, channel modeling, and emulation pertinent to operation of 3GPP networks on the lunar surface, and advances in 3GPP waveforms beneficial to deployment of lunar networks.

Scope Title: Lunar 3GPP Capability Development

Scope Description:

Terrestrially, substantial investments have been made in the Third Generation Partnership Project (3GPP) standards and technology over the past several decades of 3G/4G/5G development and operation. NASA is seeking to leverage this extensive development for the deployment of cost-effective and highly capable networking systems within the lunar communications architecture. However, operating in the lunar environment can be drastically different than operating terrestrially. This subtopic seeks to encourage development that is needed to translate terrestrial 3GPP technologies into a format suitable for the lunar environment, whether in terms of hardware (radiation hardening), software (lunar analysis tools), modeling (lunar regolith propagation and scattering), etc. This technology is urgently needed to close gaps in the lunar communications architecture and support the mission objectives of the Artemis program.

NASA's Artemis program is committed to landing and establishing a sustained presence for American astronauts on the Moon in collaboration with our commercial partners. In support of this goal, a flexible, interoperable communications network that can grow as demand and number of lunar mission users establish a presence on the lunar surface is critical. The first crewed landing of Artemis III will look to conduct additional demonstrations of 4G/5G communications systems on the lunar surface. In preparation for these and other future activities, the study and development of lunar surface/space-based applications of 3GPP technologies, waveforms, and modeling will lay the foundation for the future lunar surface communications infrastructure. Examples of specific research and/or technology development areas of interest include:

- Development of 3GPP-compliant hardware for long-term survivability in the lunar environment (surface and orbit), including radiation and thermal characteristics across a lunar day/night cycle.
- Path-to-standardization development/modification of 3GPP standards/waveforms to address the unique lunar surface environment (e.g., high multipath) and/or space-based environment (e.g., high Doppler, high latency).
- Interoperability between lunar surface architecture and orbiting relay architecture, including delay tolerant networking (DTN) to bridge the gap between ad hoc surface networks and highly scheduled Earth-relay networks. DTN functionality may be demonstrated as compatibility/operational use with the DTN layer of other services, as opposed to independent implementation of DTN.
- Development of unique capabilities supporting lunar exploration that can operate within the 3GPP framework (e.g., precision Position, Navigation, and Timing (PNT) services, sidelink capability, etc.).

- Development of channel models to support analysis of 3GPP performance in lunar environments.
- Development of coverage planning and capacity analysis tools that take into account the unique properties of the lunar environment (e.g., lunar radius, regolith radio frequency transparency, lunar topography, lunar geology, propagation through dust clouds, accumulation of dust layer on devices, etc.).
- Sidelink architectures for mission-critical suit-to-suit communication in disconnected environments, including 5G ProSe/V2X and multi-protocol (e.g., 5G + Wi-Fi) solutions.

Proposals to this subtopic should consider application to a lunar communications architecture consisting of surface assets (e.g., astronauts, science stations, robotic rovers, vehicles, and 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 (SWaP) suitable for small satellite (e.g., 50 kg) or CubeSat operations and 3GPP waveforms capable of withstanding relatively high Doppler rates (when considering Non-Terrestrial Network (NTN) links). Proposed solutions should highlight advancements to provide the needed communications capability while minimizing use of onboard resources, such as power and propellant. Proposals should consider how the technology can mature into a successful demonstration in the lunar architecture. If a proposal suggests or implies modification of 3GPP standards, the proposer should demonstrate a familiarity/history of participation in the relevant standard-making bodies and successful contributions to those organizations. The intent of this subtopic is to leverage existing terrestrial technologies and standards with only the minimum customization necessary for space/lunar usage, while acknowledging that there do exist fundamental differences that need to be addressed (e.g., lunar surface propagation modeling).

Expected TRL or TRL Range at completion of the Project: 4 to 6

Primary Technology Taxonomy:

- Level 1: TX 05 Communications, Navigation, and Orbital Debris Tracking and Characterization Systems
- Level 2: TX 05.3 Internetworking

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware
- Analysis
- Software

Desired Deliverables Description:

Phase I will study technical feasibility, infusion potential for lunar operations, and clear/achievable benefits, and show a path towards a Phase II implementation. Phase I deliverables 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 (Technology Readiness Level [TRL] 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 of prototype hardware/software is encouraged.

Phase II will emphasize hardware/software/waveform/model development with delivery of a specific product for NASA targeting future demonstration missions. 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 capability or hardware component(s) and evaluate performance in the lunar architecture for greater infusion potential. 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. Algorithms and channel models must be implemented in software and should be ready to be run on an appropriate general-purpose processor.

Opportunities and plans should be identified for technology commercialization. Software applications and platform/infrastructure deliverables shall be compliant with the latest NASA standards. The deliverable shall be demonstrated in a relevant emulated environment and have a clear path to Phase III flight implementation on a SWaP-constrained platform.

State of the Art and Critical Gaps:

NASA's Draft LunaNet Interoperability Specification has baselined 3GPP release 16 or later for short-to-medium range wireless networking with mobility and roaming.

The technology need for the lunar communication architecture includes:

- SWaP-efficient 3GPP hardware deployable as hosted payloads on lunar missions (habitats, rovers), surface assets (Commercial Lunar Payload Services), landers, or orbital assets.
- Connectivity between surface and orbital assets for trunk links with continuous coverage of the lunar south pole and far side.
- Effective characterization of 3GPP network performance in the lunar environment through channel modeling and emulation.
- Efficient use of lunar communication spectrum while avoiding the generation of interference (e.g., sensitive radio astronomy science concerned with very low out-of-band emissions).

Critical gaps between the state of the art and the technology need include:

- Space qualification of terrestrial 3GPP hardware and standards for the lunar environment, especially radiation tolerance. Other environmental concerns include survivability at extreme temperatures (-180 °C to +130 °C on the lunar surface, RF front end only).
- Implementation of 3GPP-capable systems on platforms with minimized size, weight and power (SWaP).
- Adaptive networking, including device-to-device connectivity when one or more devices cannot see a tower.
- Maximizing uplink (user to the base station) bandwidth using existing 3GPP technologies.
- Long-term 3GPP architecture development for sustained Artemis activity (permanent tower infrastructure and backhaul, etc.)
- Precision PNT over the surface link to augment availability and precision of overhead navigation assets.

This subtopic addresses shortfalls identified in the Civil Space Shortfall Ranking including:

- [Ranked 19th] ID 1558: High-Rate Communications Across the Lunar Surface
- [Ranked 4th] ID 1557: Position, Navigation, and Timing (PNT) for In-Orbit and Surface Applications

Relevance / Science Traceability:

Leveraging the vast investment in terrestrial 3GPP technologies over the past several decades is a critical opportunity for NASA's lunar communications architecture to deploy highly capable, reliable technologies at reasonable cost, but the feasibility of operation in the lunar environment must be demonstrated, and due consideration must be given to the unique challenges of operating in the lunar environment. As activity in the lunar vicinity increases through NASA's Artemis program and through international and commercial partnerships, deployment of scalable and efficient networks is essential to mitigate complexity and reduce operational cost.

References:

Several related reference documents include:

1. 2020 NASA Technology Taxonomy: https://www.nasa.gov/sites/default/files/atoms/files/2020_nasa_technology_taxonomy.pdf
2. LunaNet Interoperability Specification: https://www.nasa.gov/sites/default/files/atoms/files/lunanet_interoperability_specification_version_4.pdf
3. International Communications System Interoperability Standards (ICSIS): https://nasasitebuilder.nasawestprime.com/idss2/wp-content/uploads/sites/45/2020/10/communication_reva_final_9-2020.pdf
4. IOAG Future Lunar Communications Architecture Report: https://www.ioag.org/Public%20Documents/Lunar%20communications%20architecture%20study%20report%20FINAL%20v1.3.pdf
5. Space Frequency Coordination Group Recommendation SFCG 32-2R3: https://www.sfcgonline.org/Recommendations/REC%20SFCG%2032-2R5%20(Freqs%20for%20Lunar%20Region).pdf
6. CCSDS 883.0-B-1: https://public.ccsds.org/Pubs/883x0b1.pdf

H10.04: In-line Commodity Purity Analysis (SBIR)

Lead Center: SSC
Participating Center(s): N/A

Subtopic Introduction:

In NASA and commercial aerospace processes involving hydrogen, oxygen, methane, air, nitrogen, and helium, real-time in-line analysis of gas purity is critical for ensuring product quality, process efficiency, and compliance with stringent standards for mission success. Current methods involve significant down-time and touch-labor to install and take a sample with a certified vessel, to transfer the sample vessel to an analysis lab, and to distribute that sample to various instruments for specific species analysis. Current standards often suffer from limitations in real-time monitoring, accuracy under environmental and system conditions, the capability to maintain calibration, and the ability to detect trace impurities. Additionally, the size of systems does not allow for sampling in the process stream or at ideal locations, often requiring complex sample delivery and calibration systems that must be environmentally controlled and introduce more potential for outside contamination. Analysis of single impurities is possible, but small, lightweight, accurate systems that can analyze for all impurities in-line of process systems is not currently available. Innovations in this area are essential to address these challenges and advance the capabilities of industrial gas analysis technologies.

Scope Title: In-Line Commodity Purity Analysis

Scope Description:

This solicitation seeks innovative solutions capable of achieving real-time in-line analysis of hydrogen, oxygen, methane, air, nitrogen, and helium process streams, with a focus on detecting and quantifying impurities such as hydrocarbons, moisture, and total impurities per NASA purity standards. Analysis for applications targeted involve, but are not limited to, propellant quality and safety analysis, system pressurants, Environmental Control and Life Support Systems (ECLSS), and in-line analysis for habitats.

This solicitation is requesting innovative solutions that meet the following:

- Systems capable of continuous monitoring and analysis in real-time, directly in the process streams. Processes could involve, but are not limited to:
    - Transfer systems supplying propellants to storage and run tanks for engine and propulsion systems and components.
    - Pressurants for propellant tanks (e.g., flight, launch, ground test, and surface systems).
    - Propulsion system and vehicle component actuation and purging (flight, launch, ground test, and surface systems).
    - Gasses for ECLSS for future Surface and On-orbit habitats.
    - Gases from In Situ Resource Utilization (ISRU) processes.
- Target process streams are hydrogen, oxygen, methane, air, nitrogen, and helium.
- Real-time analysis can be up to once a minute with the eventual goal of enabling system response to prevent downstream hazards or contamination.
- Ability to detect hydrocarbons, moisture, and total impurities at trace levels per NASA MSFC-STD-3535.
    - Additional needs could include the measure O_2, H_2, and CH_4 at high concentrations of the gas, measure H_2O, CO, CH_4, H_2, HF, HCl, H_2S at ppm levels for O_2 production, measure H_2O and expected impurities for PEM and Alkaline electrolyzers, measure cross-over gases on alternative lines (ex. H_2 on O_2 side) at ppm levels.
- For ECLSS and habitats, the ability to detect contaminants and quality per NASA-STD-3001_VOL_1 - NASA Spaceflight Human-System Standard Volume 1, Crew Health.
- For liquid methane analysis, systems should be able to identify potentially hazardous mixtures, specifically with LM/LOX.
- Technologies should be operable with gases directly from cryogenic fluids, varying harsh environmental conditions, and potentially reduced gravity environments.
    - Applications should target sample locations from process streams as close to the point of use as possible. This involves vapor/gas temperatures just above cryogenic liquid conditions up to high temperatures required for environmental and system conditioning and/or resulting from ISRU processes and can involve a broad range of pressures.
    - Environmental conditions can range from terrestrial to lunar, Martian, and on-orbit temperatures and atmospheres.
- These sensors must operate for long durations where concerns include calibration/measurement drift, accuracy, time response, and contaminants. The system should include provisions for calibration routines that ensure accuracy and reliability over extended operational periods. Considerations should also prevent introducing cross-contamination of samples and systems.
- Considerations should be made for reduced size, weight, and power to enable installation flexibility and potential for supporting flight systems.
- The system should be compatible with existing process systems or easily integrated into new installations.

This topic is applicable to both NASA and the commercial aerospace industry as well as industries such as refining, petrochemical production, gas processing, and semiconductor manufacturing, where precise gas purity analysis is crucial for process optimization and product quality assurance.

Successful development of this technology will lead to an analysis system able to provide real-time monitoring for commodity purity in propellant, transfer, ECLSS systems, and in situ commodity production systems. Testing can be conducted at Stennis Space Center (SSC) to verify performance. If successful, the analyzer could provide a new capability for cost effective operations that would be of interest for future test customers, commodity transfer elements, and ISRU production elements.

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:

- Level 1: TX 13 Ground, Test, and Surface Systems
- Level 2: TX 13.1 Infrastructure Optimization

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Phase I desired deliverables for all the above technologies

- Research to demonstrate technical feasibility
- Proposed technical specifications
- Performance metrics
- Proof of concept
- Describe a path toward Phase II

Phase II desired deliverables for all the above technologies:

- Hardware prototype demonstration
- Delivery of a demonstration unit at the completion of the Phase II contract

State of the Art and Critical Gaps:

The state of the art for this subtopic includes mass spectrometers, gas chromatography, flame ionization detection, photoionization detection, and others, as well as combined/hybrid systems. Each method has unique setup, process, calibration, and environmental requirements and response. Additionally, each has its own level of detection specifications and characteristics such as sample required and source-to-detector distance, among others. These systems have not been fully integrated due to these issues, as well as the installation requirements to perform in-line sampling for transfer, ECLSS, habitat, and in situ systems. In most cases, the most accurate and reliable standard is to transfer a sample to a lab with each of these independent systems available for complete analysis. This method involves significant touch labor, down-time, personnel safety processes and procedures, facility resources, multiple independent instruments, and introduces additional contamination and failure points. Introducing additional failure points and potential for inaccurate analysis results in extended down-time and additional analysis and labor requirements.

Ground, lunar and Martian surface, and in-space transfer systems require the need to verify commodity purity to ensure mission success. This capability will only become more critical as touch labor availability is reduced and in situ commodity production ramps up within NASA programs and missions. The desired innovation would allow measurements to occur “in-line,” decreasing the complexity of securing the system to obtain samples and removing a touch labor point. The results of the analysis would also be available in real time, allowing rapid response to anomalies and improved operational efficiency.

A sustained lunar presence will rely on robust fluid management technologies to ensure on-demand availability of critical fluids. Capabilities to autonomously control flow will be desired. In addition, supervised-autonomous commodities conditioning across a network of storage locations and transfer lines (including consumption monitoring along with production and delivery tracking) will be desired to ensure on demand availability. The ability to verify compliance with purity standards in situ is vital for fluids with specific purity requirements prior to delivery.

Sensors to monitor process gases (oxygen, hydrogen, methane, air, etc.) in ISRU systems and directly within process streams are needed to ensure efficient and safe system operation. These sensors must operate for long durations where concerns include calibration/measurement drift, accuracy, time response, and contaminants. Instruments include pressure, temperature, gas flows, gas constituent contents, dew point/humidity, and contaminants. The detailed needs of the sensors will depend on the ISRU process implemented, but could include: measure O_2, H_2, and CH_4 at high concentrations of the gas; measure H_2O, CO, CH_4, H_2, HF, HCl, and H_2S at ppm levels for O_2 production; measure H_2O and expected impurities for PEM and Alkaline electrolyzers; measure cross-over gases on alternative lines (e.g., H_2 on O_2 side) at ppm levels.

This subtopic directly addresses the following shortfalls. Additional related shortfalls are indirectly supported and the complete systems to address those will require these technologies.

- 1583: Produce propellants and mission consumables from extracted in-situ resources.
- 1613: Surface-based fluid management for sustained lunar evolution.
- 1580: Extraction and separation of oxygen from extraterrestrial minerals.

Relevance / Science Traceability:

This subtopic is relevant to

- Moon to Mars architecture development of liquid propulsion systems and verification testing.
- Space Technology Mission Directorate (STMD) strategies (GO: develop rapid, safe, and efficient space transportation; and LIVE: sustainable Living and Working farther from Earth).
- Exploration Systems Development Mission Directorate-Space Operations Mission Directorate (ESDMD-SOMD).
- Autonomous Systems Lab (ASL).
- Ground test and support facilities at SSC and KSC.
- Other cryogenic fluid management, launch support, and propulsion system development centers, and ISRU elements.

References:

1. Stennis Space Center Home Page: https://www.nasa.gov/centers/stennis/home/index.html:
2. Technology Development and Transfer at Stennis Space Center: https://technology.ssc.nasa.gov/
3. NASA Technology Taxonomy: https://www.nasa.gov/offices/oct/taxonomy/index.html
4. NASA Strategic Space Technology Investment Plan: https://www.nasa.gov/wp-content/uploads/2015/03/strategic_space_technology_investment_plan_508.pdf
5. NASA Moon to Mars Architecture: https://www.nasa.gov/moontomarsarchitecture/
6. NASA STMD Strategic Framework: https://techport.nasa.gov/strategy
7. Standard for Propellants and Pressurants used for Test and Test Support Activities at SSC and MSFC: https://standards.nasa.gov/sites/default/files/standards/MSFC/A/0/msfc-std-3535a.pdf
8. A-STD-3001_VOL_1 - NASA Spaceflight Human-System Standard Volume 1, Crew Health: https://standards.nasa.gov/sites/default/files/standards/NASA/C//nasa-std-3001-vol-1-rev-c-signature.pdf

9. ISO 19229:2019 Gas analysis — Purity analysis and the treatment of purity data: https://www.iso.org/obp/ui/en/#iso:std:iso:19229:ed-2:v1:en
10. Trace level analysis of reactive ISO 14687 impurities in hydrogen fuel using laser-based spectroscopic detection methods: https://www.sciencedirect.com/science/article/pii/S0360319920334637?via%3Dihub
11. Development and evaluation of a novel analyser for ISO14687 hydrogen purity analysis: https://iopscience.iop.org/article/10.1088/1361-6501/ab7cf3
12. Sampling methods for renewable gases and related gases: challenges and current limitations: https://link.springer.com/content/pdf/10.1007/s00216-022-03949-0.pdf
13. Development of a cross-contamination-free hydrogen sampling methodology and analysis of contaminants for hydrogen refueling stations: https://www.sciencedirect.com/science/article/abs/pii/S0360319922036540?via%3Dihub
14. Characterization of natural gas by Raman spectroscopy and its application for in-situ measurements: https://journals.bg.agh.edu.pl/DRILLING/2018.35.1/125.php
15. From Light Pipes to Substrate-Integrated Hollow Waveguides for Gas Sensing: A Review: https://pubmed.ncbi.nlm.nih.gov/36785552/
16. Civil Space Shortfalls: https://www.nasa.gov/spacetechpriorities/

H12.09: In-Suit Detection of Venous Gas Emboli (SBIR)

Lead Center: JSC
Participating Center(s): N/A

Subtopic Introduction:

Given that extravehicular (EVA) suit operations are conducted in a reduced pressure environment relative to the vehicle or habitat, there is a risk of decompression sickness (DCS) during EVA in weightlessness and partial gravity during planned exploration missions. For many years prebreathe protocols with 100% oxygen (O_2) have been performed prior to EVA by Space Shuttle and International Space Station (ISS) astronauts to reduce DCS risk. These protocols have been supported by resources readily re-supplied from the ground. Resources, including crew time, will be constrained during lunar stays and missions to Mars, and astronauts will be expected to perform multiple EVAs within a mission. Additionally, studies have shown that partial-gravity exploration EVAs may potentially have a higher risk of DCS. Efficacious DCS risk mitigation activities could decrease consumable use and crew time while maintaining or reducing risk and maximizing EVA performance, thus extending the availability of resources, protecting reserves for contingency scenarios, and elevating the potential to achieve mission objectives. Manipulating vehicle or habitat and suit environments (e.g., breathing gas composition, pressure, etc.) can impact the requirements for DCS risk mitigation, and many of these environments are not yet defined, particularly for commercial providers. Further, contingency scenarios for unplanned vehicle, habitat, or spacesuit decompression result in significant risk of serious DCS and must be protected against for Mars missions.

Scope Title: In-Suit Detection of Venous Gas Emboli

Scope Description:

Astronauts are at risk of developing DCS during pressure transitions, such as transitioning from a pressurized habitable atmosphere to a lower pressure spacesuit during an EVA. Though denitrogenation protocols have been successful in mitigating DCS during microgravity EVA operations on the International Space Station (ISS), studies have shown that partial-gravity exploration EVAs will incur increased workloads and potentially a higher risk of DCS. [1,2].

DCS is assumed to result from the formation of bubbles in tissues and blood (venous gas embolism, or VGE), and there is an association between VGE after exposure to reduced pressures and the occurrence of DCS. NASA-STD-3001 [3] defines allowable limits for incidence of DCS (up to 15% allowable per EVA for Type I DCS) and VGE (up to 20% incidence of high grade VGE). During EVA operations, actual or suspected DCS will most often result in EVA termination. Detection of VGE in real time during EVA operations may improve prediction of DCS and potentially could be used for real-time management and treatment of DCS. NASA has previously used ultrasound imaging to detect VGE and score the severity during reduced pressure EVA simulations in a hypobaric chamber [4] but currently there is no method to detect VGE during operations in a pressurized spacesuit.

Expected TRL or TRL Range at completion of the Project: 4 to 6

Primary Technology Taxonomy:

- Level 1: TX 06 Human Health, Life Support, and Habitation Systems
- Level 2: TX 06.2 Extravehicular Activity Systems

Desired Deliverables of Phase I and Phase II:

- Hardware
- Prototype
- Research

Desired Deliverables Description:

PHASE I: Demonstrate the feasibility of a non-invasive sensor or device through limited laboratory testing that is capable of detecting blood and/or tissue bubbles and can be worn comfortably by an individual performing upper and lower body activity simulating the work done by astronauts during microgravity and lunar EVA. At the completion of Phase I, the prototype device does not need to be in the form required to fit inside the EVA suit, but the approach should be adaptable to achieve that end goal.

Required Phase I deliverables will include:

1. Development or procurement and modification of a physical prototype capable of accurate and reliable monitoring of VGE using the Eftedal-Brubakk score (or similar metric of decompression stress).
2. A test and evaluation plan to validate accuracy of data collection.
3. Demonstration of a wearable prototype device in a laboratory setting, ideally at NASA Johnson Space Center in the EVA and Environmental Physiology Laboratory.
4. Delivery of at least one working prototype to NASA for independent evaluation.
5. Documented development plan to achieve the aims of Phase II.

PHASE II: Validate the accuracy and precision of a prototype non-invasive sensor to detect and quantify VGE in a form that can be worn comfortably in a pressurized spacesuit environment and not interfere with upper body movements required to perform an EVA in weightlessness or a partial gravity environment. The plan will ensure that the system can be used during suited ground-based EVA simulations to collect and analyze data for subject comfort, and to test VGE detection algorithms.

Required features for the final product should include:

- Must be compatible with use inside a spacesuit during an EVA.
- Non-invasive and low-profile form factor.

- Ability to operate in reduced pressure (~4-8 psia) and elevated oxygen (>95%) environments for up to 8 hr.
- Must not require user input or control for monitoring for VGE or similar metric of decompression stress after device donning and initialization.
- Must record VGE metrics/events along with timestamp for later transmission and analysis.
- Must have ability to detect and grade systemic VGE or similar metric over at least 10 cardiac cycles per recorded event.

Ideal features for the final product would be:

- Should have ability to acquire 4-chamber view of the heart (similar to apical or parasternal views).
- Should have ability to acquire VGE or similar metric of decompression stress without interrupting EVA activities (i.e., no stop/rest needed).
- Should have ability to transmit composite VGE or DCS metric/data in near-real time.

State of the Art and Critical Gaps:

This capability would provide the ability to monitor and manage the risk of DCS in real-time in astronauts during exploration EVA operations. This subtopic addresses shortfall 1529: EVA and IVA Suit System Capabilities for Mars Mission in the Civil Space Shortfall Ranking list.

Relevance / Science Traceability:

This is relevant to the Space Operations Mission Directorate (SOMD) because of its applicability in human research and exploration. For example, this technology would assist in the success and closure of gaps EVA-303 and EVA-401 as identified in the Risk of Injury and Compromised Performance due to EVA Operations by NASA's Human Research Program (https://humanresearchroadmap.nasa.gov/). This subtopic also maps to the shortfall "EVA and IVA Suit System Capabilities for Mars Missions" for Advanced Habitation Systems.

References:

1. Abercromby AFJ, Conkin J, Gernhardt ML. Modeling a 15-min extravehicular activity prebreathe protocol using NASA’s exploration atmosphere (56.5 kPa/34% O2). Acta Astronautica. 2015; 109:76-87.
2. Conkin J, Pollock NW, Natoli MJ, Martina SD, Wessell JH III, Gernhardt ML. Venous gas emboli and ambulation at 4.3 psia. Aerosp Med Hum Perform. 2017; 88(4):370–376.
3. NASA-STD-3001. NASA Spaceflight Human-System Standard Volume 2: Human Factors, Habitability, and Environmental Health. Revision D.
4. Garbino A, Hew-Yang MY, Estep PN, Siders B, Dillon L, Suri K, Ramsburg C, Marshall-Goebel K, Abercromby AFJ. Development, Validation and Approval of A Planetary Extravehicular Activity Prebreathe Protocol: NASA Exploration Atmosphere Tests 1 & 2. Presented at Aerospace Medical Association (AsMA) 2024 Conference. Chicago, IL. 202.

H15.01: Autonomous Capabilities for Lunar Surface Mobility Systems (SBIR)

Related Subtopic Pointers: S11.01, T8.08
Lead Center: JSC
Participating Center(s): ARC, GRC, GSFC, JPL, MSFC

Subtopic Introduction:

The NASA Extravehicular Activity (EVA) and Human Surface Mobility (HSM) Program (EHP), seeks to advance the technologies associated with human mobility in support of NASA's Artemis missions. The EHP vision is to provide safe, reliable, and effective EVA and HSM capabilities that allow astronauts to survive and work outside the confines of a spacecraft on and around the Moon. Artemis missions will return humans to the surface of the Moon using innovative technologies to explore more of the lunar surface than ever before. NASA will collaborate with commercial and international partners and establish the first long-term presence on the Moon. Then, we will use what we learn on and around the Moon to take the next giant leap: sending the first astronauts to Mars.

EHP Flight Projects are Exploration EVA suits (xEVA suits) and tools, Lunar Terrain Vehicle (LTV), and Pressurized Rover (PR).

Artemis crewed missions are planned to have durations on the order of weeks. While crewmembers are away, NASA surface assets and vehicles are anticipated to continue operations to perform post-crew-departure activities, scientific and exploration objectives, vehicle relocation to a future landing site, and crew arrival preparations. Technologies are specifically sought which will enable these autonomous or semi-autonomous mobility systems to operate while crew is away. NASA is interested in advancements that will improve the operational cadence and performance of these mobility systems and increase the system's independence from ground operator intervention. These technologies will need to be operable and effective in the harsh environmental conditions of the lunar south pole, e.g., temperature extremes, radiation, and harsh lighting. New capabilities in this domain will mature Artemis mission concepts of operation, improve mission outcomes, and provide industry with the ability to offer improved lunar surface services to NASA or international partner space agencies.

Scope Title: Efficient On-board Autonomy for Robust High-Progress-Rate Driving Under Lunar Surface Environmental Conditions

Scope Description:

Autonomous mobility is essential for enabling Artemis mission success during uncrewed periods, yet current state-of-the-art uncrewed lunar surface mobility does not provide the required speed-made-good or long-duration robustness to meet required mission performance. The desired high-progress-rate is expected to be 1-2 orders of magnitude higher than Mars rovers. Current reliance on ground operators will also dramatically limit the operational impact surface rovers will have in-between crew visits. Limited situational awareness and communication challenges (time delay, latency, bandwidth limitations, etc.), coupled with challenging mobility requirements that exceed the level of performance demonstrated by prior lunar surface systems, necessitate advances in autonomous navigation in order to achieve NASA's Moon-to-Mars objectives.

The lunar environment presents unique challenges beyond those encountered by terrestrial autonomous vehicles, including: the lack of precise localization infrastructure (e.g., Global Positioning System or GPS), harsh and low-angle sunlight, and a monochromatic environment. Additionally, autonomy solutions must be suitable for use on resource-constrained, space-rated computing or establish a path to flight by leveraging new flightworthy processor architectures.

To achieve high-progress-rate driving on the lunar surface while being robust to the many hazards present, technology areas of interest include, but are not limited to:

- Autonomous navigation, path planning, localization, mapping, or simultaneous localization and mapping (SLAM**)** algorithms suitable for the lunar surface environment and optimized for deployment on lunar-worthy computing platforms (existing and/or new high performance spaceflight processors in development).
- Evolution of surface navigation techniques suitable to the GPS-denied lunar surface environment, such as Visual Inertial Odometry, Pedestrian Dead Reckoning, and usage of radio frequency (RF) beacons, that provide vehicle location to better than 10m.
- Hazard detection and avoidance, feature segmentation, and other perception-based algorithms and behaviors robust to the unique features of the lunar south pole region (lunar lighting; terrain texture, color, and lack of defining landmarks; etc.).
- Intelligent terrain assessment and classification (slopes, regolith density, etc.) to determine safe driving paths.
- Machine learning approaches to autonomous driving development compatible with limited datasets and training opportunities available for lunar surface mobility.
- Novel approaches to increase efficiency, decrease required power, or eliminate reliance on off-board computing for autonomous mobility algorithms.

A significant body of research and prior/current commercialization efforts exist in related technology areas as applied to terrestrial applications, and innovative ways to translate this work to lunar-worthy solutions is encouraged. New capabilities are also sought to address unique lunar surface challenges and expand autonomous rover capability. All proposed technologies, however, must be explicitly targeted to lunar surface applications with a viable path to operation on-board surface mobility systems leveraging flight-rated processors. To establish this, infusion path proposals are encouraged, but not required, to:

- Target near-term integration and testing on flight-proven computing platforms and/or new, in-development, high-performance spaceflight processors likely to provide extended life in the lunar south pole environment (Note: New processor development is not in scope within this subtopic, but integrated testing is seen as beneficial).
- Use industry-standard software interfaces, architectures, and frameworks that align with relevant NASA and commercial space robotic efforts to reduce future integration effort and facilitate multi-platform adoption of offered technology.
- Provide analog testing and demonstration to establish performance in lunar surface conditions.

Expected TRL or TRL Range at completion of the Project: 2 to 6

Primary Technology Taxonomy:

- Level 1: TX 10 Autonomous Systems
- Level 2: TX 10.1 Situational and Self Awareness

Desired Deliverables of Phase I and Phase II:

- Software
- Prototype
- Research
- Analysis

Desired Deliverables Description:

Desired deliverables for this scope include software algorithms and/or example programs that demonstrate one or more technology areas of interest. Greater maturity and complexity will differentiate Phase II deliverables from Phase I.

Phase I deliverables may include:

- Background research and feasibility studies.
- Conceptual design, trade studies, and description of proposed solution.
- In some instances, an initial proof-of-concept implementation and/or testing (using either hardware or simulation).

Phase II deliverables may include:

- Software source code, user manual/instructions, documentation.
- Test and/or performance data.
- Demonstration of software prototype on robot, rover, or flight computing hardware.

State of the Art and Critical Gaps:

Terrestrial autonomous driving capabilities are still in the fledgling stages of widespread implementation and adoption. These state-of-the-art technologies still require oversight by a driver. For consumer applications on public roads, that driver is in the vehicle. For controlled environments, such as military or mining operations, a driver could be remotely overseeing the vehicle's operations. These current technologies rely on many resources that are not yet available on the Moon, such as GPS, rich datasets for training machine learning algorithms, high-performance embedded processors, high-speed wireless communications, and machine vision algorithms created to exploit terrestrial features (e.g., stop signs, road markings, etc.). Furthermore, the existing operational paradigm for Mars rovers will not be able to meet the desired cadence for lunar surface operations, and the lunar surface poles present unique challenges concerning lighting conditions and hazards. Adaptations or extensions of these approaches must be developed to translate existing levels of performance to the lunar surface, and further innovative technologies are needed to expand mobile surface system capabilities to meet future operational requirements and enable mission success.

This scope helps to address Civil Space Shortfall 1304, Robust, High-Progress-Rate and Long-Distance Autonomous Surface Mobility.

Relevance / Science Traceability:

The main NASA target for infusion of this subtopic's successful proposals is EHP. Several areas of EHP responsibility could use efficient on-board autonomy, including the Lunar Terrain Vehicle and Pressurized Rover. High-progress-rate driving on the lunar surface will enable productivity during uncrewed periods between Artemis missions.

References:

1. NASA Cross-Program Design Specification for Natural Environments (DSNE), current version Revision I as released on the NASA Technical Reports Server (NTRS). [SLS-SPEC-159 Cross-Program Design Specification for Natural Environments (DSNE) REVISION I.pdf (nasa.gov)]
2. Artemis information: https://www.nasa.gov/artemisprogram

3. EHP information: https://www.nasa.gov/suitup
4. Civil Space Shortfalls: https://www.nasa.gov/spacetechpriorities/

Scope Title: Sensing and Perception Systems Suitable for Extended Use on the Lunar Surface

Scope Description:

Accurate sensing and perception are critical for enabling autonomous mobility on the lunar surface. Current state-of-the-art approaches to autonomous mobility on Earth typically rely on a variety of sensors that do not have corresponding lunar surface analogs. For example, lunar-worthy lidar (laser imaging, detection, and ranging) for rover navigation on the Moon is not currently available as a matured technology, and the performance and survivability of sensors used terrestrially have not been established in the lunar environment. This introduces considerable risk to surface mobility system design and/or a significant limit to operational effectiveness if advances are not made.

This scope targets new sensor hardware that will survive long-duration lunar surface operation and provide performance levels at or beyond existing terrestrial state-of-the-art to enable robust lunar surface autonomous mobility. Technology areas of interest include:

- Availability of lidar hardware (systems and components) suitable for long-duration use in the lunar environment (e.g., lighting conditions, radiation, temperature, dust).
- Novel approaches to efficient data processing/point cloud generation.
- Other sensing modalities with application to lunar navigation.

Innovative approaches to adapting terrestrial autonomous vehicle sensors to lunar conditions are welcomed, as is new sensor hardware design. Unique sensing modalities not typically used for mobility are appropriate if associated driving performance can be clearly established as exceeding current capabilities. Adapting sensors with prior spaceflight heritage, or established flight-like design, to the lunar surface mobility use-case is acceptable as well, if the proposed innovation leads to greater autonomous capability for surface rovers.

A clear understanding of existing relevant state-of-the-art sensors and how the proposed technology compares in performance must be demonstrated. And in all cases, new sensors must have a viable path to lunar surface operation, be designed for integration into human-scale lunar surface rovers, and be compatible with autonomous driving algorithms or approaches. To facilitate infusion, proposals are encouraged but not required, to:

- Use industry-standard hardware and software interfaces and architectures to reduce future integration effort and ease adoption.
- Limit dependence on third-party proprietary technologies that might complicate NASA or commercial adoption of the technology.
- Target near-term demonstration of sensor technology in a relevant mobility context.

Expected TRL or TRL Range at completion of the Project: 2 to 6

Primary Technology Taxonomy:

- Level 1: TX 04 Robotics Systems
- Level 2: TX 04.1 Sensing and Perception

Desired Deliverables of Phase I and Phase II:

- Hardware
- Software
- Prototype
- Research
- Analysis

Desired Deliverables Description:

Desired deliverables for Phase I include:

- Background research and feasibility studies.
- Conceptual design, trade studies, and description of proposed solution.
- In some instances, an initial proof-of-concept implementation and/or testing using either hardware or simulation (which may be particularly relevant for novel adaptations to existing designs).

Desired deliverables for Phase II ideally include:

- Initial sensor prototype and corresponding design details.
- Test/performance data in an analog environment with associated analysis.
- Integrated demonstration in a surface mobility context.

State of the Art and Critical Gaps:

Existing state-of-the-art consists of sensors used for terrestrial autonomous mobility. Commercial lidar technology is unproven in lunar surface conditions, however, and other technologies could be applied, e.g., radar. Flight development to date has largely focused on in-space applications, not surface applications. Therefore, direct focus on lunar surface survivability and performance requirements associated with surface mobility is needed.

Devices with lower power and less constrained thermal requirements are needed, as are sensors suitable for long-duration operation in the radiation, dust, and thermal environment of the lunar south pole. Surviving the lunar night is a critical gap, and the ability to operate throughout the lunar night would greatly expand surface system capabilities.

Mobility based on visual cameras is significantly hindered by lighting conditions at the lunar south pole and robust sensors that overcome this challenge are needed.

This scope addresses Civil Space Shortfall 1548, Sensing for Autonomous Robotic Operations in Challenging Environmental Conditions.

Relevance / Science Traceability:

EHP missions provide immediate infusion potential for the subject sensor technologies, with highly relevant projects like the Lunar Terrain Vehicle, Pressurized Rover, and other future mobility systems all requiring robust lunar-worthy perception sensing. The current EHP Autonomous Mobility and Operations Roadmap identifies lunar-worthy perception sensing (and lunar-worthy lidar in particular) as a significant near-term priority.

Comparable Science Mission Directorate (SMD) activities on the lunar surface, epitomized by the high-priority Endurance-A mission called out in the latest Planetary Science Decadal, are also enabled by long-life sensors for autonomous navigation.

References:

1. NASA Cross-Program Design Specification for Natural Environments (DSNE), current version Revision I, as released on the NASA Technical Reports Server (NTRS). SLS-SPEC-159 Cross-Program Design Specification for Natural Environments (DSNE) REVISION I.pdf (nasa.gov)
2. Artemis information: https://www.nasa.gov/artemisprogram
3. EHP information: https://www.nasa.gov/extravehicular-activity-and-human-surface-mobility/
4. Civil Space Shortfalls: https://www.nasa.gov/spacetechpriorities/

Scope Title: Supervised Autonomy and Shared Control Paradigms for Remote Surface Operations

Scope Description:

As NASA begins Artemis missions, the communications environment will be different from decades of human spaceflight operations in low-Earth orbit (LEO). Whereas communications latency to the International Space Station is on the order of hundreds of milliseconds, the time it takes for signals to reach the Moon is expected to be approximately 3 seconds, and it can take as much as 24 minutes each way to Mars. Additionally, less bandwidth is expected to be available, along with extended periods of communication blackout and/or intermittent communication connections, especially when crew is not present. This communications scenario drives a need for increased autonomy in surface mobility systems. Existing approaches to remote command and control in LEO or on Mars are not suited for the unique lunar surface time delay and other operational constraints. And unlike current operations on the Martian surface, lunar surface operations (along with future Mars exploration activities) will occur at a faster, human-scale, operational cadence (both with and without crew), necessitating both a greater real-time response to remote commands and autonomous onboard decision making. These two components must also work in tandem, and cohesive integration is critical to realizing effective human-robot coordination during surface operations.

Enabling the wide range of robotic surface operations outlined in NASA's Moon-to-Mars objectives, including important near-term surface mobility tasks, requires the development and implementation of new supervised autonomy and shared control paradigms.

Technology areas of interest include but are not limited to:

- Novel supervisory control techniques to accommodate intermediate time delays, data latencies, and unreliable/intermittent communication.
- Integrated command and control interfaces for remote operators to oversee lunar surface activity (extensible to multiple and/or varied surface mobility systems).
- Autonomous recognition of objects/areas of interest for science investigation.
- Intelligent path planning and waypoint generation over long distances.
- Contextual data prioritization for communicating relevant system health information over limited bandwidth.
- Task primitives or task parameterization related to surface mobility.
- Improved autonomy for planning, scheduling, and execution.

All technologies must provide a demonstrable advance over current state-of-the-art solutions and offer a viable path to adoption in lunar surface operations. Dual-use technologies with broad applicability to robotic operations in other space environments or mission scenarios are encouraged, as is relevance to terrestrial needs for improved supervisory control and remote autonomous operations, but impact to near-term lunar surface mobility objectives is a high priority.

An emphasis on interoperability, modularity, and compatibility with multiple robots and existing control architectures/frameworks is strongly encouraged to facilitate infusion and the development of fully integrated human-robot supervisory control solutions.

Expected TRL or TRL Range at completion of the Project: 2 to 6

Primary Technology Taxonomy:

- Level 1: TX 04 Robotics Systems
- Level 2: TX 04.4 Human-Robot Interaction

Desired Deliverables of Phase I and Phase II:

- Software
- Prototype
- Research
- Analysis

Desired Deliverables Description:

Phase I deliverables include:

- Background research and feasibility studies.
- Conceptual design, trade studies, and description of proposed solutions.
- Initial software algorithms and/or example programs demonstrating desired technical advances.

Desired deliverables for this scope include software algorithms and/or example programs that demonstrate one or more of the items listed in the technology areas of interest. Greater maturity and complexity will differentiate Phase II deliverables from Phase I.

Deliverables for Phase II will be of greater maturity and complexity than Phase I deliverables and may include:

- Software source code and/or block diagrams, user manual/instructions, documentation.
- Test and/or performance data with associated analysis.
- Demonstration of software prototype on representative robot(s), rover(s), or flight computing hardware.

State of the Art and Critical Gaps:

The current state-of-the-art consists of the following areas (followed by specific shortcomings/gaps that still need to be addressed to meet lunar surface operational needs):

- Mars science rover operations: Large communication delays prevent real-time operations, but this also allows for significant off-line human/operator analysis and planning before robot execution. Human decision making and robot/rover autonomy must be better integrated in the lunar surface setting.
- ISS robotic operations: Lower time delays and direct human-in-the-loop command and control allow for less autonomy than is needed during remote lunar surface operations.
- Low TRL robotic manipulation: A large body of low TRL research exists developing supervised autonomy and remote human-robot interaction, typically in structured environments or zero-time-delay situations. Extending these approaches to robotic mobility and developing technology products robust to the unstructured environment of the lunar surface is needed.
- Terrestrial remote robotic applications (e.g., military, undersea, etc.): Even in these scenarios, remote operator situational awareness is better than can currently be achieved on the lunar surface. Remote

command and control of terrestrial assets can leverage Earth-based infrastructure not available to lunar surface mobility systems.

This scope addresses Civil Space Shortfalls 1532 (Autonomous Planning, Scheduling, and Decision-Support to Enable Sustained Earth-Independent Missions) and 1541 (Intuitive and Efficient Human-Robot Interaction for Safe Teaming and Remote Supervisory Control).

Relevance / Science Traceability:

NASA's Moon-to-Mars objectives highlight the need for "local, regional, and global surface mobility in support of a continuous lunar presence" (LI-6) and the need to "operate robotic systems that are used to support crew on the lunar or Martian surface, autonomously or remotely from the Earth or from orbiting platforms" (OP-10). These specific objectives and others like them speak to the immediate relevance of supervised autonomy and remote shared control paradigms and products to NASA's near-term lunar surface activities and the broader desire to expand and sustain lunar surface operations. Focusing this technology development on surface mobility specifically serves to enable initial uncrewed activities, enhance early crew missions, and provide a path to rapid spaceflight operational infusion for commercial offerors.

Successful proposals to this subtopic will directly address EHP program needs and mature needed technology outlined in the current EHP Autonomous Mobility and Operations roadmap. As the number of surface assets grows over the course of Artemis missions, the need for more robust supervised autonomy extending across a broader set of surface systems becomes even more important to ensure effective interoperation.

References:

1. NASA Cross-Program Design Specification for Natural Environments (DSNE), current version Revision I, as released on the NASA Technical Reports Server (NTRS): SLS-SPEC-159 Cross-Program Design Specification for Natural Environments (DSNE) REVISION I.pdf (nasa.gov)
2. Artemis information: https://www.nasa.gov/artemisprogram
3. EHP information: https://www.nasa.gov/extravehicular-activity-and-human-surface-mobility/
4. Civil Space Shortfalls: https://www.nasa.gov/spacetechpriorities/

H15.02: Simulation and Modeling of Lunar Mobility System Interaction with Lunar Regolith (SBIR)

Related Subtopic Pointers: S17.03, Z-LIVE.04
Lead Center: JSC
Participating Center(s): ARC, GRC

Subtopic Introduction:

The NASA Extravehicular Activity (EVA) and Human Surface Mobility (HSM) Program (EHP) seeks to advance the technologies associated with human mobility in support of NASA’s Artemis missions. The EHP vision is to provide safe, reliable, and effective EVA and HSM capabilities that allow astronauts to survive and work outside the confines of a spacecraft on and around the Moon. Artemis missions will return humans to the surface of the Moon using innovative technologies to explore more of the lunar surface than ever before. NASA will collaborate with commercial and international partners and establish the first long-term presence on the Moon. Then, NASA will use what is learned on and around the Moon to take the next giant leap: sending the first astronauts to Mars.

EHP Flight Projects are Exploration EVA suits (xEVA suits) and tools, the Lunar Terrain Vehicle (LTV), and the Pressurized Rover (PR).

Following a Phase II award, successful development will produce near-flight prototype hardware and/or software that demonstrates tangible progress toward capabilities required for Artemis surface mobility. In outstanding cases, flight demonstrations may be achieved by leveraging NASA or EHP assets, such as vehicles or flight opportunities. New hardware and software development is expected to leverage, as appropriate, common interfaces, modular and/or interoperable approaches, and testing opportunities with existing NASA hardware, vehicles, simulations, prototypes, or datasets in conjunction with relevant NASA projects. This approach is intended to facilitate adoption of highly relevant technologies and capabilities for NASA and commercial applications.

In this subtopic, NASA seeks new technologies to:

1. Improve the modeling and simulation of surface mobility asset interaction with lunar regolith.
2. Characterize the effects of lunar regolith and the overall environment on mobility systems.
3. Increase the robustness and resilience of surface mobility operations via the leveraging of terrain, terramechanics, and interactive dynamics data.

Scope Title: Macro and Micro Level Terramechanics Modeling and Simulation Tools

Scope Description:

Simulations that can estimate vehicle-regolith interactions with high accuracy are needed. A mix of computationally efficient semi-empirical or low fidelity and finer high accuracy/fidelity simulations contribute to understanding how lunar systems will interact with the lunar surface in dissimilar environments.

Traditional semi-empirical terramechanics modeling approaches struggle with the complex responses of compliant tires and other implements as they interact with regolith. While high-fidelity simulations can capture these complexities, they do not capture the full resolution of the terrain or are too computationally intensive to utilize for large-scale simulations. Thus, they are used for point evaluations such as tires, blades, foundations, etc.

A combination of both methods for a multi-scale and/or a parameterized approach can yield further possibilities and opportunities for integration into NASA mission frameworks. Such systems could be utilized for simulation testing to evaluate controllability and acceptability from a human perspective (i.e., augmented/virtual reality integration). Finally, both simulation methods are required to help perform verification and validation at the mission, system, and subsystem requirement levels.

Expected TRL or TRL Range at completion of the Project: 1 to 6

Primary Technology Taxonomy:

- Level 1: TX 04 Robotics Systems
- Level 2: TX 04.2 Mobility

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Software
- Hardware

Desired Deliverables Description:

Phase I deliverables may include:

- Background research and feasibility studies.
- Conceptual design, trade studies, and description of proposed solutions.
- In some instances, an initial proof-of-concept implementation and/or testing.

Phase II deliverables may include:

- Software source code, user manual/instructions, documentation.
- Test and/or performance data.
- Demonstration of prototype software.

State of the Art and Critical Gaps:

Classic terramechanics models that simulate the interaction between wheel and lunar regolith and determine mobility performance typically rely on semi-empirical methods and do not account for all the complex features of both tires (especially in the case of compliant tires) and terrain. These models are used to determine wheel sinkage, compression resistance, bulldozing resistance, and tractive force based on soil parameters, wheel parameters, and force on the wheel. They have proven useful in certain situations but have limitations. Most of these models are either only intended for rigid wheels or take a simplistic approach when dealing with compliant tires.

Physics-based models are becoming more common, but they have their own limitations. Hi-fidelity models, such as discrete element methods, can simulate interactions at the regolith particulate level but are very time- and resource-intensive to run. They are not conducive to full-system, long-duration simulations. Reduced fidelity models can help to enable the full-system simulations but then may not capture some of the complex phenomena related to the interaction between the terrain and the vehicle or tires. This is especially true for the cases where tires must be compliant, which is expected for most crewed vehicles.

In addition, existing terramechanics models determine soil resistance and tractive force in a longitudinal direction. A new capability is needed to determine soil resistance and tractive force in the lateral direction to better predict the performance of a wheel-based surface mobility system traversing a cross-slope or compound slope conditions. It is critical to understand the interaction between lunar regolith (soft soil) and a compliant tire for both hi-fidelity tire-regolith simulations and for robust and reliable vehicle-level simulations. This capability will help NASA better understand a vehicle's performance and help with evaluation and verification of a mobility system at both wheel and vehicle level.

Gaps that are highly relevant to this scope are:

- 581: ISRU System Modeling.
- 1585: Extraterrestrial Surface Environmental Simulators, Test Facilities, and Test Sites.
- 1336: Robotic Mobility for Robust, Repeatable Access to and Through Extreme Terrain, Surface Topography, and Harsh Environmental Conditions.
- 385: Regolith and Resource Delivery System

Relevance / Science Traceability:

The main NASA target for infusion of this subtopic's successful proposals is EHP. Several areas of EHP responsibility could use macro- and micro-level terramechanics modeling and simulation tools, including the LTV and PR. The technologies may also be relevant to in situ resource utilization (ISRU), habitat construction, or other areas where physical interactions with lunar regolith will occur.

This subtopic addresses Civil Space Shortfalls:

- 1304 (Robust, High-Progress-Rate, and Long-Distance Autonomous Surface Mobility).
- 1336 (Robotic Mobility for Robust, Repeatable Access to and Through Extreme Terrain and Surface Topography).

References:

1. Lunar Mobility Drivers and Needs, 2024 Moon to Mars Architecture Concept Review: https://www.nasa.gov/wp-content/uploads/2024/06/acr24-lunar-mobility-drivers-and-needs.pdf?emrc=b2dafa
2. Li, Z.Q.; Bingham, L.K., "NASA White Paper, Terramechanics for LTV Modeling and Simulation": https://ntrs.nasa.gov/api/citations/20220010732/downloads/Terramechanics_white_paper.pdf
3. "Why Artemis Will Focus on the Lunar South Pole Region," 2022 Architecture Concept Review: https://www.nasa.gov/wp-content/uploads/2023/10/acr22-wp-why-lunar-south-polar-region.pdf?emrc=ced2ac
4. Extravehicular Activity & Human Surface Mobility Program: https://www.nasa.gov/extravehicular-activity-and-human-surface-mobility/
5. Civil Space Shortfalls: https://www.nasa.gov/spacetechpriorities/

Scope Title: Simulation and Modeling of Wheeled or Tracked System Degradation from Regolith Interactions on the Lunar Surface

Scope Description:

Proposals are sought for tools to achieve simulation and modeling of wheeled or tracked system degradation from regolith interactions on the lunar surface. Other subtopics seek physical solutions for hardware that is robust to the extreme environment found on the Moon; however, this subtopic scope seeks the means to evaluate how systems, specifically mobility systems, degrade or change over long-duration exposure on the lunar surface. This environment is known to be extreme, with the presence of lunar regolith and dust particles, electric field effects, high vacuum, cosmic rays and other ionized particles, solar radiation, changing thermal emittance due to dust deposition, wide temperature ranges, and so forth as described in the NASA Cross-Program Design Specification for Natural Environments (DSNE). The performance and endurance of NASA missions can be improved with technologies to understand the impacts of the lunar environment on mobile systems.

Expected TRL or TRL Range at completion of the Project: 1 to 6

Primary Technology Taxonomy:

- Level 1: TX 04 Robotics Systems
- Level 2: TX 04.2 Mobility

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype

- Hardware
- Software

Desired Deliverables Description:

Phase I deliverables may include:

- Background research and feasibility studies.
- Conceptual design, trade studies, and description of proposed solution.
- Plans for testing or validation in a relevant lunar environment post-Phase I award.
- In some instances, an initial proof-of-concept implementation and/or testing.

Phase II deliverables may include:

- Software source code, user manual/instructions, documentation.
- Test and/or performance data.
- Demonstration of assessment techniques.

State of the Art and Critical Gaps:

State of the art for lunar applications is currently not well understood, but it is assumed that terrestrial heavy equipment manufacturers are able to assess their vehicle drive systems for durability in a variety of environments. For recent qualification of mobility systems in the Volatiles Investigating Polar Exploration Rover (VIPER) lunar mission, extensive testing with lunar simulants was performed at test facilities with lunar simulants relevant to the intended operating location. This method of testing can only occur after a prototype is constructed later in the design cycle. Analysis tools and techniques that would allow for analysis and iteration earlier in a project could hold substantial benefits for cost and schedule.

Gaps that are highly relevant to this scope are:

- 1304: Robust, High-Progress-Rate, and Long-Distance Autonomous Surface Mobility
- 1548: Sensing for Autonomous Robotic Operations in Challenging Environmental Conditions
- 1561: Advanced Modeling and Test Capabilities to Characterize Dust Effects on Hardware
- 1336: Robotic Mobility for Robust, Repeatable Access to and Through Extreme Terrain, Surface Topography, and Harsh Environmental Conditions

Relevance / Science Traceability:

Artemis missions are architected for humans to return to the Moon for greater durations. For example, the Lunar Terrain Vehicle Services contract has a requirement for 10 years of service. Tools that anticipate degradation of wheeled or tracked systems hold great value for mission planners, operators, and engineering teams to understand the health and service life of critical surface mobility assets. This can ensure well-informed decisions on sparing strategies, logistics planning, crew tasking, and mission objectives.

This subtopic addresses the following Civil Space Shortfalls:

- 1304 (Robust, High-Progress-Rate, and Long-Distance Autonomous Surface Mobility)
- 1336 (Robotic Mobility for Robust, Repeatable Access to and Through Extreme Terrain and Surface Topography)
- 1535 (Autonomous Vehicle, System, Habitat, and Infrastructure Health Monitoring and Management)

References:

1. NASA Cross-Program Design Specification for Natural Environments (DSNE) available on the NASA Technical Reports Server: https://ntrs.nasa.gov/
2. Li, Z.Q.; Bingham, L.K., "NASA White Paper, Terramechanics for LTV Modeling and Simulation": https://ntrs.nasa.gov/api/citations/20220010732/downloads/Terramechanics_white_paper.pdf
3. Lunar Mobility Drivers and Needs, 2024 Moon to Mars Architecture Concept Review: https://www.nasa.gov/wp-content/uploads/2024/06/acr24-lunar-mobility-drivers-and-needs.pdf?emrc=b2dafa
4. "2023 Moon to Mars Architecture Definition Document," ESDMD: https://www.nasa.gov/wp-content/uploads/2024/01/rev-a-acr23-esdmd-001-m2madd.pdf?emrc=b2c9ef
5. Civil Space Shortfalls: https://www.nasa.gov/spacetechpriorities/

Scope Title: Fault Detection, Failure Response, and Adaptive Operations Technologies to Avoid and/or Mitigate Terrain Impacts to Vehicle Health

Scope Description:

Proposals are sought for analysis tools, control methods, and related techniques to achieve robust wheeled or tracked vehicle interactions with the lunar surface. For many years, terrestrial vehicles have offered features such as traction control, electronic stability control, and off-road terrain mode selection to improve safety and vehicle performance. Similar capabilities can enhance autonomous, teleoperated, or crewed vehicles on the surface of the Moon. Furthermore, newer advanced driver-assistance systems could also offer benefits to vehicles that are part of the Artemis mission. In short, NASA seeks techniques, methods, or systems to enable lunar surface vehicles to identify, avoid, or recover from situations where a vehicle could get stuck.

Expected TRL or TRL Range at completion of the Project: 1 to 6

Primary Technology Taxonomy:

- Level 1: TX 04 Robotics Systems
- Level 2: TX 04.2 Mobility

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Phase I deliverables may include:

- Background research and feasibility studies.
- Conceptual design, trade studies, and description of proposed solution.
- Plans for testing or validation in a relevant lunar environment post-Phase I award.
- In some instances, an initial proof-of-concept implementation and/or testing.

Phase II deliverables may include:

- Software source code, user manual/instructions, documentation.
- Test and/or performance data.
- Demonstration of assessment techniques.

State of the Art and Critical Gaps:

Current terrestrial state-of-the-art vehicle fault detection and adaptation relies on multiple fused sensor modalities to understand the wheel soil interaction through proprioceptive and environmental sensing. Sensing can be utilized to prevent excessive suspension traverse as well as wheel slip and/or sinkage by altering command signals to induce torque vectoring, change wheel speeds, or even change the contact patch of the system (i.e., additional wheels or changes in wheel geometry such as air pressure). These changes can then be enacted to reduce harm to the vehicle by preventing excess drivetrain wear, preventing the vehicle from getting stuck, and preventing damage to wheels from unseen obstacles encountered while digging into soils. Sensors such as tire pressure monitoring systems and ride height adjusters can also alert users to abnormal wear and vehicle states prior to traverses—allowing the user to determine the risk to the vehicle. In non-terrestrial environments the ability to observe, sense, and predict is limited. Understanding the state of wheels on surface systems before failure is a difficult task due to the limited sensing ability on the lunar surface. Systems are needed to effectively predict remaining wheel lifetime/issues and avoid and recover from wheel interactions that could lead to excessive wear or damage vehicle health (e.g., rutting, loss of wheel contact, etc.).

Gaps that are highly relevant to this scope are:

- 1545: Robotic Actuation, Subsystem Components, and System Architectures for Long-Duration and Extreme Environment Operation.
- 1304: Robust, High-Progress-Rate, and Long-Distance Autonomous Surface Mobility.
- 1548: Sensing for Autonomous Robotic Operations in Challenging Environmental Conditions.
- 1532: Autonomous Planning, Scheduling, and Decision Support to Enable Sustained Earth-Independent Missions.

Relevance / Science Traceability:

The main target for infusion of this subtopic's successful proposals is EHP. Several areas of EHP responsibility could use efficient on-board autonomy, including the LTV and PR. Successful traversal of lunar surface will be improved with techniques, strategies, and algorithms developed in this subtopic scope.

This subtopic addresses Civil Space Shortfalls:

- 680 (Robust Robotic Intelligence for High-Tempo Autonomous Operations in Dynamic Mission Conditions).
- 1304 (Robust, High-Progress-Rate, and Long-Distance Autonomous Surface Mobility).
- 1336 (Robotic Mobility for Robust, Repeatable Access to and Through Extreme Terrain and Surface Topography).
- 1535 (Autonomous Vehicle, System, Habitat, and Infrastructure Health Monitoring and Management).
- 1544 (Resilient Agency: Adaptable Intelligence and Robust Online Learning for Long-Duration and Dynamic Missions).

References:

1. Li, Z.Q.; Bingham, L.K., “NASA White Paper, Terramechanics for LTV Modeling and Simulation”: https://ntrs.nasa.gov/api/citations/20220010732/downloads/Terramechanics_white_paper.pdf
2. Performance of Boeing LRV Wheels in a Lunar Soil Simulant

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3. Shape Memory Alloy (SMA) Tires - A New Paradigm in Tire Performance, NASA Technical Reports Server: https://ntrs.nasa.gov/citations/20190001039
4. Development and Implementation of Large-Scale Numerical Models for Shape Memory Mars Spring Tires: https://ntrs.nasa.gov/api/citations/20230009408/downloads/TM-20230009408.pdf
5. Mars Exploration Rover Spirit End of Mission Report, Section 3 "Loss of Mobility": https://ntrs.nasa.gov/api/citations/20160001767/downloads/20160001767.pdf
6. Path Following with Slip Compensation for a Mars Rover: https://ntrs.nasa.gov/api/citations/20110015134/downloads/20110015134.pdf
7. SRU Pilot Excavator Wheel Testing in Lunar Regolith Simulant: https://ntrs.nasa.gov/citations/20240001016
8. Rover Slip Validation and Prediction Algorithm: https://ntrs.nasa.gov/api/citations/20090041774/downloads/20090041774.pdf
9. Scalable Slip Control with Torque Vectoring Including Input-to-State Stability Analysis: https://ieeexplore.ieee.org/abstract/document/9976336
10. Push-pull locomotion: Increasing travel velocity in loose regolith via induced wheel slip: https://ntrs.nasa.gov/citations/14293496239903
11. High-slip wheel-terrain contact modelling for grouser-wheeled planetary rovers traversing on sandy terrains: https://www.sciencedirect.com/science/article/abs/pii/S0094114X20302536
12. Modelling and experimental validation of an EV torque distribution strategy towards active safety and energy efficiency: https://www.sciencedirect.com/science/article/abs/pii/S0360544221022015
13. Traction Processes of Wheels in Loose, Granular Soil: https://kilthub.cmu.edu/articles/thesis/Traction_Processes_of_Wheels_in_Loose_Granular_Soil/6724034/1
14. Civil Space Shortfalls: https://www.nasa.gov/spacetechpriorities/

Science Mission Directorate (SMD)

The Science Mission Directorate (SMD) is an organization where discoveries in one scientific discipline have a direct route to other areas of study. This flow is something extremely valuable and is rare in the scientific world. NASA science programs address fundamental research about the universe and our place in it. From exoplanet research to better understanding Earth's climate to understanding the influence of the sun on our planet and the solar system, the directorate's work is interdisciplinary and collaborative.

S11.01: Lidar Remote-Sensing Technologies (SBIR)

Related Subtopic Pointers: H15.01, S14.02, S13.01
Lead Center: LaRC
Participating Center(s): GSFC

Subtopic Introduction:

Light detection and ranging (lidar) continues to be a key technology for NASA interests in Earth science, planetary science, and spacecraft navigation. Many technological advances are on the horizon for lidar that can be effectively used for NASA science interests, including hybrid laser architectures, photonic integrated circuits, optical phased arrays, metamaterials, and detection beyond classical limits. This subtopic seeks to advance laser/lidar technologies to overcome critical observational gaps in Earth and planetary science. 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, geophysical, and topographic parameters from ground, airborne, and space-based platforms. Meeting science needs leads to four primary measurement types:

- Backscatter: Measures the profile of beam backscatter and attenuation from aerosols and clouds in the atmosphere as well as particulates in the ocean to retrieve the optical and microphysical properties of suspended particulates.
- Laser spectral absorption: Measures the profile of laser absorption by trace gases from atmospheric (aerosol/cloud) or surface backscatter and volatiles on surfaces of airless planetary bodies at multiple laser wavelengths to retrieve the concentration of gas within the measurement volume.
- Altimetry: An accurate measure of distance to hard targets in the atmosphere and ocean.
- Doppler: Measures wavelength changes in the return beam to retrieve velocity, direction of velocity vector, and turbulence.

Scope Title: Lidar Remote-Sensing Technologies

Scope Description:

This subtopic seeks advances in lidar instruments that can be used for NASA science-focused measurements or to support current technology programs. The following advances are sought:

- Transformative technologies and architectures to vastly reduce the cost, size, and complexity of lidar instruments from a system perspective or to enable detection beyond classical limits.
    - Advances are sought for operation on a wide range of compact (SmallSat, CubeSat, or Unmanned Aerial Vehicle size) packages.
    - Reduction in the complexity and environmental sensitivity of laser architectures is sought, while still meeting performance metrics for the measured geophysical observable.
    - Novel thermal management systems for laser, optical, and electronic subsystems are also sought to increase efficiency, decrease physical footprint, and transition laser systems to more compact platforms.

  - New materials concepts could be of interest for the reduction of weight for lidar-specific telescopes, optical benches, and subcomponents. Integrated subsystems combining laser, optical, fiber, and/or photodetector components are of interest for reducing the size, weight, and power (SWaP) of lidar instruments.
- Compact, efficient, tunable, and rugged narrow-linewidth pulsed lasers operating between ultraviolet and infrared wavelengths suitable for lidar.
  - Specific wavelengths of interest to match absorption lines or atmospheric transmission are: 290 to 320 nm (ozone absorption), 420 to 490 nm with particular interest at the 486 nm Fraunhofer line (ocean sensing), 532 nm (aerosols), 820 and 935 nm (water vapor lines), 1064 nm (aerosols), 1550 nm (Doppler wind), 1645 to 1650 nm (high pulse energy (>10 mJ) for methane line, and orbital debris tracking), 2000 nm (>50 mJ) Doppler wind (coherent lidar transceiver is preferred), and 3000 to 4000 nm (hydrocarbon lines and ice measurement).
  - For pulsed lasers, two different regimes of repetition rate and pulse energies are desired: from 1 to 10 kHz with pulse energy greater than 1 mJ and from 20 to 100 Hz with pulse energy greater than 100 mJ.
  - For laser spectral absorption applications, such as differential absorption lidar, a single frequency (pulse transform limited) and frequency-agile source is required to tune >200 pm on a shot-by-shot basis while maintaining high spectral purity (>1,000:1).
  - Direct generation of laser light in the 820 nm spectral band without use of nonlinear optics (e.g., parametric conversion or harmonic conversion) is sought for space-based water vapor DIAL (differential absorption lidar) applications.
  - Technology solutions employing cryogenic lasers are encouraged to help improve efficiency and enable use of new laser materials.
- Novel approaches and components for lidar receivers, matching one or more of the wavelengths listed in the bullet above.
  - Such receiver technology could include integrated optical/photonic circuitry, freeform telescopes and/or aft optics, frequency-agile ultra-narrow-band solar blocking filters for water vapor DIAL (<10 pm full width at half maximum, >80% transmission, and phase locked to the transmit wavelength), and phased-array or electro-optical beam scanners for large (>10 cm) apertures.
  - Nonmechanical scanners (beam steering) >50 cm are also desired. Integrated receivers for Doppler wind measurement at 1550, 1650, or 2000 nm wavelengths are sought for coherent heterodyne detection at bandwidths of 1 GHz or higher, combining local oscillator laser, photodetector, and/or fiber mixing.
- New three-dimensional (3D) mapping and hazard-detection lidar with compact and high-efficiency 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 SWaP to fit into a CubeSat package or smaller.
  - High-speed, low-SWaP 2D scanners are also sought for single-beam lidars that enable wide scan angles with high repeatability and accuracy.
  - New high-resolution 3D lidar with appropriate SWaP for stratospheric platforms for wildfire fuel modeling.
  - New lidar technologies are sought 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.
  - Ground and low-Earth-orbit (LEO) based lidar systems used for the detection and tracking of orbital debris targets are also of interest.

Please note that the following areas are excluded from S11.01 this year:

- Laser sources of wavelength at or around 780 nm.
- Laser sources for lidar measurements of carbon dioxide.
- Receivers for direct detection wind lidar.
- Development of telescopes unless the design is specifically a lidar component, such as a telescope integrated with other optics (consider S12.03 "Advanced Optical Systems and

Fabrication/Testing/Control Technologies for Extended-Ultraviolet/Optical to Mid-/Far-Infrared Telescopes").

- Development of detector technology unless the innovation specifically targets a particular lidar application (consider S11.04 "Sensor and Detector Technologies for Visible, Infrared (IR), Far-IR, and Submillimeter" or S12.06 "Detector Technologies for Ultraviolet (UV), X-Ray, and Gamma-Ray Instruments").
- Lidar technologies specifically for the application of robotic surface navigation (consider S13.01 "Robotic Mobility, Manipulation, and Sampling").
- Lidar technologies for geospace remote sensing (sodium layer) (consider S14.02 "In Situ Particles and Fields and Remote-Sensing-Enabling Technologies for Heliophysics Instruments").

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:

- Level 1: TX 08 Sensors and Instruments
- Level 2: TX 08.1 Remote Sensing Instruments/Sensors

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware
- Software
- Research
- Analysis

Desired Deliverables Description:

Desired deliverables, technologies, and components should be applicable to subsystem or system-level lidar technology solutions, as opposed to stand-alone components such as lasers or photodetectors of unspecified applicability to a measurement goal.

- Phase I: Research should demonstrate technical feasibility and show a path toward a Phase II prototype unit. A typical Phase I deliverable could be a technical report demonstrating the feasibility of the technology and a design that is to be built under a Phase II program. In some instances where a small subsystem is under investigation, a prototype deliverable under the Phase I is acceptable.
- 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. Higher fidelity Phase II prototypes that are fielded in harsh environments such as aircraft should seek opportunities to further evaluate and optimize performance in a relevant environment. At the end of Phase II, the technology must be a viable solution for airborne and/or space-flight applications in the near future.

State of the Art and Critical Gaps:

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 features of the Earth, Mars, Moon, and other planetary bodies. Compact, high-efficiency lidar instruments for deployment on unconventional platforms, such as unmanned aerial vehicles, SmallSats, and CubeSats, are sought.

This scope addresses shortfalls identified in the Civil Space Shortfall Ranking including:

- [Ranked 20th] ID 1626: Advanced Sensor Components: Imaging
- [Ranked 137th] ID 1602: 3D/3D+ Imaging and Tomography of Complex Features and Dynamical Processes

Relevance / Science Traceability:

The proposed subtopic addresses missions, programs, and projects identified by the SMD including: atmospheric water vapor (profiling of tropospheric water vapor supports studies in weather and dynamics, radiation budget, clouds, and aerosol processes); aerosols (profiling of atmospheric aerosols and how aerosols relate to clouds and precipitation); atmospheric winds (profiling of wind fields to support studies in weather and atmospheric dynamics on Earth and atmospheric structure of planets); topography (altimetry to support studies of vegetation and the cryosphere of Earth, as well as the surface of planets and solar system bodies); greenhouse gases (column measurements of atmospheric gases, such as methane, that affect climate variability); hydrocarbons (measurements of planetary atmospheres); gases related to air quality (sensing of tropospheric ozone, nitrogen dioxide, or formaldehyde to support NASA projects in atmospheric chemistry and health effects); and automated landing, hazard avoidance, and docking (technologies to aid spacecraft and lander maneuvering and safe operations). The NASA Airborne Science and Research Analysis program is one of the primary stakeholders for technology resulting from this subtopic.

References:

1. "Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space," National Academies: https://www.nationalacademies.org/our-work/decadal-survey-for-earth-science-and-applications-from-space
2. “Origins, Worlds, and Life: Planetary Science and Astrobiology in the Next Decade,” National Academics: https://nap.nationalacademies.org/catalog/27209/origins-worlds-and-life-planetary-science-and-astrobiology-in-the
3. "Sensing Our Earth from Above," National Aeronautics and Space Administration: https://science.larc.nasa.gov/lidar/
4. "Sciences and Exploration Directorate," National Aeronautics and Space Administration: https://science.gsfc.nasa.gov/sci/
5. "Civil Space Shortfalls," National Aeronautics and Space Administration: https://www.nasa.gov/spacetechpriorities

S11.02: Technologies for Active Microwave Remote Sensing (SBIR)

Related Subtopic Pointers: S11.03, S13.03, S16.08
Lead Center: JPL
Participating Center(s): GSFC

Subtopic Introduction:

Advancements and continued development of active microwave sensors, such as radars or active receivers for remote sensing, applied to Earth and planetary science with the goal of future mission infusion, is the target of this subtopic. Key advances in six main topic areas are deemed of high importance to support advancements needed in future missions for NASA in the next decade.

1. Surface Biology and Geology (SBG) is currently in the first phase of identifying as many feasible observing architectures and technologies as possible that achieve the Decadal Survey science objectives.

A listing of most important priorities can be found in https://science.nasa.gov/earth-science/decadal-surveys/decadal-sbg/. In addition, advances in technology and systems are needed to support biodiversity and conservation remote-sensing technology maturation efforts.

2. Surface Deformation and Change (SDC) will continue to impact future NASA mission needs, and follow-ons to the science desired for NISAR (NASA-ISRO Synthetic Aperture Radar) are already in planning. Cloud, water, and precipitation measurements increase capability of measurements to smaller particles and enable much more compact instruments. Advancements in components are needed to support these advanced measurements.
3. Low-frequency-band electronics and antennas are of great interest to subsurface studies, such as those completed by MARSIS (Mars Advanced Radar for Subsurface and Ionosphere Sounding) and SHARAD (Shallow Radar) for Mars and planned for Europa by the REASON (Radar for Europa Assessment and Sounding: Ocean to Near-Surface) on the Europa Clipper. Studies of the subsurface of other icy worlds is of great interest to planetary science, as is tomography of small bodies such as near-Earth comets and asteroids. Lastly, such low-frequency bands are also of interest to radio astronomy and sub-surface remote sensing on Earth for groundwater. Advances in deployable, steerable aperture and antenna technologies are needed to advance these techniques.
4. Photonic-RF (radio frequency) circuit technology development efforts support multiple Earth science focus areas to include SDC; Surface, Topography and Vegetation (STV), and Planetary Boundary Layer (PBL). Technologies to enable RF frequency generation (13 GHz, 35 GHz, or/and 95 GHz) and radar waveform modulation/demodulation with high RF output frequency stability and low phase noise are needed.
5. Low-power-consumption transceivers for W-band are critical for studies of atmospheric science, pressure sounding, and atmospheric composition for both Earth and planetary science. Advances in low SWaP (size, weight, and power) and improved efficiencies are needed for W-band transceivers.
6. Quantum radio and radar receivers such as Rydberg or atom-based radio sensors are poised to improve remote-sensing capabilities for Earth and planetary science applications. Key component advances in microwave-optics and stabilization systems are needed to support multiple upcoming applications including those in SDC, STV, and PBL.

For this solicitation, this subtopic seeks technology advancement needs in the following three scopes:

1. Component Advancements for Microwave Remote Sensing
2. Deployable and/or Steerable Aperture Technologies
3. Low-Power W-band Transceivers

Scope Title: Component Advancements for Microwave Remote Sensing

Scope Description:

This scope supports technologies to aid NASA in its microwave sensing missions. Component advancements are desired to improve capabilities of active microwave remote-sensing instruments, including improvements for classical radar/radio components—solid-state power amplifier (SSPA) technology, low-loss high-isolation switching, high-linearity low-noise amplifiers, and quantum radar/radio components—fiber-coupled Rydberg integrated RF-optics sensor head, arrayed vapor cell systems for atom-based Rydberg detectors, atomic correlation techniques for matched filtering, vibration stable laser systems, wave-mixing architectures and systems for high sensitivity, and compact Rydberg coupler laser stabilization systems to access target RF transitions in S-band through K-band.

Classical radar/radio components (solutions needed for any of these):

- Specifically, we are seeking L- and/or S-band solid-state power amplifiers (SSPAs) to achieve a power-added efficiency (PAE) of >50% for 1 kW peak transmit power, through the use of efficient multidevice power-combining techniques or other efficiency improvements. There is also a need for high-efficiency ultra-high-frequency (335 to 535 MHz) monolithic microwave integrated circuit (MMIC) power

amplifiers with saturated output power greater than 20 W, high efficiency of >70%, and gain flatness of 1 dB over the band.
- Switches with high power (>100 W peak and >10 W average), speed (20 KHs events) and isolation (>25 dB) are also desired with low insertion loss of <0.4 dB and <0.5 dB at V-band (64 to 70 GHz) and W-band (95 GHz +/- 200 MHz), respectively.
- Solid-state amplifiers that meet high efficiency (>50% 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 to 4 at the completion of the project (e.g., 10 W 64 to 70 GHz packaged power amplifier).
- Photonic-RF circuit supports multiple frequency radar transceiver at Ku-band (13 GHz), Ka-band (35 GHz), V-band (64 to 70 GHz), and W-band (95 GHz). Desirable features include *versatile* radar waveform modulation and demodulation, sideband rejection, high RF output frequency stability (< 10^{-9}), and lower phase noise.
- Transponder and RF tag architectures and systems (<1 g) and capability for interrogation by radar/telecom satellites for SBG and Internet of Animals to enable studying migratory routes for small birds in the 2 to 5 GHz ISM bands.
- Packaged solid-state power amplifier (SSPA) with 200+ W transmit power at Ka-band (35.6 GHz nominal) or 100 W transmit power at W-band (94 GHz nominal) with a flight-like power supply.

Quantum radar/radio components or subsystems to support STV (solutions needed for any of these):

- Six-wave mixing architecture and systems in vibration stable configurations (including laser stabilizations) are needed and highly desired for Cesium configurations with n = 20 to 88 and with high sensitivity (<5nVcm^{-1}Hz$^{-1/2}$).
- Integrated sensor head in a monolithic construction that is a thermally controlled vapor cell with dual RF couplings for atom-mixer optical front-end applications. Mechanically stable fiber-to-free-space optics/opto-mechanics.
- Fiber-coupled vapor cells for Rb and Cs systems with efficiency >40% that, through use of a dichroic, delineate the probe from coupler signal and solve the problem of collimating lens and fiber sharing.
- Arrayed-vapor-cell systems that can permit spatially separated detection of RF fields to support K-band focal plane detectors with reflector antennas. Requested are 5x5 arrays with spacing less than a wavelength. Techniques to obtain a spatially reconfigurable array within a vapor cell is also desired.
- Optimized frequency-stabilization subsystems for a compact Rydberg laser package with a coupler laser wavelength tunable to access target RF transitions at S-band, K-band, Ka-band, and W-band with absolute frequency stability at the 100 kHz level or better (goal: 10 kHz) for operation under typical vibration conditions in suborbital flight. Studies of experimental nature to directly tie linewidth and phase noise in vibration environments and their impact to overall sensitivity is highly desired.

Expected TRL or TRL Range at completion of the Project: 2 to 4

Primary Technology Taxonomy:

- Level 1: TX 08 Sensors and Instruments
- Level 2: TX 08.1 Remote Sensing Instruments/Sensors

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

- Phase I: Research should demonstrate technical feasibility as a study and provide research, analysis, and software to advance the concept toward a Phase II prototype unit.
- Phase II: Deliverables should include a design, prototype component or system, and prototype simulation or test data verifying functionality. Phase II deliverables should also include/delineate any further work that would be required to bring the technologies to full operational and/or commercial use.

State of the Art and Critical Gaps:

Advances in SDC are strongly desired for Earth remote sensing, land use, natural hazards, and disaster response. NISAR is a flagship-class mission, but it is only able to revisit locations on ~weekly basis, whereas future constellation concepts using SmallSats would decrease revisit time to less than 1 day, which is game changing for studying earthquake precursors and post-relaxation. For natural hazards and disaster response, faster revisit times are critical. MMIC devices with high saturated output power in the few to several watts range and with high PAE (>50%) are desired.

Advances in quantum radars/receivers are strongly desired. Quantum sensing (QS) has the ability to transform space-based science, particularly by substantially increasing the spatial and temporal resolution of remote-sensing measurements needed to understand Earth's climate variability. Quantum detectors configured in, or as a primary part of, novel remote sensing technologies, could assist SMD's science needs by harnessing QS-derived technology and a variety of advanced component technologies. This could potentially enable unprecedented science measurements in established areas, ranging from geodetic observation of aquifers on Earth to lunar seismometry, and in new mission concepts including experimental searches for signatures of dark energy, achieving spatiotemporal super-resolution, super-broad-band or dynamic sensing, and testing the connection between general relativity and quantum mechanics. An example of a technical challenge for the remote sensing of Earth's STV is that differences in precipitation, vegetation zones (canopy, near surface, or root), ice, and basal properties set distinctly different measurement requirements. For example, in radar remote sensing, observations of these key variables require the use of multiple bands covering the entire radio window (very high frequency (VHF) to Ka-band: 50 MHz to 40 GHz) with different configurations sensitive to amplitude, phase, or polarization of signals to enable vertical profiling with high accuracy, high spatiotemporal resolution, and tomography capability. In addition to STV, Rydberg sensors could play a key role in PBL. The PBL, also known as the atmospheric boundary layer, is the lowest part of the atmosphere, and its behavior is directly influenced by its contact with a planetary surface. Remote sensing through active/passive radars are needed to observe the PBL. Rydberg techniques support broad spectrum remote sensing of the PBL.

This scope addresses shortfalls identified in the Civil Space Shortfall Ranking including:

- [Ranked 20th] ID 1626: Advanced Sensor Components: Imaging
- [Ranked 137th] ID 1602: 3D/3D+ Imaging and Tomography of Complex Features and Dynamical Processes
- [Ranked 67th] ID 1599: Quantum Sensors That Use Atoms, Ions, and Spins

Relevance / Science Traceability:

SDC science is a continuing Decadal Survey topic, and follow-ons to the science desired for the NISAR mission are already being planned. Cloud, water, and precipitation measurements increase capability of measurements of smaller particles and enable much more compact instruments. STV is a Decadal Survey topic that will have significant impact in the following decade and that will require new and nonconventional technologies. STV touches multiple science goals, including solid Earth, ecosystems, climate, hydrology, and weather, and is challenging to fit within the cost cap. PBL is a Decadal Survey topic that will have a significant impact in understanding and monitoring the lowest part of the atmosphere where the behavior is directly influenced by its contact with a planetary surface.

References:

1. "Surface Deformation and Change (SDC)," National Aeronautics and Space Administration: https://science.nasa.gov/earth-science/decadal-sdc
2. "Planetary Boundary Layer (PBL)", National Aeronautics and Space Administration: https://science.nasa.gov/earth-science/decadal-pbl
3. "NISAR NASA-ISRO SAR Mission," Jet Propulsion Laboratory: https://nisar.jpl.nasa.gov/
4. "Radar in a CubeSat: RainCube," Jet Propulsion Laboratory: https://www.jpl.nasa.gov/missions/radar-in-a-cubesat-raincube/
5. "GACM Global Atmospheric Composition Mission," National Academies, Satellite Observations to Benefit Science and Society: Recommended Missions for the Next Decade. 2008, pp. 14: https://www.nap.edu/read/11952/chapter/9
6. "Global Precipitation Measurement Mission," National Aeronautics and Space Administration: https://gpm.nasa.gov
7. "Surface Topography and Vegetation (STV)," National Aeronautics and Space Administration: https://science.nasa.gov/earth-science/decadal-stv
8. "Civil Space Shortfalls," National Aeronautics and Space Administration: https://www.nasa.gov/spacetechpriorities

Scope Title: Deployable and/or Steerable Aperture Technologies

Scope Description:

Solutions for the following technology needs are sought:

Low-frequency deployable antennas for Earth and planetary radar sounders: Antennas capable of being hosted by SmallSat/CubeSat platforms are required for missions to icy worlds, large/small body interiors (i.e., comets, asteroids), and for Earth at center frequencies from 5 to 100 MHz, with fractional bandwidths ≥ 10%. Dual-frequency solutions or even tri-frequency solutions are desired; for example, a dual frequency antenna with a 5 to 6 MHz band and a second 85 to 95 MHz band. For low-frequency tomographic radar requirements: Deployable antenna with ~2:1 bandwidth, good pulse (transient) response, deployed volume ~1/3 wavelength at the lowest frequency (~MHz). For distributed aperture radars there is a need for daughter-craft antennas for the distributed radar covering a frequency of about 40 to 50 MHz with a gain of at least 5 dBi and with low mass, compact stow, and reasonable cost. Designs need to be temperature-tolerant; that is, not changing performance parameters drastically over flight temperature ranges of ~100 °C.

High-frequency (V-band/W-band) deployable antennas for SmallSats and CubeSats: Small-format, deployable/inflatable antennas are desired (for 65 to 70 GHz, 94 GHz, or 250 to 350 GHz) with an aperture size of ~1+ m^2 (>1.6 m for 250 to 350 GHz) that when stowed, fit into form factors suitable for SmallSats—with a desire for similar on the more challenging CubeSat format. Concepts that remove, reduce, or control creases/seams in the resulting surface, on the order of a fraction of a wavelength, are highly desired.

Technologies enabling low-mass steerable technologies, especially for L- or S-bands, including, but not limited to, antenna or RF electronics, enabling steering: Cross track +/-7° and along track +/-15°. This would enable a complete antenna system with a mass density of 10 kg/m^2 (or less) with a minimum aperture of 12 m^2. Examples of different electronics solutions include completely integrated transmit/receive (TR) modules, with all control features for steering included, or alternatively an ultra-compact TR module controller, which can control N modules, thus allowing reduction in size and complexity of the TR modules themselves.

Expected TRL or TRL Range at completion of the Project: 2 to 4

Primary Technology Taxonomy:

- Level 1: TX 08 Sensors and Instruments
- Level 2: TX 08.1 Remote Sensing Instruments/Sensors

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype

Desired Deliverables Description:

For both antenna types (low and high frequency), concepts and prototypes for targeted advances in deployment technologies are welcome and do not need to address every need for mission-ready hardware.

- Phase I: Research should demonstrate technical feasibility as a study for a design that can be advanced toward a Phase II prototype unit.
- Phase II: Deliverables should include a design, prototype component or system, and prototype simulation or test data verifying functionality. Testing should be at the appropriate TRL level of 4 or above. Phase II deliverables should also include/delineate any further work that would be required to bring the technologies to full operational and/or commercial use.

State of the Art and Critical Gaps:

Low-frequency antennas, per physics, are large and thus are deployable, even for large spacecraft. For SmallSats/CubeSats, the challenges are to get enough of an antenna aperture with the proper length to achieve relatively high bandwidths. No such 10% fractional antenna exists for the SmallSat/CubeSat form factors.

High-frequency antennas can often be hosted without deployment, but a ~1 m^2-diameter antenna on a SmallSat/CubeSat is required to be deployable. A specific challenge for high-frequency deployable antennas is to deploy the aperture with enough accuracy such that the imperfections (i.e., residual folds, support ribs, etc.) are flat enough for antenna performance.

This scope addresses shortfalls identified in the Civil Space Shortfall Ranking including:

- [Ranked 20th] ID 1626: Advanced Sensor Components: Imaging
- [Ranked 137th] ID 1602: 3D/3D+ Imaging and Tomography of Complex Features and Dynamical Processes

Relevance / Science Traceability:

Low-frequency-band antennas are of great interest to subsurface studies, such as those completed by MARSIS and SHARAD for Mars and planned for Europa by REASON on the Europa Clipper. Studying the subsurfaces of other icy worlds is of great interest to planetary science, as is tomography of small bodies such as comets and asteroids. Because of the impact of the ionosphere, low-frequency sounding of Earth is very challenging from space, but there is great interest in solutions to make this a reality. Lastly, such low-frequency bands are also of interest to radio astronomy, such as that being done for OLFAR (Orbiting Low Frequency Antenna for Radio Astronomy).

V-band deployable antennas are mission enabling for pressure sounding from space.

References:

1. "Civil Space Shortfalls," National Aeronautics and Space Administration: https://www.nasa.gov/spacetechpriorities

For low-frequency deployables, see similar missions (on much larger platforms):

2. "Europa Clipper," Jet Propulsion Laboratory: https://www.jpl.nasa.gov/missions/europa-clipper/
3. "REASON," National Aeronautics and Space Administration: https://europa.nasa.gov/spacecraft/instruments/reason/
4. "Mars Express," National Aeronautics and Space Administration: https://science.nasa.gov/mission/mars-express/
5. "Radar in a CubeSat: RainCube," Jet Propulsion Laboratory: https://www.jpl.nasa.gov/missions/radar-in-a-cubesat-raincube/

Lower frequency mission but similar for high-frequency deployables.

6. Bentum, M. J.; Verhoeven, C. J. M.; Boonstra, A. J., "OLFAR-Orbiting Low Frequency Antennas for Radio Astronomy," Proceedings of the ProRISC 2009, Annual Workshop on Circuits, Systems and Signal Processing, Veldhoven. 2009, pp. 1-6: https://research.utwente.nl/files/5412596/OLFAR.pdf

Scope Title: Low-Power W-Band Transceivers

Scope Description:

Required is a low-power compact W-band (monolithic integrated circuit or application-specific integrated circuit [ASIC] preferred) transceiver with up/down converters with excellent cancellers to use the same antenna to transmit and receive. Application is in space-landing radar altimetry and velocimetry. Wide-temperature-tolerant technologies are encouraged to reduce thermal control mass, either through designs insensitive to temperature changes or active compensation through feedback. Electronics must be tolerant to a high-radiation environment through design (rather than excessive shielding). In the early phases of this work, radiation tolerance must be considered in the semiconductor/materials choices, but it is not necessary to demonstrate radiation tolerance in a working prototype until in Phase II. For ocean worlds around Jupiter, bounding (worst-case) radiation rates are expected to be at less than 50 rad(Si)/sec—with minimal shielding—during the period of performance (landing or altimeter flyby), but overall total dose is expected to be in the hundreds of krad total ionizing dose (TID). Most cases, particularly for Earth science applications, will be less extreme in radiation.

Expected TRL or TRL Range at completion of the Project: 2 to 4

Primary Technology Taxonomy:

- Level 1: TX 08 Sensors and Instruments
- Level 2: TX 08.X Other Sensors and Instruments

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype

Desired Deliverables Description:

- Phase I: Research should demonstrate technical feasibility as a study and provide research, analysis, and software to advance the concept toward a Phase II prototype unit.
- Phase II: Deliverables should include a design, prototype component or system, and prototype simulation or test data verifying functionality. Phase II deliverables should also include/delineate any further work that would be required to bring the technologies to full operational and/or commercial use.

State of the Art and Critical Gaps:

Low-power-consumption transceivers for W-band are critical for studies of atmospheric science, pressure sounding, and atmospheric composition for both Earth and planetary science. Such transceivers currently do not exist.

Critical technology gaps in the state of the art for W-band radar transceivers for space applications that require operation in high radiation environments include:

- Radiation-Hardened Components: There is a lack of radiation-hardened transistors, amplifiers, and mixers specifically designed for W-band frequencies. Current commercial off-the-shelf (COTS) components may not withstand the radiation levels encountered in space.
- High-Power Solid-State Amplifiers: Developing high-power solid-state power amplifiers (SSPAs) that can operate efficiently at W-band frequencies while surviving high radiation doses is a significant challenge.
- Low-Noise Amplifiers (LNAs): Designing LNAs with low noise figures that maintain performance in high-radiation environments is critical, yet difficult to achieve due to the sensitivity of these components to radiation-induced degradation.
- Reliable Frequency Generation: The stability and reliability of frequency generation circuits, such as oscillators and synthesizers, at W-band under radiation exposure need improvement, as current technologies may suffer from frequency drift or failure.
- Thermal Management: Effective thermal management solutions are needed to dissipate heat generated by W-band transceivers in space, where temperature extremes and radiation can impact the performance and longevity of electronic components.
- Material Degradation: The long-term effects of radiation on materials used in the packaging and interconnects of W-band radar transceivers are not fully understood, leading to potential failures over time.
- Miniaturization and Integration: Achieving high levels of integration and miniaturization for W-band radar systems while ensuring radiation hardness is a gap that needs addressing to reduce size, weight, and power (SWaP) for space applications.
- Radiation-Induced Phase Noise: Minimizing phase noise in oscillators and signal sources, which can be exacerbated by radiation, remains a challenge at W-band frequencies, affecting the overall radar system performance.
- Reliability of MEMS and RF Switches: Microelectromechanical systems (MEMS) and RF switches used at W-band frequencies are vulnerable to radiation-induced failures, and more research is needed to improve their reliability in space.
- Testing and Validation: There is a need for more robust testing and validation methods specifically for W-band radar transceivers in simulated high-radiation environments, as current methods may not fully replicate the conditions in space.

This scope addresses shortfalls identified in the Civil Space Shortfall Ranking including:

- [Ranked 20th] ID 1626: Advanced Sensor Components: Imaging
- [Ranked 137th] ID 1602: 3D/3D+ Imaging and Tomography of Complex Features and Dynamical Processes

Relevance / Science Traceability:

Missions for science, such as those deriving from the Advanced Composition Explorer (ACE) concept are slated as future NASA missions. Landing radar and related proximity sensors for autonomous vehicles are expected to rise in relevance and need. Low-power-consumption W-band transceivers are needed for space-landing radar altimetry and velocimetry in Earth science as well as missions to a variety of planetary bodies, including ocean worlds around Jupiter.

References:

1. "Civil Space Shortfalls," National Aeronautics and Space Administration: https://www.nasa.gov/spacetechpriorities

Missions for atmospheric science and altimetry applications:

2. "ACE Advanced Composition Explorer," National Aeronautics and Space Administration: https://science.nasa.gov/mission/ace/
3. Makovsky, A.; Ilott, P.; Taylor, J., "Mars Science Laboratory," Deep Space Communications. 2016, pp. 359-497: https://descanso.jpl.nasa.gov/monograph/series13/DeepCommo_Chapter8--141029.pdf
4. "Planetary Terminal Descent and Landing Radar Final Report," 1971: No. NASA-CR-111861: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19710011019.pdf

S11.03: Technologies for Passive Microwave Remote Sensing (SBIR)

Related Subtopic Pointers: S11.02
Lead Center: GSFC
Participating Center(s): JPL

Subtopic Introduction:

Technologies that address critical challenges in passive microwave technologies are broadly applicable across a number of SMD divisions as well as the DoD/IC (U.S. Department of Defense and the Intelligence Community) and commercial entities. The ongoing development of microwave sensors such as radiometers plays a crucial role in enhancing scientific remote sensing capability while reducing the size, weight, power, and cost (SWaP-C) as compared to existing technologies.

For this solicitation, this subtopic seeks technology advancement needs in the following two scopes (not in any priority order):

1. Components or Methods to Improve the Sensitivity, Calibration, or Resolution of Microwave/Millimeter-Wave Radiometers.
2. Advanced Digital Electronic or Photonic Systems for Microwave Remote Sensing.

For this solicitation, the following scope was rotated out but may return in future years:

- Advanced Deployable Antenna Apertures at Frequencies up to Millimeter-Wave.

Scope Title: Components or Methods to Improve the Sensitivity, Calibration, or Resolution of Microwave/Millimeter-Wave Radiometers

Scope Description:

NASA requires novel solutions to the challenges of developing stable, sensitive, and high-resolution radiometers and spectrometers operating from microwave frequencies to 5 THz. Novel technologies are requested to address challenges in the current state of the art of passive microwave remote sensing. Technologies could improve the sensitivity, calibration, or resolution of remote-sensing systems or reduce SWaP-C. Components, methods, or manufacturing techniques utilizing novel techniques, such as additive manufacturing (AM), that include interconnect technologies are desired. These interconnect technologies enable highly integrated, low-loss distribution networks that integrate active components and passive devices such as power splitters, couplers, filters, antenna arrays, and/or isolators in a compact package with significant volume reduction. Companies are invited to provide unique solutions to problems in this area. Possible technologies could include:

- Low-noise receivers (e.g., total power, pseudo-correlation, polarimetric) at frequencies up to 5 THz.
- Solutions to reduce system 1/f noise over time periods greater than 1 sec.
- Internal calibration systems or methods to improve calibration repeatability over time periods greater than days or weeks.
- Noise sources from G-band up to 1 THz with > 6 dB-ENR (excess noise ratio).
- 20-200 GHz monolithic microwave integrated circuit (MMIC) low-noise amplifiers with < 4.5 dB noise figure and > 20 dB gain.
- Low-noise amplifiers that operate at 1.2 THz with > 10% bandwidth.
- Technologies, processes, or methods, such as AM, that are able to reduce SWaP-C while achieving radio-frequency (RF) performance on par with or superior to traditional manufacturing methods.
- Broadband feedhorns with 2 to 1 bandwidth with the target frequency range of 10 to 200 GHz.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:

- Level 1: TX 08 Sensors and Instruments
- Level 2: TX 08.1 Remote Sensing Instruments/Sensors

Desired Deliverables of Phase I and Phase II:

- Prototype
- Research
- Analysis
- Software

Desired Deliverables Description:

Desired deliverables for this scope include research, analysis, software, or hardware prototyping of novel components or methods to improve the performance of passive microwave remote sensing:

- Phase I: Research should demonstrate technical feasibility as a study and show a path toward a Phase II prototype unit. Depending on the complexity of the proposed work, deliverables may include demonstrations from prototype subcomponents.
- Phase II: Deliverables should include a prototype component or system with test data verifying functionality to be verified with the NASA Contracting Officer Representative once awarded. Phase II

deliverables should also include/delineate any further work that would be required to bring the technologies to full operational and/or commercial use.

State of the Art and Critical Gaps:

Depending on frequency, current passive microwave remote-sensing instrumentation is limited in sensitivity (e.g., system noise, 1/f noise, or calibration uncertainty), resolution, or in SWaP-C. Critical gaps depend on specific frequency and application.

Gaps include:

- Technologies to reduce 1/f noise with submillimeter amplifier-based receivers, particularly those using internal calibration sources such as noise sources or pseudo-correlation architectures. Other gaps include highly linear receiver front ends capable of being calibrated in the presence of radio-frequency interference (RFI) that may change the operating point of prefilter components.
- There are no integrated low-noise and medium-power RF front ends that cover the 20 to 200 GHz bandwidth and are capable of driving the broadband photonic spectrometers, or any similar designs spanning across a decade-wide instantaneous bandwidth into the G-band.
- Technologies (e.g., additive manufacturing) are sought that can result in significant volume/cost reduction with performance comparable or superior to current technologies (e.g., technologies that can integrate X-, Ku-, or Ka-band transmit/receive modules with antenna arrays and/or local oscillator (LO) distribution networks for F- and/or G-band receiver arrays). Several publications have demonstrated the feasibility of additively manufactured RF to millimeter-wave circuitry; however, there is a notable gap in research that specifically examines its reliability and effectiveness in environments pertinent to NASA and space applications. Furthermore, the current body of work predominantly focuses on subcircuits or a restricted number of parts, without adequately demonstrating the desired repeatability and reproducibility required for the development of intricate multimodule circuit networks needed for space instrumentations. There is also a gap for AM technologies with fabrication tolerances, repeatability, and material properties that enable electronic devices (e.g., mixer blocks, corrugated horn antennas, etc.) that operate in the 0.5 to 1.5 THz regime with RF performance on par with traditional manufacturing methods.
- Broadband feedhorns with 2:1 bandwidth are needed for wideband multi-channel radiometry (e.g., 18 to 36 GHz or 85 to 175 GHz). Dual polarization is a plus. Current state-of-the-art horns are difficult to manufacture and extremely costly, especially at the higher frequency ranges.

This scope addresses shortfalls identified in the Civil Space Shortfall Ranking including:

- [Ranked 20th] ID 1626: Advanced Sensor Components: Imaging
- [Ranked 137th] ID 1602: 3D/3D+ Imaging and Tomography of Complex Features and Dynamical Processes

Relevance / Science Traceability:

Critical need: Creative solutions to improve the performance of 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. Ultra-wideband spectrometry would enable significant new science of the planetary boundary layer. RF photonic spectrometers will provide an order of magnitude increase in instantaneous RF bandwidths compared to today’s spectrometers and could provide as much as 100 to 200 GHz of instantaneous RF bandwidth.

References:

1. Long, D.; Ulaby, F., "Microwave Radar and Radiometric Remote Sensing," Artech. 2015: https://mrs.eecs.umich.edu/

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Scope Title: Advanced Digital Electronic or Photonic Systems Technology for Microwave Remote Sensing

Scope Description:

Technology critical to increasing the utility of microwave remote sensing based on photonic (or other novel analog) systems, application-specific integrated circuits (ASICs), and field-programmable gate arrays (FPGAs) are showing great promise. This topic solicits proposals for such systems or subsystems to process microwave signals for passive remote-sensing applications for spectrometry or total power radiometry. Photonic (or other analog) components or systems to implement spectrometers, beamforming arrays, correlation arrays, sources (photo-mixing), and other active or passive microwave instruments having size, weight, and power (SWaP) or performance advantages over digital technology are desired.

Example applications include:

- Sources using photomixing: Up to 300 GHz and up to 1 mW.
- Electro-optic modulators that operate up to 600 GHz.
- Integrated chipsets with 20 to 200 GHz low-noise front-ends of < 4.5 dB noise figure, > 60 dB linear gain, and 15 dBm output 1 dB compression point.
- ASIC-based solutions for digital beamforming, creating one or more beams to replace mechanically scanned antennas.
- ASIC implementations of polyphase spectrometer digital signal processing with < 1 W/GHz, > 10 GHz-bandwidth spectrometer with 8192 channels, and radiation-hardened and minimized power dissipation.

All systems or subsystems should also focus on low-power, radiation-tolerant broadband microwave spectrometers for NASA applications. Proposals should compare predicted performance and SWaP to conventional RF and digital-processing methods.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:

- Level 1: TX 08 Sensors and Instruments
- Level 2: TX 08.1 Remote Sensing Instruments/Sensors

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

Demonstration of novel subsystems or systems to enable increased capability in passive microwave remote-sensing instruments are requested. Photonic systems specifically are low-TRL emerging technologies, so applicants are encouraged to identify and propose designs where photonic technology would be most beneficial. For electronic solutions, low-power spectrometers (or other applications in the Scope Description) for an ASIC or other component that can be incorporated into multiple NASA microwave remote-sensing instruments are desired:

- Phase I: Research should demonstrate technical feasibility as a study and show a path toward a Phase II prototype unit. Depending on the complexity of the proposed work, deliverables may include demonstrations from prototype subcomponents.
- Phase II: Deliverables should include a prototype component or system with test data verifying functionality. Phase II deliverables should also include/delineate any further work that would be required to bring the technologies to full operational and/or commercial use.

State of the Art and Critical Gaps:

- Photonic systems for microwave remote sensing are an emerging technology not used in current NASA microwave missions, but they have the potential to enable significant increases in bandwidth or reduction in SWaP. State-of-the-art digital electronic solutions typically consume many watts of power.
- Most digital beamforming applications focus on either specific narrowband approaches for commercial communications or military radars. NASA needs solutions that consume low power and operate over wide bandwidths.
- The state of the art for spectrometers is currently the use of conventional microwave electronics for frequency conversion and filtering. Wideband spectrometers still generally require over 10 W and are not radiation hardened. Current FPGA-based spectrometers require ~10 W/GHz.
- There are no integrated low-noise and medium-power RF front-ends that cover the 20 to 200 GHz bandwidth that are also capable of driving the broadband photonic spectrometers, or any similar designs spanning across a decade-wide instantaneous bandwidth into the G-band.

This scope addresses shortfalls identified in the Civil Space Shortfall Ranking including:

- [Ranked 20th] ID 1626: Advanced Sensor Components: Imaging
- [Ranked 137th] ID 1602: 3D/3D+ Imaging and Tomography of Complex Features and Dynamical Processes

Relevance / Science Traceability:

Photonic systems may enable significantly increased bandwidth of Earth-viewing, astrophysics, and planetary science missions. In particular, this may allow for receivers with increased bandwidth or resolution for applications such as hyperspectral radiometry.

RF photonic spectrometers will provide an order of magnitude increase in instantaneous RF bandwidths compared to today's spectrometers and could provide as much as 100 to 200 GHz of instantaneous RF bandwidth.

Ultra-wideband spectrometers are required for Earth-observing, planetary, and astrophysics missions. The rapid increase in speed and reduction in power per gigahertz in the digital realm of digital spectrometer capability is directly applicable to planetary science and enables RFI mitigation for Earth science.

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S11.04: Sensor and Detector Technologies for Visible, Infrared (IR), Far-IR, and Submillimeter (SBIR)

Related Subtopic Pointers: S12.06, S13.05, S14.02
Lead Center: JPL
Participating Center(s): ARC, GSFC, LaRC

Subtopic Introduction:

A number of NASA funded missions are envisioned in the next decade that will explore the universe, investigate climate science on Earth, and be sent to outer planets for exploration. The heart of these missions are the science instruments, and in turn, the heart of the science instrument is the detector system. This subtopic is seeking new and innovative detector and supporting systems for upcoming NASA missions. Infrared (IR) and far-infrared (Far-IR) cover a wide spectrum that is important for understanding our planet as well as the constantly changing universe around us. 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 for Earth science, planetary science, and astrophysics.

Scope Title: Sensor and Detector Technologies for Visible, Infrared (IR), Far-Infrared (Far-IR), and Submillimeter

Scope Description:

NASA is seeking new technologies or improvements to existing technologies to meet the detector needs of future missions. Selected components are needed for room-temperature operation and other components for cryogenic temperature operation.

Low-power and low-cost readout integrated electronics:

- Photodiode arrays: In-pixel digital read-out integrated circuit (DROIC) for high-dynamic-range IR imaging and spectral imaging (10 to 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.
- Microwave Kinetic Inductance Detectors (MKID)/ transition-edge sensor (TES) detectors: A radiation-tolerant, digital readout system is needed for the readout of low-temperature detectors such as 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 1,500 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 a radio-frequency (RF) system on a chip (SoC) or application-specific integrated circuit (ASIC) with combined digitizer and channelizer functionality.
- Bolometric arrays: Low-power, low-noise cryogenic multiplexed readout for large-format two-dimensional (2D) bolometer arrays with 1,000 or more pixels, operating at 65 to 350 mK. We require a superconducting readout capable of reading two TES per pixel within a 1 mm^2 spacing. The wafer-scale readout of interest will be capable of being indium-bump bonded directly to 2D arrays of membrane bolometers. NASA applications require row and column readout with very low crosstalk, low read noise, and low detector noise-equivalent power degradation.

Far-IR-/submillimeter-wave detectors:

- Novel materials and devices: New or improved technologies leading to measurement of trace atmospheric species (e.g., CO, CH_4, N_2O) 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 (e.g., thin-film YBCO or MgB_2, or multilayered engineered superconductors with tunable critical temperature) or engineered semiconductor materials, especially 2D electron gas (2DEG) and quantum wells (QWs).
- 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. Compact and efficient systems for array receiver calibration and control are also needed.

- Receiver components: Development of advanced terahertz (THz) receiver components is desired. Such components include:
    - Novel concepts for room-temperature-operated receivers for Earth science with competitive noise performance (goal of 5 times the quantum limit in the 500 to 1,200 GHz range).
    - Local oscillators capable of spectral coverage 2 to 5 THz, output power up to >2 mW, frequency agility with >1 GHz near chosen terahertz frequency, and continuous phase-locking ability over the terahertz-tunable range with <100 kHz line width. Both solid-state (low-parasitic Schottky diodes) as well as quantum cascade lasers (for f > 2 THz).
    - Components and devices such as mixers, isolators, and orthomode transducers, working in the terahertz range, that enable future heterodyne array receivers.
    - Novel receiver architectures such as single-sideband heterodyne terahertz receivers and high-precision measurement accuracy for multiple lines.
    - Application-specific integrated circuit (ASIC)-based SoC solutions are needed for heterodyne receiver backends. ASICs capable of binning >6 GHz intermediate frequency bandwidth into 0.1 to 0.5 MHz channels with low power dissipation (<0.5 W) would be needed for array receivers.
    - Novel quasi-optical devices for terahertz beam multiplexing for a large (16+) number of pixels with >20% bandwidth.
    - Low-power, low-noise intermediate-frequency (IF) amplifiers that can be used for array receivers, operated at cryogenic as well as room temperature.
    - Novel concepts for terahertz preamplifiers from 300 GHz to 5 THz.

Please note that the following areas are excluded from S11.04 this year:

- Technologies for visible detectors, with the exception of superconducting, are not being solicited this year.
- Technologies for lidar detectors are not being solicited this year.
- Superconducting detector technologies in the high energy spectrum (instead consider S12.06 “Detector Technologies for Ultraviolet (UV), X-Ray, and Gamma-Ray Instruments”).

Expected TRL or TRL Range at completion of the Project: 2 to 4

Primary Technology Taxonomy:

- Level 1: TX 08 Sensors and Instruments
- Level 2: TX 08.1 Remote Sensing Instruments/Sensors

Desired Deliverables of Phase I and Phase II:

- Analysis
- Prototype

Desired Deliverables Description:

- Phase I: Research, analysis, feasibility studies, detailed design, or determination of the trade space and detailed optimization of the design. In some circumstances, simple prototype models for the hardware can be demonstrated and tested.
- Phase II: Studies, a working prototype that can be tested at one of the NASA centers is highly desirable. Phase II deliverables should also include/delineate any further work that would be required to bring the technologies to full operational and/or commercial use.

State of the Art and Critical Gaps:

- Efficient multipixel readout electronics are needed both for room-temperature operation as well as cryogenic temperatures. We can produce millions-of-pixel detector arrays at IR wavelengths up to about 14 µm, only because there are read-out integrated circuits (ROICs) available on the market. Without these, high-density large-format IR arrays such as quantum well (QW) IR photodetectors, HgCdTe, and strained-layer superlattices 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 ROICs typically have well depths of less than 10 million electrons.
- 6- to 9-bit, ROACH-2 board solutions with 2,000 bands, <10 kHz bandwidth in each are state of the art (SOA).
- IR detector systems are needed for Earth imaging based on the recently released 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 to 100 K range are capable of D ~ 10^{12} cm-rtHz/W. Broadband (>15%) heterodyne detectors that can provide sensitivities of 5× to 10× the quantum limit in the submillimeter-wave range while operating at 30 to 77 K are an improvement in the SOA because of the higher operating temperature.
- Detector array detection efficiency <20% at 532 nm (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 3 dB gain bandwidth of around 3 GHz. A novel superconducting material such as MgB_2 can provide significant enhancement of up to 9 GHz IF bandwidth.
- Cryogenic low-noise amplifiers (LNAs) in the 4 to 8 GHz bandwidth with thermal stability are needed for focal plane arrays, MKIDs, and Far-IR imagers and polarimeters (FIPs). Several concept missions and their instruments have also identified a need for cryogenic LNAs, including Origins Space Telescope (OST) instruments, Origins Survey Spectrometers (OSSs), the Heterodyne Instrument on OST (HERO), and the Lynx Telescope. Direct current (DC) power dissipation should be only a few milliwatts.
- Another frequency range of interest for LNAs is 0.5 to 8.5 GHz. This is useful for HERO. Other NASA systems in the Space Geodesy Project (SGP) would be interested in bandwidths up to 2 to 14 GHz.
- 15 to 20 dB gain and <5 K noise over the 4 to 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 SOA readout circuit is capable of reading 1 TES per pixel in a 1 mm^2 area. 2D arrays developed by the National Institute of Standards and Technology (NIST) have been a boon for current NASA programs. However, NIST has declined to continue to produce 2D circuits or to develop one capable of a 2-TES-per-pixel readout. This work is extremely important to NASA’s filled, kilopixel bolometer array program.
- 2D cryogenic readout circuits are analogous to semiconductor ROICs operating at much higher temperatures. We can produce detector arrays of millions of pixels at IR wavelengths up to about 14 µm, only because there are ROICs available on the market. Without these, high-density large-format IR arrays such as QW IR photodiode, HgCdTe, and strained-layer superlattices would not exist.

This scope addresses shortfalls identified in the Civil Space Shortfall Ranking including:

- [Ranked 20th] ID 1626: Advanced Sensor Components: Imaging
- [Ranked 137th] ID 1602: 3D/3D+ Imaging and Tomography of Complex Features and Dynamical Processes

Relevance / Science Traceability:

- Future short-, mid-, and long-wave IR 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 supersensitive and broadband and provide imaging capability (multipixel).

- 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 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 IR Earth-observing missions.

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S11.05: Suborbital Instruments and Sensor Systems for Earth Science Measurements (SBIR)

Lead Center: LaRC
Participating Center(s): ARC, GSFC, JPL

Subtopic Introduction:

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 annual NASA Research Opportunities in Space and Earth Science (ROSES) solicitations. 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, 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.

For this solicitation, this subtopic seeks technology advancement needs in the following scope:
1. Sensors and Sensor Systems Targeting Trace Gases (returning).

For this solicitation, the following scopes were rotated out but may return in a future year:
1. Sensors and Sensor Systems Targeting Ocean (planned to return 2026).
2. Sensors and Sensor Systems Targeting Aerosols and Clouds (planned to return 2027).

Scope Title: Sensors and Sensor Systems Targeting Trace Gases

Scope Description:

This subtopic seeks sensor and sensor systems targeting trace gases. Complete instrument systems are generally desired, including features such as remote/unattended operation and data acquisition, and minimum size, weight, and power consumption.

Specific desired sensors or mated platform/sensors include:

- Small, lightweight, turn-key in-situ trace gas measurement sensors with 1-10 Hz time response that are suitable for small aircraft, UAV, or balloon deployment and capable of detecting:
    - NO, NO_2, NOx, NOy at < 50 ppt uncertainty.
    - O_3 at < 1 ppb uncertainty.
    - CH_2O at < 100 ppt.
    - Benzene, toluene at < 5% uncertainty.
    - CO, CH_4, OCS, N_2O, ethane at < 1% uncertainty.
    - SO_2 at < 100 pptv uncertainty.
    - HCl at < 40 pptv uncertainty (targeting the stratosphere).
    - Note that uncertainties apply to measurements made on airborne platforms under flight conditions (variable sample and ambient pressure and temperature, vibration, and acceleration) from the surface to the tropopause (unless specified otherwise).
- Small, turn-key remote sensors capable of detecting NO_2, CH_2O, and O_3, at < 5% uncertainty. These sensors must be capable of long term measurements to support NASA ground networks. Improved performance sun and sky viewing spectrometer subsystems that increase measurement accuracy and stability and simplify instrument calibration of sun photometers may be considered.
- Real-time, 0.1 to 1 Hz gas-phase radioisotopic (especially radiocarbon) measurements suitable for distinguishing emissions sources and for deployment on aircraft or UAVs.
- Airborne capable bulk or film retroreflector subsystems that advance NASA open path trace gas measurements (similiar to the widely used NASA LaRC Diode Laser Hygrometer). Operational at wavelengths between 2 to 12 um, or some subset of wavelengths within that range, with low return light cone divergence (<2°).
- Aircraft static air temperature sensor measurement to better than 0.1° C accuracy under upper troposphere / lower stratosphere conditions.
- Innovative, high-value sensors directly targeting a stated NASA need (including aerosols, clouds, and ocean hyperspectral UV-Vis-NIR water-leaving radiance and inherent optical properties) may also be considered. Proposals responding to this specific bullet are strongly encouraged to identify at least one relevant NASA subject matter expert.

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 state of the art.

Expected TRL or TRL Range at completion of the Project: 4 to 7

Primary Technology Taxonomy:

- Level 1: TX 08 Sensors and Instruments
- Level 2: TX 08.3 In-Situ Instruments/Sensor

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware

- Software

Desired Deliverables Description:

- Phase I: Demonstrate a clear idea of the problem to be solved, potential solutions to this problem, and an appreciation for potential risks or stumbling blocks that might jeopardize the success of the Phase I and II projects. The ideal Phase I effort would also address and hopefully overcome any major challenges to (1) demonstrate feasibility of the proposed solution and (2) clear the way for the Phase II effort. These accomplishments would be detailed in the Phase I final report and serve as the foundation for a Phase II proposal.
- 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. Field demonstrations are highly encouraged. Phase II deliverables should also include/delineate any further work that would be required to bring the technologies to full operational and/or commercial use.

State of the Art and Critical Gaps:

There is a persisting need for small sensors supporting NASA SMD research and analysis (R&A) programmatic activities and calibration validation (Cal/Val) activities with improvement over current state of the art. The scope description provides guidance on targeted advancements of the state-of-the-art that will enable and advance programs based on feedback from the Radiation Sciences, Tropospheric Composition, Upper Atmosphere Research, Ocean Biology and Biogeochemistry, Weather and Atmospheric Dynamics, Earth Surface and Interior, and Airborne Science Programs.

This scope addresses shortfalls identified in the Civil Space Shortfall Ranking including:

- [Ranked 20th] ID 1626: Advanced Sensor Components: Imaging
- [Ranked 137th] 1602: 3D/3D+ Imaging and Tomography of Complex Features and Dynamical Processes

Relevance / Science Traceability:

The subtopic is and remains highly relevant to NASA SMD and Earth Science research programs, in particular the Earth Science Atmospheric Composition, Weather and Atmospheric Dynamics, Climate Variability & Change, Carbon Cycle and Ecosystems, and Earth Surface and Interior 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, OCO-3, MAIA, TEMPO, GLIMR, SBG, A-CCP; see links in References). The solicited measurements will be highly relevant to future NASA campaigns with objectives and observing strategies similar to current and past campaigns (e.g., ARCSIX, ASIA-AQ, ACTIVATE, NAAMES, EXPORTS, CAMP2EX, FIREX-AQ, KORUS-AQ, DISCOVER-AQ; see links in References). The need horizon of the subtopic sensors and sensors systems is both near-term (<5 yr) and midterm (5 to 10 yr).

References:

NASA Airborne Science Program aircraft.

1. "Aircraft List," National Aeronautics and Space Administration: https://airbornescience.nasa.gov/aircraft

Decadal Survey Recommended Atmosphere Observing System (AOS) Mission focusing on aerosols, clouds, convection, and precipitation.

2. "Decadal Survey," National Aeronautics and Space Administration: https://science.nasa.gov/earth-science/decadal-surveys

Targets spaceborne observations of carbon dioxide and the Earth's carbon cycle.
3. "OCO-2 Orbiting Carbon Observatory-2," National Aeronautics and Space Administration: https://science.nasa.gov/mission/oco-2

Satellite Mission that extends NASA's study of carbon from the International Space Station (ISS).
4. "OCO-3 Orbiting Carbon Observatory-3," National Aeronautics and Space Administration: https://science.nasa.gov/mission/oco-3

Mission that will make radiometric and polarimetric measurements needed to characterize the sizes, compositions and quantities of particulate matter in air pollution.
5. "Multi-Angle Imager for Aerosols MAIA," Jet Propulsion Laboratory, https://www.jpl.nasa.gov/missions/multi-angle-imager-for-aerosols-maia

Satellite mission focusing on geostationary observations of air quality over North America.
6. "Mission Overview," Tropospheric Emissions: Monitoring of Pollution TEMPO: http://tempo.si.edu/overview.html

PACE Satellite Mission that focuses on observations of ocean biology, aerosols, and clouds.
7. "PACE Plankton, Aerosol, Cloud, ocean Ecosystem," National Aeronautics and Space Administration: https://pace.gsfc.nasa.gov/

SBG Satellite Mission focuses on observations of aquatic and terrestrial ecology.
8. "Welcome to Surface Biology and Geology study," Jet Propoulsion Laboratory: https://sbg.jpl.nasa.gov/

Satellite Mission observes and monitors coastal ocean biology, biogeochemistry and ecology.
9. "GLIMR," Institue for the Study of Earth, Oceans, and Space: https://eos.unh.edu/glimr

Airborne field campaign targeting the Arctic surface-aerosol-cloud-radiation system.
10. "ARCSIX," National Aeronautics and Space Administration: https://espo.nasa.gov/arcsix/content/ARCSIX

Airborne field campaign targeting pollution and urban air quality in Asia.
11. "ASIA-AQ," National Aeronautics and Space Administration: https://espo.nasa.gov/asia-aq/

Arctic-COLORS field campaign studies land-ocean interactions in a rapidly changing Arctic coastal zone, and assess vulnerability, response, feedbacks and resilience of coastal ecosystems, communities and natural resources to current and future pressures. Field work to begin in 2025 and extend to 2028.
12. "Field Campaigns and Projects," National Aeronautics and Space Administration: https://cce.nasa.gov/ocean_biology_biogeochemistry/field_campaigns.html

FORTE project combines optical and radar measurements from planes, helicopters, boats, and drones to measure water flows and carbon biogeochemistry and observe how coastal Arctic ecosystems along Alaska's North Slope respond to changing climate. Field work will begin in 2026 and continue through 2027.
13. "FORTE," National Aeronautics and Space Administration: https://espo.nasa.gov/forte/content/FORTE_0

Airborne field campaign focusing on tropical meteorology and aerosol science.
14. "CAMP2Ex," National Aeronautics and Space Administration: https://espo.nasa.gov/camp2ex

Airborne and ground-based field campaign targeting wildfire and agricultural burning emissions in the United States.
15. "FIREX-AQ," National Aeronautics and Space Administration: https://csl.noaa.gov/projects/firex-aq/

Airborne field campaign mapping the global distribution of aerosols and trace gases from pole-to-pole.
16. "ATom," National Aeronautics and Space Administration: https://espo.nasa.gov/atom/content/ATom

Airborne and ground-based field campaign focusing on pollution and air quality in the vicinity of the Korean Peninsula.
17. "KORUS-AQ," National Aeronautics and Space Administration: https://espo.nasa.gov/korus-aq/content/KORUS-AQ

Airborne and ground-based campaign targeting pollution and air quality in four areas of the United States.
18. "DISCOVER-AQ ," National Aeronautics and Space Administration: https://science.nasa.gov/mission/discover-aq

Earth Venture suborbital field campaign targeting the North Atlantic phytoplankton bloom cycle and impacts on atmospheric aerosols, trace gases, and clouds.
19. "NAAMES North Atlantic Aerosols and Marine Ecosystems Study," National Aeronautics and Space Administration:
https://science.nasa.gov/mission/naames

Field campaign targeting the export and fate of upper ocean net primary production using satellite observations and surface-based measurements.
20. “EXPORTS EXport Processes in the Ocean from RemoTe Sensing," National Aeronautics and Space Administration:
https://oceanexports.org/

Shortfalls
21. "Civil Space Shortfalls," National Aeronautics and Space Administration: https://www.nasa.gov/spacetechpriorities

S12.01: Exoplanet Detection and Characterization Technologies (SBIR)

Lead Center: JPL
Participating Center(s): GSFC

Subtopic Introduction:

Following the National Academies' Astro2020 decadal survey ("Pathways to Discovery in Astronomy and Astrophysics for the 2020s" [Ref. 6]), NASA's Astrophysics Roadmap outlines a path to continue the search for the answer to the fundamental question "Are we alone?" Technology is needed to support exoplanet detection and architectures as plans and investments for next-generation telescopes and observatories are executed. This subtopic seeks innovative technology from devices that are used in high-contrast testbeds, to components that have been demonstrated to meet flight requirements, to enabling demonstrations of components that could enable new instrument architectures. One primary priority is for technology that will operate in space as part of the future great observatory the Habitably Worlds Observatory (HWO).

For this solicitation, this subtopic seeks technology advancement needs in the following scope:

1. Control of Scattered Starlight with Coronagraphs.

For this solicitation, the following scopes were rotated out but may return in a future year:

- Control of Scattered Light with Starshades.
- Technology for Extreme Precision Radial Velocity.

Scope Title: Control of Scattered Starlight With Coronagraphs

Scope Description:

Imaging and spectroscopic characterization of faint astrophysical objects that are located within the obscuring glare of much brighter stellar sources is a unique problem. 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 1 million to 10 billion over an angular spatial scale of 0.05 to 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 scope focuses on advances in coronagraphic instruments that operate at visible and near-infrared (IR) wavelengths. 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 that include, but are not limited to, the following areas:

- Starlight diffraction control and characterization technologies:
  - Diffraction control masks for coronagraphs, which include transmissive scalar, polarization-dependent, spatial apodizing, and hybrid metal/dielectric masks, including those with extremely low reflectivity regions that allow them to be used in reflection.
  - Systems to measure spatial optical density, phase in-homogeneity, 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 control technologies:
  - Small-stroke, high-precision, deformable mirrors 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, power consumption, connectivity, stability, and performance precision of current devices.
  - High-precision, stable, deformable mirrors whose nominal surface can carry optical prescriptions for dual use as imaging optics such as off-axis parabolas and apodizing elements. Similar to other technologies, scalable actuator arrays between hundreds and thousands of actuators are encouraged.
  - Driving electronics, including multiplexers and application-specific integrated circuits (ASICs) with ultra-low power dissipation for electrical connection to deformable mirrors.
- Optical coating and measurement technologies:
  - Instruments capable of measuring polarization crosstalk and birefringence to parts per million.
  - Polarization-insensitive coatings for large optics.
  - Methods to measure the spectral reflectivity and polarization uniformity across large optics.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:

- Level 1: TX 08 Sensors and Instruments
- Level 2: TX 08.2 Observatories

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

- Phase I: Proof of concept, including relevant research, analysis, and detailed designs.
- Phase II: Prototype with successful demonstration of an appropriate TRL performance test. The extent of the prototype development and testing will vary with the technology and will be evaluated as part of the Phase II proposal. Phase II deliverables should also include a plan for further work that would be required to bring the technologies to full operational and/or commercial use.

State of the Art and Critical Gaps:

Coronagraphs have been demonstrated to achieve high contrast in moderate bandwidth in laboratory environments. 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. 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 10^{10}, but they require thousands of wires, and overall wavefront quality and stroke remain concerns.

This scope addresses shortfalls identified in the Civil Space Shortfall Ranking including:

- [Ranked 141st] ID 1604: Find, Study Habitable Zone Earth-like Exoplanets and Search for Biosignatures.

Relevance / Science Traceability:

This scope is a priority for NASA SMD in support of the Astrophysics division. Technologies from this subtopic are directly applicable to mission concept studies such as Habitable Exoplanets Observatory (HabEx), Large Ultraviolet Optical Infrared Surveyor (LUVOIR), starshades, and any space telescopes that could potentially be used for exoplanet imaging and characterization. The HWO project office (including the Technology Maturation Project Office (HTMPO) established Aug 1, 2024) as well the Exoplanet Explorers Program (ExEP) are key stakeholders of this subtopic, with long-term technology maturation goals aligned with the Astrophysics Technology Roadmap and aligned with the "Astro2020 Decadal Survey" [Ref. 6].

References:

1. "Exoplanet Exploration—Planets Beyond Our Solar System," National Aeronautics and Space Administration: https://exoplanets.nasa.gov
2. "Exoplanet Exploration Program," National Aeronautics and Space Administration: https://exoplanets.nasa.gov/exep/
    - Specifically the technology pages and those addressing coronagraphs: https://exoplanets.nasa.gov/exep/technology/technology-overview/
    - Key documents: https://exoplanets.nasa.gov/exep/resources/documents/
3. Mazoyer, J.; Baudoz, P.; Belikov, R.; Crill, B.; Fogarty, K.; et at., "High-Contrast Testbeds for Future Space-Based Direct Imaging Exoplanet Missions," Bulletin of the American Astronomical Society. 2019, Vol. 51, No. 7, pp. 101: https://baas.aas.org/pub/2020n7i101/release/1

4. "Goddard Space Flight Center," National Aeronautics and Space Administration: https://www.nasa.gov/goddard
5. "Enduring Quests Daring Visions: NASA Astrophysics in the Next Three Decades," National Aeronautics and Space Administration: https://smd-cms.nasa.gov/wp-content/uploads/2023/09/secure-astrophysics-roadmap-2013.pdf
6. "Pathways to Discovery in Astronomy and Astrophysics for the 2020s," National Academies: https://www.nationalacademies.org/our-work/decadal-survey-on-astronomy-and-astrophysics-2020-astro2020
7. "HWO News," National Aeronautics and Space Administration: https://science.nasa.gov/astrophysics/programs/habitable-worlds-observatory/news
8. "Cosmic Origins," National Aeronautics and Space Administration: https://cor.gsfc.nasa.gov/
9. "Astrophysics Biennial Technology Report 2024," National Aeronautics and Space Administration: https://apd440.gsfc.nasa.gov/images/tech/2024_ABTR.pdf
10. "Current Technology Gap Priorities," National Aeronautics and Space Administration: https://apd440.gsfc.nasa.gov/tech_gap_priorities.html
11. "Civil Space Shortfalls," National Aeronautics and Space Administration: https://www.nasa.gov/spacetechpriorities

S12.02: Precision Deployable Optical Structures and Metrology (SBIR)

Related Subtopic Pointers: S12.03, T12.01
Lead Center: JPL
Participating Center(s): GSFC

Subtopic Introduction:

Space telescopes continue to require larger apertures for the primary mirror systems but also require precision components for the entirety of the optical chain. This subtopic seeks technologies to achieve large apertures, ultra-stable systems, or other novel deployable space structures not achievable with current state of the art. These innovations are expected to support priority NASA Astrophysics missions including the that of the future Habitable Worlds Observatory (HWO).

The need exists for continued innovation on optical systems and fabrication technologies as applied to ultraviolet (UV) to far-infrared (IR) telescopes. New composite materials, advanced and nanotechnology manufacturing, and new optical techniques could provide the necessary advancements for the new challenging astrophysical missions. Future space astronomy missions from UV 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. HWO calls for a 6 m class aperture. Future cryogenic missions demand operational temperatures as low as 4 K. Methods to construct large telescopes in space are also under development. Additionally, sunshields for thermal control and Starshades for exoplanet imaging and baffles for micrometeoroid protection require deployment schemes to achieve 30 to 70 m class space structures.

For this solicitation, this subtopic seeks technology advancement needs in the following two scopes (not in any priority order):

1. Precision Optical Metering Structures and Instruments.
2. Deployable baffle design for Habitable Worlds Observatory (HWO) (new).

Scope Title: Precision Optical Metering Structures and Instruments

Scope Description:

This subtopic addresses the need to mature technologies that can be used to fabricate 5 to 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. Technology is sought for a range of missions from CubeSats to Pioneers to Explorers to Flagships. 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 of thermal expansion/coefficient of moisture expansion (CTE/CME) materials/structures to enable highly dimensionally stable optics, optical benches, and 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 submicron-level repeatability.
    - Mechanical connections providing microdynamic 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 to 50 m class).
    - Packaging techniques to enable more efficient deployable structures.
- Metrology:
    - Techniques to verify dimensional stability requirements at subnanometer-level precision (10 to 100 pm).
    - 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 m in 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 transition them into a future NASA program(s).

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:

- Level 1: TX 12 Materials, Structures, Mechanical Systems, and Manufacturing
- Level 2: TX 12.2 Structures

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype

- Hardware

Desired Deliverables Description:

- Phase I: Demonstration of the functionality and/or performance of a system/subsystem with model predictions to explain observed behavior as well as make predictions of future designs.
- Phase II: System/subsystem units with successful demonstration of appropriate TRL performance tests. The extent of the development and testing will vary with the technology and will be evaluated as part of the Phase II proposal. Phase II deliverables should also include a plan for further work including scaling to future flight sizes. Phase II deliverables should also include a plan for further work that would be required to bring the technologies to full operational and/or commercial use.

State of the Art and Critical Gaps:

The James Webb Space Telescope (JWST) represents the state of the art in large deployable telescopes. HWO will drive telescope/instrument stability requirements to new levels. The mission concepts responsive to the 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.

This scope addresses shortfalls identified in the Civil Space Shortfall Ranking including:

- [Ranked 88th] ID 1575: Thermal and Vibrational Isolation for Ultra-stable Science Payloads
- [Ranked 171st] ID 1495: Advanced Manufacturing for Improved Dimensional Control of Large Scale Space Structures
- [Ranked 161st] ID 1605: Peer Back Farther in Time to the Early Universe
- [Ranked 141st] ID 1604: Find, Study Habitable Zone Earth-like Exoplanets and Search for Biosignatures

Relevance / Science Traceability:

This scope is a priority for NASA SMD in support of the Astrophysics division. These technologies are directly applicable to the HWO mission concept. Ultrastable optomechanical systems were listed as a "critical" technology gap with an "urgent" priority in the Large UV/Optical/IR Surveyor (LUVOIR) Science and Technology Definition Team (STDT) Final Report for the Astro2020 Decadal Survey and continue to be highly applicable to HWO. Depending on the scale of proposed innovation, stakeholders in different mission classes from CubeSats to Flagships exist.

References:

1. "Habitable Worlds Observatory," National Aeronautics and Space Administration: https://cor.gsfc.nasa.gov/studies/habitable-worlds/hwo.php
2. "Cosmic Origins," National Aeronautics and Space Administration: https://cor.gsfc.nasa.gov/
3. "Exoplanet Discovery," National Aeronautics and Space Administration: https://exoplanets.nasa.gov/what-is-an-exoplanet/technology/
4. "NASA in-Space Assembled Telescope (iSAT) Study," National Aeronautics and Space Administration: https://exoplanets.nasa.gov/exep/technology/in-space-assembly/iSAT_study/
5. "NASA Astrophysics," National Aeronautics and Space Administration: https://science.nasa.gov/astrophysics
6. "Astrophysics Technology Development," National Aeronautics and Space Administration: https://www.astrostrategictech.us/

7. "Astrophysics Biennial Technology Report 2024," National Aeronautics and Space Administration: https://apd440.gsfc.nasa.gov/images/tech/2024_ABTR.pdf
8. "Current Technology Gap Priorities," National Aeronautics and Space Administration: https://apd440.gsfc.nasa.gov/tech_gap_priorities.html
9. "Pathways to Discovery in Astronomy and Astrophysics for the 2020s," National Academies: https://www.nationalacademies.org/our-work/decadal-survey-on-astronomy-and-astrophysics-2020-astro2020
10. "Civil Space Shortfalls," National Aeronautics and Space Administration: https://www.nasa.gov/spacetechpriorities

Scope Title: Deployable Baffle Design for Habitable Worlds Observatory

Scope Description:

This scope calls for the demonstration of technologies to protect the HWO from micrometeoroid impacts while providing thermal isolation and the necessary optical properties to perform sensitive observations in UV/Vis/NIR bands. The JWST's open architecture has exposed a vulnerability to micrometeoroid impacts. Based on the JWST experience, a meteoroid protection system for the HWO is desired. The HWO telescope is described to have the following operating requirements:

- Ultrastable to enable high contrast observations of exoplanets. The stability requires millikelvin control of temperatures of the primary and secondary mirrors, as well as their supporting structures.
- The telescope concept of operations involves rotations about 3 degrees of freedom. The design has a multilayer thermal isolation shield surrounding the telescope to isolate it from the changes in the solar orientation.
- The telescope operates near room temperature which requires significant internal heating resources to compensate for the isolation from the sunlight.
- The coronagraph instrument is highly sensitive to stray light. It is desirable to design the internal layer of the baffle with this in mind.
- The nominal HWO primary is a segmented, 6 m diameter mirror and the length of the telescope may require a baffle length of 30 m or more.

Advances are sought to support a large deployable meteoroid shield HWO baffle design with the following needs:

- (Highest priority) Optimized ballistic properties: minimize micrometeoroid impacts on the mirrors and structure.
- (Highest priority) On-orbit thermal thermal-optical performance: provide thermal isolation for the needed ultra-stability of the structure and mirrors.
    - The solar absorption and thermal emittance of the surfaces may be controlled with optical coatings.
- (High priority) Stray light suppression: provide low-scatter across a broad band (from 100 nm to 2 um).
- (High priority) Provide a shield and deployment system, which minimizes mass, where processes used to make the shield must be scalable to practical sizes.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:

- Level 1: TX 08 Sensors and Instruments
- Level 2: TX 08.2 Observatories

Desired Deliverables of Phase I and Phase II:

- Analysis
- Research
- Prototype
- Hardware
- Software

Desired Deliverables Description:

- Phase I: Perform analysis and describe implementation approach for the optical shield design to inform the effectiveness and feasibility of the proposed ideas.
- Phase II: Demonstrate the new materials or deployment methodology at a meter-class scale. Phase II deliverables should also include/delineate any further work that would be required to bring the technologies to full operational and/or commercial use.

State of the Art and Critical Gaps:

Beta cloth was developed for the Apollo program and has been the “gold standard” for micrometeoroid protection for many decades. However, new materials and processes may be available today to significantly improve ballistic protection, and/or the thermal-optical performance of a multilayer shield. A reliable means to deploy and (possibly) service the shield on-orbit is desirable to reduce mission risks.

This scope addresses shortfalls identified in the Civil Space Shortfall Ranking including:

- [Ranked 88th] ID 1575: Thermal and Vibrational Isolation for Ultra-stable Science Payloads
- [Ranked 171st] ID 1495: Advanced Manufacturing for Improved Dimensional Control of Large-Scale Space Structures
- [Ranked 81st] 1576: Micrometeoroid Robust Protection of In-space Observatories
- [Ranked 141st] ID 1604: Find, Study Habitable Zone Earth-like Exoplanets and Search for Biosignatures

Relevance / Science Traceability:

This scope is a priority for NASA SMD as a critical enabling technology needed in support of the HWO mission. SMD ranked shortfall 1576 Micrometeoroid Robust Protection of In-space Observatories which specifically mentions HWO at rank #22 amongst all the STMD published Civil Space Shortfall Rankings [Ref. 6].

References:

1. Arnold, J.; Christiansen, E. L.; Davis, A.; Hyde, J.; Lear, D.; Liou, J. C.; et al., "Handbook for designing MMOD protection," 2009, No. JSC-64399, Version A: https://ntrs.nasa.gov/citations/20090010053
2. "Astrophysics Biennial Technology Report 2024," National Aeronautics and Space Administration: https://apd440.gsfc.nasa.gov/images/tech/2024_ABTR.pdf
3. "Current Technology Gap Priorities," National Aeronautics and Space Administration: https://apd440.gsfc.nasa.gov/tech_gap_priorities.html
4. "The 2022 Exoplanet Exploration Program Technology Gap List," National Aeronautics and Space Administration: https://exoplanets.nasa.gov/internal_resources/2269/
5. "HWO News," National Aeronautics and Space Administration: https://science.nasa.gov/astrophysics/programs/habitable-worlds-observatory/news
6. "Civil Space Shortfalls," National Aeronautics and Space Administration: https://www.nasa.gov/spacetechpriorities

S12.03: Advanced Optical Systems and Fabrication/Testing/Control Technologies for Extended-Ultraviolet/Optical to Mid-/Far-Infrared Telescopes (SBIR)

Related Subtopic Pointers: S12.02, S12.04, S16.04
Lead Center: MSFC
Participating Center(s): GRC, GSFC, JPL, LaRC

Subtopic Introduction:

Accomplishing NASA's high-priority science at all levels (Flagship, Probe, Medium-Class Explorers (MIDEX), Small Explorers (SMEX), CubeSat, rocket, Pioneer, and balloon) requires low cost, ultra-stable, normal-incidence mirror systems with low mass-to-collecting area ratios. A mirror system is defined as the substrate (material and core structure), supporting structure with associated mechanisms, and active wavefront or thermal sense and control systems. After performance (diffraction limit, wavefront stability, and collecting area), the most important metrics are affordability, or areal cost (cost per square meter of collecting aperture), and mass. The ability to predict 'in-use' performance via validated, integrated structural thermal optio-mechanical performance (STOP) modeling is also important.

This subtopic solicits technology solutions ranging from advanced mirror/structure materials to innovative fabrication and test processes/tools that address technology gaps identified by the "2024 Astrophysics Biennial Technology Report", "Current Technology Gap Priorities", and the "2022 Exoplanet Exploration Program Technology Gap List". Proposals should show traceability to an identified technology gap and present a feasible plan to develop the proposed technology for infusion into a potential NASA Mission.

For this solicitation, this subtopic seeks technology advancement needs in the following three scopes (not in any priority order):

1. Technologies for Advanced Optical System Architectures.
2. Technologies for Fabrication, Test, and Control of Optical Components and Telescopes.
3. Precision Multi-Layer Optical Coatings on Highly Curved Lenses (new).

Scopes #1 and #2 solicit technologies for all potential missions. Scope #1 seeks mirror system solutions. Scope #2 seeks technologies to manufacture, test, and control mirror surfaces. Scope #3 solicits focused 'special' technology needs that are reviewed for each solicitation.

For this solicitation, the following special topics were rotated out from last year (2024) but may return in a future year:

- Polarization birefringence mapper.
- Integrated flexure interface.
- Near-angle scatter.

Scope Title: Technologies for Advanced Optical System Architectures

Scope Description:

This scope solicits mirror system technologies solutions that enable or enhance telescopes for missions of any size (from Balloon or CubeSat to Flagship) operating at any wavelength from Ultraviolet/optical (UVO) to Mid/Far-Infrared (Mid-IR/Far-IR). There are two specific needs to enable/enhance HWO (Habitable World Observatory):

- Mirror system substrate technologies (i.e., designs, assembly technologies, material choices, material combinations, etc.) to produce 1.5 m to 3.5 m size 80% (nominal) light-weighted mirrors with greater than 150 Hz first mode and less than 5 ppb/K coefficients of thermal expansion (CTE) homogeneity.
- Mirror support structure technologies (i.e., designs, assembly technologies, material choices, material combinations, etc.) to produce 6 m to 8 m primary mirror assemblies with greater than 150 Hz first mode and less than 5 ppb/K CTE homogeneity (for thermal stability of structure).

HWO desires a 6 m aperture telescope with better than 500 nm diffraction-limited performance (40 nm rms transmitted wavefront) achieved either passively or via active control operating at 270 K to 300 K (nominal). Optical components need to have less than 5 nm rms surface figures. Additionally, to enable coronagraphy, the HWO requires total telescope wavefront stability of less than 3 pm rms. This stability specification places severe constraints on the dynamic mechanical and thermal performance. Potential enabling technologies include: (1) ultra-stable mirror substrate and support structures with first mode greater than 150 Hz, (2) mirror substrate CTE homogeneity less than 5 ppb/K, (3) athermal telescope structures and mirror struts, (4) ultra-stable joints with low CTE, vibration compensation or isolation of greater than 140 dB, and (5) active thermal control less than 1 mK. Mirror areal density depends upon available launch vehicle capacities to Sun-Earth L2 (ranging from 15 to 150 kg/m^2 depending on potential launch vehicle). Regarding areal cost, a good goal is to keep the total cost of the primary mirror at or below \$100M. Thus, a 6 m class mirror (with ~30 m^2 of collecting area) should have an areal cost of less than \$3.5M/m^2.

Potential balloon science missions are either in the extreme UV (EUV), UVO, or in the Infrared (IR)/Far-IR: EUV missions require optical components with surface slopes of less than 0.1 µrad; UVO science missions require 1 m class telescopes diffraction limited at 500 nm; and Mid-IR missions require 2 m class telescopes diffraction limited at 5 µm. In all cases, telescopes must be able to maintain diffraction-limited performance for elevation angles ranging from 10° to 65° over a temperature range of 220 K to 280 K. Also, the telescopes need to have a total mass of less than 300 kg and be able to survive a 10g shock (on landing) without damage. For packaging reasons, the primary mirror assembly should have a radius of curvature 3 m (nominal) and a mass less than 150 kg.

Potential Far-IR space missions require telescopes with apertures up to 6 m monolithic or 16 m segmented with diffraction-limited performance as good as 5 µm (400 nm rms transmitted wavefront) operating at lower than 10 K (survival temperature from 4 k to 315 K). Mirror substrate thermal conductivity at 4 K must be greater than 2 W/m·K. Ideally, the mirror should have less than 100 nm rms surface figure change from 300 K to 10 K. Mirror areal density goal is 25 kg/m^2 for the primary mirror substrate and 50 kg/m^2 for the primary mirror assembly (including structure). Areal cost goal is total cost of the primary mirror at or below \$100K/m^2. Potential solutions include but are not limited to: (1) materials with low CTE, homogenous CTE, and high thermal conductivity, (2) metal alloys, nanoparticle composites, carbon fiber, graphite composites, ceramic or SiC materials, and (3) additive manufacture or direct precision machining.

CubeSat missions need low cost, compact, scalable, diffraction-limited, and athermalized off-axis reflective and on-axis telescopes. One potential mission is for Near-Infrared/Short-Wave-Infrared- (NIR/SWIR-) band optical communication. A NIR/SWIR optical-communication system needs to have an integrated approach that includes fiber optics, fast-steering mirrors, and applicable detectors.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:

- Level 1: TX 08 Sensors and Instruments
- Level 2: TX 08.2 Observatories

Desired Deliverables of Phase I and Phase II:

- Analysis
- Prototype
- Hardware
- Research

Desired Deliverables Description:

- Phase I: Optical component or telescope system of at least 0.25 m or a relevant subcomponent of a system leading to a successful Phase II delivery and a preliminary design and manufacturing plan that demonstrates feasibility. Preliminary design should address how optical, mechanical (static and dynamic), and thermal designs and performance analyses will be done to show compliance with all requirements. Past experience or technology demonstrations that support the design and manufacturing plans will be given appropriate weight in the evaluation.
- Phase II: Flight-qualifiable and scalable optical system, sub-system, or relevant components (with TRL in the 4 to 5 range) with the required performance. 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 II would have a credible plan to deliver for the allocated budget a fully assembled and tested telescope assembly that can be integrated into the potential mission, as well as 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 analyses).

State of the Art and Critical Gaps:

Current state of the art (SOA) reveals a critical technology gap where no 6 meter mirror assembly has demonstrated that it can meet both of the HWO requirements of greater than 150 Hz first mode and less than 5 ppb/K CTE homogeneity.

In terms of cost, current SOA 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×, to between $\$100K/m^2$ and $\$1M/m^2$.

In support of balloon science missions, current SOA for balloon mission mirrors require light-weighting to meet balloon mass limitations and have difficulty meeting Optical Mid-IR diffraction-limited performance over the wide temperature range because of the coefficient of thermal expansion limitations and gravity sag change as a function of elevation angle.

In support of CubeSats, current SOA optical communications on-axis or axisymmetric designs are problematic because of the central obscuration. Off-axis designs provide superior optical performance because of the clear aperture; however, they are more complex to design, manufacture, and test.

This scope addresses shortfalls identified in the Civil Space Shortfall Ranking including:

- [Ranked 88th] ID 1575: Thermal and Vibrational Isolation for Ultra-stable Science Payloads
- [Ranked 171st] ID 1495: Advanced Manufacturing for Improved Dimensional Control of Large Scale Space Structures
- [Ranked 161st] ID 1605: Peer Back Farther in Time to the Early Universe
- [Ranked 141st] ID 1604: Find, Study Habitable Zone Earth-like Exoplanets and Search for Biosignatures

Relevance / Science Traceability:

This scope supports multiple mission's concepts within the NASA SMD Astrophysics Division. These missions require new concepts ranging from advanced mirror/structure materials to innovative fabrication and test processes/tools that address technology gaps identified by the 2024 Astrophysics Biennial Technology Report [Ref. 2] and the 2022 Exoplanet Exploration Program Technology Gap List [Ref. 4]. It is expected that contributions from this subtopic will enable and advance large-aperture ultra-stable telescopes and large-aperture cryogenic telescopes.

Additionally, this scope matures technologies for potential balloon missions flying higher than 45,000 ft to perform UV and Mid-IR/Far-IR science at wavelengths inaccessible from the ground.

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7. "Columbia Scientific Balloon Facility," National Aeronautics and Space Administration: https://www.csbf.nasa.gov/docs.html
    - Additional information about scientific balloons.
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    - An example of an on-axis design has been utilized in the Lunar Laser Communications Demonstration (LLCD).
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    - An example of an off-axis design is being developed by the Jet Propulsion Laboratory (JPL) for Deep Space Optical Communications (DSOC).
10. "Civil Space Shortfalls," National Aeronautics and Space Administration: https://www.nasa.gov/spacetechpriorities

Scope Title: Technologies for Fabrication, Test, and Control of Optical Components and Telescopes

Scope Description:

The ability to fabricate, test, and control optical surfaces is enabling for future missions of all spectral bands (UV, optical, IR and FIR). This scope solicits technology advances that enable the manufacture of optical components (of all diffraction limits, sizes, and operating temperatures) for a lower cost. Achieving this goal requires technologies that (1) enable/enhance the deterministic manufacture of optical components to their desired optical prescription, (2) control of the shape of optical components in flight, and (3) fully characterize surface errors.

While proposals are welcomed over a broad technology range, for 2025, there are two prioritized needs:

- Super-polishing of 1.0 to 3.5 meter mirrors for HWO.
- Computer controlled polishing of 0.2 to 2.0 meter Far-IR mirrors.

HWO Super-Polishing:

- Preliminary analysis indicates that to image and characterize Earth-like planets around Sun-like stars with an internal coronagraph, the HWO telescope requires mirrors with microroughness of less than 0.3 nm rms and correlation length of 10 to 50 micrometers. Thus, technologies and processes are needed to super-polish lightweight (i.e., thin facesheet and pocketed core structure) 1.0 to 3.5 meter class concave and convex mirrors with microroughness of less than 0.3 nm rms and correlation length of 10 to 50 micrometers.

Far-IR Computer Controlled Polishing:

- To reduce cost, FIR space and balloon missions are planning to use aluminum telescope mirrors, but these missions are also striving for shorter diffraction limited performance. The challenge is that cryogenic deformation and gravity-sag deformation impacts diffraction limited performance. To achieve the desired performance, technology and processes are needed to computer control polish 0.2 to 2.0 meter class concave and convex aluminum mirrors to a final surface figure of less than 500 nm rms and roughness less than 30 nm rms.

Additionally, offerors are invited to submit proposals for any technology that enables or enhances the fabrication, test, or control of optical components or telescope. Given that deterministic optical fabrication is relatively mature, technology advances are solicited that primarily reduce cost, particularly for large mirrors. Technology that increases remove rate (to reduce processing time) while producing smoother surfaces (less mid- and high-spatial frequency error) are potentially enhancing.

To achieve high-contrast imaging for exoplanet science using a coronagraph instrument, systems must maintain wavefront stability to <3 pm rms during critical observations. This requires new technologies and techniques for: (1) wavefront sensing, metrology, verification, and validation of wavefront stability, and (2) sensing and control of segment-to-segment alignment. Also, actuators are needed to align and co-phase segmented-aperture mirrors to diffraction-limited tolerances. Depending upon the mission, these mechanisms may need precisions of <1 nm rms and the ability to operate at temperatures as low as 10 K.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:

- Level 1: TX 08 Sensors and Instruments
- Level 2: TX 08.2 Observatories

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Hardware
- Software
- Prototype

Desired Deliverables Description:

Desired deliverables for the following technologies are outlined below.

- HWO Super-Polishing:
    - Phase I:
        - Documented process for super-polishing surfaces to microroughness of less than 0.3 nm rms and correlation length of 10 to 50 micrometers that can be scaled to large-aperture (1.0 to 3.5 m) light-weight concave and convex mirrors.
        - Demonstration of the process on a 0.25 meter (or larger) class lightweight mirror with an architecture traceable to 1.0 to 3.5 m class.
        - Delivery of the mirror for independent characterization and assessment.
    - Phase II:
        - Demonstrate the process on a 0.5-meter (or larger) flight-traceable mirror.
        - Demo mirror for independent characterization and assessment.
        - Full documentation of process.
        - Credible plan for scaling process up to HWO flight-like mirrors.
- Far-IR Computer Controlled Polishing:
    - Phase I:
        - Identify, define, and test machine automated finishing concepts which start with diamond turned surfaces and produce the required surface finish for Aluminum infrared mirrors.
        - Final technical report and a roadmap cost model for future development of the technology and the machine & tooling required to finish the mirror.
    - Phase II:
        - Design, build and implement an automated 2.0 meter mirror machine which can cryo-null polish or gravity-sag compensation diamond turned aluminum mirrors to a specified figure less than 500 nm rms and roughness less than 30 nm rms.
        - Demonstration of machine's capability by figuring/finishing a 1.2 to 1.8 m aluminum mirror provided by MSFC.

State of the Art and Critical Gaps:

The current SOA for super-polishing of surfaces is mature for 1.0 meter class EUV lithograph surfaces. The problem is that these surfaces are typically on solid mirrors or lenses with either spherical or shallow aspheric prescriptions. The ability to super-polish 1.0 to 3.5 meter class lightweight aspheric space mirrors to microroughness of less than 0.3 nm rms and correlation length of 10 to 50 micrometers has never been demonstrated because no previous mission has ever required such a surface.

Deterministic polishing of Far-IR mirrors is mature. There are multiple small and large companies offering commercial products and services. The Webb beryllium mirrors and the Roman ULE mirror were fabricated by deterministic processes. However, processes have not been developed and refined for 0.2 to 2.0 meter Far-IR aluminum mirrors. Also, technology advances are required to enhance these processes and reduce their cost, particularly for large mirrors.

This scope addresses shortfalls identified in the Civil Space Shortfall Ranking including:

- [Ranked 88th] ID 1575: Thermal and Vibrational Isolation for Ultra-stable Science Payloads
- [Ranked 171st] ID 1495: Advanced Manufacturing for Improved Dimensional Control of Large-Scale Space Structures
- [Ranked 161st] ID 1605: Peer Back Farther in Time to the Early Universe
- [Ranked 141st] ID 1604: Find, Study Habitable Zone Earth-like Exoplanets and Search for Biosignatures

Relevance / Science Traceability:

This scope supports multiple mission's concepts within the NASA SMD Astrophysics Division. These missions require mature fabrication/test and wavefront control technologies. Fabrication and testing technologies for deterministic optical manufacturing are enabling/enhancing for large monolithic and segmented aperture telescopes for missions ranging from UV to optical to Far-IR. Control technologies are enabling for coronagraph-equipped space telescopes and segmented space telescopes. The HWO mission concept is the target for HWO Super-Polishing, and the recently selected for Phase A PRIMA (PRobe far-Infared Mission for Astrophysics) is targeted Far-IR Computer Controlled Polishing.

References:

1. "Astrophysics Biennial Technology Report 2024," National Aeronautics and Space Administration: https://apd440.gsfc.nasa.gov/images/tech/2024_ABTR.pdf
2. "Current Technology Gap Priorities," National Aeronautics and Space Administration: https://apd440.gsfc.nasa.gov/tech_gap_priorities.html
3. "The 2022 Exoplanet Exploration Program Technology Gap List," National Aeronautics and Space Administration: https://exoplanets.nasa.gov/internal_resources/2269/
4. "PRIMA: The PRobe far-Infared Mission for Astrophysics," California Institute of Technology: https://prima.ipac.caltech.edu/
5. "Civil Space Shortfalls," National Aeronautics and Space Administration: https://www.nasa.gov/spacetechpriorities

Scope Title: Precision Multi-Layer Optical Coatings on Highly Curved Lenses

Scope Description:

There is an ever increasing need to reduce size and weight of space-based optical systems for scientific imaging and laser communications (e.g., Edwards 2017 [Ref. 2]; Gatlin et al. 2024 [Ref. 3]). These applications require very narrow spectral bandpass filters, often on the order of 1 to 3 nanometers, and large apertures to maximize signal-to-noise ratio. However, the constrained incidence angle allowance (< 5 degrees) required by the multi-layer hard coatings applied to flat plate filters is prohibitive to the design of compact optical systems with wide field-of-view (e.g., Verker et al. 1997 Ref. 4). Breaking through this design barrier calls for the ability to apply precision optical coatings on lenses with significant optical power.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:

- Level 1: TX 08 Sensors and Instruments
- Level 2: TX 08.2 Observatories

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware
- Software
- Research
- Analysis

Desired Deliverables Description:

- Phase I: Demonstrate the capability to maintain a uniform coating on a curved surface and verify uniform bandpass characteristics across the optical element.
- Phase II: Produce a curved, large format (e.g., 50 to 100 mm diameter) very narrow (1 to 3 nm) bandpass filter with the required performance that is flight qualifiable and can be integrated into a wide field of view imaging system, such as that used by low-Earth orbit lightning mapping instruments. Phase II deliverables should also include/delineate any further work that would be required to bring the technologies to full operational and/or commercial use.

State of the Art and Critical Gaps:

Optical interference filter manufacturing processes apply multiple coatings to achieve high transmission across the desired passband while blocking outside of this range. Various deposition techniques exist to add thin films onto a substrate. Both vapor and chemical deposition have been successfully used to produce interference filters capable of high transmission across a 1 nm wide passbands. These have been achieved on planar surfaces and very small format curved surfaces. Achieving such narrow passbands on large and highly curved surfaces requires new coating techniques capable of precisely maintaining the uniformity of each layer within the stack.

This scope addresses shortfalls identified in the Civil Space Shortfall Ranking including:

- [Ranked 141st] ID 1604: Find, Study Habitable Zone Earth-like Exoplanets and Search for Biosignatures

Relevance / Science Traceability:

This special scope addresses the need to reduce the size and weight of optical remote sensing instruments so that they can be utilized in small satellite and CubeSat constellations. Technologies will enable future SMD missions across Earth science, heliophysics, and planetary science. In particular, NASA is seeking to develop new compact lightning mapping technology to address the need for additional satellite-based observations of deep convection and extreme weather that is mentioned in the recent Decadal Survey for Earth Science and Applications [Ref. 5].

References:

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    - General information on micrometeoroid protection.
2. Edwards, B. L., "NASA's current activities in free space optical communications," International Conference on Space Optics—ICSO 2014, 2017, Vol. 10563, pp. 255-263: https://doi.org/10.1117/12.2304175
3. Gatlin, P.; Quick, M.; Lang, T.; Bitzer, P.; Walker, D.; Koshak, W.; et al., "Future Lightning Instruments for Weather and Climate Monitoring From LEO," 104rd American Meteorological Society (AMS) Annual Meeting. 2024: https://ntrs.nasa.gov/api/citations/20240000838/downloads/AMS_2024_FutureLEO_monitoring_Gatlin.pdf
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7. "Astrophysics Biennial Technology Report 2024," National Aeronautics and Space Administration: https://apd440.gsfc.nasa.gov/images/tech/2024_ABTR.pdf
8. "Current Technology Gap Priorities," National Aeronautics and Space Administration: https://apd440.gsfc.nasa.gov/tech_gap_priorities.html
9. "Civil Space Shortfalls," National Aeronautics and Space Administration: https://www.nasa.gov/spacetechpriorities

S12.04: X-Ray Mirror Systems Technology, Coating Technology for X-Ray-UVOIR (Ultraviolet-Optical-Infrared), and Free-Form Optics (SBIR)

Related Subtopic Pointers: S12.03
Lead Center: GSFC
Participating Center(s): JPL, MSFC

Subtopic Introduction:

The National Academies' Astro 2020 Decadal Report identifies studies of optical components and the ability to manufacture, coat, and perform metrology needed to enable future X-ray observatory missions. The Astrophysics Decadal Report also specifically calls for optical coating technology investment for future Ultraviolet (UV), optical, exoplanet, and Infrared (IR) missions, and the Heliophysics 2014-2033 Roadmap identifies the coating technology for space missions to enhance the rejection of undesirable spectral lines and to improve space/solar-flux durability of extreme UV (EUV) optical coatings as well as coating deposition to increase the maximum spatial resolution. In addition, future optical systems for NASA's low-cost missions, CubeSat and other small scale payloads, are moving away from traditional spherical optics to non-rotational symmetric surfaces with anticipated benefits of free-form optics such as fast wide field and distortion free cameras.

For this solicitation, this subtopic seeks technology advancement needs in the following three scopes (not in any priority order):

1. X-Ray Mirror Systems Technology.
2. Coating Technology for X-Ray-UVOIR.
3. Free-Form Optics.

Scope #1 solicits novel techniques and enhancements to X-ray manufacturing, coating, testing, assembling as well as complete mirror systems. Scope #2 solicits coating technology including carbon nanotubes (CNTs) for a wide range of wavelengths from X-ray to IR (X-ray, EUV, UV, vacuum UV (VUV), visible, and IR). Scope #3 solicits free-form optics design, fabrication, and metrology for CubeSat, SmallSat, and various coronagraph instruments.

Scope Title: X-Ray Mirror Systems Technology

Scope Description:

NASA large X-ray observatories require low cost, ultra-stable, preferably lightweight mirrors with high reflectance optical coatings and effective stray light suppression. A number of improvements advancing state of the art (SOA) such as 1 arcsec or better angular resolutions and 1 to 5 m^2 collecting areas are needed for this technology. Cost improvements are sought including reduction in the areal cost of a telescope to a target goal of $1M to $100K per square meter. This scope seeks to address the multiple technologies, including (priorities are labeled with highest being the most critical to filling gaps in NASA needs, though proposals addressing any of the areas will still be considered and reviewed based on merit):

- (Highest priority) Improvements to manufacturing (machining, rapid optical fabrication, slumping, or replication technologies), metrology, performance prediction, and testing techniques; active control of mirror shapes.
  - One specific solution needed in X-ray mirror manufacturing is a technology for diamond turning of high aspect ratio mandrels. Without this capability there is a technical constraint on high energy astrophysics missions.
- (Highest priority) New structures for holding and actively aligning mirrors in a telescope assembly to enable X-ray observatories while lowering the cost per square meter of the collecting aperture.
- (Higher priority) Effective designs of stray light suppression.
- (Higher priority) Epoxies that impart little to no stress on the mirrors during application and curing. For silicon mirrors, the epoxies should absorb IR radiation (with wavelengths between 1.5 and 6 µm that traverse silicon with little or no absorption) and therefore can be cured quickly with a beam of IR radiation.
- (High priority) New advanced technology computer numerical control (CNC) machines to polish the inside and/or outside of a full shell substrate (between 100 and 1,000 mm in height, 100 to 2,800 mm in diameter, varying radial prescription along azimuth, ~2 mm in thickness), grazing-incidence optics to X-ray-quality surface tolerances (with surface figure error <1 arcsec half-power diameter (HPD), radial slope error <1 µrad, out-of-round <2 µm).

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:

- Level 1: TX 08 Sensors and Instruments
- Level 2: TX 08.2 Observatories

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Typical deliverables for this scope is an X-ray optical mirror system—demonstration, analysis, reports, software, and hardware prototype:

- Phase I: Reports, analysis, and demonstration.
  - Analysis: Modeling and analytical techniques to predict the suitability of the proposed design.
  - Demonstration: end product proposed can achieve specified requirements.
- Phase II: Analysis, demonstration, and prototype. Breadboard and test results that show sufficient data verifying the performance of the proposed design. Phase II deliverables should also include/delineate any further work that would be required to bring the technologies to full operational and/or commercial use.

State of the Art and Critical Gaps:

Particular gaps to be covered seeking solution in this scope are lightweight, low cost, ultra-stable mirrors for large X-ray observatories, stray light suppression systems for large, advanced X-ray observatories, and ultra-stable, inexpensive, lightweight X-ray telescopes using grazing incidence optics for high-altitude balloon-borne and rocket-borne missions.

X-ray optics manufacturing, metrology, coating, testing, and assembly is very costly and time consuming. SOA (state of the art) of ~10 arcsec angular resolution requires improvement. In addition, X-ray space mirrors cost $4M to $6M per square meter of optical surface area, and this effort seeks innovative solutions that will result in a cost reduction for precision optical components by 5 to 50 times, to less than $1M to $100K per square meter.

Current stray light suppression is bulky and ineffective for wide field of view telescopes. Effective stray light suppression systems including baffle designs are needed to enable large ultra-stable Astrophysics observatories.

Current SOA in CNC polishing of full shell substrate, grazing incidence optics yields better than 2.5 arcsec HPD on the 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.

This scope addresses shortfalls identified in the Civil Space Shortfall Ranking including:

- [Ranked 168th] ID 1606: Observe Some of the Most Energetic Phenomena in the Universe
- [Ranked 88th] ID 1575: Thermal and Vibrational Isolation for Ultra-stable Science Payloads
- [Ranked 171st] ID 1495: Advanced Manufacturing for Improved Dimensional Control of Large Scale Space Structures

Relevance / Science Traceability:

The 2020 National Academies' Decadal Report specifically identifies optical components and the ability to manufacture and perform precise metrology on them needed to enable several different future missions. In addition, advanced mirror technology for X-ray optics continues to be a NASA Astrophysics technology gap priority. The scope supports interests from within the NASA SMD Astrophysics division that support mission concepts for large X-ray observatories while enhancements into areas such as stay light control can be of benefit to other proposed mission concepts.

References:

1. "NASA Astrophysics," National Aeronautics and Space Administration: https://science.nasa.gov/astrophysics
    - Overview that will provide context for proposers, and many useful links including the Astrophysics Fleet Mission Chart and the Decadal Survey.
2. "Astrophysics Technology Development," National Aeronautics and Space Administration: https://www.astrostrategictech.us/
    - Searchable database of non-SBIR funded proposals (e.g., SATs, APRAs) indicating where NASA is investing in technology.
3. "Astrophysics Biennial Technology Report 2024," National Aeronautics and Space Administration: https://apd440.gsfc.nasa.gov/images/tech/2024_ABTR.pdf
4. "Current Technology Gap Priorities," National Aeronautics and Space Administration: https://apd440.gsfc.nasa.gov/tech_gap_priorities.html
5. "Decadal Survey on Astronomy and Astrophysics 2020 (Astro2020)," National Academies: https://www.nationalacademies.org/our-work/decadal-survey-on-astronomy-and-astrophysics-2020-astro2020

6. "Solar and Space Physics: A Science for a Technological Society," National Academies: http://nap.edu/13060
7. "Civil Space Shortfalls," National Aeronautics and Space Administration: https://www.nasa.gov/spacetechpriorities

Scope Title: Coating Technology for X-Ray-UVOIR (Ultraviolet-Optical-Infrared)

Scope Description:

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 can be funded in the current cost environment. The most common forms of coating used on precision optics are anti-reflective (AR) and highly reflective (HR) coatings. The current coating technology of optical components is needed to support the 2020 Astrophysics Decadal process. NASA seeks to sustain systematic investment into advanced coating technologies to mature alongside mirror technology over the next decade from TRL 3 to 6. Telescope optical coatings need to meet a low-temperature operation requirement with a desire to achieve 35 K in the future.

Many 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 carbon nano tube (CNT) coatings. Similarly, scattered light suppression for gravitational-wave observatories and lasercom (laser communication) systems where simultaneous transmit/receive operation is required could be achieved by a highly absorbing coating such as CNT. Ideally, the application of CNT coatings needs to:

- Achieve broadband (visible plus Near-IR (NIR)) reflectivity of 0.1% or less.
- Resist bleaching or significant albedo changes over a mission life of at least 10 years.
- Withstand launch conditions such as vibration, acoustics, etc.
- Tolerate both high continuous-wave (CW) and pulsed power and power densities without damage: ~10 W for CW and ~0.1 GW/cm^2 power density, and 1 kW/nsec pulses.
- Adhere to a multilayer dielectric or protected metal coating, including ion beam sputtering (IBS) coating.

NASA's Laser Interferometer Space Antenna (LISA) mission requires a telescope that operates simultaneously in transmission and reception. An off-axis optical design is used to avoid having the secondary mirror send the transmitted beam directly back at the receiver. Very low reflectivity coatings will help further suppress scattered light from the telescope structure and mounts. In addition, the ability to fabricate very low reflectivity apodized petal shaped masks at the center of a secondary mirror may enable the use of an on-axis optical telescope design, which may have some advantages in stability as well as in fabrication and alignment because of its symmetry. The emerging cryogenic etching of black silicon has demonstrated bidirectional reflectance distribution function (BRDF) ultralow reflectance with specular reflectance of 1×10^{-7} in the range of 500 to 1064 nm. The advancement of this technology is desired to obtain ultralow reflectivity:

- Improve the specular reflectance to 1×10^{-10} and hemispherical reflectance to 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 features.
- Explore etching process and duration.
  - Software tools to simulate and assist the anisotropic etching by employing a 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 (EMT).

The following metrics will be utilized in the evaluation of proposed coating technology:

- 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).
- EUV:
  - Reflectivity >90% from 6 to 90 nm onto a <2-m mirror substrate.
- Large UV/Optical/IR Surveyor:
  - Broadband reflectivity >70% from 90 to 120 nm (Lyman UV, LUV) and >90% from 120 nm to 2.5 µm (VUV/visible/IR).
  - Reflectivity non uniformity <1% from 90 nm to 2.5 µm.
  - Induced polarization aberration <1% for 400 nm to 2.5 µm spectral range from mirror coating applicable to a 1 to 8-m substrate.
- 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 1064 nm.
    - High reflectivity, R > 0.9995.
    - Performance in a space environment without significant degradation over time (e.g., under radiation exposure or outgassing).
    - High polarization purity, low optical birefringence over a range of incident angles from ~5° to ~20°.
    - Low coating noise (thermal, photothermal, etc.) for high-precision interferometric measurements.
    - Ability to endure applied temperature gradients (without destructive effects, such as delamination from the substrate).
    - Ability to clean and protect the coatings and optical surfaces during mission integration and testing without degrading coating performance.
- Nonstationary optical coatings:
  - Used in reflection and transmission that vary with location on the optical surface.
- CNT coatings:
  - Broadband visible to NIR, total hemispherical reflectivity of 0.01% or less.
  - Adherence to the multilayer dielectric or protected metal coatings.
- Black-silicon cryogenic etching (new):
  - Broadband UV to IR, reflectivity of 0.01% or less.
  - Adherence to the multilayer dielectric (silicon) or protected metal.

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:

- Level 1: TX 08 Sensors and Instruments
- Level 2: TX 08.2 Observatories

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Desired deliverables for this scope include analysis, reports, software, demonstration of the concept, and prototype for the coating technology:

- Phase I: Reports, analysis, and demonstration.
    - Analysis: Modeling and analytical techniques to predict the suitability of the proposed design
    - Demonstration: End product proposed can achieve specified requirements
- Phase II: Analysis, demonstration, and prototype. Breadboard and test results that show sufficient data verifying the performance of the proposed design. Phase II deliverables should also include/delineate any further work that would be required to bring the technologies to full operational and/or commercial use.

State of the Art and Critical Gaps:

Current coating SOA includes EUV is defined by heliophysics (80% reflectivity from 60 to 200 nm) and X-Ray-UVOIR defined by Hubble's MgF_2-overcoated aluminum on 2.4-m mirror. This coating has birefringence concerns and marginally acceptable reflectivity between 100 and 200 nm. The Habitable Worlds Observatory (HWO) needs a process to be developed and validated that can deposit coatings with high reflectivity from 100 to 2500 nm on concave mirrors of diameter from 1.5 to 6 m with approximately 1% reflectance and 1% polarization form birefringence uniformity over at least 100 x 100 spatial sampling. The range described as 100 to 250 nm is relevant to HWO, and the ideal coating UV reflectivity should be close to unity across those wavelengths. HWO is seeking a high throughput. LISA requires low-scatter HR coatings and low-reflectivity coatings for scatter suppression near 1064 nm. Polarization-independent performance is important. Nulling polarimetry/coronagraphy is needed for exoplanets imaging and characterization, dust and debris disks, extra-galactic studies, and relativistic and nonrelativistic jet studies.

This scope addresses shortfalls identified in the Civil Space Shortfall Ranking including:

- [Ranked 141st] ID 1604: Find, Study Habitable Zone Earth-like Exoplanets and Search for Biosignatures
- [Ranked 161st] ID 1605: Peer Back Farther in Time to the Early Universe
- [Ranked 168th] ID 1606: Observe Some of the Most Energetic Phenomena in the Universe
- [Ranked 162nd] ID 1607: Detect New Astronomical Messenger - Gravitational Waves

Relevance / Science Traceability:

Coatings for X-ray, EUV, LUV, UV, visible, and IR telescopes are needed in support of mission’s priorities outlined in the Astrophysics Decadal including future UV/optical and exoplanet missions. This includes LISA, future exoplanetary missions involving high-contrast imaging, and future X-ray missions. LISA requires low-scatter HR coatings and low-reflectivity coatings for scatter suppression near 1064 nm. Coating that support nulling polarimetry/coronagraphy are needed for exoplanets imaging and characterization, dust and debris disks, extra-galactic studies, and relativistic and nonrelativistic jet studies. Polarization-independent performance is important.

In addition to Astrophysics, the Heliophysics Roadmap 2014-2033 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), and Solar-C.

References:

1. "Our Dynamic Space Environment: NASA Heliophysics Science and Technology Roadmap for 2014-2033," National Aeronautics and Space Administration: https://explorers.larc.nasa.gov/HPSMEX/MO/pdf_files/2014_HelioRoadmap_Final_Reduced_0.pdf
2. "LISA: Laser Interferometer Space Antenna," National Aeronautics and Space Administration: https://lisa.nasa.gov/
    - LISA is a space-based gravitational wave observatory building on the success of LISA Pathfinder and Laser Interferometer Gravitational-Wave Observatory (LIGO). Led by the European Space Agency (ESA), the new LISA mission (based on the 2017 L3 competition) is a collaboration between ESA and NASA.
3. "High Energy Astrophysics Science Archive Research Center (HEASARC)", National Aeronautics and Space Administration: https://heasarc.gsfc.nasa.gov/
4. "NASA Athena Project," National Aeronautics and Space Administration: https://asd.gsfc.nasa.gov/athena/
5. "The X-ray Observatory," National Aeronautics and Space Administration: https://www.greatobservatories.org/xray
6. "HWO News," National Aeronautics and Space Administration: https://science.nasa.gov/astrophysics/programs/habitable-worlds-observatory/news
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10. [10] "Astrophysics Biennial Technology Report 2024," National Aeronautics and Space Administration: https://apd440.gsfc.nasa.gov/images/tech/2024_ABTR.pdf
11. [11] "Current Technology Gap Priorities," National Aeronautics and Space Administration: https://apd440.gsfc.nasa.gov/tech_gap_priorities.html
12. [12] "Civil Space Shortfalls," National Aeronautics and Space Administration: https://www.nasa.gov/spacetechpriorities

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 free-form optics that provide non-rotationally symmetric optics allowing for better packaging while maintaining desired image quality. This scope seeks novel methods and technologies that support free-form optics for packaged-constrained imaging systems. Specific advances are sought:

- Design: innovative design methods/tools for free-form systems, including applications for novel reflective optical designs with large fields of view (>30°) and fast F/#s (<2.0).
- Fabrication:
    - 10 cm diameter optical surfaces (mirrors) with free-form optical prescriptions >1 mm, spherical departure with surface figure error <10 nm rms, and roughness <5 Å.

    - 10 cm diameter blazed optical reflective gratings on free-form surface shapes with >1 mm departure from a best fit sphere and grating spacings from 1 to 100 µm.
    - larger mirrors for flagship missions for UV and coronagraph applications, with 10 cm to 1m diameter surfaces having figure error <5 nm rms and roughness <1 Å rms.
- Metrology: accurate metrology of free-form optical components with large spherical departures (>1 mm), independent of requiring prescription specific null lenses or holograms.

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:

- Level 1: TX 08 Sensors and Instruments
- Level 2: TX 08.2 Observatories

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Desired deliverables for this scope include optical components—demonstration, analysis, design, metrology, software, and hardware prototype:

- Phase I: Reports, analysis, and demonstration.
    - Analysis: Modeling and analytical techniques to predict the suitability of the proposed design.
    - Demonstration: End product proposed can achieve specified requirements.
- Phase II: Analysis, demonstration, and prototype. Breadboard and test results that show sufficient data verifying the performance of the proposed design. Phase II deliverables should also include/delineate any further work that would be required to bring the technologies to full operational and/or commercial use.

State of the Art and Critical Gaps:

The field of free-form optics is in the early stages of development where improving optical surfaces with large field of view and fast F/#s is highly desirable. Currently, design and fabrication of free-form 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 the operational temperature range of unobscured systems. In addition to the free-form fabrication, the metrology of free-form optical components is difficult and challenging because of 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.

This scope addresses shortfalls identified in the Civil Space Shortfall Ranking including:

- [Ranked 141st] ID 1604: Find, Study Habitable Zone Earth-like Exoplanets and Search for Biosignatures
- [Ranked 161st] ID 1605: Peer Back Farther in Time to the Early Universe
- [Ranked 168th] ID 1606: Observe Some of the Most Energetic Phenomena in the Universe

Relevance / Science Traceability:

NASA missions with alternative low-cost science and small size payload are increasing. Free-form optics and their metrology techniques could enable cost effective manufacturing of these surfaces enabling new CubeSat, SmallSat, and NanoSat class missions. Additionally, design studies for large observatories such as Origins Space Telescope (OST) and Large UV/Optical/IR Surveyor HWO have demonstrated improved optical performance over a larger field of view afforded by free-form optics. Such programs will require advances in free-form metrology to be successful.

References:

1. West, G. J.; Howard, J. M., "Applications for Freeforms Optics at NASA" European Photonics Industry Consortium (EPIC) Workshop. 2017, No. GSFC-E-DAA-TN48197: https://ntrs.nasa.gov/api/citations/20170010419/downloads/20170010419.pdf
2. Howe, A.; Hovis, C.; Khreishi, M.; Ohl, R., "Alignment and Testing for a Freeform Telescope," 2018, No. GSFC-E-DAA-TN62021: https://ntrs.nasa.gov/api/citations/20180007557/downloads/20180007557.pdf
3. Khreishi, M.; Ohl, R.; Howard, J.; Papa, J.; Hovis, C.; Howe, A., "Freeform Surface Characterization and Instrument Alignment for Freeform Space Applications," Freeform Optics. 2019, pp. FM4B-6: https://ntrs.nasa.gov/api/citations/20190025929/downloads/20190025929.pdf
4. "Cosmic Origins," National Aeronautics and Space Administration: https://cor.gsfc.nasa.gov/
5. "Astrophysics Biennial Technology Report 2024," National Aeronautics and Space Administration: https://apd440.gsfc.nasa.gov/images/tech/2024_ABTR.pdf
6. "Current Technology Gap Priorities," National Aeronautics and Space Administration: https://apd440.gsfc.nasa.gov/tech_gap_priorities.html
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S12.06: Detector Technologies for Ultraviolet (UV), X-Ray, and Gamma-Ray Instruments (SBIR)

Related Subtopic Pointers: S11.04, S13.05, S16.07, S16.08, T8.06
Lead Center: JPL
Participating Center(s): GSFC, MSFC

Subtopic Introduction:

Technologies that support Ultraviolet (UV), X-ray, and gamma ray detector and instruments are needed to support missions and programs aligned with the National Academies' Astro2020 Decadal Survey (“Pathways to Discovery in Astronomy and Astrophysics for the 2020s” [Ref. 3]) and the NASA's Astrophysics Roadmap. Advancements in UV detector capabilities have potential to impact the detector system decisions currently being assessed for Habitable Worlds Observatory (HWO), and X-ray astrophysics has potential short-term needs in instruments for a Probe Class that could launch within a decade.

This subtopic covers detector requirements for a broad range of wavelengths from UV through gamma ray for applications in astrophysics as well as 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, low noise, and enhanced energy resolution.

For this solicitation, this subtopic seeks technology advancement needs in the following two scopes (not in any priority order):

1. Semiconductor Detector Technologies (updated).
2. Superconductor Detector Technologies (new).

Scope Title: Semiconductor Detector Technologies

Scope Description:

The scope seeks Near-UV (NUV), Far-UV (FUV), X-ray, and gamma ray semiconductor detector technologies. Additive manufacturing of interconnect technology development is a science-enabling technology for HWO that is under development based on recommendation of the 2020 Astrophysics Decadal Survey [Ref. 3]. Specific technology areas include, but are not limited to, the bulleted list below (priorities are labeled with highest being the most critical to filling gaps in NASA mission needs, though proposals addressing any of the areas will still be considered and reviewed based on merit):

- (Highest priority) Large format, high resolution NUV (200 to 400 nm) and UV-Visible detectors with formats suitable for mosaicking into very large (e.g., gigapixel) focal plane arrays. Key performance metrics include array and pixel size, read noise and dark counts, and quantum efficiency.
- (Highest priority) Large format, high resolution far FUV (100 to 200 nm) photon counting detectors. Key performance metrics include form factor (e.g., array size, pixel or resolution element size), background noise (read noise, dark signal, clock-induced charge, etc.), and quantum efficiency (30 to 40% in band). Relevant technologies examples include microchannel plates (MCPs), electron multiplying charge coupled devices (EMCCDs), Skipper CCD and complementary metal oxide semiconductor (CMOS) arrays, etc.
- (Highest priority) Solar-blind (visible-blind) FUV detectors with $1x10^{-5}$ out of band rejection for wavelengths > 300 nm. Includes stand-alone or device-integrated filter technologies that enable solar-blind FUV observations.
- (Highest priority) Supporting technologies that would help enable the X-ray Surveyor mission that requires the development of X-ray microcalorimeter arrays with much larger field of view, 10^5 to 10^6 pixels, of pitch 25 μm to 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.
- (Highest priority) Novel concepts for improving superconducting magnetic shielding such as superconducting inks or additive manufacturing are of interest for detector focal planes with challenging shielding geometries and other requirements.
- (Highest priority) Filters with supporting grids are sought that, in addition to increasing filter strength, also enhance electromagnetic interference (EMI) shielding (1 to 10 GHz) and thermal uniformity for decontamination heating. X-ray transmission of greater than 80% at 600 eV per filter is sought, with IR transmission of less than 0.01% and UV transmission of less than 5% per filter. A means of producing filter diameters as large as 10 cm should be considered.
- (Highest priority) Detectors with fast, low-noise, megapixel X-ray imaging arrays with moderate spectral resolution. X-ray imaging arrays covering wide fields of view (≥ 60 x 60 mm) with excellent spatial resolution (i.e. < 16 μm pixels, or equivalent X-ray position resolution) and moderate spectral resolution (comparable to modern scientific CCDs) are desired. These detectors must have good detection efficiency across the soft X- ray band pass (0.2 to 12 keV) and excellent detection in the low energy (0.2 to 1 keV) end of this band pass is essential. Fast frame rates (i.e. > 20 to 100 frame/s) are desired to minimize pileup, reduce non-X-ray background, and maximize time resolution.
- (Higher priority) Detectors with fast readout that can support high count rates and large incident flux from the EUV and X-rays for heliophysics applications, especially solar-flare measurements.
- (Higher priority) Significant improvement in wide-bandgap 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:

  - Extreme-UV (EUV) photon counting, a linear mode gain > 1×10^6 at a breakdown reverse voltage between 80 and 100 V.
  - Detection capability of better than 6 photons/pixel/s down to 135 nm wavelength.
- (High priority) Solid-state detectors with polarization sensitivity relevant to astrophysics as well as planetary and Earth science applications; for example, in spectropolarimetry, as well as air quality and aerosol monitoring for O_3, NO_2, SO_2, H_2S, and ash detection. Refer to National Research Council's Earth Science Decadal Survey (2018) [Ref. 16].
- (High priority) Solar-blind EUV sensor technology with high pixel resolution, large format, high sensitivity and high dynamic range, and low voltage and power requirements with or without photon counting.
- (High priority) Solar X-ray detectors with small independent pixels (10,000 count/sec/pixel) over an energy range from < 5 to 300 keV.
- (High priority) Supporting technologies for packaging of UV detector focal planes with suitable device interfaces (such as microshutter arrays), including additive manufacturing of electronics (AME) of conductive materials to create high-density, well-isolated interconnects in fine feature sizes (down to 50 µm wide on planar substrates that include up to a 1.5 mm sidewall). In NASA 2022 Astrophysics Strategic Technology Gaps [Ref. 5], see gap "High Throughput, Large-Format Object Selection Technologies for Multi-Object and Integral Field Spectroscopy."

Proposed efforts must be directly linked to a requirement for a NASA mission and proposals should reference current NASA missions and mission concepts where relevant. These include, but are not limited to: Explorers, Discovery, Cosmic Origins, Physics of the Cosmos, Solar-Terrestrial Probes, Vision Missions, and Earth Science Decadal Survey missions.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:

- Level 1: TX 08 Sensors and Instruments
- Level 2: TX 08.1 Remote Sensing Instruments/Sensors

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

- Phase I: Results of tests and analysis of designs.
- Phase II: Prototype hardware or hardware for further testing and evaluation is desired. Phase II deliverables should also include/delineate any further work that would be required to bring the technologies to full operational and/or commercial use.

State of the Art and Critical Gaps:

This scope aims to develop and advance detector technologies focused on UV, X-ray, and gamma-ray spectral ranges. The science needs in this range span multiple fields, including astrophysics, planetary science, and UV heliophysics. Several solid-state detector technologies promise to surpass the traditional image-tube-based detectors. Silicon-based detectors leverage enormous investments and promise high performance detectors, and more complex materials, such as gallium nitride and silicon carbide, offer intrinsic solar-blind response. This scope supports efforts to advance technologies that significantly improve the efficiency, dynamic range, noise, radiation tolerance, spectral selectivity, reliability, and manufacturability in detectors.

This scope addresses shortfalls identified in the Civil Space Shortfall Ranking including:

- [Ranked 20th] ID 1626: Advanced Sensor Components: Imaging.
- [Ranked 168th] ID 1606: Observe Some of the Most Energetic Phenomena in the Universe.
- [Ranked 141st] ID 1604: Find, Study Habitable Zone Earth-like Exoplanets and Search for Biosignatures.

Relevance / Science Traceability:

This scope is supported by multiple programs and divisions with NASA SMD. Supported divisions and programs include Astrophysics, Heliophysics, the Explorers Program, and the Planetary Missions Program Office. Mission concepts developed as part of Astro2020 Decadal Survey [Ref. 3] that could be supported by technology developed under this subtopic include Habitable Exoplanet Observatory (HabEx), Large UV/Optical/IR Surveyor (LUVOIR), and the LYYX Mission concept.

Technology advances from this scope can support lunar science/missions (UV spectroscopy to understand Lunar water cycle and minerology), gravitational wave science (swift detection of X-ray and UV counterparts of gravitation wave sources), planetary science (Europa Clipper water/plume detection, Enceladus, Venus), and Earth science (ozone mapping, pollution studies).

References:

1. "NASA Astrophysics," National Aeronautics and Space Administration: https://science.nasa.gov/astrophysics
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5. "Astrophysics Biennial Technology Report 2024," National Aeronautics and Space Administration: https://apd440.gsfc.nasa.gov/images/tech/2024_ABTR.pdf
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15. "Civil Space Shortfalls," National Aeronautics and Space Administration: https://www.nasa.gov/spacetechpriorities

Scope Title: Superconductor Detector Technologies

Scope Description:

Superconducting detector technology, especially single-photon devices, are being investigated for NASA astrophysical applications in future space missions, such as HWO. Distant sources in astrophysics are naturally in the “photon-starved” regime, which makes them suitable for quantum applications. This necessitates the exploitation of quantum effects to obtain the highest sensitivity observations allowed by nature. Most NASA astrophysics investments to date have focused on quantum technologies related to single-photon detectors or ultrasensitive bolometers, which can achieve high sensitivity and optimal performance by using quantum effects such as superconductivity, quantum interference, quantum capacitance, quantum tunneling, and quasiparticle trapping. Some of these include superconducting nanowire single-photon counting detectors (SNSPDs), kinetic inductance detectors (KIDs), transition edge sensors (TESs), superconducting quantum interference devices (SQUIDs), and various types of superconducting bolometers. Many of these technologies are critical for future X-ray and UV missions. This scope seeks to develop and mature innovative architectures, subsystems, and processes that would enable future start of the art improvements to these superconductor devices (TESs, KIDs, SNSPDs, etc.) including novel and/or innovative readouts, shielding, superconducting material components, nanofabrication techniques, etc.

Please note that the following areas are excluded from S12.06 this year:

- Superconducting detector technologies primarily for visible and infrared applications (offerors are suggested to consider S11.04 “Sensor and Detector Technologies for Visible, Infrared (IR), Far-IR, and Submillimeter”).
- Quantum technologies for multiplexing into large arrays and quantum absorbers (offerors are suggested to consider T8.06 “Quantum Sensing/Measurement and Communication").
- Cryogenic technologies, such as cryocoolers or adiabatic demagnetization refrigerators (ADRs) (offerers are suggested to consider S16.07 "Cryogenic Systems for Sensors and Detectors").

Expected TRL or TRL Range at completion of the Project: 2 to 4

Primary Technology Taxonomy:

- Level 1: TX 08 Sensors and Instruments
- Level 2: TX 08.1 Remote Sensing Instruments/Sensors

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

- Phase I: Results of tests and analysis of designs.
- Phase II: Prototype hardware or hardware for further testing and evaluation is desired. Phase II deliverables should also include/delineate any further work that would be required to bring the technologies to full operational and/or commercial use.

State of the Art and Critical Gaps:

There are a number of superconductor device candidates that hold promise for future astrophysics needs. SNSPDs have a very favorable path to scaling to large arrays and have the lowest demonstrated noise of any photon counting detector. Further work is required to demonstrate arrays that have, for example, higher quantum efficiency, higher count rates, lower power operation, and higher operational temperature requirements all in one device. MKIDs (microwave kinetic inductance detectors) are well poised for improvements quantum efficiency, array size, and power consumption (via custom readout schemes).

This scope addresses shortfalls identified in the Civil Space Shortfall Ranking including:

- [Ranked 20th] ID 1626: Advanced Sensor Components: Imaging.
- [Ranked 73rd] ID 1598: Quantum Sensors That Use Photons.
- [Ranked 168th] ID 1606: Observe Some of the Most Energetic Phenomena in the Universe.

Relevance / Science Traceability:

Superconducting detector technology, especially single-photon devices, are being investigated for NASA astrophysical applications in future space missions include HWO. The HWO project office (including the Technology Maturation Project Office (HTMPO) established Aug 1, 2024) as well as the Astrophysics Program Office are invested in the results from this subtopic as advancements in single-photon counting detector technologies mature over the next few years.

References:

1. "Astrophysics Division Technology," National Aeronautics and Space Administration: https://science.nasa.gov/astrophysics/programs/astrophysics-division-technology/
2. "Enduring Quests Daring Visions: NASA Astrophysics in the Next Three Decades," National Aeronautics and Space Administration: https://smd-cms.nasa.gov/wp-content/uploads/2023/09/secure-astrophysics-roadmap-2013.pdf
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S13.01: Robotic Mobility, Manipulation, and Sampling (SBIR)

Related Subtopic Pointers: H9.03, S11.01, S13.03, S13.04, S16.05, S16.07, Z-ENABLE.04
Lead Center: JPL
Participating Center(s): ARC, GRC, GSFC, JSC, MSFC

Subtopic Introduction:

The NASA Planetary Science Decadal Survey for the 2023-2032 decade identifies missions to solar system bodies, including Earth's Moon, Mars, Venus, Enceladus, Ceres, asteroids, and comets. These missions require new mobility, manipulation, sampling, and sample preservation technologies. Mobility systems will provide long-range day and night driving access to scientifically important terrains, sampling systems will acquire samples for in situ analysis and return to Earth, manipulation will provide deployment of the sampling systems and handling of the samples, and sample preservation will maintain sample integrity.

For this solicitation, this subtopic seeks technology advancement needs in the following two scopes (not in any priority order):

1. Robotic Mobility, Manipulation, and Sampling.
2. Sample Preservation for Sample Return Missions (new).

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, as well as acquisition and handling of samples for in situ analysis or return to Earth. For example, an Endurance-A rover mission to Earth's moon needs wheel, long-life actuator, sampling, manipulation, and autonomy technologies to enable fast and long-distance traverse, sample acquisition, and sample storage.

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. Minimization of mass and the ability to work reliably in a harsh mission environment are important characteristics for the tools. 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, dust) are of particular interest. Proposals should address one specific area of interest that may include the following (not in any priority order):

- Surface navigation technologies for long-range day and night driving.
- Perception and illumination hardware components and algorithms for challenging lighting conditions.
- Sample collection, handling, and verification components and systems.
- Variable-altitude Venus's balloon technology.
    - For example, mini IR camera dropsonde, descent rate limiting spooling systems, compact solar array deployment.

Proposals should show an understanding of relevant science needs and engineering constraints and present a feasible plan, including a discussion of challenges and appropriate testing, to fully develop a technology and infuse it into a NASA program.

Expected TRL or TRL Range at completion of the Project: 2 to 4

Primary Technology Taxonomy:

- Level 1: TX 04 Robotics Systems
- Level 2: TX 04.3 Manipulation

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Desired deliverables for this scope include hardware, software, and designs for component robotic systems.

- Phase I: Proof of concept, including relevant research, analysis, and designs.
- Phase II: Prototype with test results from appropriate TRL performance tests. A full-capability unit of at least TRL 4 should be delivered. Phase II deliverables should also include/delineate any further work that would be required to bring the technologies to full operational and/or commercial use.

State of the Art and Critical Gaps:

Planetary surface mobility systems are currently limited to relatively benign terrain and operator commanded motions. The Mars 2020 Ingenuity and Titan Dragonfly rotorcraft indicate the potential for enhanced mobility from aerial systems. Scoops, powder drills, and rock core drills, and their corresponding handling systems, have been developed for sample acquisition on missions to Mars and asteroids. Nonflight systems have been developed for sampling on comets, Venus, Enceladus, Titan, and Earth's Moon. Some of these environments still present risk and have gaps that need to be addressed. Ocean worlds exploration presents new environments and unique challenges not met by existing mobility and sampling systems. New mobility, manipulation, and sampling technologies are needed to enable new types of missions and missions to different and challenging environments. Longer distance rovers with sampling systems are such a need for a mission to Earth's Moon.

This scope addresses shortfalls identified in the Civil Space Shortfall Ranking including:

- [Ranked 5th] ID 1545: Robotic Actuation, Subsystem Components, and System Architectures for Long-Duration and Extreme Environment Operation.
- [Ranked 9th] ID 1304: Robust, High-Progress-Rate, and Long-Distance Autonomous Surface Mobility.
- [Ranked 18th] ID 1548: Sensing for Autonomous Robotic Operations in Challenging Environmental Conditions.

Relevance / Science Traceability:

This scope supports multiple programs within NASA SMD. The Mars program has had infusion of technologies such as a force-torque sensor in the Mars 2020 mission. Recent awards support the Ocean Worlds program with surface and deep drills. Sample return missions can be supported such as from Ceres, comets, and asteroids. Products from this subtopic have been proposed for New Frontiers program missions. With renewed interest in returning to Earth's Moon, the mobility and sampling technologies could support a future long-distance traverse and sampling rover mission to the Moon. The NASA Planetary Exploration Science Technology Office (PESTO) has identified many gap needs for these technologies in future NASA missions, including advanced perception, aerial access, manipulation and sampling in extreme environments, extreme terrain mobility, long range access, sample handling and verification, and sub-surface access. The NASA Decadal Survey for the 2023 to 2032 decade [Ref. 6] further identifies various future missions that require these technologies, including missions to Ceres, comets, asteroids, Enceladus, Venus, Mars, and Earth's Moon.

References:

1. "NASA Planetary Exploration Science Technology Office (PESTO)," National Aeronautics and Space Administration: https://www1.grc.nasa.gov/space/pesto/
2. "Mars Exploration: Missions," National Aeronautics and Space Administration: https://mars.nasa.gov/programmissions/
3. "Solar System Exploration," National Aeronautics and Space Administration: https://solarsystem.nasa.gov/
4. "Ocean Worlds," National Aeronautics and Space Administration: https://www.nasa.gov/specials/ocean-worlds/
5. "New Frontiers," National Aeronautics and Space Administration: https://science.nasa.gov/planetary-science/programs/new-frontiers/
6. "Origins, Worlds, and Life: Planetary Science and Astrobiology in the Next Decade," National Academics: https://nap.nationalacademies.org/catalog/27209/origins-worlds-and-life-planetary-science-and-astrobiology-in-the
7. "Civil Space Shortfalls," National Aeronautics and Space Administration: https://www.nasa.gov/spacetechpriorities

Scope Title: Sample Preservation for Sample Return Missions

Scope Description:

Technologies are sought to enable sample preservation from human and robotic sample return (SR) lander missions. These are challenging missions in NASA's portfolio, but also offer great scientific promise given the vast array of science instruments available on Earth to study the retrieved samples. The mission destinations envisioned are Earth's Moon, planet or planet moons (e.g., Mars, Enceladus, Europa) or dwarf planets (e.g., Vesta, Ceres), and comets. Specifically, technologies are sought to address one or more of the following challenges (not any priority order) associated with SR missions:

- Cryogenic sample preservation techniques (e.g., maintaining collected sample at low/cryogenic temperatures).
    - Technical challenge includes development of thermal control systems while considering redundancy and limited power consumption to ensure volatiles are conserved.
- Sample integrity (e.g., preventing sample contamination, preserving samples in their original chemical and biological condition, surviving reentry).
    - Once acquired, samples must be structurally and thermally preserved through safe landing and transport to JSC for analyses. Sample integrity technology solutions that address the long, high radiation return trip, as well as the dynamic and high temperature environment of reentry, are sought. Materials and technologies that offer thermal isolation in addition to energy absorption are highly desirable given the reentry environment.
- Large cryogenic freezer worthy technologies.
    - Technologies sought include cryogenic conditioning that maintains stable (minimal thermal cycling) temperatures at or below 120 K with a goal of 20 K and holding securely a variety of containers sizes, shapes, and compositions consistent with robotic and human sampling operations. A minimum sample mass of 5 kg should be considered.
    - Other desirable aspects of this technology include recording internal freezer temperatures at more than one location within the freezer, protection from radiation and magnetic environments

at any stage of end-to-end sample return process, adaptability to a variety of potential return vehicles, containment to prevent contamination to sample or environment, operating in a vacuum, and maintaining acceptable temperatures unpowered for durations sufficient to transfer samples between elements and to an Earth-based laboratory.

Expected TRL or TRL Range at completion of the Project: 2 to 6

Primary Technology Taxonomy:

- Level 1: TX 04 Robotics Systems
- Level 2: TX 04.3 Manipulation

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Desired deliverables for this scope include hardware, software, and designs for sample preservation technologies.

- Phase I: Proof of concept, including relevant research, analysis, and detailed designs.
- Phase II: Working prototype with test results from appropriate TRL performance tests (such as at representative scale and environment), supporting analysis, design, and hardware specifications, and operating instructions. Phase II deliverables should also include/delineate any further work that would be required to bring the technologies to full operational and/or commercial use.

State of the Art and Critical Gaps:

The kind of SR missions targeted in this solicitation are those that require landing on an extraterrestrial body. Samples may be collected robotically or by humans for return to Earth. The return of volatile containing samples is among the highest priority for sample science and are among the most challenging to collect and preserve from the sample site to the laboratory. Near-term goals of exploring the Moon target the return of volatile samples from permanently shadowed regions, which may be as cold as 20 K. Samples are expected to be collected by human crew using various tools including drill cores and tubes that allow multi-kilogram quantities to be collected from surface and subsurface. Samples will be transported on person and within mobility assets to return vehicles. To maximize the science return of samples, maintaining collection temperatures is imperative. Challenges and gaps of returning samples at cryogenic temperatures exist across the end-to-end process from transport on the lunar surface to handling in the laboratory.

This scope addresses shortfalls identified in the Civil Space Shortfall Ranking including:

- [Ranked 66th] ID 1620: Conditioned stowage to maintain science and/or nutritional integrity.

Relevance / Science Traceability:

Medium- and large-class SR missions address fundamental science questions such as whether there is evidence of ancient life or prebiotic chemistry in the sampled body. This scope supports multiple programs and missions within NASA SMD identified in the NASA Decadal Survey for the 2023 to 2032 decade [Ref. 6] that require these technologies, including missions to Ceres, comets, asteroids, Enceladus, Venus, Mars, and Earth's Moon. The large freezer worthy technology item within scope is coordinated with the JSC Astromaterials Research and Exploration Science Division and Astromaterials Acquisition and Curation Office.

References:

1. "Lunar Exploration Analysis Group Lunar Exploration Road Map," Lunar Exploration Analysis Group: https://www.lpi.usra.edu/leag/roadmap/
2. "Moon to Mars Architecture Definition Document," National Aeronautics and Space Administration: https://www.nasa.gov/wp-content/uploads/2024/01/rev-a-acr23-esdmd-001-m2madd.pdf
3. "Artemis III Science Definition Team Report," National Aeronautics and Space Administration: https://www.nasa.gov/wp-content/uploads/2015/01/artemis-iii-science-definition-report-12042020c.pdf
4. "Moon to Mars Strategy and Objectives Development," National Aeronautics and Space Administration: https://www.nasa.gov/wp-content/uploads/2023/04/m2m_strategy_and_objectives_development.pdf
5. "Mars Sample Return," National Aeronautics and Space Administration: https://science.nasa.gov/mission/mars-sample-return/
6. “Origins, Worlds, and Life: Planetary Science and Astrobiology in the Next Decade,” National Academics: https://nap.nationalacademies.org/catalog/27209/origins-worlds-and-life-planetary-science-and-astrobiology-in-the
7. "Astromaterials," National Aeronautics and Space Administration: https://science.nasa.gov/astromaterials/
8. "Astromaterials Acquisition and Curation Office," National Aeronautics and Space Administration: https://curator.jsc.nasa.gov/index.html
9. "Civil Space Shortfalls," National Aeronautics and Space Administration: https://www.nasa.gov/spacetechpriorities

S13.03: Extreme-Environments Technology (SBIR)

Related Subtopic Pointers: S11.02, S13.01, S13.05, S13.06, Z-LIVE.04
Lead Center: JPL
Participating Center(s): GRC, GSFC, LaRC

Subtopic Introduction:

NASA's missions support a diversity of environments with extreme conditions that are not observed on Earth. Traditional approaches for building a spacecraft for these environments call for the use of environmental protective housings to keep the instruments and other hardware in Earth-like conditions. These environmental protective housings are mass- and power-intensive with large size, weight, and power (SWaP). To eliminate the need for environmental protective housings, this subtopic solicits technologies for producing space systems and instruments that can directly operate in the extreme environments of NASA missions.

Scope Title: Extreme Environments Technology

Scope Description:

Space technologies and systems are sought that can operate without environmental protective housing in the extreme environments of NASA missions. These extreme environments include high temperatures and pressures for deep-atmospheric probes to the gas giants, as well as conditions marked by extremely low temperatures and high radiation—such as -180 °C with 2.9 MRads at Europa. Additionally, very low-temperature environments, reaching as low as -240 °C, can be found on the surfaces of Titan and other ocean worlds like Europa, Ganymede, Mars, in the Moon's permanently shadowed craters, as well as on asteroids, comets, and other small bodies. Furthermore, NASA's long-duration missions must contend with significant temperature fluctuations and high levels of cosmic radiation. NASA is interested in expanding its ability to explore the deep atmospheres and surfaces of planets, asteroids, and comets using long-lived (>10 days) balloons, rovers, and landers.

High reliability, ease of maintenance, low SWaP, and low outgassing characteristics are highly desirable. Special interest lies in the development of the following technologies (not in any priority order):

- Wide-temperature-range and low-temperature-capable:
  - Precision mechanisms: (e.g., beam-steering, scanner, linear, and tilting multi-axis mechanisms).
  - Feedback sensors with subarcsecond/nanometer precision.
  - Long-life, long-stroke, low-power, and high-torque force actuators with subarcsecond/nanometer precision.
  - Long-life bearings/tribological surfaces/lubricants
- Radiation-tolerant/radiation-hardened:
  - Low-power, low-noise, mixed-signal control electronics for precision actuators and sensors.
  - Low-power and wide-operating-temperature radio-frequency (RF) electronics.
  - Low-power/ultralow-power, low- and wide-operating-temperature, low-noise mixed-signal electronics for spaceborne systems such as guidance and navigation avionics and instruments.
  - Low- and wide-operating-temperature power electronics and energy storage devices.
  - Low- and wide-operating-temperature sensors and actuators for autonomous robotic missions.
- High temperature:
  - Analog and digital electronics, electronic components, and in-circuit energy storage (e.g., capacitors, inductors, etc.) elements.
  - Actuators and gearboxes for robotic arms and other mechanisms.

This year, proposals that would benefit in situ studies of planets with extreme environments are highly desired. Specific examples include techniques that would be beneficial to systems that will descend through kilometers of cryogenic ice in ocean worlds, acquire and communicate scientific observations during descent, and sample and concentrate meltwater and interior oceans.

Please note that the following areas are excluded from S13.03 this year:

- Components or mechanisms primarily designed to function in these extreme dusty surface environments (offerors are suggested to consider Z-LIVE.04 “Components for Extreme Environments").
- Radiation-tolerant/radiation-hardened, low-power, wide-temperature-tolerant W-Band transceivers (offerors are suggested to consider S11.02 "Technologies for Active Microwave Remote Sensing").
- Radiation-hardened electronic controller hardware for Stirling-based systems (offerers are suggested to consider S13.06 "Dynamic Power Conversion").

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:

- Level 1: TX 08 Sensors and Instruments
- Level 2: TX 08.X Other Sensors and Instruments

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware
- Research
- Analysis

Desired Deliverables Description:

Desired deliverables for this scope should demonstrate the innovation identified in the proposal enabling direct operation in extreme environments.

- Phase I: Research results, analysis, and technology development work. Planned path for a Phase II hardware demonstration, including validation of extreme-environment operation.
- Phase II: Proof-of-concept working prototypes. A demonstration unit for functional and environmental testing of at least TRL 5 should be delivered. Phase II deliverables should also include/delineate any further work that would be required to bring the technologies to full operational and/or commercial use.

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. The current state of practice for development of space systems is to place the hardware developed with conventional technologies into bulky and power-inefficient environmentally protective housings. These housings in turn severely increase the mass of the space system and limit the life of the mission and the corresponding science return. To advance the state of practice, technologies that enable low-SWaP, highly efficient systems that can readily survive and operate in these extreme environments without the need for the environmental protection systems are highly desired.

This scope addresses shortfalls identified in the Civil Space Shortfall Ranking including:

- [Ranked 1st] ID 1618: Survive and Operate through the Lunar Night.
- [Ranked 5th] ID 1545: Robotic Actuation, Subsystem Components, and System Architectures for Long-Duration and Extreme-Environment Operation.
- [Ranked 6th] ID 1552: Extreme-Environment Avionics.

Relevance / Science Traceability:

This extreme-environments technology subtopic has high relevance to NASA SMD. Low-temperature survivability is required for surface missions to Titan (-180 °C), Europa (-220 °C), Ganymede (-200 °C), small bodies, and comets. Mars diurnal temperatures range from -120 °C to +20 °C. For the Europa Clipper with a mission life of 10 years, the radiation environment is estimated at 2.9 Mrad TID (total ionizing dose) behind 0.1-in.-thick aluminum. Lunar equatorial region temperatures swing from -180 °C to +130 °C during the lunar day/night cycle, and the shadowed lunar pole temperatures can drop to -240 °C. To be able to support future missions, the NASA Planetary Exploration Science Technology Office (PESTO) continues to prioritize technology developments in extreme environments.

References:

1. "IEEE Conference on Aerospace," (Selected publications) IEEE Xplore: https://ieeexplore.ieee.org/xpl/conhome/1000024/all-proceedings
2. "Outer Planets Assessment Group," (Selected publications) Lunar and Planetary Institute: https://www.lpi.usra.edu/opag/
3. “Origins, Worlds, and Life: Planetary Science and Astrobiology in the Next Decade,” (Selected publications) National Academics: https://nap.nationalacademies.org/catalog/27209/origins-worlds-and-life-planetary-science-and-astrobiology-in-the
4. "Europa Clipper Mission," National Aeronautics and Space Administration: https://europa.nasa.gov/mission/about/
5. "NASA Planetary Exploration Science Technology Office (PESTO)," National Aeronautics and Space Administration:

https://www1.grc.nasa.gov/space/pesto/
6. "Civil Space Shortfalls," National Aeronautics and Space Administration: https://www.nasa.gov/spacetechpriorities

S13.04: Contamination Control and Planetary Protection (SBIR)

Related Subtopic Pointers: S13.01, S15.02
Lead Center: JPL
Participating Center(s): GSFC

Subtopic Introduction:

The contamination control (CC) and planetary protection (PP) subtopic develops new technologies or supports new applications of existing technologies to measure, manage, and mitigate the presence of undesired microbial, particulate, and molecular sources. The goal is to produce clean and characterized spacecraft, instrumentation, or hardware. Understanding potential CC and PP contaminants and preventing the contamination of our spacecraft and instruments supports the integrity of NASA sample science and mitigates other potential impacts to spacecraft function.

Scope Title: CC and PP Implementation and Verification

Scope Description:

Novel approaches to measuring, managing, and mitigating microbial, particulate, and molecular (including water vapor) contamination sources supports NASA's ability to produce compelling scientific results (CC), ensure nominal hardware operations (CC), and comply with planetary protection requirements to prevent forward contamination (the transfer of viable organisms from Earth to another planetary body) and backward contamination (the transfer of material from another planetary body that may pose a biological threat to Earth's biosphere). Innovative approaches to address CC and PP changes are sought:

- Analytical and physics-based modeling technologies and techniques to quantify and validate submicron particulate contamination.
- Low-energy surface material coatings to prevent or minimize contamination.
- Modeling and analysis of particles and molecules to ensure hardware and instrumentation meet organic contamination requirements.
- Improved technologies for detecting and verifying low levels of organic compounds on spacecraft surfaces.
    - This includes assessment of DNA from low-biomass surfaces (<0.1 ng/L DNA) from 1 to 5 m^2 of surfaces.
- Development of new technologies for producing ultra-pure reagents and technologies for testing and validating the low level of analyses of interest associated with low biomass sampling.
- Improvement of methods to lyse cells/spores.
- Improvements to spacecraft cleaning and sterilization that are compatible with spacecraft materials and assemblies.
- Technologies to prevent recontamination and cross-contamination throughout the spacecraft lifecycle (build, test, launch, cruise, operations).
- 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., ultraviolet or plasma) for surfaces.
- Development of analytical and modeling-based methodologies to address bioburden and probabilistic risk assessment biological parameters to be used as alternatives to demonstrate requirement compliance.

- Enabling end-to-end sample return functions to ensure containment and pristine preservation of materials gathered on NASA missions (e.g., development of technologies that support in-flight verification of sample containment or in-flight correctable sealing technologies).
- Advanced technologies to detect and verify organic compounds and biologicals on spacecraft hardware prior to launch.
- Advanced technologies that demonstrate the capacity to sample and deliver sampled material from a planetary body while retaining critical volatiles.
- Advanced technologies that store, seal, and contain samples with an appropriate sensitivity to static or changing environmental conditions during transport from the planetary body where samples are collected to the return to Earth (e.g., cold storage sampling for lunar sample material collection and transport to Earth, low-leak-rate storage for biological containment—consistent with Federal containment policies—for transport to Earth from Europa, Enceladus, Mars, and Titan).

Expected TRL or TRL Range at completion of the Project: 2 to 6

Primary Technology Taxonomy:

- Level 1: TX 07 Exploration Destination Systems
- Level 2: TX 07.3 Mission Operations and Safety

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Desired deliverables for this scope include technologies, approaches, techniques, models, and/or prototypes, including accompanying data validation reports and modeling code demonstrating how the product will enable spacecraft compliance with PP and CC requirements.

- Phase I: As relevant to the proposed effort, a proof-of-concept study for the approach to include data validation and modeling.
- Phase II: As relevant to the proposed effort, detailed modeling/analysis or prototype for testing. Phase II deliverables should also include/delineate any further work that would be required to bring the technologies to full operational and/or commercial use.

State of the Art and Critical Gaps:

Contamination Control (CC):

CC requirements and practices are evolving rapidly as planetary mission science objectives emerge that target detection of organics and life. These requirements and practices are also driven by critical Earth and astrophysical science future missions that need more sensitive detectors. Ultraviolet, low-level particulate (atmospheric aerosols), and low-level organic (Earth pollution monitoring of volatile organic compounds) detection drives stricter requirements and improved characterization of flight-system- and science-hardware-induced contamination. The development of novel technology to expand the current methods for clean launch capabilities (purge, environmental control systems) is also a critical gap as future missions may not require a cruise stage or other protective housing over the main operational flight hardware. Other critical gaps for CC include:

- Instrument-induced contamination modeling, characterization, and mitigation.
- Testing and measurement of outgassing rates down to 3.0×10^{-15} g/cm^2/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 and molecular transport modeling and analysis for general contamination mission needs as well as PP forward contamination scenarios of simple and complex spacecraft geometries with electrostatic loads, vibro-acoustic/launch loads, and particle detachment and attachment capabilities in continuum, rarefied, and molecular flow environments.
- Modeling and analysis of particulate flux for assessment of general contamination and PP-specific backward contamination scenarios using dynamic approaches (e.g., direct simulation Monte Carlo (DSMC) and Bhatnagar Gross Krook (BGK) formulations).
- Launch barrier technologies and modeling of launch flux.

Planetary Protection (PP):

PP state of the art encompasses technologies from the 1960s to 1970s Viking spacecraft era along with more recent advancements in sterilization and sampling technologies. The predominant means to control biological contamination on spacecraft surfaces is to use combinations of heat microbial reduction processing and mechanical removal via solvent cleaning processes (e.g., isopropyl alcohol cleaning). Notably, for NASA-approved vapor hydrogen peroxide approaches, concentration variability, delivery mechanisms, and material compatibility concerns currently limit flight mission infusion. After microbial reduction, during spacecraft integration and assembly, hardware is protected in a cleanroom environment (ISO 8 or better) using protective coverings. For example, terminal sterilization with recontamination prevention has been conducted for in-flight biobarriers employed for entire spacecraft (Viking) or spacecraft subsystems (Phoenix spacecraft arm). Environmental assessments are implemented to understand recontamination potential for cleanroom surfaces and air. Biological cleanliness is then verified through the culture-based method NASA standard assay. Although the NASA standard assay is performed on the cleanroom surfaces, DNA-based methodologies have been adopted by spaceflight projects to include 16S and 18S ribosomal-ribonucleic-acid- (rRNA-) targeted sequencing, with metagenomic approaches currently undergoing development. Rapid cleanliness assessments can be performed to inform engineering staff about biological cleanliness during critical hardware assembly or tests that include the total adenosine triphosphate (tATP) and limulus amoebocyte lysate (LAL) assays. These are not currently accepted as a verification methodology. Variability in detector performance thresholds in the low biomass limit remain a hurdle in the infusion of ATP luminometers for spaceflight verification and validation. Gaps for PP include:

- Probabilistic modeling for biological contamination to drive biological assurance cases for spacecraft cleanliness.
    - This is rapidly becoming an emerging need to help define parameters and develop upstream models for understanding biological cleanliness, distributions of biological contamination, behaviors of these biologicals on spacecraft surfaces, and transport models.
- Assessment of DNA from low-biomass surfaces (<0.1 ng/L DNA), using current technologies, from 1 to 5 m^2 of surface.
- Sampling devices that are suitable for reproducible (at a certification level) detection of low biomass and compounds (e.g., viable organisms, DNA) but also compliant with spaceflight environmental requirements (e.g., cleanroom particulate generation, electrostatic discharge limits).
- Quantification of a spectrum of viable organisms.
- Enhanced microbial reduction/sterilization modalities that are flight-materials compatible.
- Recontamination prevention/mitigation systems.

This scope addresses shortfalls identified in the Civil Space Shortfall Ranking including:

- [Ranked 70th] ID 1590: Planetary Protection

Relevance / Science Traceability:

The development of such technologies is of high interest to NASA SMD and would enable missions to:

1. Be responsive to PP and CC engineering and science requirements, as they would be able to assess or detect prelaunch or preoperational viable organisms and other particulate and organic contaminants.
2. Establish microbial reduction and protective technologies to achieve acceptable microbial bioburden and organic contamination levels for sensitive life detection in spacecraft and instruments to mitigate risk and inadvertent false positives.
3. Ensure compliance with sample return PP and science requirements.
4. Support model-based assessments of PP requirements for biologically sensitive missions (e.g., outer planets and sample return).

References:

1. Tribble, A. C.; Boyadjian, B.; Davis, J.; Haffner, J.; McCullough, E., "Contamination Control Engineering Design Guidelines for the Aerospace Community," 1996: https://ntrs.nasa.gov/api/citations/19960044619/downloads/19960044619.pdf
2. "IEST-STD-CC1246: Product Cleanliness Levels—Applications, Requirements and Determination," Institute of Environmental Sciences and Technology: www.iest.org/Standards-RPs/Recommended-Practices/IEST-STD-CC1246
3. "ISO-14644-1:2015: "Cleanrooms and associated controlled environments—Part 1: Classification of air cleanliness by particle concentration," International Organization for Standardization: www.iso.org/obp/ui/#iso:std:iso:14644:-1:ed-2:v1:en
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S13.05: In Situ Instruments and Instrument Components for Lunar and Planetary Science (SBIR)

Related Subtopic Pointers: S11.04, S12.06, S13.03, S16.08
Lead Center: JPL
Participating Center(s): ARC, GRC, GSFC, MSFC

Subtopic Introduction:

To narrow the critical gaps between the current state of the art and the technology needed for the ever-increasing science and exploration requirements, in situ technologies are becoming essential bases to achieve SMD's planetary science goals. Of particular interest are technologies to support future missions described in the National Research Council Planetary Decadal Survey report "Origin, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023-2032" (hereafter referred to as the Planetary Decadal Survey) and/or in the "Artemis III Science Definition Team (SDT) Report."

For this solicitation, this subtopic seeks technology advancement needs in the following scope:

1. In Situ Instruments and Instrument Components for Lunar and Planetary Science.

Proposers should show an understanding of relevant space science needs, present a feasible plan to fully develop a technology, and infuse it into a NASA program. Proposers should provide a comparison metric for assessing proposed improvements compared to existing flight instrument capabilities.

Scope Title: In Situ Instruments and Instrument Components for Lunar and Planetary Science

Scope Description:

In situ technologies are being sought to increase instrument resolution and sensitivity; reduce mass, power, and volume; and/or increase data rates without loss of scientific capability. The proposed technologies must directly address lunar and/or planetary science instrumentation needs and 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. 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.

This year, instruments and instrument components are sought that provide significant advances in the following areas (those that are of higher priority are indicated, though proposals addressing any of the areas will still be considered and reviewed based on merit):

- (Higher priority) Technologies relevant to detection and/or identification of organic molecules (including biomolecules), salts, and/or minerals on Mars, ocean worlds, and other bodies. Examples include high-resolution gas or liquid chromatographs, miniaturized mass spectrometers and their drive electronics (e.g., radio frequency (RF) tanks) and front-end/back-end advancements (e.g., electrospray ionization sources, lasers, ion mobility sources/separators, RF guides/funnels, pumps), isotope analyzers, dust detectors, organic analysis instruments with chiral discrimination, x-ray spectrometers, laser-induced breakdown spectroscopy, electrochemical methods, nanopore technologies, etc.) These developments should be geared towards analyzing and handling very small sample sizes (microgram to milligram) and/or low column densities/abundances.
- Imagers, spectrometers, and the associated components that provide high performance in low-light environments (visible and Near-Infrared (NIR) imaging spectrometers, thermal imagers, etc.).
- Instruments capable of monitoring the bulk chemical composition and physical characteristics of gas samples and ice particles such as the plume (density, velocity, variation with time, etc.).
- (High priority) Seismometers, mass analyzers, heat flow probes, and trace-gas detectors with improved robustness and high-g-force survivability that are applicable to impactor deployment to planetary surfaces.
- (High priority) In situ sensors and instrument technologies for operation in extreme environment conditions (e.g., temperature, pressure, radiation) such as Europa or Venus.
- Technologies for quantifying lunar water and measuring the D/H ratio in lunar water and other solar system destinations.
- Technologies that allow "fly-through" sample collection during high-speed (>1 km/sec) passes through plumes and can maximize total sample mass collected while passing through tenuous plumes. This includes 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, such as cold double-walled isolators for sample manipulation at -80 ºC and biohazard safety level 4 (BSL-4) conditions.
- Instruments for quantifying the lunar regolith for meeting in situ resource utilization (ISRU) and in situ construction needs.

  - The technologies must characterize at least one of the following key properties of regolith, which are thought to affect the operation of ISRU and construction processes:
    1. Mineral phase composition and elemental analysis.
    2. Softening and melting points.
    3. Melt viscosity.
  - The target performance metrics are:
    1. Temperature stability of +/- 5 °C.
    2. System stability and repeatability <3%.
  - The major mineral phases of interest are those found in the lunar highlands regolith, which is primarily composed of anorthosite rock. The quantification of mineral phases such as pyroxenes, olivine, iron sulfides (Troilite), apatite, and anorthite are desired.
  - The instruments sought are envisioned to run in batch mode to periodically sample the lunar regolith feed into ISRU and construction processes and must be able to operate for at least 1 year, with a goal of 5 years, without substantial maintenance in the dusty regolith environment.
  - The proposed instruments must be able to operate on the lunar surface in temperatures (with thermal mitigations) of up to 110 °C during sunlit periods and as low as -170 °C during periods of darkness.
- (High priority) Mass spectrometers with innovative, low-cost, liquid-compatible ion guide subsystems designed for use with ambient soft-ionization sources such as electrospray ionization (ESI) and atmospheric pressure chemical ionization (APCI) in environments relevant to Mars and Enceladus. Of particular interest is a miniaturized ion trap mass spectrometer that meets the following requirements using ESI/APCI:
  - Mass-to-charge (m/z) range of 70 to 1000.
  - Resolution of full width at half maximum 0.75 Da across the full m/z range.
  - Detection limits of 0.05 mg/L histidine, 1 mg/L stearic acid, and 1 mg/L ergosterol in a continuous fluid stream at a flow rate of at least 1 μL/min.

Please note that the following areas are excluded from S13.05 this year:

- Surface platform sampling technologies (offerors are suggested to consider S13.01 “Robotic Mobility, Manipulation, and Sampling.”).
- Detector technologies for visible, infrared (IR), far-IR, and submillimeter or Ultraviolet (UV), X-Ray, and Gamma-Ray Instruments (offerors are suggested to consider S11.04 “Sensor and Detector Technologies for Visible, Infrared (IR), Far-IR, and Submillimeter” or S12.06 "Detector Technologies for Ultraviolet (UV), X-Ray, and Gamma-Ray Instruments").
- Laser systems applicable to quantum sensors using cold-Cs-based atom interferometers (offerers are suggested to consider S16.08 “Quantum Sensing: Atomic sensors, optical atomic clocks, and solid-state systems.”).
- Analog-to-Digital Converters (ADCs).
- Field Programmable Gate Arrays (FPGAs).

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:

- Level 1: TX 08 Sensors and Instruments
- Level 2: TX 08.3 In-Situ Instruments/Sensor

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware
- Research
- Analysis

Desired Deliverables Description:

In addition to requirements outlined in the solicitation "Reporting and Required Deliverables," proposals shall identify planned deliverables.

- Phase I: Feasibility assessment, proof-of-concept demonstration (TRL 2 to 3), concept of operations, simulations and/or measurements, and a plan for further development to be performed in Phase II. Documentation of the proposed innovation, its status at the end of the Phase I effort, and the evaluation of its strengths and weaknesses compared to the state of the art. For low-cost innovations, proposal must specify and outline a plan to meet the cost target of the delivered instrument at the end of Phase II.
- Phase II: Component and/or breadboard development with the delivery of specific hardware for NASA (TRL 4 to 5). The working prototype of the proposed hardware should be standalone with any needed interface specifications, along with documentation of development, capabilities, and measurements. Phase II deliverables should also include/delineate any further work that would be required to bring the technologies to full operational and/or commercial use.
- Offerors may seek to utilize JPL facilities including an ESI/APCI source and TVAC chambers for development and testing of mass spectrometers on a no-cost basis to reduce the development costs. A facilities user agreement must be submitted as part of the proposal package.

State of the Art and Critical Gaps:

There are ever-increasing science and exploration requirements and challenges for diverse planetary bodies with respect to in situ instruments. For example, there are urgent needs for the exploration of icy or liquid surfaces on Europa, Enceladus, Titan, Ganymede, Callisto, etc., and plumes from planetary bodies, such as Enceladus, as well as a growing demand for in situ technologies amenable to small spacecraft. Technologies are continually being sought that achieve much higher resolution and sensitivity with significant improvements over existing capabilities, such as lower mass, power, volume, and data rate.

This scope addresses shortfalls identified in the Civil Space Shortfall Ranking including:

- [Ranked 20th] ID 1626: Advanced Sensor Components: Imaging.
- [Ranked 152nd] ID 1601: Enable Observation of Whole Top to Bottom Dynamic Ecosystems.
- [Ranked 115th] ID 1627: Advanced Sensor Components for Heliophysics and Lunar-Based Astronomy.

Relevance / Science Traceability:

The development of in situ instrument technologies is of high interest to NASA SMD as these technologies play indispensable roles for NASA's New Frontiers and Discovery missions to various planetary bodies. The NASA Decadal Survey for the 2023 to 2032 decade identifies various future missions that require these technologies, including missions to Ceres, comets, asteroids, Enceladus, Venus, Mars, and Earth's Moon. Overall low-cost mass spectrometer technologies are sought to expand life detection instrument capabilities while meeting or exceeding science measurement requirements set by the Mars Life Explorer and the Enceladus OrbiLander mission study report and are of interest to the JPL SCHAN instrument.

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S13.06: Dynamic Power Conversion (SBIR)

Related Subtopic Pointers: S13.03, S16.05, Z-ENABLE.01
Lead Center: GRC
Participating Center(s): N/A
Subtopic Introduction:

NASA is considering high efficiency dynamic power conversion technologies for use in Radioisotope Power Systems (RPS) to power science missions for the Moon and other solar system bodies of interest. This is mapped by NASA SMD's strategic technology investment plan for space power and energy storage enabling higher power systems using the same amount of fuel, enabling more spacecraft to support a single mission, or requiring less fuel for offered power levels. Technologies are sought maturing high efficiency and robust dynamic power conversion integrated with a RPS power source that provides thermal-to-electric power conversion with low mass, long life, and high reliability for use on RPS powered space probes, landers, and rovers.

Scope Title: High Efficiency Power Conversion Technologies

Scope Description:

High efficiency RPS are sought across a wide range of power, from 1 to 100 watts for RPS applications. Lower power conversion could convert heat from one or more small isotope heat sources to a few watts for powering battery chargers or sensors on small science stations or distributed networks. Higher power conversion could convert hundreds to thousands of thermal watts made available from one or more large isotope heat sources, such as the General Purpose Heat Source (GPHS) or an alternative isotope heat source, to hundreds of watts for powering large orbiting or surface spacecraft. Waste heat could also be removed from the power convertor for keeping spacecraft components warm enough to survive very cold environments. Proposals are sought that address the following technical challenges:

1. Efficient, robust power conversion:

- Free-Piston Stirling cycle convertors capable of long life (17 years) and high efficiency (>30%) that are robust and reliable for 100-class generator concepts. There is an interest in lower power convertors (20 to 40 watts electrical output) to support small RPS concepts.
- High power density convertor alternator designs are sought to survive combined temperature and radiation environments, with robust organic and magnet materials. Alternators should be able to survive for long periods (17 years) at elevated temperatures and radiation levels (over 200 °C and $2x10^{14}$ n/cm^2 + $1x10^3$ krad).
- Thermal management technologies, such as heat pipes, that are directly coupled to Stirling heater heads and robust high-temperature multi-layer insulation (MLI) designs for insulating an isotope source operating at elevated temperatures (900 to 1000 °C).

2. Radiation-hardened electronic controllers and power processing:

- Electronic controller hardware for Stirling-based systems with a credible path to flight and able to control one or more dynamic convertors. There is a special interest in controller architectures able to manage multiple convertors and controllers able to control a single convertor and an active balancer without relying on feedback from vulnerable short-lived sensors.
- Increasing the radiation tolerance of electronic components found in controllers and accompanying power processing systems to values greater than $5x10^{11}$ n/cm^2 + $3x10^2$ krad + 40 MeV-cm^2/mg (linear energy transfer). Higher tolerance will enable a reduction in shielding mass and is strongly desired.

- Increasing specific power density (w/kg) of controllers with high density capacitive and magnetic filtering and buffering.
- Sensors and hardware systems integrated with innovative control algorithms and data processing to enable robust, autonomous operation of Stirling-based systems.

Please note that the following areas are excluded from S13.06 this year:

- Static power conversion technologies (offerors are suggested to consider Z-ENABLE.01 "Enabling Power and Thermal Technologies").

Expected TRL or TRL Range at completion of the Project: 2 to 5

Primary Technology Taxonomy:

- Level 1: TX 03 Aerospace Power and Energy Storage
- Level 2: TX 03.1 Power Generation and Energy Conservation

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

- Phase I: Results of studies, modeling, and/or component testing to demonstrate basic feasibility.
- Phase II: Prototype hardware that has demonstrated basic functionality in a laboratory environment, the appropriate research and analysis used to develop the hardware, and maturation options for flight designs. Phase II deliverables should also include/delineate any further work that would be required to bring the system to full operational and/or commercial use.

State of the Art and Critical Gaps:

RPS are critical for long-duration NASA missions to dark, dusty, and harsh environments. There have been twelve major RPS powered robotic spacecraft deployed over the past 51 years that have successfully explored our solar system, including: Pioneer (2), Viking (2), Voyager (2), Galileo, Ulysses, Cassini, New Horizons, Curiosity, and Perseverance. Those power systems used thermoelectric generators with high reliability, but low efficiency, where solar power wasn't practical. Past RPS contain Plutonium-238; however, future RPS could use alternatives, like Americium-241. Current work is focused on maturing high efficiency dynamic power conversion technologies that would be integrated with a radioisotope heat source to provide thermal-to-electric power conversion.

Dynamic energy conversion offers long-lived generators for spacecraft power with significantly higher efficiency, up to a factor of four. New high efficiency convertors can enable robust, high-temperature and radiation-tolerant designs. In addition to 10 watt-class convertors, advances in much smaller and lower power dynamic power convertors are sought that would convert lower amounts of heat for applications such as distributed sensor networks, small spacecraft, and other systems that take advantage of lower power electronics for the exploration of surface phenomenon on the moon and other bodies of interest.

This scope addresses shortfalls identified in the Civil Space Shortfall Ranking including:

- [Ranked 1st] ID 1618: Survive and operate through the lunar night
- [Ranked 21st] ID 1596: High Power Energy Generation on Moon and Mars Surfaces
- [Ranked 93rd] ID 1597: Power for Non-Solar-Illuminated Small Systems
- [Ranked 35th] ID 1390: Power and Data Transfer in Dusty Environments

Relevance / Science Traceability:

Highly efficient Stirling RPS could enable long-lived robotic science missions to other worlds identified in the Decadal Survey "Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023-2032" [Ref. 5]. As a part of planned science missions, highly efficient Stirling power conversion can provide power and heat on landers and rovers so they may operate in dark, dusty locations throughout the solar system. NASA's RPS Program Office is developing highly efficient RPS technologies for more efficient use of precious nuclear fuel on future RPS powered missions.

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S14.01: Space Weather Research-to-Operations and Operations-to-Research (R2O2R) (SBIR)

Related Subtopic Pointers: Z-EXPAND.04, T5.06
Lead Center: MSFC
Participating Center(s): ARC, GSFC, JSC, LaRC

Subtopic Introduction:

The term “space weather” refers broadly to variations in the particle and radiation environment in the solar system caused by variable solar conditions. In particular, changes in solar features (e.g., sunspots, filaments) can generate eruptive events (e.g., solar flares, coronal mass ejections) that may result in hazards to spacecraft, astronauts, and even ground-based technologies and infrastructure (e.g., power grids, pipelines). Space-weather events can also disrupt communications, navigation, and electric power subsystems. Because of the importance of these technologies to our national interest in the digital age, NASA’s Heliophysics Division invests in activities intended to improve our understanding of space weather phenomena and to enable novel monitoring, prediction, and mitigation capabilities.

The national direction for this work is overseen by the Space Weather Operations, Research, and Mitigation (SWORM) Working Group. This Federal interagency coordinating body operates under 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 (NSWSAP) and in the Promoting Research and Observations of Space Weather to Improve the Forecasting of Tomorrow (PROSWIFT) Act.

NASA's role under the PROSWIFT Act includes enhancing the understanding of the fundamental physics of the Sun-Earth system through space-based observations, modeling, and monitoring space weather for NASA's space missions. Efforts encompass the development of operational and commercial space-weather capabilities to protect astronauts, ensure the function of spacecraft, and support the success of NASA's space missions. This work also safeguards national assets on the ground and in space, facilitating the ongoing exploration of the universe.

In support of space-weather Research-to-Operations and Operations-to-Research (R2O2R), this subtopic solicits new, enabling space-weather technologies as part of NASA's response to national objectives. Space weather is a broad umbrella encompassing science, engineering, applications, and operations. 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 it into a specific activity listed within the NSWSAP and the PROSWIFT Act.

For this solicitation, this subtopic seeks technology advancement needs in the following three scopes (not in any priority order):

1. Space-Weather Forecasting and Nowcasting Technologies, Techniques, and Applications
2. Decision-Making Applications for Space-Weather Awareness
3. Space-Weather Instrumentation

Scope Title: Space-Weather Forecasting and Nowcasting Technologies, Techniques, and Applications

Scope Description:

Innovative technologies and techniques that explore and enable the transition of tools, models, data, and knowledge between research and operational environments are solicited. This work includes the preparation and validation of existing science models that may be suitable for transition to operational use. This work is especially compelling when it incorporates educational opportunities available to many research institutions, such as space-weather schools and analysis boot camps. Areas of particular interest include but are not limited to:

- Environmental characterization tools that NASA can employ to enhance the protection of crewed and uncrewed missions operating in cis-lunar space, at lunar-surface locations, during deep space transit, in orbit around Mars, or on the Martian surface.
- Nowcasts 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 assist end users such as spacecraft operators.
- Approaches that potentially lead to short-range (hours) and/or two to three-day forecasts of atmospheric drag effects on satellites and improve the quantification of orbital uncertainties in low-Earth-orbit (LEO) altitude ranges (up to ~2,000 km).
- Techniques that enable nowcasting and/or predicting the characterization of ionospheric variability that induces scintillations, which impact communication and global navigation and positioning systems.

Longer range (2 to 3 days) forecasting of solar particle events (SPEs), and an improved all-clear SPE-forecasting capability is also desired.

Coordination with existing NASA capabilities, such as the Space Radiation Analysis Group (SRAG) at JSC, the Community Coordinated Modeling Center (CCMC) at GSFC, and the Short-term Prediction Research and Transition (SPoRT) Center at MSFC, is appropriate and encouraged.

Please note that the following areas are excluded from S14.01 this year:

- Technologies for non-Earth orbit conjunction risk assessment processes and tools (consider T5.06 "Non-Earth Orbit Conjunction Risk Analysis").
- Technologies for LEO conjunction risk assessment processes and tools (consider Z-EXPAND.04 "Low Earth Orbit (LEO) Sustainability").

Expected TRL or TRL Range at completion of the Project: 3 to 7

Primary Technology Taxonomy:

- Level 1: TX 11 Software, Modeling, Simulation, and Information Processing
- Level 2: TX 11.X Other Software, Modeling, Simulation, and Information Processing

Desired Deliverables of Phase I and Phase II:

- Software
- Analysis
- Research
- Prototype

Desired Deliverables Description:

Deliverables sought are products or services that enable end-user action as applied to space-weather forecasting and nowcasting including, but not limited to, space-weather hazard assessments, real-time situational awareness, or protective mitigation action planning. Deliverables can be in the form of new data, new techniques, and/or predictive models that are prepared/validated for transition into operations:

- Phase I: Proof-of-concept data and/or detailed technique or model development plans that have sufficient fidelity to assess technical, management, cost, and schedule risk. Deliverables should also delineate the scope and benefit of the proposed products that could be realized as a result of Phase II and what further scope and benefit necessarily require further development after Phase II.
- Phase II: Functioning prototype versions of the proposed technologies tested in a realistic environment or within a standard space-weather-community development and validation framework, such as the CCMC. The extent of the prototype development and testing will vary with the technology and will be evaluated as part of the Phase II proposal. Phase II deliverables should also include/delineate any further work that would be required to bring the technologies to full operational and commercial use.

State of the Art and Critical Gaps:

Our understanding of the fundamental processes involved in space-weather phenomena is incomplete, and we will likely require data that we do not know yet. Many data sets currently being acquired are intended for research use and are unavailable or not validated for real-time space-weather analysis. The research environment advances understanding rather than the improvement of operational products, and no mechanisms exist to broadly enable the larger community to participate in the improvement of operational models. Resultantly, a substantial "valley of death" exists, and the results of space-weather research do not always include associated advances in operational capabilities. Barriers may also exist for small research institutions to enter the space-weather field.

The current state-of-the-art models at CCMC include MagPy, University of Malaga Solar Energetic Particle Model (UMASEP), SEPMOD, and Ovation Prime [Ref. 7]. Advances in state of the art would include improvements in lead time for solar events and/or higher-quality predictions of thermospheric and magnetospheric plasma conditions that may affect orbiting spacecraft.

This scope addresses shortfalls identified in the Civil Space Shortfall Ranking including:

- [Ranked 59th] ID 1603: Situational Awareness Sensors and Tools for Astronauts
- [Ranked 16th] ID 1526: Radiation Monitoring and Modeling (Crew and Habitat)
- [Ranked 62nd] ID 1589: Space Situational Awareness

Relevance / Science Traceability:

This subtopic supports NASA Goal 1.2: Understand the Sun, solar system, and universe from the NASA 2022 Strategic Plan. Applied research projects directly address NASA's role within the SWORM Working Group. Technology advances support the NASA Space Weather Program which establishes an expanded role for NASA in space-weather science under a single element; it is consistent with the recommendation of the National Research Council (NRC) Decadal Survey, OSTP/SWORM NSWSAP, and the PROSWIFT Act. The Heliophysics Living With a Star (LWS) Program has established a path forward to meet NASA's obligations to the research relevant to space weather and is a significant source of input to the NASA Space Weather Program.

Space weather also impacts programs under NASA ESDMD that are critical to planning Artemis and for NASA's Moon-to-Mars exploration planning. Understanding space weather is also crucial for the successful operations of NASA SOMD, which is responsible for continuing missions in Earth orbit. Programs under these directorates include Orion, Space Launch System, Exploration Ground Systems, Gateway, Human Landing System, and Extravehicular Activity and Human Surface Mobility. Both human and robotic missions are vulnerable to the radiation effects caused by space weather in near-Earth, cis-lunar, and interplanetary space; thus, solutions to predict and mitigate these effects are necessary for safe operations.

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Scope Title: Decision-Making Applications for Space-Weather Awareness

Scope Description:

Innovative techniques and solutions are solicited that establish value-added, space-weather products and services using space-weather data in novel ways or tailoring existing operational space-weather products to address the needs of specific end-user groups. The NSWSAP and the PROSWIFT Act specifically highlight the need to test, evaluate, and deploy technologies, applications, and devices to mitigate the effects of space weather on communication systems, geomagnetic disturbances on the electrical power grid, or satellite radiation events. The policy and legislation also call for developing processes to improve the transition of research approaches to operations, support operational partners, and to serve society. Proposals of interest could include, but are not limited to:

- Describing and developing standards and best practices to improve the equipment resilience to space-weather events.
- Efforts to bridge the gap between heliophysics, geophysics science, and society; these proposals would apply NASA data to the decision-making process of an end user to mitigate the effects of space-weather events. This work will empower innovative projects by using NASA space-weather data in novel ways. It will support decision making by a diverse community of users with whom NASA may not frequently engage. Integrating NASA data into the decision-making process of a particular user or user community is essential for this solicitation.
- Efforts to explore new markets for space-weather data and services and to expand existing operational space-weather products. This work will facilitate the creation of value-added products to improve the resilience of equipment and systems to space-weather events.
- A description of a process that of how space weather impacts decision-making, how an organization currently makes that decision, and how NASA data will be integrated into and benefit that process.

Of specific interest are non-operational applications (i.e., not National Oceanic and Atmospheric Administration (NOAA) or Department of Defense (DoD)) with nontraditional users (e.g., a user who has not used NASA data before). An example of project success could be demonstrating that an organization uses NASA's space-weather data in decision-making, leading to real, measurable improvements in their operations. Both commercial applications and noncommercial applications are of high interest and are encouraged. Many existing or planned commercial constellations may include valuable space-weather-exploitable data (e.g., iridium system magnetometer data or space-based radio occultation for ionospheric specification). Other possible data sources are global-navigation-satellite-system- (GNSS-) equipped constellations (for total electron content (TEC) and/or drag information) and imaging constellations (tapping into unused nighttime observations of aurorae).

Expected TRL or TRL Range at completion of the Project: 3 to 7

Primary Technology Taxonomy:

- Level 1: TX 11 Software, Modeling, Simulation, and Information Processing
- Level 2: TX 11.X Other Software, Modeling, Simulation, and Information Processing

Desired Deliverables of Phase I and Phase II:

- Software
- Research
- Analysis
- Prototype

Desired Deliverables Description:

Deliverables sought are products or services that enable end-user action as applied to decision making for space weather, including, but not limited to, planning protective mitigation actions. Deliverables can be in the form of new standards, new techniques, and/or predictive models that are prepared/validated for transition into operations:

- Phase I: Proof-of-concept data and/or detailed technique, application, or model development plans that have sufficient fidelity to assess technical, management, cost, and schedule risk. Deliverables should also delineate the scope and benefit of the proposed products that could be realized as a result of Phase II and what further scope and benefit necessarily require further development after Phase II.
- Phase II: Functioning prototype versions of the proposed technologies tested in a realistic environment or within a standard space-weather-community development and validation framework, such as the CCMC. The extent of the prototype development and testing will vary with the technology and will be evaluated as part of the Phase II proposal. Phase II deliverables should also include/delineate any further work that would be required to bring the technologies to full operational and commercial use.

State of the Art and Critical Gaps:

Severe space-weather events are a recurring threat to the national interest, including critical power and communications infrastructure, space-based assets, and the missions of astronauts and spacecraft. Extreme space-weather events can cause substantial harm to national security and economic vitality. Continued preparations for space-weather events are a crucial aspect of American resilience that bolsters national security and facilitates continued U.S. leadership in space ventures. A robust space-weather program is essential for the success of NASA missions.

Current state of the art for models at CCMC include SEP Scoreboard, Space Radiation Intelligence System Framework for Solar Energetic Particle Forecasts (SPRINTS-SEP), and Solar Particle Radiation Advanced Warning System - Advanced Solar Particle Events Casting System (SAWS-ASPECS) [Ref. 11]. This scope seeks to address the critical gap for applications that integrate nontraditional space-weather-related datasets for use by nontraditional users of NASA data sources.

This scope addresses shortfalls identified in the Civil Space Shortfall Ranking including:

- [Ranked 59th] ID 1603: Situational Awareness Sensors and Tools for Astronauts
- [Ranked 120th] ID 1600: Enable Paradigm for System Science to Include Interactions Between Subsystems

Relevance / Science Traceability:

This subtopic supports NASA Goal 1.2: Understand the Sun, solar system, and universe from the NASA 2022 Strategic Plan. Applied research projects directly address NASA's role within the SWORM Working Group. Technology advances support the NASA Space Weather Program which establishes an expanded role for NASA in space-weather science under a single element; it is consistent with the recommendation of the NRC Decadal Survey, OSTP/SWORM NSWSAP, and the PROSWIFT Act. The Heliophysics Living With a Star (LWS) Program has established a path forward to meet NASA's obligations to the research relevant to space weather and is a significant source of input to the NASA Space Weather Program.

Space weather also impacts programs under NASA ESDMD that are critical to planning Artemis and for NASA's Moon-to-Mars exploration planning. Understanding space weather is also crucial for the successful operations of NASA SOMD, which is responsible for continuing missions in Earth orbit. Programs under these directorates include Orion, Space Launch System, Exploration Ground Systems, Gateway, Human Landing System, and Extravehicular Activity and Human Surface Mobility. Both human and robotic missions are vulnerable to the radiation effects caused by space weather in near-Earth, cis-lunar, and interplanetary space; thus, solutions to predict and mitigate these effects are necessary for safe operations.

References:

1. "Promoting Research and Observations of Space Weather to Improve the Forecasting of Tomorrow Act," Pub. L. No. 116-181, 134 Stat. 886 (2020): https://www.congress.gov/116/plaws/publ181/PLAW-116publ181.pdf
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3. "SWORM: Space Weather Operations, Research and Mitigation Subcommittee," SWORM Interagency Working Group: https://www.sworm.gov/index.html
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7. "Space Weather Phase 1 Benchmarks," Space Weather Operations, Research, and Mitigation Subcommittee Committee on Homeland and National Security: https://www.sworm.gov/publications/2018/Space-Weather-Phase-1-Benchmarks-Report.pdf

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11. "Community Coordinated Modeling Center," National Aeronautics and Space Administration: https://ccmc.gsfc.nasa.gov/
12. "Exploration Systems Development Mission Directorate," National Aeronautics and Space Administration: https://www.nasa.gov/exploration-systems-development-mission-directorate
13. "Space Operations Mission Directorate," National Aeronautics and Space Administration: https://www.nasa.gov/directorates/space-operations
14. "NASA Strategic Plan 2022," National Aeronautics and Space Administration: https://www.nasa.gov/wp-content/uploads/2023/09/fy-22-strategic-plan-1.pdf
15. "Civil Space Shortfalls," National Aeronautics and Space Administration: https://www.nasa.gov/spacetechpriorities

Scope Title: Space-Weather Instrumentation

Scope Description:

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. Ideas are solicited for instrument concepts, flight architectures, and reporting systems to enhance 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 on CubeSats or flown as hosted payloads on commercial-flight opportunities. To be considered for investment, proposed technologies should demonstrate comparable, or better, precision and accuracy when compared to the current state of the art.

Expected TRL or TRL Range at completion of the Project: 3 to 7

Primary Technology Taxonomy:

- Level 1: TX 08 Sensors and Instruments
- Level 2: TX 08.X Other Sensors and Instruments

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware
- Analysis

Desired Deliverables Description:

Deliverables sought are novel or improved instrumentation for near to real-time space-weather data collection.

- Phase I: Proof-of-concept with model development plans that have sufficient fidelity to assess technical, management, cost, and schedule risk. Deliverables should also delineate the scope and benefit of the proposed products that could be realized as a result of Phase II and what further scope and benefit necessarily requires further development after Phase II.
- Phase II: Functioning prototype versions of the proposed technologies with a demonstrated concept tested in a realistic environment or within a standard space-weather-community development and validation framework, such as the CCMC. The extent of the prototype development and testing will vary with the technology and will be evaluated as part of the Phase II proposal. Phase II deliverables should also include/delineate any further work that would be required to bring the technologies to full operational and commercial use.

State of the Art and Critical Gaps:

The Space Weather Science and Observation Gap Analysis for NASA states that most measurement gaps can be solved with current technology. Effective and innovative uses of that technology have the potential for elucidating and possibly solving many space-weather observational and forecasting issues. However, sparse spatial/temporal/spectral coverage is a problem that includes observations of high-altitude current systems that feed Ground Induced Currents (GICs), thermospheric expansion of the atmosphere, measurement of neutrals, and measurement of conditions in very low-Earth-orbit (< approximately 500 km). Space weather requires relevant instrumentation supporting standardized measurements from a distributed system over many different locations in fine grids using commercial spacecraft (and/or aircraft). Ultimately, such instrumentation could utilize commercially owned and operated payloads, and augment government-owned resources to measure ionospheric, magnetospheric, or heliospheric conditions throughout the full range of their respective locations.

Current and upcoming NASA missions and concepts representing the state of the art include but are not limited to: Tandem Reconnection and Cusp Electrodynamics Reconnaissance Satellites (TRACERS), HelioSwarm, Polarimeter to Unify the Corona and Heliosphere (PUNCH), Electrojet Zeeman Imaging Explorer (EZIE), SunRISE, and Extreme Ultraviolet High-Throughput Spectroscopic Telescope (EUVST).

This scope addresses shortfalls identified in the Civil Space Shortfall Ranking including:

- [Ranked 59th] ID 1603: Situational Awareness Sensors and Tools for Astronauts
- [Ranked 120th] ID 1600: Enable Paradigm for System Science to Include Interactions Between Subsystems

Relevance / Science Traceability:

This subtopic supports NASA Goal 1.2: Understand the Sun, solar system, and universe from the NASA 2022 Strategic Plan. Applied research projects directly address NASA's role within the SWORM Working Group. Technology advances support the NASA Space Weather Program which establishes an expanded role for NASA in space-weather science under a single element; it is consistent with the recommendation of the NRC Decadal Survey, OSTP/SWORM NSWSAP, and the PROSWIFT Act. The Heliophysics Living With a Star (LWS) Program has established a path forward to meet NASA's obligations to the research relevant to space weather and is a significant source of input to the NASA Space Weather Program.

Space weather also impacts programs under NASA ESDMD that are critical to planning Artemis and for NASA's Moon-to-Mars exploration planning. Understanding space weather is also crucial for the successful operations of NASA SOMD, which is responsible for continuing missions in Earth orbit. Programs under these directorates include Orion, Space Launch System, Exploration Ground Systems, Gateway, Human Landing System, and Extravehicular Activity and Human Surface Mobility. Both human and robotic missions are vulnerable to the radiation effects caused by space weather in near-Earth, cis-lunar, and interplanetary space; thus, solutions to predict and mitigate these effects are necessary for safe operations.

References:

1. "Promoting Research and Observations of Space Weather to Improve the Forecasting of Tomorrow Act," Pub. L. No. 116-181, 134 Stat. 886 (2020): https://www.congress.gov/116/plaws/publ181/PLAW-116publ181.pdf
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3. "SWORM: Space Weather Operations, Research and Mitigation Subcommittee," SWORM Interagency Working Group: https://www.sworm.gov/index.html
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7. "Space Weather Phase 1 Benchmarks," Space Weather Operations, Research, and Mitigation Subcommittee Committee on Homeland and National Security: https://www.sworm.gov/publications/2018/Space-Weather-Phase-1-Benchmarks-Report.pdf
8. "Space Weather Research-to-Operations and Operations-to-Research Framework," Space Weather Operations, Research, and Mitigation Subcommittee Committee on Homeland and National Security: https://www.whitehouse.gov/wp-content/uploads/2022/03/03-2022-Space-Weather-R2O2R-Framework.pdf
9. Executive Order 138653, C.F.R. 12041 (2019), "Coordinating National Resilience to Electromagnetic Pulses (EMPs)." https://www.govinfo.gov/content/pkg/FR-2019-03-29/pdf/2019-06325.pdf
10. "The Space Weather Science and Observation Gap Analysis," Johns Hopkins Applied Physics Laboratory (APL): https://www.sciencedirect.com/science/article/pii/S0273117723005057
11. "Exploration Systems Development Mission Directorate," National Aeronautics and Space Administration: https://www.nasa.gov/exploration-systems-development-mission-directorate
12. "Space Operations Mission Directorate," National Aeronautics and Space Administration: https://www.nasa.gov/directorates/space-operations
13. "NASA Strategic Plan 2022," National Aeronautics and Space Administration: https://www.nasa.gov/wp-content/uploads/2023/09/fy-22-strategic-plan-1.pdf
14. "Tandem Reconnection And Cusp Electrodynamics Reconnaissance Satellites-A (TRACERS)," National Aeronautics and Space Administration: https://nssdc.gsfc.nasa.gov/nmc/spacecraft/display.action?id=TRACERS

15. "HelioSwarm," National Aeronautics and Space Administration: https://science.nasa.gov/mission/helioswarm
16. "PUNCH Polarimeter to Unify the Corona and Heliosphere," National Aeronautics and Space Administration: https://science.nasa.gov/mission/punch
17. "Ezie Electrojet Zeeman Imaging Explorer," National Aeronautics and Space Administration: https://science.nasa.gov/mission/ezie
18. "SunRISE Sun Radio Interferometer Space Experiment," National Aeronautics and Space Administration: https://science.nasa.gov/mission/sunrise
19. "EUVST Extreme Ultraviolet High-Throughput Spectroscopic Telescope," National Aeronautics and Space Administration: https://science.nasa.gov/mission/euvst
20. "Civil Space Shortfalls," National Aeronautics and Space Administration: https://www.nasa.gov/spacetechpriorities

S14.02: In Situ Particles and Fields and Remote-Sensing-Enabling Technologies for Heliophysics Instruments (SBIR)

Related Subtopic Pointers: S11.01, S11.04, S16.08
Lead Center: GSFC
Participating Center(s): MSFC

Subtopic Introduction:

The 2013 National Research Council's "Solar and Space Physics: A Science for a Technological Society" Decadal motivates technologies that support: "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." Development of advanced remote-sensing and in situ instrument technologies and components suitable for heliophysics missions for both solar and geospace science applications are sought. Advanced sensors for the detection of neutral and ionized gases (atoms, molecules, and ions) and their motions (winds and ion drifts); energetic particles (electrons and ions), including their energy distribution and pitch angles; thermal plasma populations, including their temperature; and direct-current (DC) and wave electric and magnetic fields in space along with 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 ionospheric and upper atmospheric composition of the planets and their moons.

These in situ 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.

For this solicitation, this subtopic seeks technology advancement needs in the following two scopes (not in any priority order):

1. Enabling Technologies for Remote-Sensing Heliophysics Instruments.
2. Enabling Technologies for In Situ Particles and Fields Heliophysics Instruments.

Scope Title: Enabling Technologies for Remote-Sensing Heliophysics Instruments

Scope Description:

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 scope solicits instrument development that provides substantial advances in the following areas:

- Technologies to enable remote sensing of magnetic fields in the solar corona. For example, technologies that enable high- signal-to-noise ratio (SNR) observation of off-limb Ly-Alpha.
- Technologies that enable remote sensing of neutral winds in the upper atmosphere. That may include:
    - Light detection and ranging (LIDAR) systems for high-power, high-frequency geospace remote sensing, such as lasers for detecting the sodium layer.
    - Technologies for precise radiometry at terahertz (THz) bands corresponding to upper atmosphere thermal emissions in the 1-5 THz range, particularly at 4.7 THz. This includes, but is not limited to:
        - Technologies that reduce the size, mass, and power of THz radiometry instrumentation, for example by increasing the operating temperature of THz detectors.
        - Technologies that enable THz spectroscopy, for example by use of a THz local oscillator for heterodyne mixing.
        - Technologies that improve the SNR of THz instrumentation, particularly at 4.7 THz.
        - Technologies to enable imaging of THz radio observations.
    - Nitric oxide sensors that can quantify NO abundances in both daytime and nighttime conditions in Earth's mesosphere-lower thermosphere.
- Technologies or components enabling auroral, airglow, geospace, and solar imaging at visible, Far- and Extreme-Ultraviolet (FUV/EUV), and soft X-ray wavelengths (e.g., mirrors and gratings with high-reflectance coatings, multilayer coatings, narrowband filters, blazed gratings with high ruling densities, and diffractive and metamaterial optics).
- Electromagnetic sounding of ionospheric or magnetospheric plasma density structures at radio frequencies from kHz to >10 MHz.
- Passive sensing of ionospheric and magnetospheric plasma density structures using transmitters of opportunity (e.g., global navigation satellite system (GNSS) or ground-based transmissions).
- Technologies that enable observations of bright solar flares without saturation in wavelength range from EUV to x-rays. That includes but is not limited to:
    - Fast-cadence solid-state detectors or camera systems (e.g., charge-coupled device (CCD), complementary metal-oxide semiconductor (CMOS)) for imaging in the EUV with or without intrinsic ion suppression.
    - Fast-cadence solid-state detectors or camera systems for imaging soft or hard x-rays (~0.1 to hundreds of keV), preferably with the ability to detect individual photons.
    - Technologies that attenuate solar x-ray fluences by flattening the observed spectrum by a factor of 100 to 1,000 across the energy range encompassing both low- and high-energy x-rays—preferably flight programmable.
    - Technologies to improve or enable very long focal lengths or imaging spatial resolutions in the EUV to x-ray range, particularly those that are suitable for observing very bright sources.
    - Technologies to improve focusing optics for hard x-rays in the 1 to 300 keV range.
- Technologies to either reduce the size, complexity, or mass or to improve the imaging resolution of solar telescopes used for imaging solar x-rays such as those that enable smoothly laminating silicon micropore optics with materials that enhance the grazing incidence reflectivity of soft x-rays in the energy range from 0.1 to 2 keV.
- Technologies to improve or enable the rejection of background x-rays in the 1 to 300 keV range such as those that:

    - Shield or block background particles from a detector.
    - Provide anticoincidence detection of background x-rays.
- Technologies, including metamaterials and micro-electro-mechanical systems (MEMS) that enable polarization, wavelength, or spatial discrimination without macroscale moving parts.
- Technologies to improve upon coronagraphs, such as those that:
    - Improve solar occultation technologies, including solar shades for UV and EUV observations.
    - Reduce the size, mass, and power.
    - Better enable solar coronagraphs to be used in deep-space missions (beyond Earth orbit).

Proposers are strongly encouraged to relate their proposed development to NASA's future heliophysics goals and missions. Proposed instrument components and/or architectures should be as simple, reliable, and low risk as possible, while enabling compelling science. Novel instrument concepts (e.g., quantum sensors) are highly encouraged, particularly if they enable a new class of scientific discovery. Technology developments relevant to multiple environments and platforms are also desired. Proposers should convincingly demonstrate an understanding of relevant space science needs and present a feasible plan to complete the proposed technology development and infuse it into a NASA program.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:

- Level 1: TX 08 Sensors and Instruments
- Level 2: TX 08.1 Remote Sensing Instruments/Sensors

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware
- Analysis

Desired Deliverables Description:

- Phase I: Analysis or test report, a prototype of an instrument subcomponent, or a full working instrument prototype. Phase I does not necessarily need to include any testing. However, the proposal should describe expected test regimen for the completed technology including required facilities or equipment and provide a general timeline for testing (including Phase II and beyond).
- Phase II: Prototype or demonstration of a working instrument or subcomponent, which may also include analysis or test reports. Phase II deliverables should also include/delineate any further work that would be required to bring the technologies to full operational and/or commercial use.

State of the Art and Critical Gaps:

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 possess lower mass and volume while requiring less power. The 2023 Heliophysics Strategic Technology Office (HESTO) Gap and Trend Analysis report specifically identified technology gaps associated with remote sensing of coronal magnetic fields and remote sensing of neutral winds in the upper atmosphere. In addition, there is a growing demand for remote-sensing technologies amenable to CubeSats and SmallSats.

This scope addresses shortfalls identified in the Civil Space Shortfall Ranking including:

- [Ranked 115th] ID 1627: Advanced Sensor Components for Heliophysics and Lunar-Based Astronomy

Relevance / Science Traceability:

Remote-sensing 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" Decadal. Improvements in these instrument technologies enable further scientific advancement for upcoming NASA missions such as Solar Terrestrial Probe (STP), Living With a Star (LWS), as well as a host of smaller spacecraft in the Missions of Opportunity and Explorers Program.

References:

1. "NASA Science Missions," National Aeronautics and Space Administration: https://science.nasa.gov/science-missions/

Example missions

2. "Solar and Space Physics: A Science for a Technological Society," National Academies: http://nap.edu/13060

Details of the specific requirements

3. "Our Dynamic Space Environment: NASA Heliophysics Science and Technology Roadmap for 2014-2033," National Aeronautics and Space Administration: https://explorers.larc.nasa.gov/HPSMEX/MO/pdf_files/2014_HelioRoadmap_Final_Reduced_0.pdf
4. "Solar and Space Physics: A Science for a Technological Society," National Academies: http://nap.edu/13060
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6. "Civil Space Shortfalls," National Aeronautics and Space Administration: https://www.nasa.gov/spacetechprioritieshttps://www.nasa.gov/spacetechpriorities

Scope Title: Enabling Technologies for In Situ Particles and Fields Heliophysics Instruments

Scope Description:

Technologies are being sought for in situ particle and fields measurements for heliophysics instruments that achieve much higher resolution and sensitivity with significant improvements over existing capabilities including reduced mass, power, and size of electronics. This subtopic solicits instrument development that provides significant advances in the following areas:

- Technologies for the development of high-voltage control elements (e.g., optocouplers or transistors) and ultra-high-voltage power supplies for space (50 to 100 kV), including approaches that lead to the reduction in size, mass, and power of high-voltage power supplies.
- Technologies for the development of magnetic core material suitable for incorporation into science-grade flux-gate magnetometers.
- Technologies for the development of compactly stowed, lightweight, long, straight, and rigid booms as part of deployment mechanisms for sensitive electric and magnetic instrumentation compatible with CubeSats or SmallSats.
- Technologies for the rapid and cost-effective fabrication of electrostatic analyzer components.
- Technologies for improved detection of low-energy (<10 keV) ions and electrons.
- Technologies for the efficient conversion of neutrals (<1 keV) to charged particles.
- Technologies for reduction in size, mass, and power of electric and magnetic field wave instrumentation.

- Technologies for black coatings that are effective at rejecting extreme ultraviolet (EUV) photons for high angles of incidence (>45 deg) and resistant to atomic oxygen.
- Technologies for rapid (up to ~10 MHz) multi-channel counting of pulses from microchannel plate detectors and photomultiplier tubes.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:

- Level 1: TX 08 Sensors and Instruments
- Level 2: TX 08.3 In-Situ Instruments/Sensor

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware
- Research

Desired Deliverables Description:

- Phase I: Analysis or test report, a prototype of an instrument subcomponent, or a fully working instrument prototype. Phase I does not necessarily need to include any testing. However, the proposal should describe expected test regimes for the completed technology including required facilities or equipment and provide a general timeline for testing (including Phase II and beyond).
- Phase II: Prototype or demonstration of a working instrument or subcomponent which may also include analysis or test reports. Phase II deliverables should also include/delineate any further work that would be required to bring the technologies to full operational and/or commercial use.

State of the Art and Critical Gaps:

Critical gaps within particles and fields instruments are:

- Most charged-particle instruments need to apply high voltage to electrodes or grids in order to select the energy-per-charge of ions and electrons in space. High voltage in charged-particle instrumentation is typically limited to ~10 kV. Higher voltage supplies are needed to enable instrumentation capable of improved composition and heavy-ion measurements. The availability of high-voltage optocouplers (HVOCs) suitable for spaceflight is severely limited. Metal-oxide-semiconductor field-effect transistor (MOSFET) high-voltage technology (SiC) is currently limited to stand-off distances of a few kilovolts. Still, it may present an alternative solution to HVOCs in stepping circuits.
- Suitable magnetic core material for incorporation into science-grade flux-gate magnetometers has become extremely limited. New vendors of core materials are critical for the continuation of high-quality magnetic-field measurements.
- There is a growing demand for particle and field technologies amenable to CubeSats and SmallSats. The ability to deploy electric field sensors on CubeSat or SmallSats is limited yet of critical need for the ever-increasing number of Heliophysics constellation missions.
- Electrostatic analyzer components are typically manufactured using traditional machining techniques. New technologies (e.g., additive machining, new analyzer concepts) are needed to enable cost-effective fabrication and assembly of multiple instruments for new multispacecraft mission concepts.
- Low-energy (<10 keV/e) charged particle measurements are typically achieved through secondary electron multiplication via channel electron multipliers (CEMs) or microchannel plates (MCPs). New technologies are needed to enable the detection of low-energy charged particles with reduced need for high-voltage and/or significant contamination-control requirements.

- Conversion efficiencies for neutral particles for energetic neutral atom (ENA) instrumentation are currently very low for particles under 1 keV. New technologies are needed to improve the detection efficiency of lower-energy ENAs.
- Charged particle instrumentation relies heavily on black coatings to limit the ability of solar EUV to reach sensitive detectors. Black coatings need to demonstrate suppression at solar wavelengths such as Lyman-alpha. Incident photons often hit the surface at near grazing angles of incidence such that simply developing black coatings for strong EUV absorption at normal incidence is insufficient. Instruments can also be deployed in atomic oxygen-rich environments in Low Earth Orbit.
- Detectors for in situ particle instrumentation such as microchannel plates or photomultiplier tubes generate small currents or voltages that require special front-end electronics in order to be processed (e.g., charge-sensitive preamplifiers, discriminators).

This scope addresses shortfalls identified in the Civil Space Shortfall Ranking including:

- [Ranked 115th] ID 1627: Advanced Sensor Components for Heliophysics and Lunar-Based Astronomy

Relevance / Science Traceability:

Particle and field instruments and technologies are essential for achieving the SMD's Heliophysics goals, summarized in the National Research Council's "Solar and Space Physics: A Science for a Technological Society" Decadal. In situ instruments and technologies play indispensable roles for NASA's Living with a Star (LWS) and Solar Terrestrial Probes (STP) mission programs, as well as for a host of spacecraft in the Explorers Program, Discovery Missions, and New Frontiers Missions.

References:

1. "Solar and Space Physics: A Science for a Technological Society," National Academies: http://nap.edu/13060
2. "NASA Science Missions," National Aeronautics and Space Administration: https://science.nasa.gov/science-missions/

Relevant example missions include NASA Magnetospheric Multiscale (MMS) mission, Fast Plasma Investigation, Solar Probe, Solar Terrestrial Relations Observatory (STEREO), and Geospace Dynamics Constellation)

3. "Civil Space Shortfalls," National Aeronautics and Space Administration: https://www.nasa.gov/spacetechpriorities

S15.02: In Situ Sample Preparation and Analysis for Biological and Physical Sciences in a Microgravity Environment (SBIR)

Related Subtopic Pointers: S13.04, S15.03, S17.03
Lead Center: GRC
Participating Center(s): ARC, KSC, MSFC

Subtopic Introduction:

The Biological and Physical Sciences Division (BPS) within NASA's SMD sponsors long-duration microgravity research aboard the International Space Station (ISS). Experimental samples traditionally have been prepared in ground-based laboratories and launched to the ISS where experiments are conducted. Limited analyses of test samples can be conducted aboard the ISS, but most experiments require preserving, storing, and returning the samples to Earth where detailed analyses are conducted. Consequently, the pace of scientific discovery has been sluggish due to the inability to quickly conduct the iterative process of research that includes the ability to either synthesize or adjust sample composition on-orbit based on real-time diagnostic measurements. In addition, the lack of timely crew interaction with experimental hardware has impacted the operation of experiment hardware. Technologies are sought to enable and advance in situ sample analysis and preparation in the microgravity environment, either in low Earth orbit (LEO) or beyond low Earth orbit (BLEO).

For this solicitation, this subtopic seeks technology advancement needs in the following three scopes (not in any priority order):

1. Compact Devices for Sample Analysis in Space (previously "Sample Analysis").
2. Experimental Hardware for Autonomous Biological Research in the Space Environment (returning).
3. Handling Powders (new).

For this solicitation, the following scopes were rotated out but may return in a future year:

- Enabling Materials Science Technology.

Scope Title: Compact Devices for Sample Analysis in Space

Scope Description:

Technologies that enable analysis for biological or chemical samples while in the microgravity environment would progress fundamental science experiments being conducted aboard the ISS. This scope seeks proposals for innovative compact devices for measuring and transmitting data from both biological specimens (such as tissue on a chip, 3D organoids, such as cells, proteins, and metabolites) and chemical compositions (from colloidal and polymer solutions) undergoing reactions or other manipulations. Devices that conduct non-invasive measurements, allow continuous data acquisition (longitudinal data), or have buffer storage capabilities for at least a few weeks are highly desirable.

Expected TRL or TRL Range at completion of the Project: 2 to 6

Primary Technology Taxonomy:

- Level 1: TX 08 Sensors and Instruments
- Level 2: TX 08.3 In-Situ Instruments/Sensor

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype

Desired Deliverables Description:

- Phase I: Feasibility study detailing evidence with demonstrated proof-of-concept prototype component technologies in the laboratory or in a relevant environment and stating the future path toward hardware demonstration in orbit. If the Phase I proposal is the modification of existing hardware, development and test of a bench-top prototype may be included. A preliminary assessment of the technology business case (cost and revenue forecast, market size, potential customers, etc.) is also required.
- Phase II: Preliminary design concept of operations, development and test of an engineering development unit in a relevant environment (ground or space), and a report containing detailed interface specifications and performance envelopes, supporting test results, and an updated business case analysis and/or application plan including potential users. Concepts that can achieve flight demonstration on a suborbital flight or on the ISS during Phase II are especially valuable. Phase II deliverables should also include/delineate any further work that would be required to bring the technologies to full operational and/or commercial use.

State of the Art and Critical Gaps:

Currently, most samples require preserving, storing, and returning the samples to Earth where detailed analyses and experiments can be conducted in specialized facilities or controlled environments. Not only does the process of returning the samples to Earth (also known as downmassing) delay analysis and interpretation of the results, samples may be compromised during transport by the inability to sustain the sample state due to gravity-induced settling, thermal transients, vibration or other effects associated with downmassing samples.

This scope addresses shortfalls identified in the Civil Space Shortfall Ranking including:

- [Ranked 105th] ID 1533: Autonomous Robotic Sample Identification, Classification, Collection, Manipulation, Verification, and Transport

Relevance / Science Traceability:

This scope is in direct support of NASA's recent policy to enable commercial and marketing activities to take place aboard the ISS. This scope is coordinated with the BPS Division within NASA SMD which sponsors long-duration microgravity research aboard the ISS and is in direct alignment with the Commercially Enabled Rapid Space Science (CERISS) initiative within BPS.

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5. "Civil Space Shortfalls," National Aeronautics and Space Administration: https://www.nasa.gov/spacetechpriorities

Scope Title: Experimental Hardware for Autonomous Biological Research in the Space Environment

Scope Description:

Fundamental research in the biological response to the space environment is crucial for assessing and mitigating health risks to human explorers. To enable autonomous biological research in the space environment, technologies are sought that are capable of autonomously providing life support to experimental organisms and generating measurements necessary for studying their growth and activity. The proposed hardware should accommodate a model organism(s) relevant to the NASA's science goals which include microorganisms, plants, or mammalian cell culture and organoids.

Proposals must identify a science research concept and the relevance of the hardware capabilities to achieving that research; they must also identify one or more target platforms among the following: BLEO platforms (Commercial Lunar Payload Services (CLPS) lunar lander, Lunar Gateway, free-flyer, Artemis) or LEO platforms (ISS, commercial space station).

Instruments that are modular (allow users to easily interchange sensors, growth chambers, or other components) and extensible (allow easy addition of new capabilities) are strongly desired.

The instrument must be capable of (requirements):

- Autonomous operation: control system enabling full experiment execution and data storage without user intervention once it is activated. Systems that can also accommodate "on-the-fly" remote modification of execution scripts, modification between individual experiments, and/or real-time control for troubleshooting are encouraged; at minimum, the system must be capable of fully autonomous operation for one experiment.
    - Control of environmental conditions including the following: temperature, lighting, ambient CO_2 and O_2, humidity, pressure, pH, ionic strength, dissolved gases, dissolved nutrients, waste products, agitation, etc. Proposals must specify the model organism and target platform. Concepts must not fully depend on environmental control to be provided by the platform.
    - Measurement of parameters in real time, appropriate to the model organism; e.g., changes in dissolved gases or metabolites in growth medium, optical absorbance and fluorescence, imaging, nucleic acid extraction and sequencing/gene-expression analysis, protein extraction and analysis, cytometry, fluorescence-activated cell sorting (FACS), and gene and protein microarray analysis (with appropriate sample preparation).
    - Autonomy may be enabled/enhanced by artificial intelligence (AI)/machine learning (ML) methods.
- Independent operation from the gravity environment: full function at any gravitational level from micro-g up to terrestrial gravity or even hypergravity, if relevant.
    - Storage and control, including metering or dilution series as warranted, of appropriate growth media and experimental reagents such as dyes, antagonists, drugs, etc.
    - Appropriate mitigation of bubble formation in fluidic systems, whether due to physical setup and conditions or organismal respiration.
    - Dry/lyphilized storage combined with capability for rehydration/reconstitution/revitalization of sensitive reagents, nutrients, or microorganisms where necessary to support long-duration experimental scenarios.
- Late load capability: capacity for organisms and perishable reagents to be loaded and/or replenished in a sterile manner, without complete disassembly of the instrument.

The instrument must also be capable of one or more of the following (additional desired features):

- Capability for continuous culture or multigeneration iterative culture.
- Feedback control: ability for growth measurements or other biological data to feed back into control parameters; e.g., for chemostat implementation, triggering subculturing, etc.
- Systems that support statistical robustness through replicate experiments; e.g., in multiwell formats where suitable.
- 1g/partial-g control: built-in centrifuge to create artificial gravity at relevant levels (e.g., Moon, Mars, Earth as control) if deployed in a low-gravity environment.

- Capability for post-experiment sample preservation, including cell fixation, preservation of nucleic acids/proteins, tissue preservation, seed storage, etc.

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:

- Level 1: TX 08 Sensors and Instruments
- Level 2: TX 08.3 In-Situ Instruments/Sensor

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype

Desired Deliverables Description:

- Phase I: Feasibility study detailing evidence with proof of concepts stating the future path toward hardware autonomous prototype demonstration in orbit. Development and test of a bench-top prototype components may be included depending on the scope of the proposal. A preliminary assessment of the technology business case (cost and revenue forecast, market size, potential customers, etc.) is also required.
- Phase II: Preliminary design and concept of operations, development, and test of an engineering development unit, and a report containing detailed interface requirements, performance envelopes, supporting test results and an updated business case analysis and/or application plan with tentative business partners and/or endorsements by principal investigators. Concepts that can achieve flight demonstration on a suborbital flight or on the ISS during Phase II are especially valuable. Phase II deliverables should also include/delineate any further work that would be required to bring the technologies to full operational and/or commercial use.

State of the Art and Critical Gaps:

The priority to move toward autonomous biological research in space is reflected by recent experiments which were conducted without human crew present (BioExp-1 and BioSentinel experiments associated with Artemis I). Very limited availability crew time (e.g., Artemis, Gateway) or none at all (e.g., free flyers, CLPS landers) will continue to be a characteristic for upcoming research opportunities BLEO. Other constraints include limits on mass and power consumption, data transfer rates, the need for self-sufficiency in controlling the incubation environment (e.g., temperature, gas composition), and the need to maintain organisms in stasis during lengthy pre-launch and transit periods prior to experiment initiation. As many future flight opportunities will not allow sample return, experimental hardware must therefore be capable of taking measurements sufficiently complex to enable hypothesis testing in situ. Platforms within LEO (ISS and upcoming commercial space stations) will also benefit from versatile and adaptable instruments capable of autonomous biological experimentation.

Many experimental hardware suites already designed for use on the ISS meet the functionality requirements listed above but not the requirement for autonomous operation. Many biological CubeSats meet the requirement for autonomy but do not have the diverse experimental capabilities. Most existing instruments for biological research in space have been custom-built for a specific organism or set of experiments and lack the desired modularity and extensibility.

This scope addresses shortfalls identified in the Civil Space Shortfall Ranking including:

- [Ranked 105th] ID 1533: Autonomous Robotic Sample Identification, Classification, Collection, Manipulation, Verification, and Transport

Relevance / Science Traceability:

This scope is in direct support of NASA's recent policy to enable commercial and marketing activities to take place aboard the ISS and BLEO. This hardware will support multiple of the research goals specified in the Space Biology Science Plan (2016-2025). This scope is coordinated with the BPS Division within NASA SMD which sponsors long-duration microgravity research aboard the ISS and is in direct alignment with the CERISS initiative within BPS.

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10. "Civil Space Shortfalls," National Aeronautics and Space Administration: https://www.nasa.gov/spacetechpriorities

Scope Title: Handling Powders

Scope Description:

To enable experiments or support transport, techniques and technologies are sought for handling solid particles such as powders and granules in a reliable and safe manner in the microgravity environment aboard the ISS. Granule sizes can range from 100 microns to 2 millimeters.

Techniques and technologies are sought to enable handling of solid powders and granules:

- The controlled transfer of predetermined amounts of material from one container.
- Depositing or injecting these materials into liquids with splashing or satellite droplet formation.
- Effective control of the gas-liquid interfaces during mixing and solid dissolution processes.

Expected TRL or TRL Range at completion of the Project: 1 to 4

Primary Technology Taxonomy:

- Level 1: TX 08 Sensors and Instruments
- Level 2: TX 08.3 In-Situ Instruments/Sensor

Desired Deliverables of Phase I and Phase II:

- Prototype
- Research
- Analysis

Desired Deliverables Description:

- Phase I: Feasibility study with proof of concepts in the laboratory and stating the future path toward hardware demonstration in a microgravity environment (drop towers, suborbital, ISS and commercial low Earth destinations). Depending on the scope of the proposal and targeted TRLs, bench-top prototype development or testing may be included. A preliminary assessment of the technology business case (cost and revenue forecast, market size, potential customers, etc.) is also required.
- Phase II: Preliminary design and concept of operations, development, and test of an engineering development unit, and a report containing detailed interface requirements and performance envelopes, results of testing, and an updated business case analysis and/or application plan. Concepts that can achieve flight demonstration on a suborbital flight or on the ISS during Phase II are especially valuable. Phase II deliverables should also include/delineate any further work that would be required to bring the technologies to full operational and/or commercial use.

State of the Art and Critical Gaps:

Currently, most samples require preserving, storing, and returning the samples to Earth where detailed analyses and experiments can be conducted in specialized facilities or controlled environments. In order to enable in situ experiments in the microgravity space environment with solid particles, special techniques and technologies are sought in order to handle powders in a safe and reliable matter for biological and chemical science experiments. While the technique to measure small quantities of mass has been baselined, significant gaps still exist in controlled and precise solid particle transfer and complex solid particle interactions with other states of matter.

Relevance / Science Traceability:

This scope is in direct support of NASA’s recent policy to enable commercial and marketing activities to take place aboard the ISS and beyond LEO. This scope is coordinated with the BPS Division within NASA SMD which sponsors long-duration microgravity research aboard the ISS and is in direct alignment with the CERISS initiative within BPS.

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S15.03: Environmental Monitoring for Micro-G and Partial-G Experiments (SBIR)

Related Subtopic Pointers: S15.02, S17.03
Lead Center: ARC
Participating Center(s): GRC

Subtopic Introduction:

NASA's Division of Biological and Physical Sciences (BPS) within SMD sponsors research to better understand the space environment and its impact on physical and biological systems. While the absence of Earth gravity may be the most striking aspect of the space environment, many environmental features are changed: Radiation levels are increased, light quality and cycles are different, atmospheric compositions are changed, and the distribution and dynamics of gas and liquids are altered. Interpreting the results of experiments performed in space requires high-quality measurements of these environmental parameters. Ideally, these measurements would reference quality and feature high temporal and spatial resolution. However, the spaceflight research environment is constrained by high launch costs, restricted amounts of crew time, and the need for tight physical packaging. Technologies are needed that can measure and report environmental parameters of biological and physical experiments performed in space.

For this solicitation, this subtopic seeks technology advancements in the following two scopes (not in any priority order):

1. Continuous Environmental Sensing to Monitor the Space-Built Environment and Its Microbiome.
2. Fire Detection Sensing for Space Research.

Scope Title: Continuous Environmental Sensing to Monitor the Space-Built Environment and Its Microbiome

Scope Description:

For human explorers to survive deep space, the environmental qualities of a space habitat are crucial for maintaining health. The environment comprises not only physical factors (e.g., temperature, humidity, light, and particulate matter) but also biological factors. This includes the activity of plants in modulating the atmosphere and the microbiome of the built environment. As has been observed in the International Space Station (ISS), space habitats are unique, continually evolving environments. Space habitats are also increasingly envisioned as places to plant crops of food, including plant habitats that are open to the crew cabin. Constant environmental monitoring can help identify and mitigate potential risks to crop production and the microbiological safety of the food grown in space. Spatially resolved measurements of parameters such as humidity, temperature, radiation, vibration, and partial pressures of gas are essential to allowing us to understand how microbial communities develop in human habitats and, subsequently, to predict and control their dynamics.

Technology is sought to provide continuous and maximally automated biomonitoring and physico-chemical monitoring systems capable of generating highly localized data and working in a variety of environments relevant to space habitats (e.g., non-standard atmosphere composition, atmosphere pressure, airflow rates, gravity levels, etc.). The result should be science-enabling environmental data to contextualize studies of the built microbiome, plant growth, or other investigations sponsored by BPS. Data should be easily available in real time, with little or no crew time required for download and transfer to a computer for analysis and interpretation.

The hardware is required to:

- Measure at least one environmental variable relevant to human/microbial/plant health in space. Proposals should demonstrate advancement over current commercially available sensors that could be easily adapted to spaceflight. This may include measuring more than one variable simultaneously or measuring one variable in a spaceflight-adapted format. Examples include humidity, temperature, radiation, vibration, major or trace gases, volatile organic compounds, particulate concentrations, and light.
    - Measurements may involve environmental assessments such as sampling cabin atmosphere, interacting with surfaces, monitoring plant growth substrate, assessing food safety, or measuring incident radiation.
    - Measurements may also include monitoring of biomarkers (e.g., fluorescence) if the method is minimally invasive.
    - If a parameter not specified here is proposed, the proposal should include sufficient background information to justify the choice of parameter.
    - For radiation detection, devices that can separate the dose as a function of particle types (e.g., photons, neutrons, protons, higher Z particles) are desired.
- Operate at a variety of environments relevant to space habitats (e.g., non-standard atmosphere composition, atmosphere pressure, airflow rates, gravity levels, etc.). Target habitats for operation include ISS, commercial low-Earth-orbit (LEO) destinations, Gateway (a future space station in lunar orbit), a future lunar surface habitat, pressurized rovers, and vehicles in transit to the Moon or Mars.
- Take continuous measurements at a cadence relevant to the parameter of choice. Devices that have buffer storage capabilities for at least a few weeks are desired.
- Require a minimum of crew time for operation, including data measurement, recording, and transfer to a computer system for dissemination.
- Have reasonable mass, volume, and power requirements in light of typical requirements for space habitats.

Please note that the following areas are excluded from S15.03 this year:

- Measurements that involve extensive extraction and analysis of biological samples (e.g., DNA sequencing). (Proposers are suggested to consider S15.02 "In Situ Sample Preparation and Analysis for Biological and Physical Sciences in a Microgravity Environment.")

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:

- Level 1: TX 08 Sensors and Instruments
- Level 2: TX 08.3 In-Situ Instruments/Sensor

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype

Desired Deliverables Description:

- Phase I: Feasibility study detailing evidence with proof of concepts stating the future path toward hardware prototype demonstration in orbit. Development and test of bench-top prototype components may be included depending on the scope of the proposal. A preliminary assessment of the technology business case (cost and revenue forecast, market size, potential customers, etc.) is also required.
- Phase II: Preliminary design and concept of operations, development, and test of an engineering development unit, and a report containing detailed interface requirements, performance envelopes, supporting test results, and an updated business case analysis and/or application plan with tentative business partners and/or endorsements by principal investigators. Concepts that can achieve flight demonstration on a suborbital flight or on the ISS during Phase II are especially valuable. Phase II deliverables should also include/delineate any further work that would be required to bring the technologies to full operational and/or commercial use.

State of the Art and Critical Gaps:

The ISS has served as a microbial observatory since its initial construction and includes several data streams reporting habitat-level measurements of human-health-relevant parameters, such as radiation exposure, temperature, and humidity. Many of these parameters are not measured at the temporal or spatial scale relevant to plant and microbial health in the indoor environment.

Consistent monitoring is labor-intensive and captures only some kinds of relevant data (e.g., the most recent quantification of airborne microbial particulates on the ISS was published in 2006 "Survey of environmental biocontamination on board the International Space Station" [Ref. 6]). Some constant monitoring technologies exist for ground laboratories. For instance, commercial particle size analyzers, including ones with the capability to measure biofluorescent particles, may be used in clean rooms. Much of this technology can be prohibitively large and is not compatible with microgravity or partial gravity, or unusual atmospheric pressure levels.

This scope addresses shortfalls identified in the Civil Space Shortfall Ranking including:

- [Ranked 7th] ID 1519: Environmental Monitoring for Habitation

Relevance / Science Traceability:

This capability would enable many kinds of biology studies addressing the Key Science Questions (KSQs) of the 2023 BPS Decadal Survey. Particularly, this type of monitoring would enable topics in the Adapting to Space theme (i.e., "How does the space environment alter interactions between organisms?") and the Living and Traveling in Space theme (i.e., "What principles guide the integration of biological and abiotic systems to create sustainable and functional extraterrestrial habitats?"). Results from this scope will be critical for supporting future research in LEO and on the Moon and may additionally be of interest to the Human Research Program or the Mars Program Office.

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9. "Civil Space Shortfalls," National Aeronautics and Space Administration: https://www.nasa.gov/spacetechpriorities

Scope Title: Fire Detection Sensing for Space Research

Scope Description:

A spacecraft fire represents one of the most dangerous scenarios for a crewed space mission. Material combustion in reduced gravity or microgravity differs compared to combustion in Earth gravity, because buoyant flow is reduced or not present, which alters heat and mass transfer during the combustion reaction and thereby affects material ignitability and flame-spread rates. The influence of gravity on fundamental combustion physics must be determined for relevant materials to understand how a fire may start and/or propagate in space. As NASA plans a return to the Moon, fundamental combustion experiments are targeted by BPS for inclusion on future lunar landers. These experiments will require combustion product sensors that can operate autonomously with minimal power consumption and low physical footprints.

The need for science-enabling technologies for reduced gravity combustion experiments fundamentally aligns with the need for improved fire detection systems for future space missions. Technology improvements are needed to selectively detect smoke at concentrations low enough and within relevant particle size ranges such that the detector will alarm in a potential slow-moving spacecraft fire scenario.

Proposals should address the need for combustion product monitoring (e.g., smoke particles, gases, or a combination) for applications in both combustion experiments and fire detection systems. Specifically, proposals should address the need for sensing strategies that selectively detect smoke and/or do not rely on a priori knowledge of combustion product concentrations or properties (e.g., smoke particle sizes/morphologies) for successful data collection and analysis. Sensors should operate autonomously and continuously and should be suitable for applications in desired experimental and/or habitat atmospheres, including reduced pressures and elevated O_2 concentrations. Data should be easily available in real time, with little or no crew time required for download and transfer to a computer for analysis and interpretation.

The hardware is required to:

- Measure at least one particulate-phase parameter relevant to fire detection and/or reduced gravity combustion in space. Examples of particulate-phase parameters include particle mass concentrations, particle number concentrations, particle size distributions, and particle charge distributions.
  - Measurement of two or more parameters is highly desired.
  - Measurements may involve measuring complementary gas-phase parameters in parallel with aerosol measurement(s).
  - If a parameter not on this list is proposed, the proposal should include sufficient background information to justify the choice of parameter.
- Be capable of operating over a wide dynamic concentration range. Capability of measuring aerosol concentrations over 1 mg/m^3 is desired.
- Measure aerosol concentrations over a broad size range. Capability of measuring particles with diameters from 10 to 300 nm is highly desired. Particle size distribution measurement capability is desired.
- Operate over a variety of environments relevant to space habitats (e.g., non-standard atmosphere composition, reduced atmosphere pressure, airflow rates, gravity levels, etc.). Target habitats for operation include the International Space Station (ISS), commercial low-Earth-orbit (LEO) destinations, Gateway, a future lunar surface habitat, pressurized rovers, and vehicles in transit to the Moon or Mars.
- Take continuous measurements at a cadence relevant to the parameter of choice.
- Minimize crew time for operation, including data measurement, recording, and transfer to a computer system for dissemination.
- Have reasonable mass, volume, and power requirements in light of typical requirements for space habitats.

Expected TRL or TRL Range at completion of the Project: 2 to 6

Primary Technology Taxonomy:

- Level 1: TX 08 Sensors and Instruments
- Level 2: TX 08.3 In-Situ Instruments/Sensor

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype

Desired Deliverables Description:

- Phase I: Feasibility study detailing evidence with proof of concepts stating the future path toward hardware prototype demonstration in orbit. Development and test of bench-top prototype components may be included depending on the scope of the proposal. A preliminary assessment of the technology business case (cost and revenue forecast, market size, potential customers, etc.) is also required.
- Phase II: Preliminary design and concept of operations, development, and test of an engineering development unit, and a report containing detailed interface requirements, performance envelopes, supporting test results, and an updated business case analysis and/or application plan with tentative business partners and/or endorsements by principal investigators. Concepts that can achieve flight demonstration on a suborbital flight or on the ISS during Phase II are especially valuable. Phase II deliverables should also include/delineate any further work that would be required to bring the technologies to full operational and/or commercial use.

State of the Art and Critical Gaps:

Though they have generally been designed for terrestrial applications, a broad variety of aerosol measurement technologies, including smoke detectors, are available on the commercial market. Although surrogate aerosol measurements (e.g., optical particle counters) are increasingly available and offer size, mass, and cost benefits, they often are limited in their applicability across relevant aerosol size/concentration ranges, and/or they require a priori knowledge of analyte properties for proper operation and data interpretation. These gaps limit NASA’s ability to choose from currently available commercial off-the-shelf (COTS) sensors for a lunar-g combustion experiment or fire detection system where particle properties and concentrations may not be fully known.

The ISS smoke detector represents the state of the art (SOA) for spacecraft fire detection. The detector is a forward-light-scattering detector subject to frequent false alarms due to the overlap of smoke particle and nuisance dust particle properties. False alarms are avoided on the ISS by turning off smoke detectors during dust-generating activities (e.g., vacuuming). Given the wide variety of potential spacecraft smoke and nuisance pollutant properties (both particulate and gas phase), a sensor system integrating multiple orthogonal properties is desired to positively identify early fires while avoiding false alarms from nuisance airborne pollutants.

The current SOA for scientific reference-quality particle mass concentration measurements is a tapered element oscillating microbalance (TEOM; Thermo Fisher Scientific). The physical footprint (43.2 x 48.3 x 139.7 cm) and mass of the instrument (83 lbs) prohibits its use in a spacecraft. The Electrical Low Pressure Impactor (ELPI; Dekati Technologies) is one example of a reference-quality instrument for high time-resolved (1^{-10} second resolution) measurements of particle number and charge concentrations over a wide range of particle sizes (6 nm to 10 um), yet also features a physical footprint prohibitive to space flight (40.7 x 45.4 x 24.2 cm and 48.5 lbs, not including the specialized vacuum pump).

Other aerosol measurement devices available on the market, like optical aerosol counters, require assumptions to be made about particle properties (e.g., density) or are limited in applicable range due to aerosol scattering physics (e.g., light scattering techniques that do not detect particles smaller than ~300 nm). Most reference-quality instruments available commercially have limited applicability at pressures below Earth ambient. There is a need for proposed technologies to address one or more of these measurement capability gaps while maintaining a low physical footprint to enable inclusion in future combustion experiment rigs and/or a future fire detection sensor network.

This scope addresses shortfalls identified in the Civil Space Shortfall Ranking including:

- [Ranked 10th] ID 1520: Fire Safety for Habitation

Relevance / Science Traceability:

This capability will enable fundamental combustion science to address the “Probing Phenomena Hidden by Gravity or Terrestrial Limitations” theme of the 2023 BPS Decadal Survey, specifically KSQ #10: “What are the fundamental laws that govern the behavior of systems that are far from equilibrium?” Technologies from this scope will support BPS fundamental combustion experiments, including potential follow-ons to the Flammability of Materials on the Moon (FM2) lunar lander payload. These may also be of interest to the Mars Campaign Office for Spacecraft Fire Safety experiments and Life Support Systems particulate-monitoring flight demonstrations.

References:

1. Mulholland, G. W.; Meyer, M.; Urban, D. L.; Ruff, G. A.; Yuan, Z.; Bryg, V.; Cleary, T.; Yang, J., "Pyrolysis Smoke Generated Under Low-Gravity Conditions," Aerosol Science and Technology. 2015, Vol. 49, Iss. 5, pp. 310–321: https://doi.org/10.1080/02786826.2015.1025125
2. Meyer, M.E.; Urban, D. L.; Mulholland, G. W.; Bryg, V.; Yuan, Z. G.; Ruff, G. A.; Cleary, T.; Yang, J., "Evaluation of Spacecraft Smoke Detector Performance in the Low-Gravity Environment," Fire Safety Journal. 2018, Vol. 98, pp. 74–81: https://doi.org/10.1016/j.firesaf.2018.04.004
3. Urban, D.; Dietrich, D.; Brooker, J.; Meyer, M.; Ruff, G., "Fire Detection Tradeoffs as a Function of Vehicle Parameters," International Conference on Environmental Systems (ICES 2016). 2016: https://ntrs.nasa.gov/citations/20170000248
4. "Decadal Survey on Biological and Physical Sciences Research in Space 2023-2032," National Academies: https://www.nationalacademies.org/our-work/decadal-survey-on-life-and-physical-sciences-research-in-space-2023-2032
5. "Civil Space Shortfalls," National Aeronautics and Space Administration: https://www.nasa.gov/spacetechpriorities

S16.03: Guidance, Navigation, and Control (SBIR)

Related Subtopic Pointers: H9.03, S13.01
Lead Center: GSFC
Participating Center(s): JPL, MSFC

Subtopic Introduction:

NASA seeks novel and innovative guidance, navigation, and control (GNC) technologies. These spacecraft GNC technologies will be critically enabling technologies for new science missions. Size, weight, power, cost, and performance (SWaP-CP) improvements over commercial-off-the-shelf (COTS) capabilities will enable new form factors and improved accuracies for established science measurements. Continual advancement within GNC technologies include improving system safety and longevity and reducing environmental impact of aerospace vehicle operations. These improvements will enable scientists to continue to enhance our knowledge of the universe, our planet, and the processes therein. This crosscutting subtopic supports mission capability requirements in all SMD mission areas including Earth science, astrophysics, planetary science, and heliophysics.

For this solicitation, this subtopic seeks technology advancement needs in the following scope:

- GNC Sensors and Actuators.

For this solicitation, the following separate scope was discontinued:

- Star-Tracker Technologies for CubeSats.

Scope Title: Guidance, Navigation, and Control Sensors and Actuators

Scope Description:

Component technology developments are sought for the range of flight sensors and actuators required to provide innovative, groundbreaking, and high-impact improvements (including SWaP-CP) and new capabilities in spacecraft GNC technologies. Technologies that apply to most spacecraft platform sizes (from CubeSats/SmallSats, to International Space Station [ISS] payloads, to flagship missions) will be considered. Technology advances should consider the relevant operating environment (including radiation) for one or more applicable science or exploration needs.

Advances are sought in the following areas:

- Spacecraft attitude determination and control systems:
    - Sensors and actuators that enable capabilities for large space telescopes/platforms, with improvements in SWaP requirements.
    - Relative navigation sensors enabling precision formation flying, astrometric alignment of a formation of vehicles.
    - Flight sensors that support onboard terrain-relative navigation for landing and sample-return capabilities.
    - Alternatives to cold gas attitude control systems (ACS) for sounding rocket platforms on short-duration flights.
    - Other GNC technologies for enabling the collection of distributed science measurements.
- Pointing control systems:
    - Mechanisms that enable milliarcsecond-class (<0.1 arcsec-level pointing knowledge and arcsecond-level control) pointing performance on any spaceborne pointing platforms, including micro-thrusters.
    - Active and passive vibration isolation systems or innovative actuation feedback.
- CubeSat-ready star trackers: A star tracker that itself spins or maintains a consistent frame of reference while its host CubeSat spins, or one that can process observations significantly faster than the current state of the art, is a critical enabling technology for observations that normally would require a spinning antenna.
    - Provide 0.05° or better pointing angle accuracy (in roll, pitch, and yaw) while the CubeSat is spinning up to 20 rpm in low Earth orbit (300 to 1,000 km altitude).
    - SWaP should be comparable to existing star trackers (~0.2 U, ~0.25 kg, ~1 W).

Proposals should show an understanding of the current state of the art (including COTS capabilities) and identify one or more relevant science or exploration needs from a NASA mission or mission concept under consideration by SMD. The GNC technology must identify the proposed innovation and present a feasible plan to fully develop the technology to a TRL level suitable for infusion (5 or 6).

Please note that the following areas are excluded from S16.03 this year:

- Robotic surface navigation technologies (offerers are suggested to consider S13.01 “Robotic Mobility, Manipulation, and Sampling”)
- Autonomous flight navigation technologies (offerers are suggested to consider H9.03 “Flight Dynamics and Navigation Technologies")

Expected TRL or TRL Range at completion of the Project: 4 to 6

Primary Technology Taxonomy:

- Level 1: TX 17 Guidance, Navigation, and Control (GN&C)
- Level 2: TX 17.X Other Guidance, Navigation, and Control

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware
- Software
- Analysis
- Research

Desired Deliverables Description:

- 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. Proof of concepts for risk reduction are desired.
- Phase II: Technology development efforts shall deliver a hardware component/prototype with supporting software at TRL 5 to 6. Delivery of final documentation, test reports, data, and analysis required. A plan to scale the technology for commercialization or NASA infusions should be included.

State of the Art and Critical Gaps:

Continual advances are sought in spacecraft GNC given the rapid pace of the space industry and commercial technology. Highly integrated, low-power, low-weight, and radiation-hard component sensor technologies and multifunctional GNC components are needed to enable new mission concepts. In particular, innovative spacecraft GNC technologies are needed in order to support future thrusts toward autonomous navigation including proximity operations, terrain-relative navigation, precision landing, hazard avoidance, and AutoNav demos. Novel solutions may also enable distributed science measurements and spacecraft constellation, formations, and swarms.

This scope addresses shortfalls identified in the Civil Space Shortfall Ranking including:

- [Ranked 41st] ID 1430: Small Spacecraft Propulsion
- [Ranked 37th] ID 1563: Aerocapture for Spacecraft Deceleration and Orbit Insertion
- [Ranked 80th] ID 1625: Intelligent Multi Agent Constellations for Cooperative Operations
- [Ranked 88th] ID 1575: Thermal and Vibrational Isolation for Ultra stable Science Payloads

Relevance / Science Traceability:

GNC is a mission capability requirement in all NASA SMD program areas of Earth science, astrophysics, planetary science, and heliophysics. Consequently, improvements supporting this GNC subtopic have broad impacts, enabling and enhancing SMD mission concepts across programs and supporting technology program offices.

References:

1. "NASA Science," National Aeronautics and Space Administration: https://science.nasa.gov
2. "NASA Artemis Campaign," National Aeronautics and Space Administration: https://www.nasa.gov/specials/artemis/
3. "Mars Sample Return Mission," National Aeronautics and Space Administration: https://mars.nasa.gov/msr
4. "Mars Exploration: Missions," National Aeronautics and Space Administration: https://mars.nasa.gov/programmissions/
5. "Jet Propulsion Laboratory Missions," National Aeronautics and Space Administration: https://www.jpl.nasa.gov/missions
6. "Origins, Worlds, and Life: Planetary Science and Astrobiology in the Next Decade," National Academics: https://nap.nationalacademies.org/catalog/27209/origins-worlds-and-life-planetary-science-and-astrobiology-in-the

7. "Pathways to Discovery in Astronomy and Astrophysics for the 2020s," National Academies: https://nap.nationalacademies.org/catalog/26141/pathways-to-discovery-in-astronomy-and-astrophysics-for-the-2020s
8. "Solar and Space Physics: A Science for a Technological Society," National Academies: http://nap.edu/13060
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10. McBryde, C. R.; Lightsey, E.G., "A Star Tracker Design for CubeSats," 2012 IEEE Aerospace Conference. 2012, pp. 1-14: https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=6187242
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13. "Civil Space Shortfalls," National Aeronautics and Space Administration: https://www.nasa.gov/spacetechpriorities

S16.04: Suborbital Platform Technologies (SBIR)

Related Subtopic Pointers: S13.03
Lead Center: GSFC
Participating Center(s): N/A

Subtopic Introduction:

The Suborbital Program managed by GSFC's Wallops Flight Facility (WFF) provides suborbital platforms like high-altitude balloons, sounding rockets, and aircraft (crewed and uncrewed) for the scientific community to advance research in astrophysics, heliophysics, Earth science, and planetary science. In addition, these platforms provide access for TRL advancement for programs within NASA STMD, SMD, and HEOMD, as well as programs supported by other organizations like the Department of Defense.

The Suborbital Program consistently returns fast turnaround, cutting edge science; provides important technology development for future programs; and trains the next generation of researchers, technologists, and program managers. The suborbital program is critical to maintaining the health of university laboratories capable of carrying out space missions. The suborbital program fills a critical niche by delivering science that is impossible to do from the ground, and it does it much more cost effectively than orbital missions. The suborbital program remains a key part of NASA's portfolio, addressing a wide variety of high-profile scientific problems, developing and testing technology important for future missions, and training the next generation of instrumentalists and project leaders.

Suborbital platforms are a key mission set for advancing technology from early-stage development as well as maturation and demonstration of component technologies. These small- and medium-sized projects, missions, and programs are essential for NASA. Specifically, Astro2020 recommends that NASA should increase funding levels for supporting technology components (i.e., suborbital platforms) of the Astrophysics Research and Analysis Program (APRA). Additionally, it emphasizes that the sounding rocket program "provides unique, irreplaceable opportunities for accessing space. It is important to maintain this capability."

The goals of this subtopic are:

- To enhance suborbital platforms which will enable new or more missions to be accomplished in previously impossible geographic locations, altitude regimes, or for extended durations. Generally, light weighting to reduce weight/mass, miniaturization to reduce volume for suborbital platform systems/subsystems and increasing data rates for transmitting and receiving science and other telemetry data associated with the suborbital platform and payload.
- To enhance suborbital flight test capabilities which enable rapid technology and instrument development for technology readiness level advancement, science, and Artemis missions. Suborbital platforms provide critical, low-cost access to space for flight testing before orbital, lunar, or planetary missions are implemented.

For this solicitation, this subtopic seeks technology advancement needs in the following three scopes (not in any priority order):

1. Free-Space Optical Communications for a Stratospheric Balloon Platform (updated).
2. Improved Thermal Mitigation for Entry, Descent and Landing (EDL) (new).
3. Hole-Detection Technology for Stratospheric Scientific Balloons (new).

For this solicitation, the following scope was rotated out but may return in future years:

- High-Altitude Platform Systems (HAPS) Capability Demonstration.

Scope Title: Free-Space Optical Communications for a Stratospheric Balloon Platform

Scope Description:

Stratospheric platforms, like scientific balloons, are capable of gathering between 10 and 1,000 GB/day, but current satellite communications links used during long duration flights are limited to short bursts at 1 Mbps (most often limited to 300 kbps because of older satellite technology). Further, coverage dropouts over the Pacific Ocean persist, causing periods of low transmission rates. Recent research and development in optical communications systems show promise for improving the telemetry capabilities for balloon missions.

The specific requirements for successful implementation from a balloon platform in the 90,000 to 150,000 ft altitude range are specific to stratospheric balloon flight and exclude aircraft-borne and spacecraft-borne instruments. Although modifications to those instruments may provide an acceptable solution, such a solution is not optimized for balloon mass, operational cost, and power limitations, nor does it consider the unique pointing challenges or atmosphere.

The typical balloon paths may make ground receiving challenging. Therefore, this solicitation is focused on solutions using existing satellite networks, as well as those in the process of deployment. Size, Weight, Power, Cost (SWaP-C) are the typical trades for all flight solutions. Of these trades, cost is of greatest importance to stratospheric balloon platforms.

Expected TRL or TRL Range at completion of the Project: 3 to 7

Primary Technology Taxonomy:

- Level 1: TX 05 Communications, Navigation, and Orbital Debris Tracking and Characterization Systems
- Level 2: TX 05.1 Optical Communications

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

For this scope, the primary driver for these units is the lowest cost for small volume acquisition.

- Phase I: Research must prove that a bench unit developed in Phase II will meet all flight requirements.
    - Design and analysis of a low-cost, low-SWaP optical terminal.
    - Design must meet structural and environmental requirements for flight with the NASA Balloon Program Office.
    - Documentation of trades between functionality, power, and cost.
    - Plan for utilization of existing satellite networks or those in the process of deployment.
        - Identification of all required hardware with a full bill of materials.

- Phase II:
    - A prototype system tested in a laboratory setting.
    - A full concept of operations within the context of a sample balloon mission (to be selected from past NASA missions).
    - The Balloon Program Office would support flight testing of the prototype for TRL advancement, but thermal and vacuum qualification at a subsystem level would need to meet the minimum requirements to move towards a potential Phase III award.

State of the Art and Critical Gaps:

The development of free-space optical communications performed to date by government, commercial, and university organizations has been focused on ground, aircraft, or space-based terminals. They utilize either the Consultative Committee for Space Data Systems (CCSDS) or Space Development Agency (SDA) communications standards and are rarely compatible. A low-cost solution would likely rely on SDA protocols, but commercial terminals are not designed for flight at 100,000 ft or for low cost, low power use cases. Balloon-to-ground communication would require further tradeoff between functionality, power consumption, and cost, and no solution exists that is within the requirements of a stratospheric system.

This scope addresses shortfalls identified in the Civil Space Shortfall Ranking including:

- [Ranked 55th] ID 1586: Enhanced Access to Orbital and Suborbital Space for Flight Demonstration and Test.
- [Ranked 119th] ID 1434: Communication Technology and Capabilities for Small Spacecraft.

Relevance / Science Traceability:

The NASA Balloon Program Office launches 12 to 20 large missions per year worldwide. These missions perform groundbreaking science and require massive telemetry links to retrieve data. Recovery of the payload is not always guaranteed, and current missions are generating from 10 to 1,000 GB/day. The Balloon Program Office would like to provide this platform enhancement to encourage development of higher resolution instruments.

References:

1. "Space Communications and Navigation (SCaN)," National Aeronautics and Space Administration: https://www.nasa.gov/directorates/space-operations/space-communications-and-navigation-scan-program/
2. "Scientific Balloons," National Aeronautics and Space Administration: https://www.nasa.gov/scientificballoons
3. "Civil Space Shortfalls," National Aeronautics and Space Administration: https://www.nasa.gov/spacetechpriorities/

Scope Title: Improved Thermal Mitigation for Entry, Descent and Landing (EDL)

Scope Description:

The NASA Sounding Rockets Program provides low cost, suborbital access to space in support of space and Earth sciences research. NASA Sounding Rockets Program Office (SRPO) utilizes a variety of vehicle systems comprised of surplus and commercially available rocket motors, capable of lofting scientific payloads of 250 lbs up to 1,300 lbs, to altitudes from 100 km to 1,500 km. SRPO launches sounding rocket vehicles worldwide, from both land-based and water-based ranges, based on the science needs to study phenomenon in specific locations. Of particular interest are thermal mitigation systems for re-entry of payloads from high-altitude (400 to 800 km) sounding rocket vehicles.

Specific elements may include, but are not limited to:

- Materials science, research, and development (e.g., alternatives to aluminum).
- Structural design modifications (e.g., lattice structures, generative design, etc.).
- Heat shields, insulation, or other thermal mitigations.

The sounding rocket science community consistently requests more science observation time in space, reaching altitudes of 400 to 800 km. Recovery from these altitudes benefits the Sounding Rocket Program. Science Principal Investigators (PIs) wish to recover their instruments and there is an advantage for NASA to recover payload systems for re-flight. To recover a high-altitude payload, it must survive re-entry, and thus, the SRPO desires solutions to mitigate, in a mass-efficient manner, the thermal environment the payload endures as it re-enters the Earth's atmosphere.

The SRPO, located at NASA GSFC's WFF, provides suborbital launch vehicles, payload development, and field operations support to NASA and other government agencies. SRPO works closely with the Sounding Rocket User Community to provide launch opportunities facilitating a broad spectrum of science applications. The approximately 20 suborbital missions flown annually by the program provide researchers with unparalleled opportunities to build, test, and fly new instrument and sensor design concepts while simultaneously conducting worldclass scientific research. Operations are conducted from fixed launch sites such as Wallops Test Range (Virginia), Poker Flat Research Range (Alaska), and White Sands Missile Range (New Mexico), as well as Andoya Rocket Range (Norway) and Esrange (Sweden). Launch operations are also conducted from mobile sites set up by the Wallops Test Range. Mobile "campaigns" have been conducted from Australia, Puerto Rico, Brazil, and the Kwajalein Atoll. The mobile capability offered by the Wallops Test Range allows scientists to conduct their science "where it occurs". Coupled with a hands-on approach to instrument design, integration and flight, the short mission lifecycle helps ensure that the next generation of space scientists receive the training and experience necessary to move on to NASA's larger, more complex space science missions. The cost structure and risk posture under which the program is managed stimulates innovation and technology maturation and enables rapid response to scientific events.

With the capability to fly higher than many low Earth orbiting satellites and the ability to launch on demand, sounding rockets offer, in many instances, the only means to study specific scientific phenomena of interest to many researchers. Unlike instruments on board most orbital spacecraft or in ground-based observatories, sounding rockets can place instruments directly into regions where and when the science is occurring to enable direct, in situ measurements. The mobile nature of the program enables researchers to conduct missions from strategic vantage points worldwide. Telescopes and spectrometers to study solar and astrophysics are flown on sounding rockets to collect unique science data and to test prototype instruments for future satellite missions. An important aspect of most satellite missions is calibration of the space-based sensors. Sounding rockets offer calibration and validation flights for many space missions, particularly solar observatories, such as the Solar Dynamics Observatory (SDO).

A thermal mitigation system for re-entry of a high-altitude sounding rocket payload shall:

- Align with the low-cost structure and higher risk posture of the SRPO, as defined in NASA Procedural Requirements for Research and Technology Program and Project Management. Assume that a substantial increase of funding to the SRPO budget to execute the proposed innovation is not a viable solution.
- Fit within the payload section, which is housed in an aluminum skin, typically 0.125 in. thick and diameters of 17.26 in. or 22.00 in.
- Be limited to less than 60% of the mass of a typical 0.125 in. aluminum skin.
- Not substantially alter the concept of operations for sounding rockets (i.e. spin-stabilized, solid rocket motors, parachute recovery systems, etc.).
- Establish a process to define requirements, conduct research, perform engineering studies, conduct qualification efforts, and implement the proposed innovation.
- Describe the type(s) of hardware, software, or operational aspect(s) of the innovation in the context of how the innovation will fit into existing sounding rocket infrastructure and help enhance the SRPO ability to meet requirements for high-altitude payload re-entry.
- If the problem is solved, success looks like a thermal mitigation system for payloads that is low cost, less than 60% of the mass of the typical sounding rocket aluminum skin, and enables recovery of payloads that have flown to altitudes of 400 to 800 km. The resulting solution should be aligned with the low-cost structure and higher risk posture of the SRPO, as defined in NASA Procedural Requirements for Research and Technology Program and Project Management. Assume that a substantial increase of funding to the SRPO budget to execute or procure the proposed innovation is not a viable solution.
- Typical environmental testing for most sounding rockets is anticipated for the proposed technology solution. Testing includes but is not limited to static and dynamic balance, vibration testing, spin deployment testing, mass properties measurements, bend testing, and thermal vacuum testing.

Expected TRL or TRL Range at completion of the Project: 2 to 7

Primary Technology Taxonomy:

- Level 1: TX 14 Thermal Management Systems
- Level 2: TX 14.X Other Thermal Management Systems

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

For this scope, the primary driver for this technology is the lowest cost for small volume acquisition.

- Phase I: Research must prove that a prototype developed in Phase II will meet all flight requirements.
    - Design and engineering analysis of a thermal mitigation system. Design must meet structural and environmental requirements for flight with the NASA Sounding Rocket Program Office. Initial requirements listed below and in the "Scope Description" section.
    - Documentation of trades between functionality, power (if applicable), and cost of appropriate technologies.
    - Identification of all required hardware with a full bill of materials.

- Phase II:
    - A prototype system tested in a laboratory setting (testing can occur in facilities at WFF).
    - Thermal and vacuum qualification at a subsystem level at a minimum.

Collaborating with the SRPO at WFF is a possibility, and interested organizations are encouraged to discuss options and details.

State of the Art and Critical Gaps:

Currently, many technologies exist for thermal management and mitigations of spacecraft. There is a wide range of solutions for managing thermal conditions on a spacecraft. These technologies are typically used on orbiting spacecraft and may not be suitable for the highly dynamic and relatively short flight environment for a sounding rocket. In general, technology that enables thermal mitigation for re-entry of high-altitude sounding rocket payloads is a critical gap that needs significant development for enabling longer science observations time while also enabling recovery of the payload.

This scope addresses shortfalls identified in the Civil Space Shortfall Ranking including:
- [Ranked 114th] ID 1624: Advanced thermal management technologies for diverse applications.
- [Ranked 55th] ID 1586: Enhanced Access to Orbital and Suborbital Space for Flight Demonstration and Test.

Relevance / Science Traceability:

The NASA Sounding Rocket Program Office launches 15 to 20 missions per year worldwide. For several decades, the sounding rocket science community has been requesting enhanced capabilities and extended science observation times at higher altitudes. Principal Investigators characterize the goal for extended time as at least 100 seconds of scientific observation occurring at over 100 km in altitude. The ability to launch and recover sounding rocket payloads from higher altitudes will provide the program additional mission capabilities to enable Astrophysics and Heliophysics investigations that could not previously be done.

Additionally, it will provide the sounding rocket program with a key capability to provide responsive access to suborbital space. Advancement and additional access of NASA and commercial suborbital and LEO capabilities can further expand NASA use of rapid and lower cost commercial spaceflight for technology development and demonstration. Specifically, higher altitude suborbital flights, and/or the ability to host payloads on recoverable orbital rocket stages, could provide longer duration microgravity as well as access to speeds and heating conditions more relevant to planetary entry/re-entry testing.

References:

1. "Sounding Rockets Program Office," National Aeronautics and Space Administration: https://sites.wff.nasa.gov/code810/
2. "Report of the Sounding Rocket Working Group (SRWG) Sub-committee on High Altitude Rockets to Increase Astrophysics and Solar Observing Time," NASA SRWG Sub-committee on High Altitude Rockets to Increase Astrophysics and Solar Observing Time: https://rscience.gsfc.nasa.gv/keydocs/HARIASOT_SRWG_Sub-committee_Report.pdf
3. "Sounding Rockets Program Technology Roadmap," National Aeronautics and Space Administration: https://sam.gov/api/prod/opps/v3/opportunities/resources/files/e15c95b2ad85493e9ff349176e2c2f69/download?&status=archived&token=
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Scope Title: Hole-Detection Technology for Stratospheric Scientific Balloons

Scope Description:

Stratospheric scientific balloons exist on the order of tens of millions of cubic feet in volume of polyethylene film with load tape and tendons. During the manufacturing process, there are processes to identify and repair holes/tears. However, holes/tears that develop during the launch and flight can only be identified by poorer-than-expected performance of the balloon, which can be due to many factors, only one of which is a hole. Additionally, because of the uncertainty of the location and size of the hole and its resulting impact on balloon flightworthiness, once a leak is detected, a balloon flight is terminated to limit its risk to the public. Due to the destruction of the balloon during termination operations, holes in balloons that developed during launch and flight are impossible to identify and characterize. As a result, holes, although an occasional and repeated cause of mission failure, remain a large unknown in balloon flights.

Scientific balloons range in volume from about 1 to 60 million cubic feet (MCF) (0.03 to 1.7 million cubic meters, MCM) and don't fill out to full volume until at altitudes from 90,000 to 110,000 ft (27.4 to 33.4 km). At these altitudes, pressure is 7 to 18 millibars and temperatures occur on the order of -10 to -30 °F (-23 to -34 °C). However, the minimum temperatures ascending through the atmosphere occurs at the tropopause, as low as -116 °F (-82 °C). The balloon is made of a clear, polyethylene film with load tape and/or tendons.

Successful implementation of an in-flight hole detection system would be utilized on both zero-pressure balloons, which have vents that remain open to the atmosphere and superpressure balloons, which maintain a slight positive internal pressure (on the order of 180 Pa or 0.0261 psi). This solicitation seeks for innovative solutions that can identify the existence of a hole, and solutions that can additionally determine the size and/or location are high of interest.

Expected TRL or TRL Range at completion of the Project: 3 to 7

Primary Technology Taxonomy:

- Level 1: TX 08 Sensors and Instruments
- Level 2: TX 08.1 Remote Sensing Instruments/Sensors

Desired Deliverables of Phase I and Phase II:

- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Low cost for small volume acquisition is critical.

- Phase I: Research must prove that a bench unit developed in Phase II will meet requirements for flight.
    - Design and analysis of hole-detection system.
    - Documentation of trades between functionality, power, and cost of appropriate technologies.
    - Identification of all required hardware with a full bill of materials.

- Phase II:
    - A prototype system tested in a laboratory setting (testing can occur with scaled balloon at WFF).
    - Thermal and vacuum qualification at a subsystem level at a minimum.

State of the Art and Critical Gaps:

Currently, technology exists that can quickly identify defects in blown film (balloon film manufacturing method) using machine vision. This optical technology, to date, has only been used on balloon film in the pre-manufacturing stage. Because the balloons are sealed by hand in the factory, in-person inspections identify defects/errors in manufacturing. In the field, technicians inspect the balloon as it is laid out, inflated, and deployed. However, full inflation does not occur until at altitude. Cameras installed on the flight train or the gondola do not provide a wide enough point of view to observe holes in the balloon at altitude. In general, technology that enables in situ measurements at altitude for the balloon's characteristics is a critical gap that needs significant development within the program for assessing balloon health and flight performance and behavior.

This scope addresses shortfalls identified in the Civil Space Shortfall Ranking including:

- [Ranked 55th] ID 1586: Enhanced Access to Orbital and Suborbital Space for Flight Demonstration and Test.

Relevance / Science Traceability:

The NASA Balloon Program Office launches 12 to 20 large missions per year worldwide. In the past two years, out of thirteen launched missions, three of them either had leaks or were presumed to have leaks and were subsequently terminated accordingly. The ability to accurately detect leaks and appropriately assess balloon health will provide the balloon program additional measures to protect the safety of the public. Understanding where and when balloon holes develop and propagate during flight can also enable improved balloon design and launch operations processes.

This type of remote sensing technology also has wide-ranging application in space technology applications for planetary exploration.

References:

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2. "Scientific Balloons," National Aeronautics and Space Administration: www.csbf.nasa.gov/balloons.html

3. Ren, Z.; Fang, F.; Yan, N.; Wu, Y., "State of the art in defect detection based on machine vision," International Journal of Precision Engineering and Manufacturing-Green Technology. 2022, Vol. 9, Iss. 2, pp. 661-691: https://link.springer.com/article/10.1007/s40684-021-00343-6
4. Taherimakhsousi, N.; MacLeod, B. P.; Parlane, F. G.; Morrissey, T. D.; Booker, E. P.; Dettelbach, K. E.; Berlinguette, C. P., "Quantifying defects in thin films using machine vision," npj Computational Materials. 2020, Vol. 6, Iss. 1, ppl. 111: https://www.nature.com/articles/s41524-020-00380-w.pdf
5. "Civil Space Shortfalls," National Aeronautics and Space Administration: https://www.nasa.gov/spacetechpriorities/

S16.05: Thermal Control Systems (SBIR)

Related Subtopic Pointers: S13.01, S13.06, Z-LIVE.02, Z-GO.02, Z-LIVE.04, T12.10
Lead Center: GSFC
Participating Center(s): JSC, LaRC, MSFC

Subtopic Introduction:

NASA is searching for innovative thermal control technologies that enable lunar science and support solar system exploration. Upon successful development, these technologies will empower NASA's robots and astronauts to conduct unprecedented lunar exploration, enabling them to accomplish a greater scope of scientific research than ever before.

For this solicitation, this subtopic seeks technology advancement needs in the following three scopes (not in any priority order):

1. Coatings for Extreme Environments for Thermal Radiators and Complex Surfaces.
2. Thermal Technologies for Lunar Science.
3. Artificial Intelligence for Spacecraft Thermal Control Systems.

Scope Title: Coatings for Extreme Environments for Thermal Radiators and Complex Surfaces

Scope Description:

Thermal coatings are an integral part of a space mission and are essential to the survivability of the spacecraft and instrument. Radiator surface coatings with desired emissivity and absorptivity provide a passive means for instrument temperature control. A growing number of uses for these coatings include radiator surfaces with complex geometries and topographies. Existing stable, dissipative radiator coating systems are challenging to apply onto these complex geometry systems, and new formulations are desired to provide improved optical performance with added durability and manufacturability with less sensitivity to thickness control requirements. Radiator coatings are desired to maintain optical stability in extreme temperature exposures as well as long-duration, intense ultraviolet (UV) and solar wind exposures for near-solar missions. Additionally, with NASA's new initiative to return to the Moon, a new coating technology that will keep surfaces clean with minimized solar absorptance or infrared (IR) emittance impacts is needed. These dust-mitigating coating systems and cleaning techniques may employ active tilt/maneuvering systems such as rotating surfaces to aid in dust removal. It is desired that the processing time for coated hardware, because of strict humidity and temperature-controlled application and cure conditions, be reduced. Examples of technologies include, but are not limited to, the following:

- Highly stable, dissipative white coatings in intense, long-duration UV and solar wind environments.
- Operator-sprayed coatings that have high structural/adhesive tolerance to coating thickness variation while in widely varying thermal cycling vacuum environments for application to complex hardware where thickness control is challenging or impractical.
- Stable, dissipative coatings with accelerated, elevated cure schedules and those independent of humidity control for use with aluminum or carbon composite substrates.
- Coating systems with dust-mitigating and cleaning properties for lunar and Martian environments.

Proposers must identify and characterize which space environment their technology is relevant to and which SMD missions they envision benefiting from the innovation.

Please note that the following areas are excluded from S16.05 this year:

- Coatings for high temperature radiators (offerors are suggested to consider Z-GO.02 “Space Nuclear Propulsion").
- Coatings for human spacecraft, habitats, or vehicles (offerors are suggested to consider Z-LIVE.02 "Spacecraft Thermal Management").
- Coatings designed primarily for dust mitigation and not thermal control (offerors are suggested to consider Z-LIVE.04 “Components for Extreme Environments").

Expected TRL or TRL Range at completion of the Project: 2 to 5

Primary Technology Taxonomy:

- Level 1: TX 14 Thermal Management Systems
- Level 2: TX 14.3 Thermal Protection Components and Systems

Desired Deliverables of Phase I and Phase II:

- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

- Phase I:
  - Successful development of coating formulations that lead to the desired dust mitigation.
  - Delivery of test coupon demonstrating proof of concept and feasibility.
  - Samples of the hardware for further testing at NASA facilities.
- Phase II:
  - Results of performance characterization tests.
  - Results of stability test of the coating formulations and their mechanical durability test under the influence of simulated space and lunar environmental conditions.
  - Delivery of test coupon(s).
  - Phase II deliverables should also include/delineate any further work that would be required to bring the technologies to full operational and/or commercial use.

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 fully coat complex, irregular surfaces only with significant effort and expertise, but these coatings are porous and can become imbedded with dust and particulates. Additionally, these coatings lack the stability of other historic non-dissipative systems and are sensitive to structural stability issues with vacuum thermal cycling when their thickness is outside a narrow range.

Currently, no single thermal control material appears to provide stability and durability and meet optical property requirements for sustained durations in extreme environments on complex substrates.

This scope addresses shortfalls identified in the Civil Space Shortfall Ranking including:

- [Ranked 1st] ID 1618: Survive and operate through the lunar night
- [Ranked 114th] ID 1624: Advanced thermal management technologies for diverse applications
- [Ranked 47th] ID 844: Passive Dust Mitigation Technologies for Diverse Applications
- [Ranked 156th] ID 1437: Dynamic and Capable Thermal Control for Small Spacecraft

Relevance / Science Traceability:

Many SMD missions will greatly benefit from an improved, durable thermal coating system for extreme environments. Every mission that does not have a flat radiator surface and cannot afford the 4-week processing time and required time to develop techniques for application to complex substrates will benefit. These projects will include large flagship-scale projects to SmallSat and CubeSat systems and any lunar-related project and projects involved with robotic science rovers and landers.

References:

1. O'Connor, K. M.; Abraham, N. S., "Lotus Dust Mitigation Coating and Molecular Adsorber Coating," 2015, No. GSFC-E-DAA-TN26955: https://ntrs.nasa.gov/search.jsp?R=20150020486
2. "Civil Space Shortfalls," National Aeronautics and Space Administration: https://www.nasa.gov/spacetechpriorities

Scope Title: Thermal Technologies for Lunar Science

Scope Description:

The lunar environment poses significant challenges to small (less than a half meter in each direction) and low-power (~100 W or less) payloads, rovers, and landers required for lunar science. The lunar day/night cycle is approximately 1 Earth month. During that time, surface temperatures on the lunar surface can reach 400 K at local solar noon or drop to below 100 K during the lunar night—and even colder in permanently shadowed regions. These hot and cold conditions can last several Earth days, because of 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, but the gravity field may provide advantages that could be utilized. This call seeks to solicit innovative proposals to enable lunar science in the difficult lunar environment. The Farside Seismic Suite (FSS) represents a typical-size instrument for lunar science [Refs. 3 and 4].

Example technologies include, but are not limited to, the following:

- Advanced two-phase passive and active thermal control systems (TCSs) as well as single-phase active loops that may be turned off. Novel heat transfer fluids for these TCSs that are more efficient, nontoxic and freeze resistant.
- Zero- or low-power non-consumable/regenerative heat generation sources.
- High-thermal-capacitance thermal storage. New phase change materials with the latent heat greater than 500 kJ/kg, metal-to-mass ratio of 1:1, densities less than 700 kg/m^3, and melting temperatures from 0 to +330 K. Materials should be easily handled, nontoxic, chemically compatible, not corrosive or explosive, and reliably reproducible. Furthermore, new types of thermal energy storage are also desired.
- Advanced thermal insulation for application in Moon, Mars, and Venus's environments.

- Variable heat rejection (>10:1 turndown ratio) and passive switching with high turndown ratios (e.g., >400:1). Furthermore, small form factors are also desired.
- High-performance thermal interface materials (TIMs) for thermal coupling to vibrating components.
- Advanced thermostats and alternative passive technologies operating below 210 K.

Technologies should show substantial increase over the state of the art. Technology proposals should address power usage in day and night/shadow, mass, heat transport when turned on, heat leak when turned off, temperature drops through the system, heat storage/release amount, sensitivity to lunar topography and orientation, and so forth.

Expected TRL or TRL Range at completion of the Project: 2 to 5

Primary Technology Taxonomy:

- Level 1: TX 14 Thermal Management Systems
- Level 2: TX 14.X Other Thermal Management Systems

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

Desired deliverables include:

- Phase I: Conceptual design, physics-based analysis or model, and proof-of-concept hardware.
- Phase II: Proof-of-concept hardware tested against simulated loads in proposed environments. Phase II deliverables should also include/delineate any further work that would be required to bring the technologies to full operational and/or commercial use, including plans to develop payloads for flight demonstration of relevant technologies 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. ALSEPs (Apollo Lunar Surface Experiments Packages) 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. Because interest in lunar science and the development of abilities to deliver payloads to the lunar surface is resurgent, the capability to operate through the entire lunar environment is critical. In the absence of perpetual power supplies like radioisotope thermoelectric generators (RTGs), thermal management approaches to accommodate the lunar extremes, extended day/night cycles, and shadowed regions are seen as enabling.

This scope addresses shortfalls identified in the Civil Space Shortfall Ranking including:

- [Ranked 1st] ID 1618: Survive and operate through the lunar night
- [Ranked 114th] ID 1624: Advanced thermal management technologies for diverse applications

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. In addition, thermal technologies for lunar science are highly desired to support payloads that will utilize Commercial Lunar Payload Services (CLPS) contracts. The CLPS payload accommodations will vary depending on the service provider and mission characteristics. CLPS missions will typically carry multiple payloads for multiple customers. Smaller, simpler, and highly self-sufficient payloads are more easily accommodated and would be more likely to be considered for a NASA-sponsored flight opportunity. Flight opportunities are expected to continue well into the future, and it is also expected that larger and more complex payloads will be accommodated going forward.

References:

1. "NASA's Exploration Campaign: Back to the Moon and on to Mars," National Aeronautics and Space Administration: https://science.nasa.gov/earth/moon/nasas-exploration-campaign-back-to-the-moon-and-on-to-mars/
2. "NASA Prepares for Performing New Science on the Moon," Jet Propulsion Laboratory: https://www.jpl.nasa.gov/news/news.php?release=2007-068
3. "Farside Seismic Suite," National Aeronautics and Space Administration: https://www.jpl.nasa.gov/missions/the-farside-seismic-suite
4. Panning, M. P.; Kedar, S.; Bowles, N.; Bugby, D.; Calcutt, S.; Cutler, J.; et al., "Farside Seismic Suite (FSS): Surviving the lunar night and delivering the first seismic data from the farside of the Moon," 53rd Lunar and Planetary Science Conference. 2022, Vol. 2678, pp. 1576: https://www.hou.usra.edu/meetings/lpsc2022/pdf/1576.pdf
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6. "The Surveyor Program," Lunar and Planetary Institute: https://www.lpi.usra.edu/lunar/missions/surveyor/
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8. Jones, E. M. (ed.); Glover, K. (ed.), "Apollo Lunar Surface Journal,": https://www.hq.nasa.gov/alsj/alsj-LRVdocs.html
9. "Apollo Lunar Surface Experiments Package, Monthly Progress Review July 1972," 1972: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19720013192.pdf
10. Garrison, M. B.; Nguyen, D. H., "Thermal Considerations for Designing the Next Lunar Lander," AIP Conference Proceedings. 2007, Vol. 880, No. 1, pp. 35-42: https://aip.scitation.org/doi/10.1063/1.2437438
11. "Commercial Lunar Payload Services," National Aeronautics and Space Administration: https://www.nasa.gov/commercial-lunar-payload-services-overview
12. "Civil Space Shortfalls," National Aeronautics and Space Administration: https://www.nasa.gov/spacetechpriorities

Scope Title: Artificial Intelligence for Spacecraft Thermal Control Systems

Scope Description:

A traditional modeling process of spacecraft TCSs involves many critical steps that are time consuming. In addition, it has limited flexibility in accommodating changes to requirements and growing complexity of the TCSs. Current NASA programs such as Artemis, CLPS, and Mars Sample Return mission are facing new challenges that require a more effective way to address them. This call seeks to solicit innovative proposals to utilize artificial intelligence (AI), generative design, and machine learning techniques for design optimizations of spacecraft TCSs.

Examples of specific approaches to be developed for spacecraft TCSs include, but are not limited to, the following:

- Shape recognition and image segmentation with convolutional neural networks (CNNs) for a more efficient generation of thermal model geometries.
- Development of algorithms for employing support vector machines (SVMs) to improve prediction of multilayer insulation (MLI) properties.
- Physics-informed neural networks (PINNs) for high-fidelity modeling of TCSs.
- Utilizing autoencoders or other unsupervised learning approaches to generate detailed thermal models from condensed representations.
- Development of genetic algorithms (GAs) to assist design evolution and maturity level.
- Advancement of language models for transferring knowledge and automating report generation.
- Generative design (GD) for TCS mass and performance optimization.
- AI-defined surrogate models for TCS design optimization and accelerating complex simulations.

Expected TRL or TRL Range at completion of the Project: 1 to 4

Primary Technology Taxonomy:

- Level 1: TX 14 Thermal Management Systems
- Level 2: TX 14.2 Thermal Control Components and Systems

Desired Deliverables of Phase I and Phase II:

- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Desired deliverables for this scope include hardware, software, and designs for component robotic systems.

- Phase I: Proof of concept demonstration of the usability of the software prototype to an envisioned mission or concept.
- Phase II: Functioning prototype (or better) that demonstrates the potential to meet the performance goals of the software. Any delivered math models should include supporting data that validate the assumptions used within the model. Phase II deliverables should also include/delineate any further work that would be required to bring the technologies to full operational and/or commercial use.

State of the Art and Critical Gaps:

Thermal design and modeling have made significant advancements in recent years, reaching a state-of-the-art level in many aspects. Advanced computational tools, such as finite element analysis (FEA) and computational fluid dynamics (CFD), have allowed for more accurate prediction and optimization of thermal behavior in spacecraft TCSs. The integration of machine learning techniques has shown promise in automating thermal design processes and enhancing model accuracy. However, despite these advancements there are critical gaps that still need to be addressed. One major challenge is the lack of comprehensive thermal models that capture complex interactions between different components and thermal phenomena. Additionally, incorporating real-world variability and uncertainty into thermal models remains a challenge. Moreover, the limited availability of high-quality thermal data for model validation further hampers progress. Bridging these critical gaps will require further research and innovation to develop more robust and reliable thermal design and modeling techniques that can cater to NASA needs and applications.

This scope addresses shortfalls identified in the Civil Space Shortfall Ranking including:

- [Ranked 1st] ID 1618: Survive and operate through the lunar night
- [Ranked 98th] ID 1623: Advanced thermal modeling capabilities
- [Ranked 114th] ID 1624: Advanced thermal management technologies for diverse applications

Relevance / Science Traceability:

It is anticipated that AI will play a crucial role in advancing future space exploration both at NASA and the commercial industry. Current programs at NASA are employing and investigating AI into the design of TCS for space missions of varying destination and size including: lunar science, Mars exploration, SmallSats/CubeSats, Rovers and surface mobility, and envisioned future science missions. A demonstration of the enabling benefit of incorporating AI into TCS would be of strong interest by NASA SMD and its supporting divisions.

References:

1. Pyne, T., "From Manual to Automated: Optimizing Spacecraft Thermal Engineering Processes with AI," European Space Thermal Engineering Workshop 2023. 2023: https://indico.esa.int/event/446/contributions/8728/
2. "NASA Turns to AI to Design Mission Hardware (2023)," National Aeronautics and Space Administration: https://www.nasa.gov/feature/goddard/2023/nasa-turns-to-ai-to-design-mission-hardware
3. "NASA Artemis Campaign," National Aeronautics and Space Administration: https://www.nasa.gov/specials/artemis/
4. "Mars Sample Return," National Aeronautics and Space Administration: https://science.nasa.gov/mission/mars-sample-return/
5. "Civil Space Shortfalls," National Aeronautics and Space Administration: https://www.nasa.gov/spacetechpriorities

S16.07: Cryogenic Systems for Sensors and Detectors (SBIR)

Related Subtopic Pointers: S12.06, S13.01
Lead Center: GSFC
Participating Center(s): JPL

Subtopic Introduction:

Cryogenic cooling systems are essential for the advancement of NASA's science goals. Cryogenic cooling is required for telescopes and other instruments that detect electromagnetic radiation in the sub-millimeter (mm) through the near-infrared (IR) wavelength band, as well as ultra-sensitive detectors for sub-mm through X-ray photons. Thus, cryogenics is an essential part of many advanced NASA missions in astrophysics, Earth science, and solar system exploration. Development of miniature, low-power cryogenic coolers will enhance the science capability of SmallSats and CubeSats for Earth and lunar observations, including swarm arrays of SmallSats for high-resolution remote sensing. They also enhance the capability of small in situ instruments on landers and rovers.

Additionally, quantum mechanical behavior becomes more readily apparent at low temperatures. Many of the devices currently under development for manipulation of quantum states, such as quantum memory, require cryogenic temperatures. Thus, cryogenics will likely be necessary for future on-orbit quantum communication and sensing systems.

This subtopic seeks ideas to improve cryogenic cooling systems that cover a broad range of temperatures. At the higher cryogenic temperature range (> 20 K), smaller, lower power devices are emphasized. Such coolers would enable new capabilities, such as near- and mid-IR instruments on SmallSats and CubeSats for Earth and lunar observations, as well as instruments for outer planet missions, where power budgets are tightly constrained. In the low-temperature range (10 K > T > 4 K), improved cryocoolers are needed primarily for astrophysics, for cooling of far- and mid-IR optics, and for cooling sensitive detectors. In the very low-temperature range (T < 4 K), advances in magnetic coolers enable the use of large arrays of ultra-sensitive superconducting detectors. While these detectors are primarily needed for astrophysics, quantum communication applications are also a growing area of interest.

The subtopic also seeks ideas for related cryogenic technologies, including:

- Advanced heat transport technologies to efficiently cool remotely located detectors or transport cryocooler waste heat to radiators. This includes reliable solid-state conductors with variable thermal conductance to enable one cryocooler to efficiently cool two or more targets at significantly different temperatures with varying heat inputs.
- Advanced thermal insulation systems.
- Low-power dissipation actuators.

For this solicitation, this subtopic seeks technology advancements in the following three scopes (not in any priority order):

1. High-Efficiency Cryocoolers
2. Actuators and Other Cryogenic Hardware
3. Sub-Kelvin Cooling Systems

Scope Title: High-Efficiency Cryocoolers

Scope Description:

Low-Temperature Coolers:

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 high efficiency and with cooling power at the coldest stage that is larger than currently available. The desired cooling power is application-specific but includes a range of approximately 50 to 200 mW at 4 K. Devices that produce extremely low vibration, particularly at frequencies below a few hundred hertz, are of special interest (e.g., reverse turbo-Brayton cryocoolers or electrochemical compressor-driven systems that are free of cold-trappable species in the fluid stream). System or component-level improvements that increase efficiency and reduce complexity and cost are desirable. Examples of target missions include several concepts currently under study for far-IR and X-ray probe-class observatories recommended in the 2020 Astrophysics Decadal Survey. The use of low-temperature detectors is also under consideration for the large near-IR/optical/UV (ultraviolet) flagship mission recommended by the Decadal Survey. In addition to the large coolers, there has recently been interest in small, low-power (~10 mW) 4 K coolers for quantum communication and sensing instruments.

Miniature Coolers:

NASA seeks miniature, high-efficiency cryocoolers for instruments on Earth and planetary missions. A range of cooling capabilities is sought. Two examples include 0.2 W at 30 K with heat rejection at 300 K and 0.3 W at 35 K with heat rejection at 150 K. For both examples, an input power of ≤ 20 W and a total mass of ≤ 400 g are desired. The ability to fit within the volume and power limitations of a SmallSat or a CubeSat platform would be highly advantageous. Low-cost cryocooler electronics are also sought that are sufficiently radiation hard for lunar or planetary missions.

To support advanced instruments using MgB_2 (magnesium diboride) superconducting nanowire single-photon detectors (SNSPDs), MgB_2 kinetic inductance bolometers, low-noise amplifiers, and cryogenic microwave and millimeter-wave mixers, NASA is seeking advanced multistage cryocooler technologies that will enable these sensors to operate in a SmallSat platform. The typical cooling power required for these instruments is approximately 100 mW at 20 K. The cryocooler input power must be compatible with available power in a SmallSat platform, which is typically several tens of watts.

It is desirable that the cooler can efficiently operate over a wide heat sink temperature range, from -50 to 70 ºC.

Expected TRL or TRL Range at completion of the Project: 2 to 5

Primary Technology Taxonomy:

- Level 1: TX 08 Sensors and Instruments
- Level 2: TX 08.1 Remote Sensing Instruments/Sensors

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware

Desired Deliverables Description:

- Phase I: Proof-of-concept demonstration.
- Phase II: Desired deliverables include coolers and components (e.g., electronics) that are ready for functional and environmental testing. Phase II deliverables should also include/delineate any further work that would be required to bring the technologies to full operational and/or commercial use.

State of the Art and Critical Gaps:

Low-Temperature Coolers:

Current spaceflight cryocoolers for this temperature range include hybrid systems that feature a lower Joule-Thomson stage pre-cooled by linear piston-driven Stirling coolers or a pulse tube cooler operating at approximately 20 K. One such state-of-the-art cryocooler, the Mid-Infrared Instrument (MIRI) cooler on the James Webb Space Telescope (JWST), provides about 55 mW of cooling at 6 K. Increased cooling power and efficiency and lower operating temperature will be needed for future large space observatories. Space telescope mirrors have approached the upper limit of possible size, but resolution can still be improved by increasing platform stability. Cryogenic instruments or detectors on instruments with tight pointing requirements (most notably the proposed Habitable Worlds Observatory flagship mission) will demand orders-of-magnitude reduction in exported vibration from the cooler to the detectors. At present, several LIDAR-based laser missions also have an immediate-term need for low-vibration cooling to meet tight optical alignment requirements. The need for these advanced cryocoolers (as well as improved coronagraph stability to picometer levels) was emphasized in the Tier 1 Technology Gaps in the latest (2024) Astrophysics Biennial Technology Report.

Miniature Coolers:

Present state-of-the-art cryocoolers can achieve Carnot efficiency above 13% and specific mass lower than 0.75 kg/W of cooling at 77 K for cooling capacity under 1 W at 77 K. Cryocoolers enable the use of highly sensitive detectors, but current coolers cannot operate within the tight power constraints of outer planetary missions. There are no lightweight cryocoolers (< 3 kg) that can provide cooling below 20 K. 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.

This scope addresses shortfalls identified in the Civil Space Shortfall Ranking including:

- [Ranked 77th] ID 1621: Cryogenic cooling for science instrumentation
- [Ranked 161st] ID 1605: Peer Back Farther in Time to the Early Universe
- [Ranked 17th] ID 879: In-space and On-surface, Long-duration Storage of Cryogenic Propellant
- [Ranked 21st] ID 792: In-space and On-surface Transfer of Cryogenic Fluids

Relevance / Science Traceability:

Advanced cryocoolers are listed as a Tier 2 Technology Gap in the 2024 Astrophysics Biennial Technology Report. Future missions that would benefit from this technology include the far-IR and X-ray probe-class observatories recommended by the 2020 Astrophysics Decadal Survey. In addition, low-temperature detectors are under consideration for an exoplanet characterization instrument on the large near-IR/optical/ultraviolet flagship mission recommended by the Decadal Survey.

NASA is moving toward the use of small, low-cost satellites to achieve many of its Earth science goals 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 by, for example, enabling the use of IR detectors.

In planetary science, progress on cryogenic coolers will enable the use of far- to mid-IR sensors with orders-of-magnitude improvement in sensitivity for outer planetary missions. These will allow thermal mapping of outer planets and their moons. In addition, miniature coolers enable more capable in situ instruments on landers and rovers.

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2. "Astrophysics Biennial Technology Report 2024," National Aeronautics and Space Administration: https://apd440.gsfc.nasa.gov/images/tech/2024_ABTR.pdf
3. "Civil Space Shortfalls," National Aeronautics and Space Administration: https://www.nasa.gov/spacetechpriorities

Scope Title: Actuators and Other Cryogenic Hardware

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 (niobium-titanium) conductors, as well as devices using higher temperature superconductors that can operate above 5 K, are of interest.
- Thermal insulation is critical to reduce cooling power requirements for optics and detectors in cryogenic instruments. At low temperatures (< 70 K), thermal conduction across layers in multi-layer insulation (MLI) dominates the heat leak [Ref. 1]. Advanced concepts that reduce layer-to-layer thermal conduction are appealing. The emissivity of conventional MLI with thin aluminum coatings increases at low cryogenic temperatures, and the MLI effectiveness decreases [Ref. 2]. Innovative discrete thermal radiation insulation approaches that are suitable for temperatures from 100 to 20 K are desired. Materials

that achieve lower emissivity than the state-of-the-art, especially for solar radiation and temperatures below 70 K, are also of interest. Superior solutions for radiation insulation of bi-pods that support cryogenics payloads are also desired. The single-layer insulation (SLI) used on these bipods has a very large thermal gradient along the axis of the struts and contributes significant conductive heat loads to the cold end.
- Advanced thermal coatings with low absorptivity, suitable for cryo-radiator applications [Ref. 4]. The optical properties of thermal coatings significantly affect the performance of cryogenic radiators and sun shields. Advanced thermal coatings with low absorptivity in the visible light to short-IR spectrum and high emissivity in the long-IR band would allow radiators to achieve lower cooling temperatures. Such coatings will also enable cryo-radiators to accommodate a partial view of the Sun or Earth, thus reducing CONOP (concept of operation) constraints.
- Reliable solid-state conductors with variable thermal conductance ranging from 0.05 to 0.005 W/K to allow one cryocooler to efficiently provide cooling for two or more targets operating at significantly different temperatures. Conductors should maintain cryocoolers at their calibration temperatures even when their heat load ratios deviate significantly from design values. This technology would eliminate the need to iteratively alter the conductors to tune their conductance ratio during the cryogenic instrument calibration stage, significantly reducing cryogenic IR spectrometer integration and testing cost.
- Novel cryogenic heat pipes. Heat pipes should demonstrate exceptional effective thermal conductivity, long-distance heat transport for applications such as cryogenic radiators and large-surface cooling.
- Vibration and/or thermal conduction isolating magnetic levitation structures. These may enable future missions with very tight pointing requirements (e.g., deep space optical communication lasers similar to the one used on NASA's Psyche mission or missions like the Habitable Worlds Observatory coronagraph). Dynamic control in 6 degrees of freedom may be challenging or even impossible. However, passive systems using combinations of permanent magnets and YBCO (yttrium barium copper oxide) superconducting coils may achieve zero thermal conduction, no-contact suspensions. This is accomplished by pinning fluxons when the system is cooled to cryogenic temperatures.
- Near-zero coefficient of thermal expansion (CTE) materials and composites, especially those that exhibit favorable thermal properties for cryogenic insulation and structural support.

Expected TRL or TRL Range at completion of the Project: 3 to 4

Primary Technology Taxonomy:

- Level 1: TX 08 Sensors and Instruments
- Level 2: TX 08.1 Remote Sensing Instruments/Sensors

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware

Desired Deliverables Description:

- Phase I: Proof-of-concept test on a breadboard-level device.
- Phase II: Working prototypes ready for testing in the relevant environments. Phase II deliverables should also include/delineate any further work that would be required to bring the technologies to full operational and commercial use.

State of the Art and Critical Gaps:

- Instruments often require motors and actuators, typically for optical elements such as filter wheels and Fabry-Perot interferometers. Current cryogenic actuators are typically motors with resistive (copper) windings. Heat generation is naturally dependent on the application, with one example being a stepper

motor used to scan a Fabry-Perot cavity. Its total dissipation (resistive + hysteric) is ~0.5 W at 4 K. A flight instrument would need heat generation at least 20 times smaller.
- State-of-the-art radiation insulation technologies include spacer-free blankets [Ref. 3] and radiation insulation systems with discrete structural spacers to reduce axial conduction heat leak.
- Current conductors with a thermal switch can only operate in the ON or OFF mode, not in a mode where its thermal conductance can be varied continuously with negligible (< 50 mW) active control power in the temperature range of 120 to 180 K.
- Large cryogenic optics for the mid-IR to far-IR are a listed Tier 3 Technology Gap in the 2024 Astrophysics Biennial Technology Report. Mass-efficient solutions to conduct heat over significant distance from the optics to a cryocooler with minimal temperature gradient are desirable.

This scope addresses shortfalls identified in the Civil Space Shortfall Ranking including:
- [Ranked 17th] ID 879: In-space and On-surface, Long-duration Storage of Cryogenic Propellant
- [Ranked 21st] ID 792: In-space and On-surface Transfer of Cryogenic Fluids

Relevance / Science Traceability:

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, heat dissipation in actuators can be a significant design problem.

All cryogenic systems pose thermal management challenges and, depending on the specific case, stand to benefit from improved thermal conduction and/or isolation technologies.

Vibration-isolating support structures will be necessary in tandem with improved low-vibration coolers to reduce net exported vibration from the cryocooler to instruments with tight pointing requirements.

References:

1. Ross, R. G. "Quantifying MLI Thermal Conduction in Cryogenic Applications from Experimental Data," IOP Conference Series: Materials Science and Engineering. 2015, Vol. 101, No. 1, pp. 012017: https://iopscience.iop.org/article/10.1088/1757-899X/101/1/012017/pdf
2. Tuttle, J.; DiPirro, M.; Canavan, E.; Hait, T., "Thermal Properties of Double-Aluminized Kapton at Low Temperatures," AIP conference Proceedings. 2008, Vol. 986, No. 1, pp. 34-41: https://pubs.aip.org/aip/acp/article-pdf/986/1/34/11581523/34_1_online.pdf
3. Bugby, D.; Rivera, J.; and Britton, S., "Planetary and Lunar Environment Thermal Toolbox Elements (PALETTE) Project Year Two Results," 51st International Conference on Environmental Systems. 2022, No. ICES-2022-423: https://ttu-ir.tdl.org/bitstreams/eefa80fe-fa6a-4334-a778-bb145f480ba7/download
4. Gibson, T. L.; Nurge, M. A.; Youngquist, R. C.; Biagi, C. J.; DeFilippo, M. J.; Wendell, J. C.; Naim, E. M., "Cryogenic Thermal Coatings Final Report," 2022, No. CFT-RPT-0015: https://ntrs.nasa.gov/api/citations/20220016987/downloads/CFT-RPT-0015%20Cryogenic%20Thermal%20Coating%20Final%20Report_Basic_Native_Final_WO%20Signature%20Page.pdf
5. "Astrophysics Biennial Technology Report 2024," National Aeronautics and Space Administration: https://apd440.gsfc.nasa.gov/images/tech/2024_ABTR.pdf
6. "Civil Space Shortfalls," National Aeronautics and Space Administration: https://www.nasa.gov/spacetechpriorities

Scope Title: Sub-Kelvin Cooling Systems

Scope Description:

Future NASA missions will require sub-Kelvin coolers for extremely low temperature detectors. Systems are sought that will provide continuous cooling with high cooling power (> 5 µW at 50 mK), and high heat rejection temperature (10 K), while maintaining high thermodynamic efficiency and low system mass.

Improvements in components for adiabatic demagnetization refrigerators are also sought. Specific components include:

- High cooling-power-density magnetocaloric materials. Examples of desired materials include $GdLiF_4$, $Yb_3Ga_5O_{12}$, GdF_3, and Gd elpasolite. High-quality single crystals are preferred because of their high conductivity at low temperature, but high-density polycrystals are acceptable in some forms. Total volume must be > 40 cm^3. For polycrystalline materials, this could be composed of smaller sections.
- Compact, lightweight, low-current superconducting magnets capable of producing a field of at least 4 tesla (T) 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 A/mm^2.
    - A field/current ratio of > 0.5 T/A, and preferably > 0.66 T/A.
    - Low hysteresis heating.
    - Bore diameters ranging between 22 mm and 40 mm, and lengths ranging between 50 mm and 100 mm, depending on the application.
- Shielding with the following requirements:
    - Lightweight active or passive magnetic shielding (for use with 4-T magnets) with low hysteresis and eddy current losses as well as low remanence. Shields should reduce the stray magnetic field to < 0.1 mT at 100 mm from the outer surface. In addition to simple cylinders, toroidal and other self-shielding geometries will be considered.
    - Lightweight, highly effective outer shields that reduce an imposed B field of 500 µT on the inside of the shield to < 1 µT at a distance of 10 cm outside the shield exterior. Outer shields must operate at 4 K to 10 K and must have penetrations for low-temperature, non-contacting heat straps.
- Heat switches with on/off conductance ratio > 30,000 and actuation time of < 10 sec. Switches are sought to cover the temperature range 20 K > T > 0.03 K, though the hot/cold temperature ratio for any one switch is typically < 5. They should have an on-state conductance of > (500 mW/K) x (T/4.5 K). Devices with no moving parts are preferred.
- Suspensions with the strength and stiffness of Kevlar®, but lower thermal conductance from 4 to 0.050 K.

Expected TRL or TRL Range at completion of the Project: 2 to 4

Primary Technology Taxonomy:

- Level 1: TX 08 Sensors and Instruments
- Level 2: TX 08.1 Remote Sensing Instruments/Sensors

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware

Desired Deliverables Description:

- Phase I: For components, a subscale prototype that proves critical parameters. For systems, a proof-of-concept test.
- Phase II: For components, functioning hardware that is directly usable in NASA systems. For systems, a prototype that demonstrates critical performance parameters. Phase II deliverables should also include/delineate any further work that would be required to bring the technologies to full operational and commercial use.

State of the Art and Critical Gaps:

High-performance sub-Kelvin coolers are listed as a Tier 1 Technology Gap in the 2024 Astrophysics Biennial Technology Report. 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 three-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-hr 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.

This scope addresses shortfalls identified in the Civil Space Shortfall Ranking including:

- [Ranked 77th] ID 1621: Cryogenic Cooling for Science Instrumentation
- [Ranked 161st] ID 1605: Peer Back Farther in Time to the Early Universe
- [Ranked 17th] ID 879: In-Space and On-Surface, Long-Duration Storage of Cryogenic Propellant

Relevance / Science Traceability:

Sub-Kelvin coolers are listed as a Technology Gap in the latest (2017) Cosmic Origins Program Annual Technology Report. Missions that would benefit from this technology include several concepts presently under development for the far-IR and X-ray probe-class missions recommended in the 2020 Astrophysics Decadal Survey, as well as future far-IR and X-ray flagship missions.

References:

1. Shirron, P. J.; Kimball, M. O.; James, B. L.; Muench, T.; DiPirro, M. J.; Bialas, T. G.; et al., "Thermodynamic Performance of the 3-Stage ADR for the Astro-H Soft-X-ray Spectrometer Instrument," Cryogenics. 2016, Vol. 74, pp. 24-30: www.sciencedirect.com/science/article/pii/S001122751500137X
    - Description of the state-of-the-art sub-Kelvin cooler in the Hitomi mission with useful references therein.
2. Cryogenics, Vol. 62, pp. 129-220: https://www.sciencedirect.com/journal/cryogenics/vol/62
    - Articles describing magnetic sub-Kelvin coolers and their components.
3. "Astrophysics Biennial Technology Report 2024," National Aeronautics and Space Administration: https://apd440.gsfc.nasa.gov/images/tech/2024_ABTR.pdf
4. "Cosmic Origins," National Aeronautics and Space Administration: https://cor.gsfc.nasa.gov/
5. "Program Annual Technology Report," Cosmic Origins Program Office: https://ntrs.nasa.gov/api/citations/20170009471/downloads/20170009471.pdf
6. "Civil Space Shortfalls," National Aeronautics and Space Administration: https://www.nasa.gov/spacetechpriorities

S16.08: Quantum Sensing: Atomic sensors, optical atomic clocks, and solid-state systems (SBIR)

Related Subtopic Pointers: S11.02, S12.06, S13.05, S14.02, T8.06
Lead Center: JPL
Participating Center(s): GSFC

Subtopic Introduction:

Space exploration relies on sensors for science measurements as well as spacecraft operation. As sensing precisions push their limits, quantum phenomena inevitably must be exploited. It is expected that sensors utilizing quantum properties will offer new and significantly improved capabilities. NASA is interested in advancing quantum sensing technologies and infusing them into space science missions. In particular, this call seeks the development and maturation towards space application and qualification of atomic systems that leverage their quantum properties (e.g., optical atomic clocks, atom interferometers, and solid-state sensors).

Recent developments of laser control and manipulation of atoms have led to new types of quantum sensors and clocks. Atomic particles, being intrinsically quantum mechanical, have demonstrated their unique advantages in metrology and sensing. Perhaps the most celebrated atomic metrology tool is the atomic clock. Atomic clocks in the optical frequency domain (i.e., optical primary frequency standards) have approached, and are expected to exceed, a frequency uncertainty beyond 1 part in $1x10^{18}$. These optical clocks can be used, in turn, as precision sensors with, for example, sensitivity to the fundamental physics constants and gravity, and have been explored for detection of dark matter and time variations in those fundamental constants.

Similarly, Doppler-sensitive quantum measurements of atomic particles led to exquisite inertial sensors, exemplified by atom interferometers. Because the center of mass motion is involved, atom interferometers use atomic particles as test masses and quantum matter-wave interferometry for motional measurements. Indeed, clocks and sensors are two sides of the same coin, sharing many common physical processes, technology approaches, and salient performance features. Therefore, this subtopic combines the two subject areas for leveraged and coordinated technology advancement. For many measurements the sensitivity scales as the square of the interaction time with an atom in free space. As this time can be dramatically longer (x100) in microgravity, these technologies are a natural fit for space exploration. Applications include inertial navigation, gravity, magnetic field, atmosphere, and mass-change sensing.

For this solicitation, this subtopic seeks technology advancements in the following three scopes (not in any priority order):

1. Optical Atomic Clocks.
2. Cold Atom Interferometry.
3. Atomic and Solid-State Quantum Sensors.

Scope Title: Optical Atomic Clocks

Scope Description:

The ability to precisely measure time is a critical enabling technology across NASA technology and space applications. In particular, navigating in cislunar space and in Global Positioning System (GPS)-denied environments terrestrially has increased the need for more precise timekeeping technologies. Clocks based on atomic transitions have been the worldwide time standard for several decades, and recent technological advances in the ability to control, trap, and measure atoms and ions have pushed the stability (i.e., how consistently an atomic clock measures a unit of time) of these clocks to extraordinary levels. Recently, the Deep Space Atomic Clock (DSAC) mission successfully flew a space qualified clock based on the microwave transition of a mercury ion, demonstrating a long-term stability of 10^{-15}. However, atomic clocks based on optical transitions intrinsically improve that sensitivity level by 3 orders of magnitude, as demonstrated in laboratory and terrestrial field environments. At a stability or precision level of 10^{-17} or better, space-based optical atomic clocks would enable one-way time transfer for deep-space missions and navigational precision within a foot over months without requiring a time update. Optical clocks with this level of precision would enable dark matter and dark energy searches and could be the basis for the next gravitational wave observatory.

In order to mature optical atomic clock technologies, NASA seeks to fill the following technical gaps (priorities are labeled with highest being the most critical to filling gaps in NASA mission needs, though proposals addressing any of the areas will be considered and reviewed based on merit):

- (Highest priority) Space-qualifiable, small-size, low-power clock lasers at, or subsystems that can lead to better than fractional frequency stability of 3×10^{-15} Hz/$\sqrt{\tau}$ (where τ is the averaging time) near 0.1 to 10 sec (wavelengths for Yb+, Yb, and Sr clock transitions are of special interest).
- (Higher priority) Subsystem and components for high-performance and high-accuracy optical clocks, mostly notably Sr and Yb lattice clocks as well as Sr+ and Yb+ singly trapped ion clocks. They comprise atomic physics packages, which are necessarily laser systems and include clock lasers, optical frequency combs, as well as advanced electronics and controllers based on microprocessors or field-programmable gate arrays (FPGAs). They should have a path to a flight system.
- (Higher priority) Rugged, fiber-based, self-referenced optical frequency combs that span greater than an octave.
- (Higher priority) Technical approaches and methods for beyond state-of-the-art time transfer between orbiting and terrestrial clocks.
- (High priority) Technical approaches and methods beyond state-of-the-art for compact and miniature clocks for space with emphasis on the performance per size, power, and mass.

Expected TRL or TRL Range at completion of the Project: 1 to 5

Primary Technology Taxonomy:

- Level 1: TX 08 Sensors and Instruments
- Level 2: TX 08.3 In-Situ Instruments/Sensor

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware
- Research
- Analysis
- Software

Desired Deliverables Description:

- Phase I: Results of a feasibility study, analysis, and preliminary laboratory demonstration.
- Phase II: Prototype or demonstration hardware; summary of performance analysis; and applicable supporting documentation, data, and/or test reports. Phase II deliverables should also include/delineate any further work that would be required to bring the technologies to full operational and/or commercial use.

State of the Art and Critical Gaps:

The recent NASA Decadal Survey recommended a campaign based on optical clocks with that level of stability to probe Einstein's Equivalence Principle, the nature of dark matter, and other questions in fundamental physics. While the DSAC mission has successfully flown a space-qualified clock demonstrating a long-term stability of 10^{-15}, DSAC was a microwave ion clock. Key technologies of stabilized, narrow linewidth lasers (at wavelengths typically different than those required for Cs or Rb atom interferometry), compact ultrastable cavities, and optical frequency combs are needed to enable optical atomic clocks with better than 10^{-15} fractional stability. The scope description provides guidance on targeted technology gaps.

This scope addresses shortfalls identified in the Civil Space Shortfall Ranking including:

- [Ranked 67th] ID 1599: Quantum Sensors That Use Atoms, Ions, and Spins
- [Ranked 73rd] ID 1598: Quantum Sensors That Use Photons
- [Ranked 147th] ID 1433: Position, Navigation, and Timing for Small Spacecraft
- [Ranked 4th] ID 1557: Position, Navigation, and Timing (PNT) for In Orbit and Surface Applications
- [Ranked 14th] ID 1559: Deep Space Autonomous Navigation

Relevance / Science Traceability:

Optical atomic clocks with long-term stabilities better than 10^{-15} and beyond will be required for manned missions to Mars and for cislunar navigation. Time transfer and synchronization of terrestrial optical atomic clocks over long distances requires space-based timekeeping with similar sensitivities. Space-based optical atomic clocks at stabilities better than 10^{-17} will enable groundbreaking science such as searches for solar dark matter halos, deviations of fundamental constants, and gravitational wave detection at frequencies not accessible to LIGO (Laser Interferometer Gravitational-Wave Observatory) or LISA (Laser Interferometer Space Antenna).

References:

1. "2024 NASA Technology Taxonomy," National Aeronautics and Space Administration: www.nasa.gov/otps/2024-nasa-technology-taxonomy/
2. "NASA Strategic Technology Investment Plan 2017," National Aeronautics and Space Administration: https://www.nasa.gov/wp-content/uploads/2015/06/2017-8-1_stip_final-508ed.pdf
3. "Thriving in Space: Ensuring the Future of Biological and Physical Sciences Research: A Decadal Survey for 2023-2032," National Academics: https://nap.nationalacademies.org/catalog/26750/thriving-in-space-ensuring-the-future-of-biological-and-physical
4. "Civil Space Shortfalls," National Aeronautics and Space Administration: https://www.nasa.gov/spacetechpriorities

Scope Title: Cold Atom Interferometry

Scope Description:

Sensors based on cold atom interferometry can enable ultra precise measurements of gravitational and other inertial accelerations. Terrestrial applications have emerged utilizing laser-cooled atom sensors for inertial navigation units, gyroscopes for aviation and maritime units, gravity field mapping for mining and natural resource discovery. The microgravity environment of space presents an opportunity to leverage these sensors to improve measurements of gravity by orders of magnitude.

Advances are sought in, but not limited to: (priorities are labeled with highest being the most critical to filling gaps in NASA mission needs, though proposals addressing any of the areas will be considered and reviewed based on merit):

- (Highest priority) Space-qualifiable, high-flux, ultracold-atom sources, related components, and methods (e.g., $>1\times10^6$ total atoms near the point at <5 nK). In particular, high-brightness, ultracold sources are required for Rb or Cs. Other alkali species may be considered if applicable to a particular design.
- (Higher priority) Ultrahigh vacuum technologies and approaches for quantum sensor applications that allow small-size and low-power, completely sealed, nonmagnetic enclosures with high-quality optical access and that are capable of maintaining $<1\times10^{-9}$ Torr residual gas pressure. Consideration should be given to the inclusion of cold-atom sources of interest, such as switchable and/or regulated atom vapor pressure or flux.
- (Higher priority) Beyond-state-of-the-art photonic components at wavelengths for atomic species of interest. In particular, 852 nm (Cs) and 780 nm (Rb) are desired.
- (Higher priority) Integrated micro-optical assemblies for quantum sensor applications.
- (High priority) Efficient acousto-optic modulators: For example, low radio-frequency (RF) power ~200 mW, low thermal distortion, and ~80% or greater diffraction efficiency.
- (High priority) Efficient electro-optic modulators: For example, low-bias drift, residual amplitude modulation (AM), and return loss; fiber-coupled preferred.
- (High priority) Miniature optical isolators: For example, ~30 dB isolation or greater, ~ -2 dB loss or less. Required wavelengths at 852 and 780 nm are highly desired.
- (High priority) Robust high-speed high extinction shutters: For example, switching time <1 ms and extinction >60 dB are highly desired.
- (High priority) Flight qualifiable: For example, rugged and long-life lasers or laser systems of narrow linewidth, high tunability, and/or higher power for clock and cooling transitions of atomic species of interest. 852 nm (Cs) and 780 nm (Rb) are highly desired. Cooling and trapping lasers of 10 kHz linewidth and ~1 W or greater total optical power are generally needed, but offerors may define and justify their own performance specifications.
- (High priority) Analysis and simulation tool of a cold-atom system in trapped and free-fall states relevant to atom interferometry and clock measurements in space.

Expected TRL or TRL Range at completion of the Project: 1 to 5

Primary Technology Taxonomy:

- Level 1: TX 08 Sensors and Instruments
- Level 2: TX 08.3 In-Situ Instruments/Sensor

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Desired deliverables for this scope include an analysis and simulation tool of a cold-atom system in trapped and free-fall states relevant to an atom interferometer in space. Other types of deliverables are lasers or laser systems of narrow linewidth (~10 kHz), high tunability, and/or higher power (> 2 W) for clock and cooling transitions of atomic species of interest.

- Phase I: Results of a feasibility study, analysis, and preliminary laboratory demonstration.
- Phase II: Prototype or demonstration hardware; summary of performance analysis; and applicable supporting documentation, data, and/or test reports. Phase II deliverables should also include/delineate any further work that would be required to bring the technologies to full operational and/or commercial use.

State of the Art and Critical Gaps:

Cold-atom-based gravity gradiometers in Earth orbit will enable 10 to 100 times improvement in spatial and mass resolution of time variable gravity and improving our understanding of mass change processes on the Earth. Cold-atom gravity gradiometers will enable precise measurements of the gravity fields of the Moon and other planetary bodies in a single satellite, enabling safe landing of spacecraft. Deploying these systems into space will require the technological development of several key enabling technologies, to include compact, efficient narrow line-width laser sources, complex laser optical systems to deliver controlling pulses, ultrahigh vacuum systems, compact, bright ($>10^6$ atoms) and ultracold (<5 nK) atom sources; and simulations and analytical tools for space-borne atom sensors. The scope description provides guidance on targeted technology gaps.

This scope addresses shortfalls identified in the Civil Space Shortfall Ranking including:

- [Ranked 67th] ID 1599: Quantum Sensors that Use Atoms, Ions, and Spins
- [Ranked 73rd] ID 1598: Quantum Sensors that Use Photons

Relevance / Science Traceability:

The technologies and enabling subsystems advanced by this subtopic are critical to realizing cold-atom interferometric sensors for next-generation science missions. In particular, the 2017 Earth Science Decadal study points to cold-atom gravity gradiometry as a path toward the next generation of Mass Change missions for time-variable gravity recovery. This mission is slated to launch within the next 10 years, and technological maturation is required now. Additionally, future fundamental physics measurements such as dark matter and dark energy and gravitational wave detection utilizing cold-atom interferometers are in mission concept development. Small, compact cold-atom systems are also being developed to provide inertial navigation and positioning for systems to operate in GPS-denied environments or cislunar space.

References:

1. “NASA Strategic Technology Investment Plan 2017,” National Aeronautics and Space Administration: https://www.nasa.gov/wp-content/uploads/2015/06/2017-8-1_stip_final-508ed.pdf
2. "Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space," National Academies: https://www.nationalacademies.org/our-work/decadal-survey-for-earth-science-and-applications-from-space
3. "Mass change (MC)," National Aeronautics and Space Administration: https://science.nasa.gov/earth-science/decadal-surveys/decadal-mc/
4. "Civil Space Shortfalls," National Aeronautics and Space Administration: https://www.nasa.gov/spacetechpriorities

Scope Title: Atomic and Solid-State Quantum Sensors

Scope Description:

As indicated by the 2018 National Quantum Initiative Act and subsequent funding for research and development, NASA has identified quantum sensors as a critical area of technological maturation for future space and aviation missions. This scope solicits technological development of quantum sensors based on laser-cooled or thermal atoms or on solid-state systems beyond optical atomic clocks and cold-atom interferometers.

Advances are sought in the following (priorities are labeled with highest being the most critical to filling gaps in NASA mission needs, though proposals addressing any of the areas will be considered and reviewed based on merit):

- (Highest priority) Solid-state defect magnetometers or electromagnetic sensors: The ability to engineer spin-active defects in solid-state systems (for instance the nitrogen vacancy in diamond or silicon defects in SiC) has enabled chip-scale electromagnetic sensing. Devices based on these defects have the promise to enable ultracompact form factors and all electric (i.e., no laser required) systems. Additionally, the ability to build these systems from diamond or SiC may provide exquisite environmental tolerance in high temperatures or high radiation for planetary missions. However, technological maturation must continue with these defects to improve sensitivities to compete with existing technologies (such as flux-gate) and to design vector magnetic field capabilities.
- (Higher priority) Space-qualifiable, chip-scale atomic magnetometers: Atomic vapor magnetometers have significant benefits over flux-gate or other conventional magnetic field sensing systems in terms of in situ calibration (not requiring spacecraft maneuvers to calibrate), long-term drift, and sensitivity. However, the complexity of these systems must be reduced and the size and power minimized to be relevant to near-term missions.
- (High priority) Other innovative atomic quantum sensors for high-fidelity field measurements that have space applications and can be developed into a space-qualifiable instrument.

Please note that the following areas are excluded from S16.08 this year:

- Rydberg sensors or their subsystems/components for electric field or microwave measurements (offerers are suggested to consider S11.02 “Technologies for Active Microwave Remote Sensing”).

Expected TRL or TRL Range at completion of the Project: 1 to 5

Primary Technology Taxonomy:

- Level 1: TX 08 Sensors and Instruments
- Level 2: TX 08.1 Remote Sensing Instruments/Sensors

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

- Phase I: Relevant studies, bench-scale experiments, or breadboard demonstrations of the relevant techniques and technologies required for these quantum sensors. A typical study would include the theoretical analysis of the proposed techniques that include a discussion of the technological maturation required to develop a prototype system with a path to space qualification.
- Phase II: Delivery of a prototype system to a relevant NASA research center to enable further maturation and engineering integration into higher TRL test units and demonstrations. Phase II deliverables should also include/delineate any further work that would be required to bring the technologies to full operational and/or commercial use.

State of the Art and Critical Gaps:

NASA is interested in the development of low size, weight, and power (SWaP), rugged magnetometers and electromagnetic sensors based on laser-cooled, thermal atoms, or solid-state systems beyond optical atomic clocks and cold-atom interferometers. Examples include, but are not limited to, atom-vapor magnetometers enabling in situ calibration and high sensitivity and solid-state defect magnetometers enabling vector magnetometers in a chip scale, environment-tolerant form factor. The scope description provides guidance on targeted technology gaps.

This scope addresses shortfalls identified in the Civil Space Shortfall Ranking including:

- [Ranked 67th] ID 1599: Quantum Sensors that Use Atoms, Ions, and Spins
- [Ranked 73rd] ID 1598: Quantum Sensors that Use Photons

Relevance / Science Traceability:

These sensors have direct relevance to future missions, including Earth science balloon and small satellite missions, to study atmospheric composition using microwave signals. Enabling magnetometry with atom vapor or solid-state sensors can enable planetary missions to extremely hostile environments, such as Venus, or for heliophysics missions to analyze space weather and solar activity.

References:

1. "2024 NASA Technology Taxonomy," National Aeronautics and Space Administration: www.nasa.gov/otps/2024-nasa-technology-taxonomy/
2. "NASA Strategic Technology Investment Plan 2017," National Aeronautics and Space Administration: https://www.nasa.gov/wp-content/uploads/2015/06/2017-8-1_stip_final-508ed.pdf
3. "National Quantum Initiative Act," Public Law. No. 115-368, 132 Stat. 5092, 2018: https://www.congress.gov/115/plaws/publ368/PLAW-115publ368.pdf
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S17.01: Technologies for Large-Scale Numerical Simulation (SBIR)

Lead Center: ARC
Participating Center(s): GSFC, LaRC

Subtopic Introduction:

High performance computing (HPC) remains a critical part of NASA SMD's infrastructure needed to address fundamental questions of science and seek answers in order to understand the Sun, Earth, Solar System, and beyond. HPC serves a specific need in numerical simulation as high fidelity and efficient computing capabilities are needed to tackle large-scale research and studies to investigate complex dynamic processes up to the scale of entire science ecosystems. One of the largest challenges facing the HPC community today is the tremendous amount of refactoring that is typically required of existing large scale applications in order to address the hardware paradigm shift that has taken place over the past 5 to 10 years to usher in the exascale era, which is now upon us—and this shift is expected to continue and become even more heterogeneous in the coming years. There is an urgent need for application refactoring and performance portability in this environment. A second challenge is the emergence of the field of quantum computing and assessment of its potential to drive breakthroughs needed to analyze and solve large scale science problems currently beyond the reach of classical computing methods.

For this solicitation, this subtopic seeks technology advancement needs in the following two scopes (not in any priority order):

1. Exascale Computing.
2. Quantum Computing (new).

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 systems and to conduct high fidelity science and engineering analyses. To address these challenges, novel software technologies are sought such as artificial intelligence (AI)/machine learning (ML) that will increase the mission impact of NASA's investments in supercomputing systems and associated operations and services.

Specific objectives are to:

- Increase the achievable scale and complexity of computation, data ingest, and/or data assimilation required with large-scale numerical simulations.
- Reduce the cost of achieving a given level of application performance through the use of AI/ML tools.
- Enhance the ease of adoption of Physics-Informed Neural Networks (PINNs) which lie at the intersection of traditional physics model creation and data-driven neural networks with potential for use in many key NASA simulations.
- Enhance the efficiency and effectiveness of NASA's supercomputing operations and services.
- Enhance the supercomputer application area in data analytics that expand to other mission customers using AI/ML.
- Use of AI/ML techniques for code refactoring with the goal of improved application performance, scalability and optimization on target hardware and computing environments.

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. Novel software technologies that provide notable benefits to NASA's supercomputing users and high-end computing (HEC) facilities are sought.

The NASA supercomputing environment is characterized by:

- HEC systems operating behind a firewall to meet strict information technology (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.
- Encouragement to develop new application areas like AI/ML.

Proposals should demonstrate a relation to fields of study relevant to SMD or demonstrate the portability to SMD disciplines. Innovative computation technology directly targeting a stated NASA need outside of an SMD application will still be considered, but offerors are strongly encouraged to identify at least one relevant NASA subject matter expert and relevant project.

Proposals should demonstrate awareness of the state of the art of their proposed technology and should leverage existing commercial capabilities and research efforts where appropriate, including open-source software and open standards.

Expected TRL or TRL Range at completion of the Project: 5 to 7

Primary Technology Taxonomy:

- Level 1: TX 11 Software, Modeling, Simulation, and Information Processing
- Level 2: TX 11.6 Ground Computing

Desired Deliverables of Phase I and Phase II:

- Prototype
- Software
- Research
- Analysis

Desired Deliverables Description:

- Phase I: Technical feasibility demonstration with supporting research results demonstrating NASA relevance. Documentation of a path toward a Phase II deliverable and application of software design to support multiple disciplines (if applicable).
- Phase II: Prototype demonstration along with documentation of development and capabilities, including operating instructions. Plan scaling upwards to commercialization or infusion into NASA programs.

State of the Art and Critical Gaps:

Current and future NASA science requires at least 100x more powerful supercomputers and 1,000x higher application parallelism in 10 years without an increased energy demand. The current NASA data landscape also involves technologies for high fidelity computational simulation and data analytics are distinct and interfacing between tools is inefficient. As science data continue to grow in volume and complexity, innovative and novel software solutions are sought to further enable exascale compute capabilities while offering benefits to supercomputing users and facilities that can be readily adapted into supercomputing operations in efficient and cost-effective ways.

This scope addresses shortfalls identified in the Civil Space Shortfall Ranking including:

- [Ranked 157th] ID 1511: Advanced Computational Fluid Dynamics Tools / Capabilities.
- [Ranked 45th] ID 1568: Entry Modeling and Simulation for EDL Missions.
- [Ranked 98th] ID 1623: Advanced thermal modeling capabilities.

Relevance / Science Traceability:

Technology from this subtopic supports virtually all HEC systems and applications include the backbone computing capabilities that support NASA SMD. As the demand for HEC continues to grow, there is an increasing need for the solicited technologies in both the government and industry. Results from this subtopic will be of particular benefit to NASA's HEC projects: the High-End Computing Capability (HECC) project at ARC and the Computational & Information Sciences and Technology Office (CISTO) at GSFC. Funded SBIR contracts under this subtopic should engage in direct interactions with one or both HEC projects and with key HEC users where appropriate.

References:

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6. "Computational & Information Sciences and Technology Office," National Aeronautics and Space Administration: https://science.gsfc.nasa.gov/cisto
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Scope Title: Quantum Computing

Scope Description:

Quantum computing is one of the most enticing, novel computational paradigms with the potential to revolutionize diverse areas of future-generation computational systems. The goal of this subtopic is to develop and iteratively improve quantum, quantum-inspired, and hybrid quantum-classical workflows and work towards showing (or disproving) utility or advantage over existing classical state-of-the-art algorithms. Specifically, these methods should be deployed for solving high utility SMD problems, such as those related to: how and why Earth's climate and environment are changing; how are Earth and human systems impacting each other; how and why does the Sun vary and affect Earth and the rest of the solar system; how do planets and life originate; and how does the universe work?

Specific objectives are to:

- Identify problems of interest to SMD in areas, such as climatology, astrophysics, heliophysics [Ref. 3], which are amenable to acceleration or solution by a quantum computer and providing clear end-to-end classical and quantum resource estimates for solving the problem (i.e. exact qubit and gate counts and all classical resources, such as those found in Reference 1 using existing and novel algorithms).
- Develop and create test implementations of new quantum, quantum-inspired, or hybrid quantum-classical methods with well substantiated and significant improvements to existing state of that art quantum/hybrid methods for problems of interest to SMD, especially methods tailored to those problems rather than abstracted problem classes. Provide updated resource estimates as these new methods are developed.
- Reference and clearly articulate the comparison between developed quantum/hybrid algorithms and state of the art classical algorithms for solving the same problems.
- Clearly articulate the utility of solving the selected problems to SMD with a clear description of how utility is assessed and how current and future quantum workflow developments and their associated costs interact with that utility. This utility should reference existing state of the art classical algorithms and discuss the utility in excess of what is already provided by those algorithms.

- Develop new or augment existing resource estimation software (see for example, Zapata's Bench-Q [Ref. 4] tool for hardware resource estimates and the Rigetti Resource Estimation Software [Refs. 5, 6]) to create open-source software for estimating the classical and quantum resources needed for solving the identified SMD problems of interest that provides features or specialization not currently available.
- Develop and demonstrate the effectiveness of novel methods to ingest large NASA datasets into networked quantum, quantum-inspired, or hybrid quantum-classical computers along with well substantiated and non-trivial quantum algorithms and/or hardware to enable such networked computations.
- Create test sets/instances for the chosen problem class of varying levels of complexity and size with associated utility metrics for each set/instance. For tests that are amenable in terms of size and complexity, run the specified test sets with the developed quantum/hybrid methodologies on current generation quantum hardware.

Examples of applications of interest include the following, but are not limited to:

- Improving on image-to-image translation, noise filtering, data fusion and other data pre-processing tasks (see for example, Ref. [9]).
- Identifying actionable extreme weather event triggers.
- Optimizing data acquisition tasking and scheduling.
- Leveraging quantum computing for 2D and 3D phase unwrapping of synthetic aperture radar (SAR) data.
- Improving atmospheric and climatology modeling.
- Solutions for inverse problems (e.g., retrievals, data fusion, etc).

Expertise in the following areas may be useful in responding to this solicitation:

- Prior familiarity with problems of interest to SMD in areas such as climatology, astrophysics, and heliophysics is encouraged.
- Classical state-of-the-art techniques for solving real-world problems such as those that could be found in SMD areas.
- Familiarity with high utility problems of interest and decadal priorities to SMD in areas such as climatology, astrophysics, and heliophysics.
- Quantum algorithms and software engineering.
- Classical high-performance computing.
- Quantum circuit simulators.
- Quantum hardware: there is a suggestion to solve small test instances for the problems of interest on current Noisy Intermediate Scale Quantum (NISQ) hardware, but this hardware does not need to be provided by the proposing business. Agreements with hardware manufacturers or publicly purchasable quantum compute time is acceptable. Some familiarity with state-of-the-art quantum hardware is warranted for all aspects of the call to ensure the quantum amenability of all parts of the computational workflow.

Successful proposers are likely to include experts from all the identified areas of expertise above in order to be able to design approaches that leverage quantum computing to solving high utility problems related to SMD's mission.

While work aimed exclusively toward deliverables is acceptable, opportunities and desire to collaborate with NASA's existing quantum computing workforce on topics of mutual interest will be considered and can be created.

Please note that the following areas are excluded from S17.01 this year:

- Proposals to develop general purpose quantum capabilities without explicit and detailed reference to SMD applications.
- NISQ algorithms without explicit and detailed discussions of the scaling of those algorithms to utility scale (beyond brute force or exact classical simulations).

Expected TRL or TRL Range at completion of the Project: 3 to 4

Primary Technology Taxonomy:

- Level 1: TX 11 Software, Modeling, Simulation, and Information Processing
- Level 2: TX 11.6 Ground Computing

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Software

Desired Deliverables Description:

- Phase I: Technical feasibility demonstration with supporting research results demonstrating advancement over state of the art and identification of relevance to a NASA SMD challenge. Documentation of a path toward a Phase II deliverable.
- Phase II: Prototype demonstration on the relevant SMD challenge and software delivery along with documentation of development and capabilities, including operating instructions. Plan to scale upwards to commercialization or infusion into NASA programs.

State of the Art and Critical Gaps:

Quantum computing hardware has advanced rapidly from tiny laboratory experiments to quantum chips that can outperform even the largest supercomputers on specialized computational tasks. However, these NISQ processors are still too small and non-robust to be able to solve practical problems of interest to SMD that are intractable on classical computers. As these devices scale up and become more reliable, we have an unprecedented opportunity to invent, explore, and evaluate quantum algorithms empirically [Ref. 2].

Critical gaps include the ability to encapsulate and describe in software high-utility problem instances of interest to SMD in areas including but not limited to remote sensing, climatology, astrophysics, and heliophysics. Additional gaps include software for estimating the classical and quantum resources for solving these problems; software for estimating the utility (in dollars) to SMD for solving these problems; and software for lowering the barrier for solving SMD problems of interest with quantum and hybrid quantum-classical tool chains.

This scope addresses shortfalls identified in the Civil Space Shortfall Ranking including:

- [Ranked 157th] ID 1511: Advanced Computational Fluid Dynamics Tools / Capabilities.
- [Ranked 45th] ID 1568: Entry Modeling and Simulation for EDL Missions.
- [Ranked 98th] ID 1623: Advanced thermal modeling capabilities.

Relevance / Science Traceability:

The subtopic scope is focused on near-to-mid-term technology needs that are designed to jump start leveraging quantum computing advances made in industry for NASA SMD objectives. SMD sees this as a priority area in which engaging the commercial sector is essential. Both SMD and NASA ARC seek to remain at the forefront in terms of high-performance computing capabilities for science where advancing high-fidelity modeling and simulation with large data sets is a priority. In particular, climate and Earth science modeling has a strong desire to use SBIR and small business advances to position themselves to leverage utility-scale quantum computers as this technology matures.

References:

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4. “Bench-Q software for estimating the hardware resources required for fault-tolerant quantum computation”, DARPA Quantum Benchmarking program: https://github.com/zapatacomputing/benchqhttps://github.com/zapatacomputing/benchq
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12. "Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space," National Academies: https://www.nationalacademies.org/our-work/decadal-survey-for-earth-science-and-applications-from-space
13. "Civil Space Shortfalls," National Aeronautics and Space Administration: https://www.nasa.gov/spacetechpriorities

S17.02: Integrated Campaign and System Modeling (SBIR)

Related Subtopic Pointers: S17.03, Z-ENABLE.05, T11.05
Lead Center: JSC
Participating Center(s): GRC, GSFC, KSC

Subtopic Introduction:

This subtopic seeks innovations across a broad spectrum of modeling and simulation (M&S), digital engineering (DE), and interoperability topics with emphasis on delivering scientific hardware and capabilities with greater complexity, fewer errors, and with quicker lifecycles from concept to operations. This includes interoperability challenges such as model and simulation fidelity, time scales, precision, uncertainty representation, etc. The promise of orders-of-magnitude improvements in processing speed, quality, design robustness, reuse, etc., has created a large swell of both demand and efforts in this area. These advancements are of interest across SMD and the rest of NASA, including ESDMD (Exploration Systems Development Mission Directorate) and SOMD (Space Operations Mission Directorate). Although there is a vast range of possible topics, the emphasis is on interoperability and integrated design, testing, and looking forward to digital twins.

These efforts are exposing some of the challenges in implementing operable extensions across disciplines, domains, and life cycle phases, while taking into consideration the project/center customization and optimizations. Solutions to these challenges are desired. Ideally, the solutions are scalable and meet the needs of a variety of users/use cases.

For this solicitation, this subtopic seeks technology advancements in the following scopes:

1. Campaign and System Modeling and Simulation
2. Digital Engineering Applications for Science (updated)

Scope Title: Campaign and System Modeling and Simulation

Scope Description:

This year NASA is focused on interoperability and its impact on general modeling and simulation (M&S) challenges and solutions. 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:

- Develop 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 to:
    - Support emerging usage of autonomy, both in mission operations and flight software.
    - 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.
    - 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).
- Target models (e.g., phenomenological or geophysical models) as part of the integrated digital engineering solution space, which 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.

Please note that the following areas are excluded from S17.02 this year:

- Model-Based Systems Engineering (MBSE) approaches for the purpose of enabling approval and adoption of novel advanced air mobility vehicles for airspace operations (offerors are suggested to consider T11.05 “Model-Based Enterprise”).
- M&S for space intravehicular or extravehicular robotic autonomous manipulation and task performance (offerors are suggested to consider Z-ENABLE.05 “Extensible Perception, Manipulation, and Interoperability for Autonomous Robotic Systems”).
- Campaign design, systems analysis, alternate technology evaluation, and trade space optimization.

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:

- Level 1: TX 11 Software, Modeling, Simulation, and Information Processing
- Level 2: TX 11.3 Simulation

Desired Deliverables of Phase I and Phase II:

- Prototype
- Software
- Research
- Analysis

Desired Deliverables Description:

Desired deliverables for this scope should demonstrate the relevance of the identified innovation for NASA usage and use real data when possible.

- Phase I: Methodology and a clear proof of concept and/or prototype. Plan for next phase of maturation.
- Phase II: Working prototype suitable for demonstrations with compelling case for NASA. Use and development of the model—including all work performed to verify and validate it—should be documented. Also, at the end of Phase II, there will be a clear indication of the path to commercialization.

State of the Art and Critical Gaps:

There are currently 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.

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 subtopic 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 rather on demonstrations of capability and methodologies for achieving this.

This scope addresses shortfalls identified in the Civil Space Shortfall Ranking including:

- [Ranked 34th] ID 1532: Autonomous Planning, Scheduling, and Decision-Support to Enable Sustained Earth-Independent Missions
- [Ranked 60th] ID 1561: Advanced Modeling and Test Capabilities to Characterize Dust Effects on hardware
- [Ranked 115th] ID 1600: Enable paradigm for System Science to include interactions between subsystems
- [Ranked 120th] ID 379: Upgrade or Install Instruments on Large Space Observatories
- [Ranked 135th] ID 1625: Intelligent Multi-Agent Constellations for Cooperative Operations
- [Ranked 176th] ID 1494: Digital Transformation Technologies for Terrestrial, In-Space, On-Surface Manufacturing, and Operations

Relevance / Science Traceability:

As science missions continue to explore, they are growing in scope and complexity and will increasingly rely on modeling, simulation, and virtual qualification. The payoffs from more sophisticated integration and usage of M&S are enormous: greater scope and depth of trade space exploration, reduction in development times and iterations because of increased connectedness, and earlier verification and validation (V&V) to name a few. However, increased complexity can be exacerbated by lack of interoperability; by inconsistent management of data and workflows; and by inconsistencies in fidelity, assumptions, and scopes. There are challenges both with deploying M&S as V&V surrogates and also in V&V of the M&S itself.

There are several large, complex campaigns underway, including Artemis and Mars Sample Return. These campaigns consist of multiple spacecraft and complex inter-operations and span almost 2 decades. This complexity is exacerbated by the distribution of roles and functions across multiple organizations both within and outside the United States. The ability to share, collaborate, and manage data at a wide variety of levels, layers and disciplines will be key to success.

Several concept/feasibility studies for potential large (flagship) astrophysics missions have been published: Large UV/Optical/IR Surveyor (LUVOIR), Origins Space Telescope (OST), Habitable Exoplanet Observatory (HabEx), and Lynx. These concept studies have led into the formulation of the next grand observatory mission the Habitable Worlds Observatory (HWO), 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. In addition, every planetary mission requires significant M&S across a variety of possible trade spaces. They are also supported by the general and specific aspects of this subtopic.

References:

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Scope Title: Digital Engineering Applications for Science

Scope Description:

The explosion of DE, including Model-Based Systems Engineering (MBSE), has led to a proliferation of models, modeling processes, pedigree of models and associated data, and the integration/aggregation thereof. The model results are often combined with no clear understanding of their fidelity/credibility. Whereas some NASA personnel are looking for greater accuracy and "authoritative source of truth," others are looking for the generation and exploration of massive trade spaces. Both greater precision and greater robustness will require addressing a number of cross-cutting challenges. This explosion of interoperability, via DE, has led us to create this focus area.

NASA seeks innovative methods and tools addressing the following needs: define, design, develop, and execute future projects and programs by developing and utilizing advanced methods and tools that fully integrate all of the digital engineering and science activities across the entirety of the project/program lifecycle, and allow for interagency and NASA-industry collaboration and data-centric information exchange. Proposed solutions should introduce new data-central approaches to concurrent engineering, leverage standard industry tools where possible, allow for easier integration of disparate tools and data, and be compatible with current NASA science and systems engineering processes.

There is specific interest in new data-central approaches to concurrent engineering and the integration of tools and data for rapid generation of function or behavior of complex systems, at either the system or subsystem level across all lifecycle phases and an integrated design/science environment between NASA and its various partners to:

- Determine new approaches to perform concurrent engineering in the data-centric domain to speed the closure of engineering designs.
- Support emerging collaboration between NASA and domestic industry and international program partners, understanding standard approaches to integrating toolchains and data models, while protecting International Traffic in Arms Regulations (ITAR) and/or proprietary information.
- Support integration of existing toolchains and workflows.
- Be capable of using/developing standardized ontology(s) to enable modern information exchange, integration, and contract data deliverables to ensure all parties receive the information needed in the format expected and most useful, while minimizing integration of the products of multiple suppliers.
- Be capable of standardizing model complexity to optimize complexity vs. managing, sustaining, and model proliferation.
- Be able to provide a standard approach for the validation of models, for customizing these validations, and for profiling this pedigree, not only along with the model itself, but also with the data generated/provided by the models.
- Support the development of digital exchange standards in order to easily transform data between vendors/contractors/industry partners/government entities.

Please note that the following areas are excluded from S17.02 this year:

- MBSE approaches for the purpose of enabling approval and adoption of novel advanced air mobility vehicles for airspace operations (offerors are suggested to consider T11.05 “Model-Based Enterprise”).

- Modeling and simulation for space intravehicular or extravehicular robotic autonomous manipulation and task performance (offerors are suggested to consider Z-ENABLE.05 “Extensible Perception, Manipulation, and Interoperability for Autonomous Robotic Systems”).
- DE and MBSE for the primary purpose of fault management (offerors are suggested to consider S17.03 “Fault Management Technologies").

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:

- Level 1: TX 11 Software, Modeling, Simulation, and Information Processing
- Level 2: TX 11.2 Modeling

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Software

Desired Deliverables Description:

Desired deliverables for this scope should demonstrate how the innovation addresses NASA interests to integrate engineering and science activities across the program/project lifecycle. The solution can investigate processes, data products, and translation between the lifecycle gates. The goal is to support acceleration and streamlining of engineering or science business processes, achieve high-value collaboration and interaction, and accelerate risk-informed and evidence-based decision-making.

- Phase I: Focus on cross-cutting digital engineering capabilities described previously as can be applied to the engineering delivery of science capabilities or payloads. Methodology and a clear proof of concept and/or prototype. Plan for next phase of maturation identifying future work with NASA-focused/relevant projects and programs.
- Phase II: Working prototype suitable for demonstrations with a clear and compelling case for utilization on specific current or future NASA programs or projects. Use and development of the solution—including all work performed to verify and validate it—should be documented. Additionally, a plan indicating a path to commercialization and/or scaling to NASA infusion.

State of the Art and Critical Gaps:

The current, relevant shortfalls in the state of the art of interoperability and data-centric, concurrent DE at NASA include the following.

1. Each discipline tends to have their own tools and toolchains, which propagate historical approaches to siloed, and often, serial engineering.
2. Tools and models are emerging, but they may not be consistent with each other. These inconsistencies also occur at the workflow/process level and lower at the data exchange level.
3. A lack of a common architectures and approaches for validating data source(s) that fit within the NASA workflow. These separate but connected authoritative sources of truth are often a source of conflict during the project life cycle.
4. Vendors may provide portions of the toolchain and are often incompatible with each other. This often forces a variety of inefficiencies on NASA, including: (1) requiring manual data entry, or worse, data checking; (2) choosing the "least worst" monolithic solutions; (3) making it difficult for NASA to implement cultural changes; (4) making it difficult for NASA to avoid duplicative efforts, or worse,

contradictory efforts; and (5) making it difficult for NASA to leverage/utilize emerging technology breakthroughs.

5. Many new approaches to setting up and managing toolchains and data sources require additional, expensive, overhead and mandate adding another skill domain to the workforce in an era of flat or declining budgets.

Proposed solutions to the subtopic should lend themselves to the specific interests sought while minimizing/addressing the current challenges experienced within the state of the art.

This scope addresses shortfalls identified in the Civil Space Shortfall Ranking including:

- [Ranked 176th] ID 1494: Digital Transformation Technologies for Terrestrial, In-Space, On-Surface Manufacturing, and Operations
- [Ranked 33rd] ID 1542: Metrics and Processes for Establishing Trust and Certifying the Trustworthiness of Autonomous Systems
- [Ranked 101st] ID 512: Cooperative Interfaces, Aids, and Standards
- [Ranked 109] ID 376: Modular Design for In-Space Installation
- [Ranked 132] ID 767: Advanced Designs for Inflatable Surface Elements
- [Ranked 170] ID 1492: Materials and Process Modeling for In-Space and On-Surface Manufacturing

Relevance / Science Traceability:

NASA's robotic and human exploration efforts are complex, challenging endeavors. Requirements for any/all of these programs and projects trace back to science; either science we are doing now or science that will be enabled. Traceability between and among requirements is key; in particular, the traceability from any given requirement to the science source(s) and reference(s) that it traces to. This traceability will lead to interoperability and NASA's endgame goal: to be able to integrate seamlessly between engineering, science missions, and operations with a deeply integrated approach to tooling and data exchange across NASA and all of its partners.

It is anticipated that successful technology solutions from this subtopic can be readily used by a large number of NASA programs and projects, from large, coordinated campaigns to one-of-a-kind missions across all of NASA's mission directorates.

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S17.03: Fault Management Technologies (SBIR)

Related Subtopic Pointers: H6.25, H15.02, S15.02, S15.03, S17.02, T11.05, T6.09
Lead Center: GRC
Participating Center(s): ARC, JPL, MSFC

Subtopic Introduction:

NASA SMD seeks to answer many long-standing questions about our planet, Sun, solar system, and beyond as well as enable space exploration. 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 operation costs, system autonomy must increase in response. Fault management is a critical enabling factor in autonomous systems to determine proper corrective actions after an unplanned event, large disturbance, or fault.

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 and 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. Challenges related to linear, nonlinear, discrete, or continuous systems must be considered in the design of the approach. For example, critical subsystems such as the electric power system (EPS) and attitude control systems (ACS) require advanced FM techniques to achieve extremely high levels of mission reliability. Furthermore, interactions between subsystems should also be investigated, as the effect of faults may propagate from one critical system to another.

Despite lessons learned from past missions, spacecraft failures are still not uncommon, and reuse of FM approaches is limited. This illustrates the deficiencies in current approaches to handling faults in all phases of the flight project lifecycle. The need exists at both extremes of space exploration: At one end, well-funded, resource-rich missions continue to experience difficulties due to system complexity, computing capability that fails to keep pace with expanding mission goals, and risk-averse design. This ultimately curtails mission capability and mission objectives when traditional fault management approaches cannot adequately ensure mission success. At the other end, very small and high-risk missions are flourishing because of advances in computing, microdevices, and low-cost access to space. However, autonomy and FM are increasingly seen as essential because of the high probability of faults and extreme resource limitations that make deliberative, ground-directed fault recovery impractical.

Scope Title: Development, Design, and Implementation of Fault Management Technologies

Scope Description:

This subtopic addresses particular interest in onboard FM capabilities, namely, onboard sensing approaches, computing, algorithms, and models to assess and maintain spacecraft health. The higher goal is to provide a system capability for management of future spacecraft. Offboard components such as modeling techniques and tools, development environments, and verification and validation (V&V) technologies are also relevant, provided they contribute to novel or capable onboard FM.

Needed innovations in FM can be grouped into the following two categories:

1. FM operations approaches: This category encompasses FM "in-the-loop," including algorithms, computing, state estimation/classification, machine learning, model-based reasoning, and digital twin technologies. Further research into fault detection and diagnosis, prognosis, fault recovery, and mitigation of unrecoverable faults is needed to realize greater system autonomy and resiliency.

2. FM design and implementation tools: Also sought are methods to formalize and optimize onboard FM, such as model-based system engineering (MBSE). New technologies to improve or guarantee fault coverage, manage and streamline complex FM, and improve system modeling and analysis significantly contribute to the quality of FM design and may prove decisive in trades of new versus traditional FM approaches. Automated test case development, false positive/false negative test tools, model V&V tools, open-source software tools, and test coverage risk assessments are examples of contributing technologies.

Specific algorithms and sensor technologies are in scope, provided their impact is not limited to a particular subsystem, mission goal, or failure mechanism. Novel artificial-intelligence-inspired algorithms, machine learning, etc., should apply to this subtopic if, and only if, their design or application is specific to detection, classification, or mitigation of system faults and off-nominal system behavior. Although the core interests of this subtopic are spacecraft resilience and enabling spacecraft autonomy, closed-loop FM for other high-value systems such as launch vehicles and test stands is also in scope, particularly if the techniques can be easily adapted to spacecraft.

Expected outcomes and objectives of this subtopic are to mature the practice of FM, 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:

- Increase spacecraft resilience against faults and failures.
- Increase spacecraft autonomy through greater onboard fault estimation and response capability.
- Increase collection and quality of science data through mitigation of interruptions and fault tolerance.
- 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 the extent of testing required, completeness of verification planned, and residual risk resulting from incomplete coverage.
- Increase data integrity between multidisciplinary tools.
- Compare distributed versus centralized FM implementation.
- Standardize metrics and calculations across FM, systems engineering (SE), safety and mission assurance (S&MA), and operations disciplines.
- Bound and improve costs and implementation risks of FM while improving capability, such that benefits demonstrably outweigh the risks, leading to mission infusion.

Please note that the following areas are excluded from S17.03 this year:

- Related technologies in Digital Engineering (including digital twins) without a primary focus on resolution of system faults (consider S17.02 “Integrated Campaign and System Modeling").
- Fault management technologies as a specific component to environmental monitoring (including fire detection) technology (consider S15.03 "Environmental Monitoring for Micro-G and Partial-G Experiments").
- Fault management technologies as a specific component to autonomous biological experiment monitoring hardware (consider S15.02 "In Situ Sample Preparation and Analysis for Biological and Physical Sciences in a Microgravity Environment").
- Fault management technologies for the specific application of robotic vehicle terrain navigation (consider H15.02 "Simulation and Modeling of Lunar Mobility System Interaction with Lunar Regolith").
- Technology in support of certification or verification of autonomous systems (consider H6.25 Trusted Autonomy in Space Systems).
- Fault management technologies for the specific application of integrated human/autonomous smart habitat systems (consider T6.09 "Human-Autonomous System Integration for Deep Space Tactical Anomaly Response in Smart Habitats").

Expected TRL or TRL Range at completion of the Project: 3 to 4

Primary Technology Taxonomy:

- Level 1: TX 10 Autonomous Systems
- Level 2: TX 10.2 Reasoning and Acting

Desired Deliverables of Phase I and Phase II:

- Analysis
- Prototype
- Software

Desired Deliverables Description:

- Phase I: It is noted that research and development (R&D) undertaken in Phase I is intended to have high technical risk, so it is expected that not all projects will achieve the desired technical outcomes.
    - Initial proof of concept. Successful efforts to be considered for follow-on funding by SMD missions as risk-reduction and infusion activities.
    - 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. Describe the approach along with foundational concepts and operating theory, mathematical basis, and requirements for application. Results should include strengths and weaknesses found and the measured performance in tests where possible.
    - Demonstrate technical feasibility and NASA relevance and show a path toward a Phase II prototype demonstration as well as commercialization.
    - Additional deliverables may significantly clarify the value and feasibility of the innovation. These should demonstrate retirement of development risk, increasing maturity, and targeted applications of particular interest. Possible deliverables:
        - For innovations that are algorithmic in nature: Development code or prototype applications, demonstrations of capability, and results of algorithm stress testing.
        - For innovations that are procedural in nature: 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 should illustrate 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.
- Phase II:
    - Description of technical accomplishments of the Phase I award and how these results support the underlying commercial opportunity.
    - Description of commercial potential is best done through experiment: Results of a prototype implementation to a relevant problem, along with lessons learned and future work expected to adapt the technology to other applications.
        - Further demonstration of commercial value and advantage of the technology can be accomplished through steps taken to mature the technology and further reduce the difficulty in reducing it to practice:
            - Delivery of the technology in software form, as a reference application, or through providence of trial or evaluation materials to future customers.
            - Technical manuals, such as functional descriptions, specifications, and user guides.
            - Conference papers or other publications.
            - Establishment of a preliminary performance model describing technology metrics and requirements.

- At the conclusion of Phase II, a potential customer should have access to sufficient materials and evidence to make informed project decisions about technology suitability, benefits, and risks.

State of the Art and Critical Gaps:

Many recent 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 onboard systems.

Critical gaps in NASA FM capabilities include:

- 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.

This scope addresses shortfalls identified in the Civil Space Shortfall Ranking including:

- [Ranked 35th] ID 1532: Autonomous Planning, Scheduling, and Decision-Support to Enable Sustained Earth-Independent Missions
- [Ranked 72nd] ID 1535: Autonomous Vehicle, System, Habitat, and Infrastructure Health Monitoring and Management
- [Ranked 177th] ID 1544: Resilient Agency: Adaptable Intelligence and Robust Online Learning for Long-Duration and Dynamic
- [Ranked 48th] ID 1438: Autonomy, Edge Computation, and Interoperable Networking for Small Spacecraft
- [Ranked 85th] ID 680: Robust Robotic Intelligence for High Tempo Autonomous Operations in Dynamic Mission Conditions

Relevance / Science Traceability:

FM technologies are applicable to all SMD missions and are anticipated to be of high interest to the SMD science divisions supporting science missions with different emphases. Medium-to-large missions have very low tolerance for risk of mission failure, leading to a need for sophisticated and comprehensive FM. 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 (as an example of many similar future missions): Enable very low-cost operations and high science return from a 6U CubeSat through onboard error detection and mitigation, streamlining mission operations. Provide autonomous resilience to onboard errors and disturbances that interrupt or interfere with science observations.

- Europa Lander: Provide onboard 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, FM capabilities, and for coordinated development with flight software. Maximize science data collection during an expected short mission lifetime due to environmental challenges.
- Rovers and rotorcraft (Mars Sample Return, Dragonfly, future Mars rotorcraft): Provide onboard 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). Ensure safety of open-loop control or enable closed-loop control to prevent or mitigate failures.
- Search for extrasolar planets (observation): Provide sufficient system reliability through onboard detection, reasoning, and response to enable long-period, stable observations. Provide onboard 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).

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6. "2018 Autonomy Workshop," National Aeronautics and Space Administration: https://science.nasa.gov/technology/2018-autonomy-workshop
7. "Civil Space Shortfalls," National Aeronautics and Space Administration: https://www.nasa.gov/spacetechpriorities

Space Technology Mission Directorate (STMD)

NASA's Space Technology Mission Directorate (STMD) leads the development, demonstration, and infusion of transformational technologies that enhance NASA's efforts to explore the unknown in space, benefit life on Earth, and solve critical stakeholder needs.

Z-GO.01: Cryogenic Fluid Management (SBIR) (Previously Z10.01)

Related Subtopic Pointers: A1.09, Z-GO.02
Lead Center: GRC
Participating Center(s): JSC, MSFC

Subtopic Introduction:

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.

Scope Title: Cryogenic Fluid Management (CFM)

Scope Description:

This subtopic seeks technologies related to the following:

- Long-life bearing solutions for cryogenic fluid management (CFM) turbomachinery applications such as reverse turbo-Brayton cryocooler compressors and turboalternators. Bearings will target 100,000-400,000RPM operation in near room-temperature, <200psia, gaseous helium or neon, and an operational life of 50,000 hours. Proposers should consider development in magnetic bearings, foil bearings, or journal bearings to increase life, reliability and scalability. Active cooling is possible in all mentioned fluids but should be minimized. Phase 1 efforts should include preliminary design and analysis along with a prototype demonstration. Phase II efforts should include final design, analysis, and fabricated product along with complete characterization testing.
- Cryogenic propellant transfer pumps for optimal cryogenic fluid management transfer systems. Propellant transfer pumps should target 25 psid pressure rise for 0.5 – 1.0 kg/s of LH2, 3.0 – 4.0 kg/s for LOX, or 2.5 – 3.5 kg/s for LCH4. The operating life of any proposed solution should target 20,000 hr and 3,000 start-stop cycles. Proposers should consider design philosophy for reliability, reusability, and commonality across the different fluid pumps. Strong proposals will show understanding for transfer pump influence on receiving tank conditions before and after transfer processes. Proposals will develop sets of either LH2 and LOX or LCH4 and LOX transfer pumps. Drive control systems should be included in design. Phase 1 efforts should include preliminary design and analysis. Phase II efforts should include final design along with complete characterization testing. The final Phase II deliverable should be the set of transfer pumps.
- Develop a temperature measurement system that can measure temperature at multiple locations on a single strand/wire/fiber at least 1 meter long at cryogenic temperatures. The measurements system should operate up to 350 K and down to at least 20 K with uncertainty +/- 0.5 K between 100 K and 20 K. Goal to have measurements be 1 cm or less apart on the wire over at least half of the length. Phase 1 should physically demonstrate measurements at least down to 77 K with analytical demonstration of measurements down to 20 K. Phase II should physically demonstrate measurements down to at least 20 K, with preferred delivery of the final unit.

Expected TRL or TRL Range at completion of the Project: 2 to 4

Primary Technology Taxonomy:

- Level 1: TX 14 Thermal Management Systems
- Level 2: TX 14.1 Cryogenic Systems

Desired Deliverables of Phase I and Phase II:

- Hardware
- Prototype
- Research

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. Additional details can be found within the scope description.

State of the Art and Critical Gaps:

CFM is a crosscutting 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. The Space Technology Mission Directorate (STMD) has identified that CFM technologies are vital to NASA's exploration plans for multiple architectures, whether hydrogen/oxygen or methane/oxygen systems, including chemical propulsion and nuclear thermal propulsion. Several recent Phase II projects have resulted from CFM subtopics, most notably for cryocoolers, cryocooler electronics, liquid acquisition devices, phase separators, broad area cooling, and composite tanks.

Civil Space Shortfall Ranking https://www.nasa.gov/spacetechpriorities/

- 709: Nuclear Electric Propulsion for Human Exploration
- 702: Nuclear Thermal Propulsion for Human Exploration
- 879: In-space and On-surface, Long-duration Storage of Cryogenic Propellant
- 792: In-space and On-surface Transfer of Cryogenic Fluids
- 1221: Mars Ascent Vehicle Propulsion

Relevance / Science Traceability:

STMD has identified CFM as a key capability within its "Go" thrust that enables multiple outcomes, including Human Earth-to-Mars Transportation Systems and Reusable, Safe Launch and In-Space Propulsion Systems. Additionally, the CFM activities support the In-Situ Propellant and Consumable capability within the “Live” thrust.

STMD strives to provide the technologies that are needed to enable exploration of the solar system, both manned and unmanned systems; CFM is a key technology to enable exploration. For both liquid oxygen/liquid hydrogen and liquid oxygen/liquid methane systems, 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; liquefaction and storage are both CFM functions for the surface of the Moon or Mars. ISRU and CFM liquefaction drastically reduces the amount of mass that must be landed.

References:

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4. Chan, H.M., et al. "Fiber-Optic Sensing System: Overview, Development, and Deployment in Flight at NASA" *2015 IEEE Avionics and Vehicle Fiber Optics and Photonics Conference* Santa Barbara, CA, November 12 – 15, 2015.
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6. Johnson, W. et al. "Cryogenic Fluid In-Situ Liquefaction for Landers: Prototype Demonstration" *AIAA-2023-4748*, *2023 AIAA Ascend Conference*, Las Vegas, NV, October 23 – 25, 2023.

Z-GO.02: Space Nuclear Propulsion (SBIR) (Previously Z10.03)

Related Subtopic Pointers: S16.05, Z-LIVE.02, Z-GO.01
Lead Center: MSFC
Participating Center(s): GRC, SSC

Subtopic Introduction:
Space Nuclear Propulsion (SNP) has been identified as a critical technology for future NASA space exploration. SNP is a subtopic that develops low-TRL systems that use fission energy, rather than combustion, for propulsion. Nuclear Thermal Propulsion (NTP) uses fission energy in a heat exchanger to directly heat a propellant for thermal expansion through a traditional nozzle. Nuclear Electric Propulsion (NEP) uses a fission reactor electric power system to run electric thrusters. Both NTP and NEP have gathered interest from mission analysis results of an opposition mission to Mars and other deep space missions where solar flux is extremely low. NASA has recently partnered with the Defense Advanced Research Projects Agency (DARPA) for a flight demonstration of NTP in 2027. This subtopic focuses on recent technology challenges specific to both NEP systems and solid core NTP systems.

Scope Title: Technology Challenges

Scope Description:

Specific technologies being sought include:

1. High emissivity leads to smaller radiator area. Radiators for NEP significantly contribute to the total mass of the vehicle. NASA seeks low solar absorptivity high-emissivity coatings and/or surface treatments for space radiators operating at temperatures up to 750 K with lifetimes of 25,000 hr. The coating or surface treatment process needs to be able to be applied to an individual modular radiator panel (~15 m^2). Coatings or surface treatments also should be resilient and experience a minimal loss of properties within the relevant environment, i.e., long-duration, high-temperature operation in a vacuum, cold soak, and exposure to sunlight, radiation, and the exhaust of the electric propulsion system. Coatings need to be compatible with radiator substrate material to include titanium and carbon-carbon composites.

2. Lightweight insulators close to reactor fuel elements for minimizing heat transfer with low thermal conductivity radially between extremely high temperature fuel elements (~3,000 K) and lower temperature moderator material (~800 K). Insulator material will be exposed to high neutron flux and gamma rays as well as high pressure hydrogen.

3. Of interest is research and development in solutions for in situ inspection of a nuclear propulsion system during or after operation in space using robotics attached or separated from the spacecraft. Both system and relevant sub-system level solutions are sought. It may be expected that an experimental engine system tested at or near operational limits will impart significant thermal and mechanical stresses on the engine, reactor, and vehicle components. Stressors include but may not be limited to the gamma and neutron radiation environment, acoustic & vibrational loads, and accelerated corrosion/embrittlement/chemical impacts associated with flowing propellant or working fluids in the propulsion system. Historical ground-based studies of such systems have leveraged extensive real-time data collection during operation and detailed post-test disassembly and inspection. In the absence of existing nuclear propulsion system ground testing facilities, a significant challenge is presented to maximize the useful data acquired during and after flight engine system operation using systems or methods that are low mass and complexity and that minimally impact the design of the propulsion system. Such inspection and/or sensing systems and methods must be capable of surviving both the operational neutron/gamma radiation environment and the post-operation gamma radiation environment. Systems are likely to require total ionizing dose (TID) tolerance of greater than 1 Mrad. Novel technical hardware solutions and adaptations of existing technologies are encouraged. It is critical that the offeror states for the proposed measurements how the data, obtained either in real-time or post-operation, would be utilized to quantify parameters in the nuclear propulsion system (most especially in the nuclear reactor core) that will permit the quantification of operational lifetime margin in situations (like a flight test) where post-test disassembly and detailed inspection are not possible.

Please note that the following areas are excluded from Z-GO.02 this year:

- Coatings for science missions (seeking cold temperature, complex geometries, and low alpha at end of life) (offerors are suggested to consider S16.05 “Thermal Control Systems")
- Coatings for human spacecraft, habitats, or vehicles (offerors are suggested to consider Z-LIVE.02 “Spacecraft Thermal Management”)

Expected TRL or TRL Range at completion of the Project: 2 to 4

Primary Technology Taxonomy:

- Level 1: TX 01 Propulsion Systems
- Level 2: TX 01.4 Advanced Propulsion

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype

Desired Deliverables Description:

Desired deliverables for this technology would include research that can be conducted to determine technical feasibility of the technology during Phase I and show a path toward a Phase II hardware demonstration. Testing the technology in a simulated (as close as possible) operating 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 to 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 3 to 4). Also delivered is a prototype of the proposed technology for NASA to do further testing if Phase II results show promise for application. Opportunities and plans should also be identified and summarized for potential commercialization of the proposed technology. Unique government facilities can be used as part of Phase II.

State of the Art and Critical Gaps:

Current space radiators do not operate at the required high temperatures needed for higher power density NEP systems. Fuel element insulators were developed during the past Project Rover and Nuclear Engine for Rocket Vehicle Applications (NERVA) programs. However, the current NTP performance requires higher core temperatures. Since all nuclear engines are not coming back down to Earth after the mission due to radioactivity, the more operational and post burn examination done in space the better understanding of space nuclear propulsion operation. The reactors and surrounding subsystems are too radioactive for astronauts to check out so requires robotics. Existing terrestrial reactors contain sensors to remotely conduct radiation shielding surveys, coolant leak detection, and other functions during operations. This gap anticipates the need for that technology in operations space reactor systems and seeks innovations to perform those functions for the space environment. The examination challenge applies to all future nuclear engine concepts in space.

Civil Space Shortfall Ranking https://www.nasa.gov/spacetechpriorities/

- 709: Nuclear Electric Propulsion for Human Exploration
- 702: Nuclear Thermal Propulsion for Human Exploration
- 705: Low Power Nuclear Electric Propulsion
- 1488: Additive Manufacturing for Propulsion
- 1540: Intelligent Robots for the Servicing, Assembly, and Outfitting of In-Space Assets and Industrial-Scale Surface Infrastructure
- 612: In-Space Diagnostics for Electric Propulsion
- 1619: High Temperature Heat Rejection for Nuclear Applications

Relevance / Science Traceability:

Future mission applications include:

- Human Missions to Mars and Cislunar Space
- Robotic Science Missions to Outer Planets
- Nuclear Surface Power Systems
- Planetary Defense
- Department of Defense activities
- Department of Energy activities

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Z-GO.03: Solar Photon Sails Research and Technology Development (SBIR)

Lead Center: MSFC
Participating Center(s): N/A

Subtopic Introduction:

Solar photon sails are a propellant propulsion method that harnesses radiation pressure from solar photons to generate thrust. Photon sails are an enabling technology that enables a host of science and exploration missions, platforms for enhanced space weather observation and warnings, and missions of interest to other government agencies. For example, solar photon sails can enable: (1) science missions for heliophysics, such as high inclination solar imaging and sustained sub-Sun/Earth L1 and Earth magnetotail observations; (2) planetary science missions to locations requiring large DeltaV, such as hard to reach asteroid and Kuiper belt objects, Mercury, and others; (3) long-duration Earth and lunar pole sitters; and (4) fast transit missions, such as the interstellar probes and those to the solar gravity lens. Photon sail technologies can also form the basis for non-nuclear exploration of the outer solar system. The intent of this SBIR subtopic is to advance photon sail technologies and position NASA and the broader community to make these missions a reality.

Technologies solicited for fiscal year 2025 include near-term technologies, specifically embedded roll control devices, and mid-term technologies, specifically sail materials, coatings, and embedded roll control devices for very high temperatures.

Scope Title: Embedded Roll Control Devices: Sail Integration Innovation

Scope Description:

Innovations to embed mature roll control technologies directly into a solar sail membrane are being solicited. New roll control methods will not be considered as a part of this scope (see scope #2 for new concepts). Roll control is essential to successful photon sail-craft attitude control. Embedded roll control devices, likely near the distal ends of the sail, will save significant mass and increase characteristic acceleration, especially for longer-term missions and larger photon sail classes. Several embedded roll control technologies, such as reflective control devices and diffractive sail membranes have been developed to TRL 3-6. Innovations and process optimizations are needed to integrate these devices directly into flight solar sail builds. Integrated can be in situ during the membrane build or post processed after the membrane is complete.

- Device Torque Capability: >40e-6 N*m (over total area)
- Integrated Solution Specific Mass: <250 g/m^2
- Integrate Solution Power Draw: <5.5 Watts @ <40V operating voltage
- Temperature Operation: -30 ℃ to +60 ℃

Expected TRL or TRL Range at completion of the Project: 4 to 6

Primary Technology Taxonomy:

- Level 1: TX 01 Propulsion Systems
- Level 2: TX 01.4 Advanced Propulsion

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

In Phase I, a detailed design for integration is desired. Key performance parameters should be identified and quantified, including risk to the sail membrane (e.g., tearing), mass per unit area (roll control device plus integration materials, power cabling, etc.), and the like. A moderate fidelity prototype (TRL 4) is highly desired in Phase I.

In Phase II, maturation of the process to TRL 6 and delivery of flight ready, sail integrated roll control devices (total area TBD after Phase I) is required.

State of the Art and Critical Gaps:

State of the art for photon sail attitude control consists of reaction wheels, cold gas thrusters, and active mass translation. See, for example, NASA's NEA Scout design. The Japan Aerospace Exploration Agency (JAXA), through the Interplanetary Kite-craft Accelerated by Radiation Of the Sun (IKAROS) program, demonstrated an early version of embedded reflective control devices.

Civil Space Shortfall Ranking https://www.nasa.gov/spacetechpriorities/

- 700: Solar Sails for Propellant-less Propulsion

Relevance / Science Traceability:

Solar photon sails are a propellant propulsion method that harnesses radiation pressure from solar photons to generate thrust. Photon sails enable a host of science and exploration missions, platforms for enhanced space weather observation and warnings, and missions of interest to other government agencies. For example, solar photon sails can enable (1) science missions for heliophysics, such as high inclination solar imaging and sustained sub-Sun/Earth L1 and Earth magnetotail observations; (2) planetary science missions to locations requiring large DeltaV, such as hard to reach asteroid and Kuiper belt objects, Mercury, and others; (3) long duration Earth and lunar pole sitters; and (4) fast transit missions, such as the interstellar probes and those to the solar gravity lens. Photon sail technologies can also form the basis for non-nuclear exploration of the outer solar system. Roll control is an essential component in the attitude control subsystem to maintain control of solar sail spacecraft. While short mission durations with lower characteristic acceleration requirements can be conducted without embedded roll control devices (e.g., with SEP), the mass savings of embedded devices.

References:

Solar Sail Attitude Control:

1. Solar Sail Attitude Control and Dynamics, Part 1. Journal of Guidance Control, and Dynamics, Vol. 27, No. 4, July-August 2004. https://arc.aiaa.org/doi/pdf/10.2514/1.11134
2. Solar Sail Attitude Control and Dynamics, Part 2. Journal of Guidance, Control, and Dynamics, Vol. 27, No. 4, July-August 2004. https://arc.aiaa.org/doi/pdf/10.2514/1.11133

Reflective Control Devices:
1. Flight Status of IKAROS Deep Space Solar Sail Demonstrator. Acta Astronautica. Vol. 69, Issues 9-10, November-December 2011. https://www.sciencedirect.com/science/article/abs/pii/S0094576511001822?via%3Dihub
2. Controllable Propulsion by Light: Steering a Solar Sail via Tunable Radiation Pressure. Adv Optical Mater, 2017. https://static1.squarespace.com/static/5d832a10791b8a06dddc7b1f/t/5d85766c0d2bbb181ed81ed2/1569027715163/Ma_Advanced_Optical_Materials_2017.pdf

Diffractive Solar Sail
1. Swartzlander, G. Theory of Radiation Pressure on a Diffractive Solar Sail. Journal of the Optical Society of America, Vol. 39, Issue 9, 2022. https://opg.optica.org/josab/fulltext.cfm?uri=josab-39-9-2556&id=497589

Scope Title: Sail Materials, Coatings, and Attitude Control to Enable High Temperature Photon Sail Missions

Scope Description:

This subtopic scope solicits innovations to enable high-temperature photon sail missions. Specifically, this scope will consider new sail materials, coatings for application on existing sail materials, and new or significantly enhanced attitude control and momentum management technologies (with an emphasis on roll control). High-temperature survivability and operation is essential to enable the next class of photon sail missions, which includes missions to Mercury as well as missions with very close approach to the Sun.

All proposed technologies should define optical (e.g., reflectance and emissivity) properties as well as other essential material properties and thermal control combinations for operation at a minimum of 0.40AU with a goal of <0.15AU. Other key performance parameters should be defined and quantitatively estimated as well as compared to the state of the art.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:

- Level 1: TX 01 Propulsion Systems
- Level 2: TX 01.4 Advanced Propulsion

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

In Phase I, a detailed design should be completed, and key performance parameters should be identified and quantified including operating and survivability temperature ranges, mass per unit area (roll control device plus integration materials, sail material stack up, coating, etc.), optical characteristics and performance, and the like. A moderate fidelity prototype (TRL 3) is highly desired in Phase I.

In Phase II, maturation of the technology to TRL 5 is required. Moderate fidelity prototypes tested in key, relevant environments (e.g., thermal vacuum, radiation) is expected.

State of the Art and Critical Gaps:

State of the art for photon sail materials includes colorless polyimide 1. Coatings to date have been limited to thin-film aluminum; however, low-maturity concepts have been explored academically, including gold anodized aluminum, graphene bulk mixtures, silver, and the like. State of the art for photon sail attitude control consists of reaction wheels, cold gas thrusters, and active mass translation. See, for example, NASA's NEA Scout design. JAXA (Japan Aerospace Exploration Agency), through the IKAROS (Interplanetary Kite-craft Accelerated by Radiation Of the Sun) program, demonstrated an early version of embedded reflective control devices. Lower maturity concepts include diffractive solar sail membranes and additional formulations of liquid-crystal-based reflective control devices. In all the above, the critical gap is in thermal survivability and operation. Increasing the thermal performance to enable <0.40AU and <<0.40AU is needed.

Civil Space Shortfall Ranking https://www.nasa.gov/spacetechpriorities/

- 700: Solar Sails for Propellant-less Propulsion

Relevance / Science Traceability:

Photon sails are an enabling technology that can support a host of science, exploration, and defense missions. Photon sails can enable: (1) key missions for heliophysics, such as high inclination solar imaging and out of the ecliptic plane dust characterization; (2) key missions in planetary sciences, such as hard to reach asteroid and Kuiper belt studies; (3) long duration pole sitters, such as lunar south pole and Earth magnetotail observatories; and (4) fast transit missions, such as the interstellar probe and the solar gravity lens. Photon sail technologies can also form the basis for non-nuclear exploration of the outer solar system. Operation in very high-temperature environments is essential for several of these missions. In particular, photon sail mission concepts to Mercury require very high-temperature survivability. Further, Sundiver missions—those missions that utilize a very low perihelion—will require very high-temperature survivability.

References:

Solar Sail Attitude Control and trajectory:

1. Solar Sail Attitude Control and Dynamics, Part 1. Journal of Guidance, Control, and Dynamics, Vol. 27, No. 4, July-August 2004. https://arc.aiaa.org/doi/pdf/10.2514/1.11134
2. Solar Sail Attitude Control and Dynamics, Part 2. Journal of Guidance, Control, and Dynamics, Vol. 27, No. 4, July-August 2004. https://arc.aiaa.org/doi/pdf/10.2514/1.11133
3. Optimal Solar-Sail Trajectories for Missions to the Outer Solar System. Journal of Guidance, Control, and Dynamics, Vol. 28, No. 6, November-December 2005. https://arc.aiaa.org/doi/pdf/10.2514/1.13301

Reflective Control Devices:

1. Flight Status of IKAROS Deep Space Solar Sail Demonstrator. Acta Astronautica, Vol. 69, Issues 9-10, November-December 2011. https://www.sciencedirect.com/science/article/abs/pii/S0094576511001822?via%3Dihub
2. Controllable Propulsion by Light: Steering a Solar Sair via Tunable Radiation Pressure. Adv Optical Mater, 2017. https://static1.squarespace.com/static/5d832a10791b8a06dddc7b1f/t/5d85766c0d2bbb181ed81ed2/1569027715163/Ma_Advanced_Optical_Materials_2017.pdf

Diffractive Solar Sail

1. Swartzlander, G. Theory of Radiation Pressure on a Diffractive Solar Sail. Journal of the Optical Society of America, Vol. 39, Issue 9, 2022. https://opg.optica.org/josab/fulltext.cfm?uri=josab-39-9-2556&id=497589
2. Swartzlander, G. Theory of Radiation Pressure on a Diffractive Solar Sail. Journal of the Optical Society of America, Vol. 39, Issue 9, 2022. https://opg.optica.org/directpdfaccess/0245b7ba-737d-475f-958816db4c0a4dc4_497589/josab-39-9-2556.pdf?da=1&id=497589&seq=0&mobile=no

Solar Sail Material

3. Solar Sail: Materials and Space Environmental Effects. International Symposium on Solar Sailing, 2013. https://arxiv.org/pdf/1307.7327
4. Status of Solar Sail Technology Within NASA. Advances in Space Research, Vol. 48, Issue 11, December 2011. https://www.sciencedirect.com/science/article/pii/S0273117710007982
5. Solar Sailing Technology Challenges. Aerospace Science and Technology, Vol. 93, October 2019. https://www.sciencedirect.com/science/article/pii/S1270963818314391

Z-LAND.01: Parachute Systems for Maneuverability and Wireless Data Acquisition (SBIR) (Previously Z7.01)

Lead Center: ARC
Participating Center(s): JPL

Subtopic Introduction:

The Parachute Systems for Maneuverability and Wireless Data Acquisition subtopic seeks proposals for technologies that will enable maneuverability of parachutes to reduce delivery targeting errors and for wireless transmission and acquisition of in-flight data from sensors installed on a parachute canopy. Proposals will need to address the challenges associated with parachute measurements, including the need to consider the mass impact of the wireless transmitter nodes installed on the canopy and the central node/receiver located within the payload carried by the parachute. Proposals should strive for a solution that is as unobtrusive as possible to the reliable deployment, inflation, function, and performance of the parachute. Concepts for a steerable parachute guidance system should address how the system mitigates the adverse effect of winds during the subsonic descent phase.

Scope Title: Wireless Data Acquisition System for Entry, Descent, and Landing (EDL) Parachutes

Scope Description:

NASA is testing and developing strain sensors that will make local strain measurements at various points on a parachute canopy as the parachute deploys. These measurements will inform parachute design and reliability and increase understanding of parachute performance. Wiring a sensor from the parachute canopy, down suspension lines, and into a payload poses many challenges such as tangled wires with parachute lines, the chaotic and impulsive shock of parachute deployment, and added mass that could impact parachute deployment. Therefore, NASA is seeking a data acquisition system that can wirelessly transfer data from the sensors on the parachute canopy to the payload to which the parachute is attached.

Desired characteristics of the wireless data acquisition system include the following:

- Central node/data recorder that will be contained within the payload of the parachute and will receive and save sensor data sent from the outer nodes (antenna external to the payload is acceptable)
- Outer nodes co-located with sensor(s) will wirelessly transmit to the central node ≥ 30 meters away and will experience erratic movements during parachute deployment
- Modular and scalable design that can accommodate up to hundreds of measurement channels
- Physical Characteristics
    - Outer nodes should be able to withstand pressure packing up to 45 lb/ft^3 in the parachute container
    - Maximum Weight per outer node*: 2 oz
    - Maximum Size per outer node*: 2 in. x 2 in. x 0.25 in.
    - Maximum Weight of Central Node/Data Recorder*: 10 lbs
    - Maximum Size of the Central Node/Data Recorder*: 100 in^3
- Electrical Characteristics
    - Node must accept serial digital input (ex. I2C) from sensor(s)
    - Self-contained power (i.e., battery) for outer nodes and central node/data recorder
    - Time synchronization of all sensor data
    - Autonomous triggering to initiate sensor measurement
    - Minimum measurement resolution: 8-bit
    - Minimum acquisition rate per outer node input channel: 1.2 kHz
    - Minimum duration per node outer input channel: 30 seconds from trigger
    - Maximum length of time to complete recording at central node: 10 minutes
    - Measurement channels per outer node: 1-10
    - (Optional) power sensors at 5V in addition to the outer nodes

*Weight and sizes are all-inclusive (batteries, antennas, hardware, etc).

Expected TRL or TRL Range at completion of the Project: 4 to 6

Primary Technology Taxonomy:

- Level 1: TX 09 Entry, Descent, and Landing
- Level 2: TX 09.5 Flight Mechanics and GN&C for Entry, Descent, and Safe Precise Landing

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware

Desired Deliverables Description:

Phase I Deliverables: Demonstrate functionality of single node wirelessly transmitting data from a sensor to a central node/data recorder at a distance of ≥30 meters with prototype hardware. Define the design and plans for scaling to multiple nodes and time synchronization of data.

Phase II Deliverables: Demonstrate functionality of multiple nodes wirelessly transmitting data from at least 20 sensors to the central node/data recorder at a distance of ≥30 meters with prototype hardware. Demonstrate time synchronized recorded data from all sensors.

State of the Art and Critical Gaps:

There is currently no commercial off-the-shelf wireless data acquisition system (DAS) at a sufficiently high Technology Readiness Level (TRL) suitable for flight parachute instrumentation applications. NASA has a strong interest in understanding the performance and reliability of parachute-payload systems, and in-situ flight data (such as parachute strain measurements) are needed for model validation and identifying potential failure modes. Such data would give insight into overall entry and descent system reliability for both Earth and Mars entries that is currently not available. Wireless communication between outer nodes on a parachute canopy and a central node/receiver within the payload represents a significant advancement to the state-of-the-art for parachute design, development, and testing. Low size, weight, power, and cost (SWaP-C) instrumentation systems remain highly desirable.

Civil Space Shortfall Ranking https://www.nasa.gov/spacetechpriorities/

- ID 1564: Aeroshell In-Situ Flight Performance Data during EDL
- ID 1574: Validated Performance Models for Planetary Parachutes

Relevance / Science Traceability:

The solicitation directly maps to NASA's Space Technology Mission Directorate's technology shortfalls ("Validated Performance Models for Planetary Parachutes") and areas of need. Parachutes remain an unpredictable and single failure event for missions involving entry, descent, and landing (EDL). In-flight data of parachute performance is needed to improve current models that predict parachute performance. NASA New Frontiers missions, Orion Capsule Parachute Assembly System (CPAS), and future missions to Mars, as well as commercial partners, can all greatly benefit from improvements in current predictive capabilities of parachutes and from a wireless data acquisition system in general.

References:

1. Daniel Budolak, L. Hantsche, E. Rossi De La Fuente, "Strain Sensor Survey for Parachute Canopy Load Measurements." AIAA 2022-2754, AIAA Aerodynamic Decelerator Systems Technology Conference, May 2022.
2. Wahab Alshahin, J. Daum, et. al., "Design of a Parachute Canopy Instrumentation Platform," AIAA 2015-2150, AIAA Aerodynamic Decelerator Systems Technology Conference, April 2015.

Scope Title: Steerable Subsonic Parachute System to Improve Planetary Landing Accuracy

Scope Description:

Advancements are desired in a steerable parachute system for a notional low cost 600 kg payload with a target terminal descent velocity of Mach 0.26 on Mars. The desired system must be designed to be capable of the high altitude, high subsonic velocity deployment and inflation for Mars planetary entry. The desired system should also be self-guided and capable of maneuverability with a glide ratio of 0.5 shortly after deployment. Reliability and mass efficiency are of paramount importance.

Steerable subsonic parachutes for Mars entry have been analyzed and tested in previous efforts to improve landing accuracy with some success. However, since those previous programs, advancements have been made that should have a positive impact on canopy performance, mass efficiency, and cost of incorporating a subsonic steerable parachute system into the EDL sequence.

The US Army working with industry has advanced bleed air technology to utilize lightweight in-canopy actuators to affect control of the canopy flight. These advancements, in conjunction with improvements made by industry in the performance of steerable round parachutes such as the SF-10, MC-6, and high altitude bail out parachutes, provide an opportunity to bring these improvements to close these critical gaps. In addition, NASA JPL has flight-proven advancements in ground tracking and situational awareness technology from the Ingenuity program that can be utilized as inputs for a new steerable round parachute's guidance system [Ref. 1].

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:

- Level 1: TX 09 Entry, Descent, and Landing
- Level 2: TX 09.2 Descent

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

Phase I Deliverables:

- The focus of Phase I development can be investigation of suitable parachute system designs, and assessment of any prior testing of complete assemblies showing low altitude or wind tunnel proof of concepts.
- Reports documenting analysis and development results, including description of any materials, hardware, or prototypes investigated or developed.

Phase II Deliverables:

- Manufacturing scale-up and approved testing in relevant environments for applications related to Mars, Venus, and/or Titan in addition to suborbital and return to Earth.
- Test Reports providing complete documentation of the following: test set up, test parameters, units under test, and all testing accomplished, as well as lessons learned and path forward recommendations.

State of the Art and Critical Gaps:

The requirement to improve the landing accuracy of planetary spacecraft becomes ever more critical as new missions look to link up with and leverage in-situ prior missions. In order to accomplish this improvement, the sum of all factors that impact the accuracy of planetary spacecraft landing must be addressed.

The reduced spacecraft velocity, the duration of traverse time, and the unknown and variable nature of the winds during the subsonic descent under parachute combine to make this stage of the EDL process a major source of landing ellipse uncertainty. Under the current state of the art, ballistic non-guided deceleration during this stage is accomplished by either a single stage supersonic Disk Gap Band (DGB) type parachute or a multi-stage supersonic DGB transitioning to a subsonic ballistic parachute of various types. In either case, during this subsonic deceleration stage under parachute, there is currently no attempt to mitigate the deleterious effects of the wind or other atmospheric uncertainty.

Civil Space Shortfall Ranking https://www.nasa.gov/spacetechpriorities/

- ID 1564: Aeroshell In-Situ Flight Performance Data during EDL
- ID 1574: Validated Performance Models for Planetary Parachutes

Relevance / Science Traceability:

NASA needs advanced deployable aerodynamic decelerators to enhance and enable robotic and human space missions. Applications include Mars, Venus, and Titan in addition to suborbital and return to Earth. ESDMD (Exploration Systems Development Mission Directorate), SOMD (Space Operations Mission Directorate), STMD (Space Technology Mission Directorate), and SMD (Science Mission Directorate) can benefit from this technology for various exploration missions.

References:

1. H. F. Grip et al., "Flying a Helicopter on Mars: How Ingenuity's Flights were Planned, Executed, and Analyzed," 2022 IEEE Aerospace Conference (AERO), Big Sky, MT, USA, 2022, pp. 1-17, doi: 10.1109/AERO53065.2022.9843813.
2. Keith Bergeron, M. Ward, M. Costello and S. Tavan, "AccuGlide 100 and Bleed-Air Actuator Airdrop Testing," AIAA 2013-1378. AIAA Aerodynamic Decelerator Systems (ADS) Conference. March 2013.

Z-LAND.02: Entry and Descent System Technologies (SBIR) (Previously Z7.03)

Related Subtopic Pointers: T12.10
Lead Center: LaRC
Participating Center(s): ARC

Subtopic Introduction:

NASA is advancing deployable aerodynamic decelerators and 3D-woven/porous thermal protection system (TPS) concepts to enhance and enable robotic and human space missions involving entry and aerocapture phases. Applications include Mars, Venus, and Titan in addition to suborbital and return to Earth. The benefit of deployable decelerators is that the entry vehicle structure and TPS are not constrained by the launch vehicle shroud. Deployable decelerators have the flexibility to use the available shroud volume more efficiently 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 a 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. The benefit of 3D-woven/porous TPS is having a highly reliable thermal-structural component suitable for use in part or in whole on a heatshield. 3D-Woven/porous TPS enables return of human and robotic missions from the moon and Mars.

This subtopic area solicits innovative technology solutions applicable to both deployable and 3D-woven/porous TPS concepts. Specific technology development areas include (1) gas generator development for hypersonic inflatable aerodynamic decelerators (HIAD), (2) modelling of 3D-woven/porous TPS resin infusion processes, and (3) oxidation resistant coatings for 3D-woven flexible carbon fabric.

Scope Title: Gas Generators for Hypersonic Inflatable Aerodynamic Decelerators (HIADs)

Scope Description:

Development is desired of gas generator technologies to be used as inflation systems that result in improved mass efficiency and reduced system complexity over current pressurized cold gas systems for inflatable structures. Inflation gas technologies can include warm or hot gas generators, sublimating powder systems, or hybrid systems; however, the final delivery gas temperature is preferred to not exceed 50°C but must not exceed 200°C. Note that higher temperature gas deliveries require rapid deployment of additional gas to account for mass collapse at the onset of g-loading. Lightweight, high-efficiency gas inflation technologies capable of delivering gas between a range of 250 to 10,000 standard liters per minute (SLPM) are sought. This range spans a broad number of potential applications. Thus, a given response or solution need not address the entire range but can instead focus on a narrower range and application. Additionally, the final delivery gas and its byproducts must not harm aeroshell materials such as the fluoropolymer liner of the inflatable structure. Generator delivery of combustible (e.g., hydrogen) and non-combustible (e.g., nitrogen) gasses are highly desired for longer duration planetary space missions and shorter duration suborbital missions closer to Earth. Minimal solid particulate is acceptable as a final byproduct. Water vapor as a final byproduct is also acceptable for lower flow (250 to 4,000 SLPM) and short duration sub-orbital missions but is undesirable for higher flow (8,000 to 10,000 SLPM) and longer duration planetary space missions. Chillers and/or filters can be included in a proposed solution but will be included in assessing overall system mass versus amount of gas generated. Gas delivery configurations that rely on active flow-control devices are not desired. Mission applications will have inflatable volumes in the range of 1,200 to 4,000 ft^3 with final inflation pressures in the range of 15 to 45 psig. Initial concepts will be demonstrated with small-scale volumes to achieve the desired inflation pressures and temperatures. The focus of Phase I development can be subscale manufacturing demonstrations that show proof of concept and lead to Phase II manufacturing scale-up and testing in relevant environments for applications related to human-scale Mars entry, Earth return, or launch vehicle asset recovery.

Expected TRL or TRL Range at completion of the Project: 1 to 4

Primary Technology Taxonomy:

- Level 1: TX 09 Entry, Descent, and Landing
- Level 2: TX 09.1 Aeroassist and Atmospheric Entry

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Reports documenting analysis and development results, including description of any hardware or prototypes developed. The focus of Phase I can be subscale component development and manufacturing demonstrations that show proof of concept and lead to Phase-II manufacturing scale-up and testing in relevant environments for applications related to Mars and other planetary entry, Earth return, or launch vehicle asset recovery.

State of the Art and Critical Gaps:

The current state of the art for domestic gas generators is still limited due to the nascency of this technology. The U.S. remains woefully behind the rest of the world when it comes to this technology. Development of gas generator technologies that improve gas chemistries and materials, improve mass and structure efficiency, reduce system complexity, improve filtering and thermal performance, and lower costs over current pressurized cold gas systems for inflatable structures are needed.

Civil Space Shortfall Ranking https://www.nasa.gov/spacetechpriorities/

- ID 1569 – High-Mass Mars Entry and Descent Systems (Inflatable Decelerators part)

- EDL&PL-298: Ground Development and Scale-Up of Inflatable Decelerators
- EDL&PL-306: Control Technologies for Exploration Class Inflatable Decelerators

Relevance / Science Traceability:

NASA needs advanced deployable aerodynamic decelerators to enhance and enable robotic and human space missions. Applications include Mars, Venus, and Titan in addition to suborbital and return to Earth. ESDMD (Exploration Systems Development Mission Directorate), SOMD (Space Operations Mission Directorate), STMD (Space Technology Mission Directorate), and SMD (Science Mission Directorate) can benefit from this technology for various exploration missions.

References:

1. Hughes, S.J., et al., "Hypersonic Inflatable Aerodynamic Decelerator (HIAD) Technology Development Overview," AIAA Paper 2011-2524.
2. Bose, D.M, et al., "The Hypersonic Inflatable Aerodynamic Decelerator (HIAD) Mission Applications Study," AIAA Paper 2013-1389.
3. Hollis, B.R., "Boundary-Layer Transition and Surface Heating Measurements on a Hypersonic Inflatable Aerodynamic Decelerator with Simulated Flexible TPS," AIAA Paper 2017-3122.
4. Olds, A.D., et al., "IRVE-3 Post-Flight Reconstruction," AIAA Paper 2013-1390.
5. Del Corso, J.A., et al., "Advanced High-Temperature Flexible TPS for Inflatable Aerodynamic Decelerators," AIAA Paper 2011-2510.

Scope Title: Modelling of TPS Resin Infusion Processes

Scope Description:

A number of Thermal Protection System (TPS) materials are manufactured by the infusion of a resin or resin solution into a 3D woven or porous preform, followed by cure and removal of the solvent if required. An example of this is Phenolic Impregnated Carbon Ablator (PICA) that has been used in the heat shields for the Mars Science Laboratory (Curiosity), Mars 2020 (Perseverance), Stardust, and OSIRIS-Rex missions. US patent 5536562 provides information on the types of infusion of interest including PICA.

To date there has been little to no detailed modeling of these infusion and cure processes. Therefore, engineering judgement and trial and error are used when scaling up these processes to larger parts or different geometries, looking at the infusion into different preform materials, or using different resins/resin solutions rather than having process modelling to guide the activities which could potentially reduce cost and accelerate development timelines.

Advances are sought in the ability to model the resin infusion and curing processes of thermal protection materials that are manufactured by the infusion of an organic resin/resin solution into a fibrous preform, including but not limited to the rigid carbon binder/carbon fiber preform used in the manufacturing of PICA, 3D woven preforms and non-woven preforms, each of which may have variable characteristic porosity scales that could range from 10's to 100's of microns. Examples of desired model capabilities include, but are not limited to, influence of porosity scale on quality of infusion; characterizing thermal gradients, off-gassing, and shrinkage during cure; and optimization of process parameters. Such capabilities will aid in the development of resin infusion and cure processes to eliminate defects due to poor infusion and to reduce cost and time associated with adapting these processes to larger scales, different shapes, different preform materials, and different resins.

Expected TRL or TRL Range at completion of the Project: 1 to 4

Primary Technology Taxonomy:

- Level 1: TX 09 Entry, Descent, and Landing
- Level 2: TX 09.1 Aeroassist and Atmospheric Entry

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

The desired deliverable from Phase I would include custom software or a plugin to a commercial off the shelf package that demonstrates capabilities to model vacuum infusion of fiber-based or woven preforms with uniform porosities with small effective porosity sizes 10-100 microns with solutions having low resin/solvent as well as the cure cycle under vacuum, including off-gassing and prediction of remaining solvent. The desired deliverable from a Phase II would include an extension of Phase I to model systems with multiscale, heterogeneous porosities ranging from 10-1000 microns and the capability to track internal solvent gas evolution and flow during the cure process.

State of the Art and Critical Gaps:

Infusion process models have predominantly focused on optimizing manufacture of structural composites, which have high resin loading and relatively permeable preforms based on aligned fibers or simple weave structures. Process modeling for fiber-preform or woven Thermal Protection System (TPS) materials, however, is less mature given that the preforms of such systems are highly porous but can have small effective pore sizes (or multiscale porosities) and require low density loadings of resin with tight requirements on cured resin morphology. Thus, for TPS materials, both diffusion and permeation of resin-solvent solutions and liquid-gas equilibrium during heating and cure play a large role in determining the quality of the final material.

Civil Space Shortfall Ranking https://www.nasa.gov/spacetechpriorities/

- ID 1569 – High-Mass Mars Entry and Descent Systems
- EDL&PL-406: Exploration Class Mid L/D System
- ID 1572 – Performance-Optimized Low-Cost Aeroshells for EDL Missions
  - EDL&PL-297: Efficient Backshell TPS
- EDL&PL-300: Efficient Heatshield TPS
- EDL&PL-302: High-Mass, High-Velocity Earth Entry Thermal Protection Systems
- EDL&PL-303: Mass-Efficient Large Aeroshell Structures
- EDL&PL-407: Multi-Use Ablative TPS
- EDL&PL-413: Efficient Reusable TPS
- EDL&PL-414: Cost Efficient TPS Certification
- ID 1568 (Maybe) – Entry Modeling and Simulation for EDL Missions
  - EDL&PL-295: TPS Modeling & Optimization for Human Mars Exploration
  - EDL&PL-296: TPS Modeling & Optimization for Robotic Missions
  - EDL&PL-1440: Validated Thermostructural Modeling for TPS Integrated onto Aeroshell Structure

Relevance / Science Traceability:

NASA needs advanced high reliability TPS to enhance and enable robotic and human space missions. Applications include Mars, Venus, and Titan in addition to suborbital and return to Earth. ESDMD (Exploration Systems Development Mission Directorate), STMD (Space Technology Mission Directorate), and SMD (Science Mission Directorate) can benefit from this technology for various exploration missions.

References:

1. US patent 5536562 provides information on the types of infusion of interest including PICA.
2. Ellerby, Donald T., and Matthew J. Gasch. "Heatshield for extreme entry environment technology (HEEET) thermal protection system (TPS)." In Annual Conference on Composites, Materials, and Structures, no. ARC-E-DAA-TN72926. 2019.
3. Ellerby, Don, Ron Chinnapongse, Dave Driver, Matt Gasch, Ken Hamm, Jean Ma, Frank Milos et al. "Heatshield for extreme entry environment technology (HEEET) development status." In New Frontiers Technology Workshop, no. ARC-E-DAA-TN32543. 2016
4. Stackpoole, M., Sepka, S., Cozmuta, I., and Kontinos, D., “Post-Flight Evaluation of Stardust Sample Return Capsule Forebody Heatshield Material,” AIAA paper 2008-1202, Jan 2008.
5. Beck, Robin A. S., James O. Arnold, Matthew J. Gasch, Margaret M. Stackpoole, Dinesh K. Prabhu, Christine E. Szalai, Paul F. Wercinski, and Ethiraj Venkatapathy. "Conformal ablative thermal protection system for planetary and human exploration missions: an overview of the technology maturation effort." In International Planetary Probe Workshop, no. ARC-E-DAA-TN9855. 2013.
6. Stackpoole, M., Venkatapathy, E., & Violette, S. (2018, March). Sustaining PICA for future NASA robotic science missions including NF-4 and discovery. In 2018 IEEE Aerospace Conference (pp. 1-7). IEEE.

Scope Title: Oxidation resistant coatings for 3D-woven flexible carbon fabric for mechanically deployable (Adaptable Deployable Entry and Placement Technology, ADEPT) hypersonic decelerators

Scope Description:

NASA is advancing deployable aerodynamic decelerators to enhance and enable robotic and human space missions. Applications include Mars, Venus, and 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 systems are not constrained by the launch vehicle shroud. Deployable decelerators have the flexibility to use the available shroud volume more efficiently and can be packed into a much smaller volume for Earth departure, addressing potential constraints for payloads sharing a launch vehicle. Mechanically deployable hypersonic decelerators, such as the ADEPT, have been studied and developed for a variety of mission classes and scales. There are mission applications of the ADEPT technology which utilize a 3D-woven flexible carbon aeroshell to enable sample return and Earth aerocapture missions for a wide range of payload sizes and masses. Mission scenarios may require the need for extended on-orbit operations that require the carbon fabric to survive the oxidizing environment associated with not only the aerothermal heat pulse but also atomic oxygen (AO) present in LEO. Development of oxidation resistant coatings that can be applied to the 3D-woven carbon fabric and/or carbon fibers to eliminate carbon fabric mass loss due to oxidizing environments in space would enable this entry technology to support a wide variety of NASA and commercial mission applications.

Requirements to consider when developing the coating approach:

- Coating must allow for the carbon fabric to be folded and stowed prior to launch.
- Coating does not rigidize/embrittle the fabric during heating.
- Coating is effective in preventing atomic oxygen degradation.

- For fiber level coatings applied prior to weaving, the coating needs to remain intact during weaving, stowage, and deployment.

Expected TRL or TRL Range at completion of the Project: 1 to 4

Primary Technology Taxonomy:

- Level 1: TX 09 Entry, Descent, and Landing
- Level 2: TX 09.1 Aeroassist and Atmospheric Entry

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

Reports and test results documenting analysis and development results, including description of coating composition, application, and integration with woven carbon fabric and/or carbon fibers. The focus of Phase I development can be a design with some modeling and initial demonstrations of high temperature performance (survival up to 1250°C) and demonstration of coating uniformity, adhesion, and long-term stability on carbon fabric and/or carbon fibers. That would lead into Phase II, where the design is developed and demonstrated on relevant material and meeting operational requirements such as maintained coating integrity after fabric folding and unfolding with the technology being made ready for adoption by NASA missions.

State of the Art and Critical Gaps:

Currently 3D-woven carbon fabric has been manufactured, thermally tested, and integrated into small scale hypersonic heatshields for ADEPT mission application. Some applications of interest may result in carbon fabric recession primarily due to oxidation. In such instances, oxidation-resistant coatings may reduce the mass and enhance the life expectancy of carbon fabric, thereby enabling missions to Mars, Venus, and other solar system destinations in the future.

Civil Space Shortfall Ranking https://www.nasa.gov/spacetechpriorities/

- ID 1563 – Aerocapture for Spacecraft Deceleration and Orbit Insertion (Specifically TPS Materials and Associated Tech Dev)
  - EDL&PL-304: Ice Giant Aerocapture
  - EDL&PL-346: Small Spacecraft Aerocapture
- ID 1567 – Entry Capabilities for Small-Scale and Commercial Spacecraft (Specifically TPS Materials and Associated Tech Dev)
  - EDL&PL-163: High-Reliability Earth Entry Vehicles for Robotic Missions
- EDL&PL-307: Small Spacecraft EDL
- EDL&PL-308: Small Entry Vehicle Test Platform
- EDL&PL-309: Low Cost On-Demand Payload Return
- EDL&PL-344: Small Spacecraft Propellentless Deorbit Devices

Relevance / Science Traceability:

NASA needs advanced hypersonic deployable decelerators to enhance and enable robotic and human space missions. The advances would directly address the following STMD LAND Shortfalls:

- EDL&PL-302: High-Mass, High-Velocity Earth Entry Thermal Protection Systems
- EDL&PL-303: Mass-Efficient Large Aeroshell Structures
- EDL&PL-346: Small Spacecraft Aerocapture
- EDL&PL-309: Low Cost On-Demand Payload Return
- EDL&PL-344: Small Spacecraft Propellentless Deorbit Devices

References:

1. Arnold, J., et al., "Thermal and Structural Performance of Woven Carbon Cloth for Adaptive Deployable Entry and Placement Technology," AIAA Aerodynamic Decelerator Systems Technology Conference, March 25-28, 2013, Daytona Beach, FL.
2. Kazemba, C., et al, "A Versatile 3D-Woven Carbon Fabric for Broad Mission Application of ADEPT" International Planetary Probe Workshop, June 16-20, 2014, Pasadena, CA.
3. Cassell, Alan, M., et al. "System Level Aerothermal Ground Testing for the Adaptive Deployable Entry and Placement Technology." International Planetary Probe Workshop, June 13-17, 2016, Laurel, MD.
4. Cassell, A. M., et al "ADEPT, a Mechanically Deployabe Re-Entry Vehicle System, Enabling Interplanetary CubeSat and Small Satellite Missions" SmallSat 2018, Logan, UT, August 2018.

Z-LAND.03: Plume-Surface Interaction (PSI) Technologies (SBIR) (Previously Z7.07)

Lead Center: LaRC
Participating Center(s): MSFC

Subtopic Introduction:

This subtopic is focused on advancing NASA capabilities in measuring, predicting, and mitigating PSI physics. Flight instrumentation and sensors that are specifically designed to capture data relevant to PSI are desired. Innovative predictive models and tools with tractable paths to application-level utilization to characterize the induced landing environment from a terminal landing phase of flight are also sought, along with further development of tools that can ingest PSI-ejecta field data to predict the effects on a vehicle and local surface environment for mission planning and design. The following are not within scope for this subtopic: development of propulsion modeling capabilities and systems; dust mitigation and dust modeling; guidance, navigation, and control (GNC) sensors or any sensors not explicitly characterizing PSI physics; and surface operations and infrastructure.

Scope Title: PSI Instrumentation, Ground Testing, and Analysis

Scope Description:

As NASA and commercial entities prepare to land robotic and crewed vehicles on the Moon and other planetary bodies, characterization of the environments induced by propulsive descent and landing is critical to identifying and verifying requirements for landing systems, including descent and landing concept of operations, engine configuration, instrument and sensor placement and protection, vehicle stability, and surface and proximity infrastructure and operations. The ability to predict the extent to which regolith is liberated and transported in the vicinity of the lander is critical to understanding the risks posed by these PSI environment effects and for safe and reliable vehicle performance assessment. Knowledge of the surface erosion and characteristics, behavior, and trajectories of ejected particles during the landing phase is important for designing effective sensor systems and PSI risk mitigation approaches. Mission applications include lunar and planetary destinations, robotic and crewed landers, and pulsed and throttled propulsion systems.

NASA is seeking support in the following areas:

1. Ground-test data and mission-relevant test techniques across physical scales and environments, with particular emphasis on nonintrusive approaches and methodologies that advance (or restore) the state of the art.

2. PSI-specific flight instrumentation, with particular emphasis on the time-evolving surface topography and in situ measurements of particle size and particle velocity during the landing phase.

3. Solutions to alleviate or mitigate the PSI environments experienced by propulsive landers—not vehicle-specific solutions—with near-term implementation paths.

4. Innovative, validated, robust models and tools for predicting PSI physics for plumes in low-pressure and rarefied environments, time-evolving cratering and surface erosion, and near-field and far-field ejecta transport.

5. Ejecta tools or analyses that use PSI-ejecta field data to predict effects on the vehicle and surface infrastructure for landing and mission design.

NASA has plans to purchase services for payload delivery 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 PSI technologies in the lunar environment. The CLPS payload accommodations will vary depending on the particular service provider and mission characteristics, but the data to be obtained or mitigations to be demonstrated should be broadly applicable to other future landing systems and mission destinations. 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 are currently under contract, 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 5

Primary Technology Taxonomy:

- Level 1: TX 09 Entry, Descent, and Landing
- Level 2: TX 09.3 Landing

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

For PSI ground-test data, flight instrumentation, diagnostics, and mitigation approaches, Phase I deliverables should include detailed test plans, with prototype and/or component designs and demonstrations as appropriate. Phase II deliverables should include data products, hardware demonstration, and progression toward validated performance in relevant environments.

For PSI modeling, Phase I deliverables should demonstrate proof of concept and a minimum of component-level verification, with detailed documentation on future data needs to complete validation of the integrated model and uncertainty quantification methodology, as well as estimates of computational needs to achieve mission-application solutions. Phase II deliverables must demonstrate verification and validation beyond the component level, with validation demonstrated through comparisons with relevant data and documented uncertainty quantification. Significant attention should be applied to create highly robust and extremely high-performance computational simulation tool deliverables.

State of the Art and Critical Gaps:

Critical gaps relevant to PSI center on the need for validated capabilities to predict PSI environments for both lunar and planetary destinations. Past SBIR investments have yielded significant progress toward closing these gaps through advanced high-fidelity modeling tools, unique experimental and measurement techniques, and prototype sensors and flight instrumentation. These capabilities are crosscutting, directly supporting the design, development, and eventual certification of flight systems for both vacuum and atmospheric environments. PSI is a critical part of EDL. Ground testing, modeling and simulation, and flight testing/data in combination are a cornerstone of NASA's extensive, successful experience on EDL missions.

Missions are challenged by PSI risks derived from large extrapolations of existing models to flight conditions and uncertainties in fundamental knowledge of relevant gas-granular physics. Variation in characteristics of regolith and atmosphere (or lack thereof), propulsion system configuration, and concept of operations all pose challenges in applying capabilities developed for one mission application to another. Accurate predictions of PSI environments are also needed to support other efforts focused on surface operations and infrastructure, vehicle sensor design, and degraded performance potential.

The current state of the art for PSI relies on subscale, terrestrial ground testing to provide data for both semi-empirical erosion model development and validation of modeling methodologies across a range of fidelities. Modeling tools and approaches span engineering-level to fully coupled, highly parallelized, computationally expensive simulation frameworks, each with significant effort to go on validation and improvements to extend applicability. In situ measurement techniques are in development for unique flight instrumentation and sensors to directly characterize PSI physics and provide model validation data without or through minimizing the environmental limitations of terrestrial ground testing.

Civil Space Shortfall Ranking https://www.nasa.gov/spacetechpriorities/

- Gap ID: 1566 Characterization of Plume Surface Interaction

Relevance / Science Traceability:

Current and future lander architectures will depend on knowledge of PSI, such as:

- Artemis human landing system (HLS).
- Commercial robotic lunar landers (CLPS or other).
- Planetary mission landers (Mars Sample Retrieval Lander and others).
- Human Mars landers.
- Ascent vehicles operating in non-terrestrial environments and with unprepared launch sites.

References:

1. Watkins, R. N., et al., "Understanding and Mitigating Plume Effects During Powered Descents on the Moon and Mars," *white paper submitted to the Planetary Science Decadal Survey 2023-2032*, 2021. http://dx.doi.org/10.3847/25c2cfeb.f9243994
2. Metzger, P. T., et al., "Phenomenology of Soil Erosion due to Rocket Exhaust on the Moon and the Mauna Kea Lunar Test Site," *J. Geophys. Research*, Vol. 116, E6, June 2011. https://doi.org/10.1029/2010JE003745
3. Metzger, P. T., et al., "Jet-Induced Cratering of a Granular Surface with Application to Lunar Spaceports," *Journal of Aerospace Engineering*, June 2009. https://doi.org/10.1061/(ASCE)0893-1321(2009)22:1(24)
4. Mehta, M., et al., "Thruster Plume Surface Interactions: Applications for Spacecraft Landings on Planetary Bodies," *AIAA Journal*, 51(12), pp. 2800-2818, 2013. https://doi.org/10.2514/1.J052408
5. Alexander, J. D., et al., "Soil Erosion by Landing Rockets Final Report," NASA Contract NAS9-4825, July 1966. https://ntrs.nasa.gov/citations/19660026653
6. Land, N. S., and Scholl, H. F., "Scaled Lunar Module Jet Erosion Experiments," NASA TN D-5051, April 1969. https://ntrs.nasa.gov/citations/19690013268
7. Scott, R. F. and Ko, H-Y., "Transient Rocket-Engine Gas Flow in Soil," *AIAA Journal*, Vol. 6, No. 2, pp. 258-264, Feb. 1968. https://doi.org/10.2514/3.4487
8. Romine, et al., "Site Alternation Effects from Rocket Exhaust Impingement During a Simulated Viking Mars Landing, Part 1: Nozzle Development and Physical Site Alteration," NASA CR-2252, July 1973.
9. Leahy, F. B., et al., "Cross-Program Design Specification for Natural Environments (DSNE) Revision 1," SLS-SPEC-159, Oct. 2021.

Z-LIVE.01: Surface Power Technologies (SBIR) (Previously Z1.05)

Related Subtopic Pointers: T3.05
Lead Center: GRC
Participating Center(s): GSFC, JSC, MSFC

Subtopic Introduction:

Electrical power is a critically necessary utility for any future NASA mission to the Moon or Mars, and in many cases the existing power technologies developed for orbital and deep space missions are ill-suited to meet the needs of planetary surface power. Both single mission, stand-alone power systems are required, as is a more widespread surface power capability that augments and extends the reach and persistence of missions on planetary surfaces. While initial missions will need to bring their own power systems to enable initial operations, eventually multiple power sources must be connected together into a grid in order to enable continuous presence and operations. These assets are expected to be located remotely from each other, so power must be efficiently transferred over significant distances, and initial power levels are expected to be in the 10 to 100kW range, similar to the International Space Station (ISS). Additionally, significant advances in energy storage technologies are required to support planetary surface missions as the duration of time without direct view of the sun for power generation are much longer than any in-space missions. In addition, the operational environments on the lunar or Martian surfaces are much more challenging, with much wider operational temperature ranges, and dust that inhibits performance and component lifetime.

This new subtopic has three scopes that address the most pressing technology needs to enable sustained presence and operations on the lunar and Mars planetary surfaces:

- Long Distance Power Transfer for Lunar and Mars Missions
- Regenerative Fuel Cell System Component Development
- Low Temperature Batteries for Lunar and Mars Surface Missions

The first scope addresses the need to move power from one place to another over long distances.

- This capability is required for some electrical power sources, such a nuclear fission reactor, and is a desired capability for even solar power generation as it will extend the reach of surface operations, enable a more continuous and robust source of power, and allow ideal placement of solar generation assets that are 1 to 10 km from desired mission locations.

The next two scopes address the pressing need for better energy storage technologies to be coupled with vertical solar array power sources.

- The most theoretically promising technology is regenerative fuel cells that are expected to perform much better than batteries for long duration eclipses that will be seen on the lunar surface. However, NASA has found that the key components that are needed for such a system are not readily available in the commercial marketplace and are seeking small businesses that can innovate and create the small, high performance, high reliability components needed to enable such a system.
- The last technology being sought is improvements in the batteries needed for long duration operation at low temperature on the lunar and Mars surfaces. Improvements are being sought at both the cell and pack level that offer improvements over the state of the art, but all proposals must address how the new technology can be incorporated and demonstrated by Phase II into functional and operational batteries. Proposals that only address cell-level components such as anodes and cathodes will not be considered for award.

These three scopes address the highest priority surface power technology shortfalls recently identified by the Space Technology Mission Directorate.

- #1618 - Survive and Operate Through the Lunar Night
- #1592 - High Power, Long Distance Energy Transmission Across Distributed Surface Assets
- #1595 - Energy Storage to Enable Robust and Long Duration Operations on Moon and Mars Surface

Technologies developed under this subtopic would also benefit other NASA Mission Directorates, including SMD (Science Mission Directorate) and ARMD (Aeronautics Research Mission Directorate). Specific projects that could benefit from the technologies developed herein include Gateway, In-Situ Resource Utilization (ISRU), Extravehicular Activity and Human Surface Mobility Program, Surface Habitat, Planetary Exploration, and Hybrid Gas Electric Propulsion.

Scope Title: Long Distance Power Transfer for Lunar and Mars Missions

Scope Description:

This scope directly addresses STMD Shortfall #1592: High Power, Long Distance Energy Transmission Across Distributed Surface Assets.

NASA seeks innovative solutions and technologies to allow for power transfer for lunar and Mars missions. The technologies sought would include the use of low-mass, highly conductive power transmission cables or the use of high end-to-end efficiency and long-distance power beaming.

- Low-mass, highly conductive wires and terminations that can operate over the full range of lunar south polar environments (-230 °C to -100 °C) and provide reliable small gauges for long-distance power transmission in the 1 kW to 10 kW range; low-mass insulation materials with increased dielectric breakdown strength and void reductions to enable up to 1,500 Vdc cables and/or up to 3,000 Vac 3-phase cables with low inductance at 1,000 Hz; and low-loss/low-mass electromagnetic interference (EMI) shielding.
- Electrical connectors that can survive the harsh lunar environments, such as extreme temperature ranges at the south polar locations (-230 ºC to -100 ºC); can be exposed to the lunar dust during storage, usage and during connection and disconnection process; and can be connected by robots or by astronauts while wearing protective gloves. Primary power transmission lines can carry up to 50 kW of power at either (a) 1,000 Vdc or (b) 3,000 Vac 3-phase (line to line) with a frequency of 1,000 Hz.
- Power beaming end-to-end efficiency (>40%) and long-distance (>1 km) in the range of 100 W to kilowatts of power. The focus on proposals should be on the high-efficiency transmitters/receivers/converters that are the main components of interest to the electrical power discipline. Proposals are not sought on pointing or tracking technologies of those transmitters or receivers; however, the fusion of communications and/or navigation with power beaming is sought. Solutions and technologies must be scalable to future lunar mission needs such as remote robotic operations up to industrial power needs.

Expected TRL or TRL Range at completion of the Project: 4 to 5

Primary Technology Taxonomy:

- Level 1: TX 03 Aerospace Power and Energy Storage
- Level 2: TX 03.3 Power Management and Distribution

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

Typically, deliverables under Phase I proposals are geared toward a technology concept with associated analysis and design. A final report of the high-fidelity design and analysis is a minimum requirement for Phase I, but selected component development and test results are preferred.

Deliverables for Phase II should include hardware prototypes that prove performance and feasibility of the design for potential 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 that will be encountered. Operability in environments subject to temperature swings will be a critical requirement for any technology developed, especially for cabling or power-beaming concepts. In addition, proposals will have to consider lunar regolith and Mars dust storms. To enable a new Mars transportation capability for human exploration, new technology development must be started soon to address the unique needs of a mixed alternating current/direct current (AC/DC) space-rated power system to prove feasibility and provide realistic performance metrics for detailed vehicle design concepts and mission trade studies.

Civil Space Shortfall Ranking https://www.nasa.gov/spacetechpriorities/

- 1618 - Survive and Operate Through the Lunar Night
- 1592 - High Power, Long Distance Energy Transmission Across Distributed Surface Assets
- 1595 - Energy Storage to Enable Robust and Long Duration Operations on Moon and Mars Surface

Relevance / Science Traceability:

This subtopic would directly address a remaining technology gap in the lunar and Mars surface mission concepts and Mars human transportation needs. There are potential infusion opportunities with the Science Mission Directorate (SMD), Commercial Lander Payload Services (CLPS), Exploration Systems Development Mission Directorate (ESDMD), Space Operations Mission Directorate (SOMD), and Flexible Lunar Architecture for Exploration (FLARE). 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.

References:

1. The Global Exploration Roadmap, January 2018: https://www.nasa.gov/sites/default/files/atoms/files/ger_2018_small_mobile.pdf
2. Space Policy Directive-1, Reinvigorating America's Human Space Exploration Program, December 11, 2017: https://www.federalregister.gov/documents/2017/12/14/2017-27160/reinvigorating-americas-human-space-exploration-program
3. Civil Space Shortfalls: https://www.nasa.gov/spacetechpriorities/

Scope Title: Regenerative Fuel Cell System Component Development

Scope Description:

NASA is seeking innovative energy storage solutions to enable lunar missions to survive and operate through the lunar nights at both polar and non-polar locations. The objective is to develop lightweight, long-lived energy storage systems for mobile and stationary surface platforms (such as landers, equipment, crew rovers, and science packages) that can deliver power and survive the variable insolation and thermal conditions on the lunar surface. Specific energy (kJ/kg or Wh/kg) is the primary characteristic to differentiate lunar energy storage technologies.

Lunar energy storage technologies face a minimum maintenance interval ≥3 years. Operating for at least 3 years on the lunar surface without maintenance requires exceedingly reliable components beyond what the market offers. NASA has particular interest in component technologies that extend the operational life of system components. The primary failure mechanism results from extended contact (years) with ultra-high-purity deionized water, resulting in shunt currents/corrosion. The specific component research and development sought include:

1. Long-life, High Pressure Deionized (DI) Water Pump. Currently available pumps, both high-lift and recirculating pumps, require unacceptably high power and fail well before the 3-year requirement when pumping the ultra-high-purity deionized water specified by this application. Regenerative Fuel Cell (RFC) process water ranges from 4 °C to 90 °C with system pressures ranging from 15 psia (0.24 MPa) to 2,500 psia (17.2 MPa) and must remain above >10 MΩ·cm as measured at 25 °C. NASA seeks innovations of materials, coatings, bearings, dynamics seals, etc. that enable devices to move and pressurize the deionized water without introducing contaminants for the mission duration. Preference will be given to solutions resulting in pumps with the longest mean time between failures (MTBF), lowest power, and lowest mass.
2. Stable, Long-life In-situ H_2-in-O_2 Safety Sensor. This scope targets the need to verify the quality of hydrogen and oxygen product gases produced by water electrolysis equipment for personnel and

hardware safety in propellant generation, life support, and energy storage applications. Electrochemical water electrolysis results in a non-zero quantity of product gases contaminating the opposite product stream (e.g., O_2 in the H_2 stream and H_2 in the O_2 stream). Detecting improperly operating water electrolysis hardware (especially when operating at high pressures) is critically important to reduce the risk of a developing hazardous condition which endangers equipment or personnel. Existing detection technology requires low-pressure operation typically using a process to reduce the process fluid pressure and a slip-stream analysis process leg. The water, hydrogen, and oxygen gases in lunar applications are too valuable to discharge into space as part of a slip stream, and the parasitic power to repressurize the slip-steam adds system mass and reduces system reliability. The objective of this activity is to detect flammable mixtures (up to 4% H2 in O2) at process fluid pressures up to 3600 psi with 0.2% accuracy (full scale) when the process fluid is fully saturated with water vapor. It is desirable that the detection technology can recover from exposure to liquid water as water vapor can condense during system transients or off-nominal events.

3. Non-chemical Biocides for Long-life, High Pressure DI Water Electrolysis Systems. NASA seeks technologies that can prevent and/or remove biological contamination from closed-loop DI water electrolysis systems containing carbon-based materials. Chemical biological mitigation options are not acceptable because these solutions limit the operational life of the water electrolysis stacks and the pressurized ultra-high-purity water (>14 MΩ·cm at 25 °C) remains in closed loops for very long periods of time. Key metrics sought are: water conductivity range (≤ 1.0 x 10-6 1/Ω-cm @ 25 ºC), total microbial bacterial total count (≤ 1 CFU / 100 mL), total virus (Below detectable levels), total acids (≤ 500 µg/l), cyanide (≤ 20 µg/l), total alcohols (≤ 500 µg/l), total organic carbon (TOC) (≤ 500 µg/l), total phenols (Less than the EPA MCL per EPA Method 625), total volatile organics (less than the EPA MCL per EPA Method 524.2, Rev 4).

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:

- Level 1: TX 03 Aerospace Power and Energy Storage
- Level 2: TX 03.2 Energy Storage

Desired Deliverables of Phase I and Phase II:

- Prototype
- Research

Desired Deliverables Description:

Research should be conducted to demonstrate technical feasibility in a final report for Phase I and show a path toward Phase II, and when possible, deliver a demonstration unit for NASA testing at the completion of the Phase II contract. Phase I emphasis should be on component and/or material compatibility analysis and testing with the operational environment. Phase II emphasis should be placed on developing and demonstrating multiple units under specified process fluid conditions. Additionally, a path should be outlined that shows how the technology could be commercialized or further developed into space-worthy systems.

- Phase I: Test reports and technology development plan
- Phase II: Prototype hardware with test reports and an updated technology development plan

State of the Art and Critical Gaps:

1. Long-life, High Pressure Deionized Water Pump. Currently available pumps, both high-lift and recirculating pumps, require unacceptably high power and fail well before the 3-year requirement when pumping the ultra-high-purity deionized water specified by this application.

2. Stable, long-life in-situ H2-in-O2 Safety sensor needed to verify the quality of hydrogen and oxygen product gases produced by water electrolysis equipment for personnel and hardware safety in propellant generation, life support, and energy storage applications. Existing detection technology requires low-pressure operation typically using a process to reduce the process fluid pressure and a slip-stream analysis process leg. The water, hydrogen, and oxygen gases in lunar applications are too valuable to discharge into space as part of a slip stream and the parasitic power to repressurize the slip-steam adds system mass and reduces system reliability.
3. Non-chemical biocides for Long-life, High Pressure Deionized Water Electrolysis Systems that can prevent and/or remove biological contamination from closed-loop DI water electrolysis systems containing carbon-based materials. Chemical biological mitigation options are not acceptable because these solutions limit the operational life of the water electrolysis stacks and the pressurized ultra-high-purity water (>14 MΩ·cm at 25 °C) remains in closed loops for very long periods of time.

Civil Space Shortfall Ranking https://www.nasa.gov/spacetechpriorities/

- 1618 - Survive and Operate Through the Lunar Night
- 1592 - High Power, Long Distance Energy Transmission Across Distributed Surface Assets
- 1595 - Energy Storage to Enable Robust and Long Duration Operations on Moon and Mars Surface

Relevance / Science Traceability:

Regenerative fuel cells (RFC) are an alternative energy storage solution for missions with high energy requirements and restricted mass allocations that are unfavorable to existing battery solutions. RFC systems have been identified as a potential solution for both stationary and mobile crewed lunar surface assets to survive the lunar night.

References:

1. "Lunar Equator Regenerative Fuel Cell System Efficiency Analysis," P. Smith et al., NASA TM 20210014627, https://ntrs.nasa.gov/citations/20210014627
2. "Aerospace Regenerative Fuel Cell Fluidic Component Design Challenges," P. Smith et al., NASA TM 20210024659, https://ntrs.nasa.gov/citations/20210024659
3. "Regenerative Fuel Cell Power Systems for Lunar and Martian Surface Exploration," M. Guzik et al., NASA TM 20170009088, https://ntrs.nasa.gov/citations/20170009088
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5. "Energy Storage for Lunar Surface Exploration," M. Guzik et al., NASA TM 20190000472, https://ntrs.nasa.gov/citations/20190000472
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Scope Title: Low Temperature Batteries for Lunar and Mars Surface Missions

Scope Description:

Further development of advanced secondary/rechargeable battery technologies is required to enable and extend lunar surface operations for mobility, scientific exploration, habitats and ISRU operations. State-of-the-art lithium-ion batteries (LIB) lose 75% of their capacity below room temperature and generally do not operate below -40°C. New technologies must enable battery modules that can safely provide >200Wh/kg (room temperature) while also operating in ambient conditions as low as -200°C. These batteries must be capable of surviving multiple lunar day/night cycles without degradation. NASA is interested in development of advanced lithium-ion and sodium-ion chemistries. Novel battery pack/thermal management designs and technologies that enhance battery reliability and safety while reducing system weight are also of interest. Combinations of cell-level improvements and/or battery-pack-level improvements for enhanced temperature capability will be considered, but a path must be shown toward a battery module design. Solutions focused solely on an individual cell component (e.g., anode, cathode, etc.) development and demonstration will not be considered.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:

- Level 1: TX 03 Aerospace Power and Energy Storage
- Level 2: TX 03.2 Energy Storage

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware
- Research

Desired Deliverables Description:

Research should be conducted to demonstrate technical feasibility in a final report for Phase I and show a path toward Phase II, and when possible, deliver a demonstration unit for NASA testing at the completion of the Phase II contract. Phase I deliverables should include thermal data demonstrating feasibility of the design over the intended operational ranges. Phase II emphasis should be placed on developing and demonstrating the technology under as many relevant test conditions as feasible within Phase II resources. Additionally, a path should be outlined that shows how the technology could be commercialized or further developed into science-worthy systems.

- Phase I: Models, test reports and technology development plan
- Phase II: Prototype hardware with test reports and an updated technology development plan

State of the Art and Critical Gaps:

State-of-the-art rechargeable cells are limited in both capacity and temperature range. Typical rechargeable Li-ion cells operate within a narrow temperature range of -20 to 40 °C and suffer from extreme 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 about lithium plating during charge. Exploring non-lithium-based batteries can increase flexibility in operations. Sodium-ion cells have specific advantages over LIB, including higher power density, non-flammability, and superior thermal performance.

This scope is aimed at the development of lithium-ion and sodium-ion batteries that can maintain performance across the lunar temperature extremes, along with advanced thermal management and packaging techniques to allow functionality and survivability of the battery system at these temperature extremes.

Civil Space Shortfall Ranking https://www.nasa.gov/spacetechpriorities/

- 1618 - Survive and Operate Through the Lunar Night
- 1592 - High Power, Long Distance Energy Transmission Across Distributed Surface Assets
- 1595 - Energy Storage to Enable Robust and Long Duration Operations on Moon and Mars Surface

Relevance / Science Traceability:

These batteries are applicable over a broad range of exploration and science missions. Low-temperature batteries are needed to enable science and exploration missions aligned with Artemis, including supporting science missions such as Commercial Lunar Payload Services and Lunar Quest. These batteries may also serve for potential NASA decadal missions to ocean worlds (Europa, Enceladus, Titan) and the icy giants (Neptune, Uranus). Sodium-ion batteries would allow for pulse power applications such as directed energy laser systems for ISRU construction operations or beaming surface technologies. Low-temperature batteries developed under this subtopic would enhance these missions and could be enabling, particularly for missions that are highly mass- or volume- limited.

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2. NASA Science: https://science.nasa.gov/
3. Lunar Surface Innovation Consortium: https://lsic.jhuapl.edu/
4. Moon-to-Mars Architecture (Introduction): https://www.nasa.gov/MoonToMarsArchitecture
5. Recent Progress and Perspective: Na Ion Batteries Used at Low Temperatures. https://www.mdpi.com/2079-4991/12/19/3529
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Z-LIVE.02: Spacecraft Thermal Management (SBIR) (Previously Z2.01)

Related Subtopic Pointers: S16.05, Z-GO.02, Z-LIVE.04
Lead Center: JSC
Participating Center(s): GRC, GSFC, JPL, MSFC

Subtopic Introduction:

NASA seeks new technologies that will facilitate low-mass and highly reliable thermal control systems for the exploration of our solar system. Proposals should discuss how the innovation will improve upon, interface with, or replace current state-of-the-art technologies and techniques. This solicitation specifically targets proposals for new technologies and methods that clearly address one of the following areas:

- Lunar Habitat Thermal Technologies
- Freeze-Tolerant Radiators and Heat Exchangers
- High-Efficiency Space Refrigeration Systems

These areas are considered of equal priority, and no award preference is expected for one area over another.

Scope Title: Lunar Habitat Thermal Technologies

Scope Description:

NASA is seeking focused efforts to develop thermal control technologies that will enable crewed habitats to survive and operate through the lunar night for extended stays on the lunar surface. Technologies should address NASA technology shortfalls associated with long-duration habitation on the lunar surface, where surface temperatures range from -193 °C or lower in shadowed regions (including night) to 120 °C at the equatorial subsolar point. Technologies are needed that allow a single habitat or a pressurized rover to operate in all these environments as well as deep space transit from Earth to the Moon. Technologies should address reduction in mass, volume, and power usage relative to current solutions. The addition of heaters can lead to increased vehicle mass due to additional power generation and storage requirements and is 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, but are not limited to, the following:

- Methods for preventing or restoring radiator optical properties that have degraded due to exposure to the space environment (radiation, dust, etc.).
- Development of engineered solar reflective coating with high infrared (IR) transparency with the following properties:
    - Solar reflectance >0.85 (threshold) to 1 (goal).
    - IR transmittance >0.85 (threshold) to 1 (goal).
    - Is electrically dissipative, i.e., low exposed surface resistivity (to manage potential static charge buildup).
    - Is compatible with a variety of substrates: novel thermochromic materials, standard spacecraft metals, and flexible thermal control tapes.
    - This coating is expected to be applied over traditional and novel radiator coatings as a solar filter to reduce the solar absorption of those coatings.
- Heat rejection turndown, including variable emissivity radiator coatings.
- Enhancements or alternatives to traditional single-phase liquid pumped loops to enable survival and operation through the lunar night.
- Robotically actuated and blind-mate fluidic quick-disconnects (QDs) intended for use in the robotic installation/removal of external pump packages for maintainability of active thermal control systems.
    - The state of the art is described in Farrell (1995).
    - Goal is similar functionality and interfaces with reduced mass and improved manufacturability.
    - Stretch goal is to develop a QD with both robotic (Extra Vehicular Robotics) and crew member (Extra Vehicular Activity) tool interface compatibility.

Unless otherwise stated, technologies should be suitable for use with crewed vehicles having variable heat loads averaging between 2 and 10 kW and should consider dormancy (mission time while uncrewed) impacts. All technologies should support a minimum operational duration of at least 5 years and be compatible with applicable mission environments including ground processing/launch site environments (humidity, general contamination, etc.) and in-space environments (ultraviolet (UV), solar wind, etc.).

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:

- Level 1: TX 14 Thermal Management Systems
- Level 2: TX 14.2 Thermal Control Components and Systems

Desired Deliverables of Phase I and Phase II:

- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Phase I awards in this area are expected to demonstrate analytical and/or empirical proof-of-concept results that demonstrate the ability of the organization to meet the goals stated in the solicitation.

At the conclusion of a Phase II contract, deliverables are expected to include a functioning prototype (or better) that demonstrates the potential to meet the performance goals of the technology or software. Any delivered math models should include supporting data that validate the assumptions used within the model.

State of the Art and Critical Gaps:

This scope strives to reduce mass, volume, and power of a thermal control system in the next generation of robotic and human-class spacecraft and to enable long-term missions to the Moon. The current state of the art in thermal control systems is vehicle power and mass impact of greater than 25 to 30% due to old technologies still in use. Furthermore, as missions become more variable (dormancy, environments, etc.), the need for intelligent design and control (both actively and passively) within the thermal control system becomes more apparent. Namely, the need to provide variable heat rejection through the complex lunar temperature profile has provided the opportunity for many novel heat rejection system technologies to be developed and evaluated. However, among the most significant challenges associated with modulating radiator efforts is the ability to provide the desired optical properties in the solar spectra while achieving the desired IR transmission for tunable products. An engineerable solar reflective coating with high transmission in the IR spectra is expected to address this gap while also providing a general tool capability to tune solar and IR properties of static coatings. This scope also acknowledges the need to improve system robustness while minimizing impact to other systems.

Civil Space Shortfall Ranking https://www.nasa.gov/spacetechpriorities/

- 1525: Food and Nutrition for Mars and Sustained Lunar
- 1618: Survive and Operate Through the Lunar Night
- 1620: Conditioned Stowage to Maintain Science and/or Nutritional Integrity
- 1622: Novel Thermal Control Technologies to Improve Environmental Control of Habitats
- 1624: Advanced Thermal Management Technologies for Diverse Applications

Relevance / Science Traceability:

- Deep space habitats and crewed vehicles (Moon, Mars, etc.)
  - Orion
  - Gateway
  - Human Landing System (HLS)
- Mars transit vehicles
- SmallSats/CubeSats
- Rovers and surface mZ8.13bility

References:

1. Stephan, R. Overview of the Altair Lunar Lander Thermal Control System Design and the Impacts of Global Access. AIAA 2011-5001. 2011. https://ntrs.nasa.gov/api/citations/20110008550/downloads/20110008550.pdf
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Scope Title: Freeze-Tolerant Radiators and Heat Exchangers

Scope Description:

Proposals are sought to develop freeze-tolerant radiators and heat exchangers. NASA plans to develop infrastructure to enable a sustaining human presence on the Moon as part of Artemis missions. Current lunar orbit and surface habitat concepts incorporate conventional single-phase radiators and heat exchangers to reject heat. The habitats will be exposed to subfreezing environmental temperatures and ionizing ultraviolet (UV) radiation during transit to lunar orbit and at lunar south pole regions if on the surface. In addition, surface habitats will be exposed to lunar dust that will significantly degrade radiator coating properties. The goal is to develop radiators and heat exchangers that can operate without suffering damage or performance degradation on human-rated spacecraft on the lunar surface or orbit.

Current ground rules and assumptions (GRAs) include:

1. Low toxicity and low vapor pressure working fluids.
2. Operate near the lunar south pole and survive the lunar nights (lasting up to 14 days), where environmental temperatures can drop below the freezing point of heritage and candidate active thermal control system (ATCS) coolants (e.g., ammonia, water, hydrofluoroether (HFE) 7200) and as low as -213 °C (-351 °F).
3. Total heat loads varying between 2 and 15 kW, or 6,824 to 51,182 BTU/hr.
4. Dust-tolerant design that mitigates the effects of a dusty environment.
5. Electromagnetic charging shall be mitigated.

Based on these GRAs, the risk of loss of mission (LOM) due to rupturing radiator and heat exchanger coolant tubes because of freeze-thaw cycles is high, and the development of freeze-tolerant radiators and heat exchangers is necessary to reduce this risk and reduce heater power during Artemis missions.

Specifically, developments in radiators and heat exchangers are sought in these areas:

1. Lightweight, corrosion-resistant, freeze-tolerant metallic coolant tubes ranging from 0.127 to 3.81 cm (0.05 to 1.5 in.) inner diameter, 51 to 304 cm (20 to 120 in.) long and compliant with NASA STD-6016C w/Change 1.
2. Lightweight, high-strength, corrosion-resistant, freeze-tolerant nonmetallic flexible coolant tubes ranging from 0.127 to 3.81 cm (0.05 to 1.5 in.) inner diameter, 51 to 304 cm (20 to 120 in.) long and compliant with NASA STD-6016C w/Change 1.
3. Operating under turbulent flow conditions.
4. Radiators and heat exchangers with variable thermal resistance that can temporarily eliminate or reduce heat rejection. Examples include, but are not limited to, low-power (less than 1 kW) devices that are capable of suctioning, temporarily storing, then refilling the coolant to and from a radiator or heat exchanger and variable emissivity devices or materials (e.g., louvers, thermochromic and electrochromic coatings).

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:

- Level 1: TX 14 Thermal Management Systems
- Level 2: TX 14.2 Thermal Control Components and Systems

Desired Deliverables of Phase I and Phase II:

- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

Phase I Deliverables: A proof-of-concept or breadboard demonstrating technical feasibility and operability in a laboratory environment, and a report that includes analytical and model simulations in a relevant environment and heat loads to answer critical questions focused on reducing the risk of freezing radiators or heat exchangers. In addition, the report shall include recommendations for brassboard or prototype development during Phase II.

Phase II Deliverables: Delivery of a brassboard or prototype with a goal of achieving TRL 5 or 6, and laboratory testing demonstrating operability over the range of expected environmental conditions. The prototype shall be designed to conform to a NASA project/program need and include a well-developed flight demonstration and infusion plan. A report shall be written that includes functional, performance, analytical, and test results; and an evaluation of the technology's maturity level (i.e., TRL) including the risk of proceeding with the development.

State of the Art and Critical Gaps:

State of the art (SOA) ATCSs on human-rated spacecraft like the Apollo Service Module (SM) and International Space Station (ISS) use mechanically pumped, single-phase coolant to collect, transport, and reject heat, and the components that are most vulnerable to rupturing due to freeze-thaw cycles are the radiators and heat exchangers because they are exposed to the environment.

The Apollo SM radiators were designed to partially stagnate, and only the coolant tubes, not the manifolds, in the ISS radiators were designed to withstand the high-pressure transients induced by freeze-thaw cycles. This required small-inner-diameter (0.18-cm, or 0.07-in.) metallic (Inconel or stainless steel) coolant tubes with thick walls (outer diameter of 0.32 cm, or 0.125 in.), optimal spacing between tubes, and turbulent flow. Bigger inner diameters may be required for future radiators to enhance hydraulic and thermal performance but increasing the outer diameter to enable freeze tolerance will increase mass and counter thermal performance.

Similarly, the Apollo SM and ISS heat exchangers used metallic coolant tubes with large inner diameters (2.5 cm, or 1 in.) and thin walls to achieve high heat transfer coefficients but increasing the outer diameter for freeze tolerance will impact thermal performance. Inconel and stainless-steel coolant tubes were used in these systems for their higher thermal conductivity, corrosion resistance, and strength for micrometeoroid and orbital debris (MMOD) protection but consequently limit freeze protection. Therefore, nonmetallic flexible coolant tubes that are corrosion resistant with high strength are also desired to enable freeze tolerance while meeting thermal and hydraulic requirements. There are no SOA ATCSs that can vary the thermal resistance of a radiator or heat exchanger to temporarily eliminate or reduce heat rejection, but this capability is desired to enable freeze tolerance.

A lunar habitat will be exposed to high-energy, or ionized, UV radiation while traveling through the Van Allen belts and can last from hours to days. Experiments have shown exposure to more than 500 equivalent sun hours (ESH) in the Van Allen belts can degrade the radiator's Z-93 absorptivity from 0.16 to 0.24, or 50%. An absorptivity reduction of 50% results in approximately 9 to 3 kW, or two-thirds reduction in heat rejection capability based on conservation of energy. Lunar dust is copious and highly adhesive. Tests have shown Z-93 absorptivity linearly degrades with the amount of dust coverage on the coating. As little as 20% dust coverage can increase the absorptivity by 75% and decrease the heat rejection capability by 30%.

Lunar habitats stationed near the lunar south pole will be exposed to extremely cold environmental temperatures (as low as -213 °C or -351°F) during lunar nights (up to 14 days). The cold environmental temperatures are below the freezing point of heritage or candidate active thermal control system (ATCS) coolants (e.g., ammonia, water, HFE 7200). Conservation of energy analysis results showed significant heater power (up to 4 kW, or 13,648 BTU/hr) is required to prevent heritage coolants from freezing and maintain operations.

Civil Space Shortfall Ranking https://www.nasa.gov/spacetechpriorities/

- 1525: Food and Nutrition for Mars and Sustained Lunar
- 1618: Survive and Operate Through the Lunar Night
- 1620: Conditioned Stowage to Maintain Science and/or Nutritional Integrity
- 1622: Novel Thermal Control Technologies to Improve Environmental Control of Habitats
- 1624: Advanced Thermal Management Technologies for Diverse Applications

Relevance / Science Traceability:

Pressurized habitats or rovers stationed near the lunar south pole for future Artemis missions will be exposed to extremely cold environmental temperatures as low as -213 °C (-351 °F) during lunar nights (up to 14 days). These temperatures are below the freezing point of heritage or candidate ATCS coolants (e.g., ammonia, water, Freon, HFE 7200). Preliminary analysis results of the conceptual lunar surface habitat ATCS architecture showed that significant heater power (up to 4 kW, or 13,648 BTU/hr) is required to prevent the coolant from freezing and maintain operations. Thus, freeze-tolerant radiators and heat exchangers are needed to reduce heater power, avoid rupturing the coolant tubes, and reduce the risk of loss of mission (LOM).

Programs of interest include Moon to Mars, Artemis, HLS, and EHP, as well as future programs and missions to the Moon and Mars.

References:

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Scope Title: High-Efficiency Space Refrigeration Systems

Scope Description:

This subtopic targets food refrigeration systems with one of two temperature levels:

1. A cold air temperature of +5 °C, rejecting heat to a pumped liquid spacecraft cooling loop or directly to a space radiator in the range of +10 °C to +50 °C.
2. A cold air temperature of -25 °C, rejecting heat to a pumped liquid spacecraft cooling loop or directly to a space radiator in the range of +5 °C to +25 °C.

The higher temperature case may be used to maintain nutritional stability for shelf stable food systems on the way to or from Mars or on the Mars surface. The lower temperature case could allow for a new food system based on frozen foods. System coefficient of performance (COP) should exceed 45% of Carnot COP. A successful Phase II effort will yield a well-developed vapor compression, Stirling, solid state or other refrigeration system that has been at least ground tested with good evidence shown that the technology will be able to operate for at least 5 years in gravity environments ranging from 0 (interplanetary space) to 1 (Earth normal).

The technology should be scalable from heat loads of 200 to 1,000 Watts of cooling. A complete, gravity-independent food refrigeration system should be proposed, including considerations for insulated compartment and coil defrost (if necessary). The proposed refrigeration system should be optimized for one (or more) of the bounded ranges listed above and discuss how sensitive the system is to the design point.

Expected TRL or TRL Range at completion of the Project: 4 to 6

Primary Technology Taxonomy:

- Level 1: TX 14 Thermal Management Systems
- Level 2: TX 14.X Other Thermal Management Systems

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

Phase I should include analytical studies and conceptual design of the entire refrigerator system and experimental demonstration of the key cooling system component. Test and analysis should provide sufficient evidence that the proposed design is likely to achieve all project goals in a relevant environment and results should be documented in a technical report.

Phase II should demonstrate analytically and experimentally that the refrigeration system can achieve all project goals and is ready to begin spaceflight hardware construction and on-orbit technology demonstration. Technical reports and hardware deliverable are desired.

State of the Art and Critical Gaps:

Lower efficiency and/or shorter life-span food refrigeration systems occasionally have been demonstrated in space. Vapor compression systems, while highly developed for 1g, have not been able to solve the lubrication problems of 0g. Stirling coolers have been optimized for much colder temperatures and smaller heat loads in space applications. Thermoelectric coolers have suffered from low efficiency. NASA's critical gap is high efficiency, long-life and operability in 0 to 1g environments.

Civil Space Shortfall Ranking https://www.nasa.gov/spacetechpriorities/

- 1525: Food and Nutrition for Mars and Sustained Lunar
- 1618: Survive and Operate Through the Lunar Night
- 1620: Conditioned Stowage to Maintain Science and/or Nutritional Integrity
- 1622: Novel Thermal Control Technologies to Improve Environmental Control of Habitats
- 1624: Advanced Thermal Management Technologies for Diverse Applications

Relevance / Science Traceability:

STMD specializes in difficult technology development for future NASA missions. Work in this area can lead to applications such as:

- Mars food refrigerator, lunar habitat dehumidification systems and hot environment thermal control systems for ESDMD.
- Improved food refrigerators and freezers for ISS and commercial low-earth orbit platforms for SOMD.
- Improved science refrigerators and freezers for SMD.

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Z-LIVE.03: Space Resource Processing for Consumables, Manufacturing, Construction, and Energy (SBIR) (Previously Z12.03)

Lead Center: JSC
Participating Center(s): GRC, JPL, KSC, MSFC

Subtopic Introduction:

In April 2020, NASA submitted the Plan for Sustained Lunar Exploration and Development to the National Space Council. The report states that in situ resource utilization (ISRU) "will enable the production of fuel, water, and/or oxygen from local materials, enabling sustainable surface operations with decreasing supply needs from Earth."

In September 2022, NASA released the Moon to Mars objectives, which contain multiple objectives related to the characterization and utilization of resources on both the Moon and Mars.

This subtopic has three scopes listed below in order of priority based on associated shortfall rankings:

1) Lunar Ice Mining
2) Oxygen and Associated Metals from Regolith
3) Produce Propellants and Mission Consumables from Extracted In-Situ Resources

Scope Title: Oxygen and Associated Metals from Regolith

Scope Description:

Lunar regolith is approximately 45% oxygen by mass. The majority of oxygen is bound in silicate minerals. Previous efforts have shown that it is possible to extract oxygen from regolith using various techniques. NASA is interested in developing the following supporting technologies that may enable or enhance the ability to extract oxygen and metals from lunar regolith:

- ISRU Critical Data/Proof-of-Concept Hardware for Commercial Lunar Payload Services (CLPS) Demonstration
    - NASA's ISRU Envisioned Future Priorities strategic plan calls for developing and flying demonstrations to the Moon to reduce or eliminate the risk of deploying a pilot plant that will perform end-to-end regolith acquisition and processing, a system designed to operate for a minimum of 1 Earth year and deliver a minimum of 1,000 kg of oxygen or oxygen/hydrogen to a customer early next decade. However, NASA has not operated on the lunar surface since the Apollo program. To reduce the risk of ISRU oxygen, metal, and water extraction systems, NASA is interested in <25 kg payload concepts that will obtain critical data and/or proof of concept of regolith flowability, size sorting, and mineral separation techniques that may be used in subsequent demonstrations and pilot plant hardware.

Phase I should demonstrate the critical aspects of the proposed hardware with an analysis that shows a demonstration system can be built and tested in Phase II that is less than 25 kg in mass. Phase II should design, build, and test hardware to as close to flight ready as possible within the provided budget.

Expected TRL or TRL Range at completion of the Project: 4 to 5

Primary Technology Taxonomy:

- Level 1: TX 07 Exploration Destination Systems
- Level 2: TX 07.1 In-Situ Resource Utilization

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

Phase I efforts should provide a feasibility study and/or proof of concept.

Phase II efforts should demonstrate the technology using lunar regolith simulant, where applicable, and tested in a vacuum, where applicable.

State of the Art and Critical Gaps:

These technologies directly address the following existing shortfalls and gaps for ISRU:

Civil Space Shortfall Ranking https://www.nasa.gov/spacetechpriorities/

- Shortfall 1580: Extraction and Segregation of Oxygen from Extraterrestrial materials
- ISRU 562: Regolith transfer hardware for long duration ISRU operations
- ISRU 564: Oxygen Extraction from lunar regolith
- ISRU-565. Regolith tolerant valves for high temperatures
- ISRU-558: Size sorting of granular regolith over long duration operations for ISRU
- ISRU-559: Mineral separation/beneficiation methods for long term ISRU

Relevance / Science Traceability:

These technologies support the following Moon-to-Mars Objectives:

- LI-7L: Demonstrate industrial-scale ISRU capabilities in support of continuous human lunar presence and a robust lunar economy.
- LI-8L: Demonstrate technologies supporting cislunar orbital/surface depots, construction and manufacturing maximizing the use of in situ resources, and support systems needed for continuous human/robotic presence.
- OP-11LM: Demonstrate the capability to use commodities produced from planetary surface or in-space resources to reduce the mass required to be transported from Earth.
- OP-12LM: Establish procedures and systems that will minimize the disturbance to the local environment, maximize the resources available to future explorers, and allow for reuse/recycling of material transported from Earth (and from the lunar surface, in the case of Mars) to be used during exploration.

References:

1. Mueller, R.P., Townsend, III, I.I., & Mantovani, J.G. (2010). Pneumatic regolith transfer systems for in-situ resource utilization. *Earth and Space 2010: Engineering, Science, Construction, and Operations in Challenging Environments* (pp. 1353-1363). https://ntrs.nasa.gov/api/citations/20110008766/downloads/20110008766.pdf
2. Mueller, R., Townsend, I., Mantovani, J., & Metzger, P. (2010). Evolution of regolith feed systems for lunar ISRU O2 production plants. *48th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition* (p. 1547). https://ntrs.nasa.gov/api/citations/20110016131/downloads/20110016131.pdf
3. Berggren, M., Zubrin, R., Jonscher, P., & Kilgore, J. (2011). Lunar soil particle separator. *49th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition* (p. 436). https://arc.aiaa.org/doi/pdf/10.2514/6.2011-436

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. NASA is interested in developing technologies that can be used to locate water resources and then extract and separate the water and other volatiles that are found with the water.

For this scope NASA is specifically interested in the following:

- Locate and measure lunar ice resources directly and indirectly down to 10 meters and across 100’s of meters on the lunar surface.
    - To date, NASA has focused on developing surface instruments and technologies that would allow water resources (and other volatiles found with the water) to be detected and characterized down to 1 meter below the surface. Scientists have hypothesized and LCROSS data suggest that water resources may be deeper than 1 meter and potentially concentrated in the top 10 meters of regolith in PSRs. Therefore, NASA is interested in developing technologies and systems that may be able to measure ice/volatile resources (minimum of 1 wt% ice) indirectly and/or directly sample material down to 10 meters below the surface and perform operations that would allow for mapping ice/volatile resources over 100’s of meters of surface terrain.

- In-Situ Resource Extraction & Collection in Lunar PSRs:
    - Volatiles, such as water, trapped in permanently shadowed regions of the moon are a key ISRU resource. These resources may be found anywhere from just below a desiccated layer or regolith down to 10 meters in concentrations ranging from 1 to 10 wt%. The challenges include depth/access to the icy regolith, varying concentration from granular to consolidated material, maintaining excavation and regolith transfer hardware temperatures below 100 K to minimize liberation of water/volatile vapors until contained, and efficiently capturing liberated water/volatiles under lunar vacuum and surrounding temperature conditions. NASA is interested in integrated icy regolith extraction and processing, and water collection system concepts and development of critical technologies to achieve this integrated approach. Proposals should result in hardware that can extract and capture 1.5 kg of water/hour from an icy regolith mixture under lunar shadowed region temperature and vacuum environmental conditions. Any valves used in the integrated system must be tolerant to repeated exposure to lunar regolith and temperature conditions, minimize losses, and operate without maintenance for significant periods of time.

Expected TRL or TRL Range at completion of the Project: 4 to 5

Primary Technology Taxonomy:

- Level 1: TX 07 Exploration Destination Systems
- Level 2: TX 07.1 In-Situ Resource Utilization

Desired Deliverables of Phase I and Phase II:

- Prototype
- Analysis
- Hardware

Desired Deliverables Description:

Phase I efforts should provide a feasibility study and/or proof of concept.

Phase II efforts should demonstrate the technology using lunar regolith simulant where applicable.

State of the Art and Critical Gaps:

These technologies directly address the following existing shortfalls and gaps:

Civil Space Shortfall Ranking https://www.nasa.gov/spacetechpriorities/

- Shortfall 1578: Extraction and separation of water from extraterrestrial surface material
- ISRU 567: In-situ resource extraction & collection in Lunar PSRs
- ISRU 568: Lunar volatile extraction in reactors/enclosures in PSRs
- ISRU 569: Regolith tolerant valves for low temperature – lunar PSRs
- ISRU 384: Excavation of hard regolith/ice material
- 1577: Perform resource reconnaissance to locate and characterize resources and estimate reserves
- 439: Detection of subsurface ice at less than 10’s m scale

Relevance / Science Traceability:

These technologies address the following Moon to Mars objectives:

- LI-7L: Demonstrate industrial-scale ISRU capabilities in support of continuous human lunar presence and a robust lunar economy.
- LI-8L: Demonstrate technologies supporting cislunar orbital/surface depots, construction and manufacturing maximizing the use of in situ resources, and support systems needed for continuous human/robotic presence.
- OP-11LM: Demonstrate the capability to use commodities produced from planetary surface or in-space resources to reduce the mass required to be transported from Earth.
- OP-12LM: Establish procedures and systems that will minimize the disturbance to the local environment, maximize the resources available to future explorers, and allow for reuse/recycling of material transported from Earth (and from the lunar surface, in the case of Mars) to be used during exploration.

References:

1. Ethridge, E., & Kaukler, W. (2007, January). Microwave extraction of water from lunar regolith simulant. *AIP Conference Proceedings* (Vol. 880, No. 1, pp. 830-837). American Institute of Physics. https://ntrs.nasa.gov/api/citations/20070018802/downloads/20070018802.pdf
2. Ethridge, E. C. (2011). *Using Microwaves to Heat Lunar Soil* (No. M11-0244). https://ntrs.nasa.gov/api/citations/20110009919/downloads/20110009919.pdf

3. Morrison, P., Zacny, K., Vendiola, V., & Paz, A. (2019). Results and lessons learned from testing of the Planetary Volatiles Extractor (PVEX) and related ISRU concepts. *Lunar ISRU 2019-Developing a New Space Economy Through Lunar Resources and Their Utilization*, 2152, 5076. https://www.hou.usra.edu/meetings/lunarisru2019/pdf/5076.pdf

Scope Title: Produce Propellants and Mission Consumables from Extracted In-Situ Resources

Scope Description:

Once resources are extracted from the extraterrestrial source, additional processing may be required to convert them into the consumable or commodity of interest. For example, water, once extracted and purified, could be used as is, or it can be converted into oxygen and hydrogen for propulsion. Other volatiles or reaction products such as nitrogen, carbon, etc. can be processed into other consumables for life support, plant growth, etc. Carbon sources from life support systems and extraterrestrial resources can be combined with hydrogen and other collected gases to produce hydrocarbon fuels, plastics, and nutrients. This scope addresses the technologies needed to do this additional refining and can include electrolysis, gas separation systems, and reactors. These technologies must withstand the unique environments of ISRU including extreme temperatures and potentially "dirty" product streams (regolith dust, chemical contaminants) for long-term operation (years) with limited maintenance. The technologies must be applicable to commercial scales (tons of product per year).

- Mars Atmosphere Collection and Pressurization to Enhance Processing.
    - Chemical processing reactors are much more energy and conversion efficient as operating pressures increase. In the past, Mars chemical processing reactors (such as Sabatier) were designed to operate at 1 bar pressure to minimize Mars atmosphere collection and pressurization system pressure increase requirements from the 6 to 10 torr Mars atmosphere pressure. However, the 1 bar pressure caused the Sabatier reactor to have a lower CO2 conversion efficiency than what could be achieved at higher operating pressures, thereby requiring separation and recirculation of unreacted gases. Therefore, to increase carbon dioxide conversion to methane and other hydrocarbons and products of interest, NASA is interested in technologies and concepts that will acquire and pressurize the Mars atmosphere to a minimum of 3 bar and desired pressure of 5 bar. Concepts must be able to achieve a minimum of 2 kg/hr CO_2 collection and pressurization rate through one or more units and/or stages.

- Production of Monopropellants from Extracted Resources.
    - Propellant production from extraterrestrial resources has primarily focused on oxygen as the oxidizer and hydrogen or methane as the fuel for large lander and ascent vehicles. However, other propellants can be produced from in situ resources that may be better for smaller scale and less complex applications such as surface hoppers. NASA is interested in technologies and concepts that will produce propellant grade/concentration propellants from in situ resources. For example, hydrogen peroxide from extracted water, oxygen, and hydrogen, and hydrazine from extracted nitrogen and hydrogen. Proposals should aim toward achieving pilot plant scale processing rates of approximately 1,000 kg per year production, but technologies and concepts should be scalable to much larger scales in the future.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:

- Level 1: TX 07 Exploration Destination Systems
- Level 2: TX 07.1 In-Situ Resource Utilization

Desired Deliverables of Phase I and Phase II:

- Analysis
- Prototype

Desired Deliverables Description:

Phase I should show feasibility as through models and/or subscale demonstrations.

Phase II should result in a functional prototype at a relevant scale.

State of the Art and Critical Gaps:

These technologies directly address the following existing shortfalls and gaps for ISRU:

Civil Space Shortfall Ranking https://www.nasa.gov/spacetechpriorities/

- 1583: Produce propellants and mission consumables from extracted in-situ resources
- ISRU-571: Methane production with ISRU
- ISRU-1333: ISRU for Novel Products

Relevance / Science Traceability:

These technologies address the following Moon to Mars objectives:

- LI-7L: Demonstrate industrial scale ISRU capabilities in support of continuous human lunar presence and a robust lunar economy.
- LI-8L: Demonstrate technologies supporting cislunar orbital/surface depots, construction and manufacturing maximizing the use of in-situ resources, and support systems needed for continuous human/robotic presence.
- OP-11LM: Demonstrate the capability to use commodities produced from planetary surface or in-space resources to reduce the mass required to be transported from Earth.
- OP-12LM: Establish procedures and systems that will minimize the disturbance to the local environment, maximize the resources available to future explorers, and allow for reuse/recycling of material transported from Earth (and from the lunar surface in the case of Mars) to be used during exploration.

References:

1. Davis, S. M., & Yilmaz, N. (2014). Advances in hypergolic propellants: Ignition, hydrazine, and hydrogen peroxide research. *Advances in Aerospace Engineering*, *2014*(1), 729313. https://onlinelibrary.wiley.com/doi/full/10.1155/2014/729313
2. Rapp, D., Karlmann, P., Clark, D. & Carr, C. (1997, July). Adsorption compressor for acquisition and compression of atmospheric CO2 on Mars. *33rd Joint Propulsion Conference and Exhibit* (p. 2763). https://arc.aiaa.org/doi/pdf/10.2514/6.1997-2763

Z-LIVE.04: Components for Extreme Environments (SBIR) (Previously Z13.05)

Related Subtopic Pointers: H15.02, S16.05, S13.03, Z-LIVE.02
Lead Center: KSC
Participating Center(s): GRC, JSC, LaRC

Subtopic Introduction:

NASA seeks new technologies to enable sustainable lunar and Mars surface operations by developing components capable of operating and surviving in extreme environments. These are components that can operate in cold and dusty environments without active (powered) heating and that can freeze and thaw without suffering damage or performance degradation. Proposals should discuss how the technology will enhance or replace the current state-of-the-art (SOA) technologies and techniques.

This solicitation specifically targets proposals for new technologies and methods that clearly address one of the following scope areas:

- Components and mechanisms for Extreme Environments.
- Dust-Tolerant Coatings for Lunar and Planetary Environments

Scope Title: Components and Mechanisms for Extreme Environments

Scope Description:

Proposals are sought for mechanisms and mechanical systems that can operate on the dusty surface of the Moon and Mars for months to years. These systems will be exposed to the harsh extreme environments and will have little to no maintenance. These mechanisms in extreme environments must function in the presence of regolith and charged dust, micrometeoroids, plume ejecta, extreme temperature variations, high vacuum, changing gravitational conditions, cosmic rays and other high-energy ionized particles, plasma, solar ultraviolet (UV) and other electromagnetic (EM) ionizing radiation, static electricity charging, potentially magnetic interactions, and other electrically induced effects.

Proposals should be focused on the following mechanisms and technologies that can function in these environments:

1. Innovative mechanisms for connecting and protecting umbilical and connector interfaces in the presence of dust.
2. Sealing materials, fabrics, and flexible metallic seals and techniques that can seal/protect mechanisms by preventing regolith intrusion and remain compliant and functional in the extreme Moon/Mars environments.
3. Dust-tolerant electrical connectors that can function with (or mitigate) light dust coating in the relevant Moon/Mars environments.
4. Dust-tolerant ambient fluid (gas and liquid) connectors that can function with (or mitigate) light dust coating in the relevant Moon/Mars environments.
5. Surface systems cryogenic disconnects that are light weight and compatible with the extreme environments.
6. Fiber-optic connectors for high bandwidth networks in the lunar dust and thermal environments. including solutions for enabling reliable mating and de-mating of the connectors.
7. Moving components for dust protection (iris, hatch, covers, louvers, closures, hinges, joints, etc.).

Successful solutions will have the following performance characteristics:

1. Operational for extended service of 10 to 100 months with limited or no maintenance.

2. Ambient fluid connectors with MOP (maximum operating pressure) up to 3500 kPa (5000 psi), commodity temperature 0 to +100°C (32 to 212°F), and 6 to 25 mm (¼ - 1 inch) flow diameter size range.
3. Cryogenic fluid connectors with MOP (maximum operating pressure) up to 1000 kPa (150 psi), commodity temperature 20 to 100°K (-424 to -280°F), and 12 to 50 mm (1/2 - 2 inch) flow diameter size range.
4. Electrical connectors for AC or DC power with power ratings 1 to 4 kW, and connectors for data transfer RJ45 or similar capability.
5. Mechanisms will function with minimal solid film or without lubrication.
6. Mechanisms operational lifetimes actuation/motion/mate-demate cycles of 500 or higher.
7. Mechanisms will function throughout lunar temperature cycles between +127 °C (260 °F) and -173 °C (-280 °F).
8. Mechanisms used in the extreme cold of permanently shadowed regions will survive at -238 °C (-396 °F).
9. Mechanisms will function reliably with lunar regolith (simulant) coating on the exposed mechanism surfaces.
10. Mechanisms will function in the high-vacuum lunar environment of 10^{-9} Torr.
11. Mechanisms and materials will function in the lunar electrostatic and radiation environment.

Expected TRL or TRL Range at completion of the Project: 2 to 6

Primary Technology Taxonomy:

- Level 1: TX 07 Exploration Destination Systems
- Level 2: TX 07.2 Mission Infrastructure, Sustainability, and Supportability

Desired Deliverables of Phase I and Phase II:

- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

Research should be focused on solving one of the NASA technology needs listed above. Applications with direct infusion path to current and future NASA projects/programs are sought.

1. Phase I Deliverables: A proof-of-concept or brassboard demonstrating technical feasibility and operability in a laboratory environment (TRL 3 or 4 level), and a report that includes analytical and model simulations in a relevant environment to answer critical questions focused on functional performance of the mechanisms. In addition, the report shall include recommendations for brassboard or prototype development during Phase II that is directly applicable to a current or future NASA project/program.
2. Phase II Deliverables: Delivery of a brassboard or prototype with a goal of achieving TRL 5 or 6, and laboratory testing demonstrating operability over the range of expected environmental conditions. The prototype shall be designed to conform to a NASA project/program need and include a well-developed flight demonstration and infusion plan. A report shall be written that includes functional, performance, analytical, and test results; and an evaluation of the technology’s maturity level (i.e., TRL) including the risk of proceeding with the development.

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 Moon/Mars environment.

Critical Gaps:

Seals at rotary and linear joints are very common for actuation in dusty environments. Most of these seals, however, use elastomers that would off-gas and become brittle in a lunar radiation environment and at lunar temperatures. Solutions are needed that employ advanced materials, metallic seals, or nontraditional techniques that can operate in the lunar environment for an extended period of time (months to years).

Operations on the lunar surface will involve the mating/demating of electrical, fluid, and cryogenic connections. Dust on the surface of these connectors will impede their proper function and lead to failures. Solutions are needed to develop connectors that can function in dusty Moon/Mars extreme environments.

Dust-protective enclosures, flexible covers, boots, hatches, and moving covers are needed to protect delicate mechanism components.

Civil Space Shortfall Ranking https://www.nasa.gov/spacetechpriorities/

- 1618: Survive and operate through the lunar night
- 1545: Robotic actuation, subsystem components, and system architectures for long-duration and extreme environment operation
- 792: In-space and On-surface transfer of Cryogenic fluid
- 361: Surface Mating Mechanisms
- 844: Passive Dust Mitigation Technologies for Diverse Applications

Relevance / Science Traceability:

Developing mechanisms for extreme environments will be one of the biggest challenges for operation on the lunar surface for the Artemis program.

References:

1. Dust Mitigation Gap Assessment Report, International Space Exploration Coordination Group (ISECG): https://www.globalspaceexploration.org/wordpress/docs/Dust%20Mitigation%20Gap%20Assessment%20Report.pdf

Scope Title: Dust-Tolerant Coatings for Lunar and Planetary Environments

Scope Description:

Proposals are sought to develop coatings capable offering protection from dust adhesion and/or wear onto myriad components and mechanisms capable of operating on the dusty surface of the Moon and Mars for months to years. These coatings must function in the presence of regolith and charged dust, micrometeoroids, plume ejecta, extreme temperature variations, high vacuum, changing gravitational conditions, cosmic rays, and other high-energy ionized particles, plasma, solar ultraviolet (UV), and other electromagnetic (EM) ionizing radiation, static electricity charging, and other electrically induced effects.

Proposals should be focused on the following technologies that can function in these environments:

1. Innovative material compositions with exceptional abrasive and erosive wear performance against particulate damage, such as lunar or Martian regolith, as well as by high-velocity particle impact for hard good applications, such as structures for a lunar terrain vehicle, habitat, hinges, etc.

2. Flexible coating solutions for soft good applications, including fabrics, to minimize adhesion and prevent regolith intrusion while remaining compliant and functional in the extreme Moon/Mars environments.
3. Dust-tolerant material system that can persist with or mitigate light dust surface loadings relevant Moon/Mars environments.

Successful solutions will have the following performance characteristics:

1. Operational for extended service of 10 to 100 months with limited or no maintenance.
2. Performance in lunar surface temperature regime of +127 °C (260 °F) and -173 °C (-280 °F) without failure, including by cracking, delamination or spallation.
3. Demonstrated operation in the high-vacuum lunar environment of 10^{-9} Torr.
4. Impart protection from adhesion, abrasive and erosive wear, and/or high-velocity impact by lunar dust.

Operation in the lunar electrostatic and radiation environment.

Expected TRL or TRL Range at completion of the Project: 2 to 6

Primary Technology Taxonomy:

- Level 1: TX 12 Materials, Structures, Mechanical Systems, and Manufacturing
- Level 2: TX 12.1 Materials

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Research should be focused on solving one of the NASA technology needs listed above. Applications with direct infusion path to current and future NASA projects/programs are sought.

1. Phase I Deliverables: A proof-of-concept or coating demonstrating technical feasibility and operability in a laboratory environment (TRL 3 or 4 level), and a report that includes analytical and model simulations in a relevant environment to answer critical questions focused on functional performance of the coating. In addition, the report shall include recommendations for coating system or prototype development during Phase II that is directly applicable to a current or future NASA project/program.
2. Phase II Deliverables: Delivery of a dust-tolerant coating or system with a goal of achieving TRL 5 or 6, and laboratory testing demonstrating operability over the range of expected environmental conditions. The prototype shall be designed to conform to a NASA project/program need and include a well-developed flight demonstration and infusion plan. A report shall be written that includes functional, performance, analytical, and test results; and an evaluation of the technology's maturity level (i.e., TRL) including the risk of proceeding with the development.

State of the Art and Critical Gaps:

The lunar surface presents numerous challenges, including ultra-high vacuum exposure, temperature extremes, and intense radiation. Additionally, lunar regolith threatens component durability and reusability due to its abrasive nature. Low lunar gravity free floating lunar dust particles are typically < 100 micrometers (μm), capable of accumulating within cracks and crevices where cleaning tools cannot readily access. Lunar dust particles scoring, adhering or embedding into surfaces and within device-confined geometries can cause premature component wear or failure. Soft goods, including outer-layer fabrics for spacesuits and flexible webbing for inflatable habitat structures, are particularly sensitive to wear by dust. Furthermore, the interaction between the rocket plume and surface during vehicle landings and ascents creates severe erosive conditions near critical vehicle components and adjacent infrastructure.

Apollo-era materials and structures were designed with minimal protective measures in place to mitigate dust adhesion, wear, or impact due to the short-duration need. To enable a sustainable lunar presence, reusable technologies, such as ascent/descent vehicles, roving terrain vehicles, and spacesuits, will require innovative passive material solutions to persist in the dusty environment for long-duration surface operation.

Civil Space Shortfall Ranking https://www.nasa.gov/spacetechpriorities/

- 844: Passive Dust Mitigation Technologies for Diverse Applications

Relevance / Science Traceability:

Developing passive dust mitigation technologies for extreme environments will be one of the biggest challenges for operation on the lunar surface for the Artemis program.

References:

1. Loftus, David J., Tranfield, Erin M., Rask, Jon C. and McCrosssin, Clara, “The Chemical Reactivity of Lunar Dust Relevant to Human Exploration of the Moon,” Planetary Science Division Decadal Survey white paper (2020).
2. “Cross-Program Design Specification for Natural Environment (DSNE),” NASA Standard No. SLS-SPEC-159 Revision H (August 2020).
3. McKay, David S., Heiken, Grant, Basu, Abhijit, Blanford, George, Simon, Steven and Reedy, Robert, Bevan M. French, and James Papike, “The Lunar Regolith,” Lunar Sourcebook (1991), 285-356.
4. Stubbs, Timothy J., Vondrak, Richard R. and Farrell, William M., “Impact of Dust on Lunar Exploration,” Dust in Planetary Systems, (January 2007), 239-243.
5. Stiegman, Albert E. and Liang, Ranty H., “Ultraviolet and Vacuum-ultraviolet Radiation Effects on Spacecraft Thermal Control Materials,” The Behavior of Systems in the Space Environment. Dordrecht: Springer Netherlands, 1993.
6. Wiesner, Valerie, L., Wohl, Christopher, J., King, Glen C., Gordon, Keith L., Das, Lopamudra and Hernandez, Jonathan J., “Protective Coatings for Lunar Dust Tolerance,” NASA Technical Memorandum, no. 2023-0003195 (2023).

Z-LIVE.05: Regolith Excavation and Manipulation for Surface Operations and Infrastructure with Assembly and Outfitting of Lunar Surface Structures (SBIR) (Previously Z14.01)

Related Subtopic Pointers: Z-EXPAND.02, T7.04
Lead Center: KSC
Participating Center(s): GRC, JPL, LaRC

Subtopic Introduction:

NASA is interested in developing excavation and supporting technologies to mine resources by excavating regolith at the Moon's south pole and eventually in other lunar locations, including the lower latitude mare regions. Excavation of lunar regolith is enabling for in-situ resource utilization (ISRU) because the regolith will be the source of many feedstocks that can be used to make needed products in this technology area. For ISRU, excavation technologies are required to mine resources that will have been previously located and identified by resource prospecting methods. For oxygen extraction, the loose top-surface regolith may be mined because the oxygen is ubiquitously present in the form of silicates, whereas volatile resources (including water ice) are thought to be beneath an insulating overburden that may be up to 1 m deep and beyond. Mars mission data (Phoenix, Mars Reconnaissance Orbiter (MRO), etc.) have also shown that there are vast deposits of water ice in the Martian subsurface, providing Mars-forward linkage for subsurface frozen regolith excavation technologies. Regolith can also be manipulated in bulk form for civil engineering applications, such as constructing berms for landing/launch rocket engine plume impingement ejecta and emplacement of regolith overburden on hangar shell structures to provide radiation protection, thermal stabilization, and meteoroid impact shielding for assets that may be placed inside these hangars for environmental protection and shielding, such as pressurized habitats for astronauts. Furthermore, when the regolith is consolidated, either with a binder material or by fusing it through sintering, vitrification, or melting, a viable concrete-like construction material can be produced and used to build lunar infrastructure and other useful parts, such as ballast blocks for cranes and other equipment that relies on reaction forces provided by gravity.

There will be a need for building significant lunar infrastructure including a lunar power grid, lunar communications network, and other critical infrastructure such as launch/landing facilities, roads, shelters, habitats, and other facilities to support science and commercial activities.

Limited infrastructure will first arrive on the lunar surface as part of the early Artemis missions; however, it is expected that much more capable and expansive infrastructure will be needed to support a permanent presence for exploration and large-scale commercial operations. Autonomous robotic assembly and outfitting are seen as a key enabling technologies needed for the creation of this lunar infrastructure.

Assembly is the process by which a structure is created from subcomponents. The steps of an assembly process include part acquisition, placement, and joining in a human planned or algorithmic generated sequence. Execution of an assembly sequence could be performed with human supervision but may be autonomously executed with error correcting capabilities to ensure a successful result. Important features of assembly include its use of simplified components, versatility, extensive terrestrial experience base, and can be accomplished using general and/or special purpose robotic agents. Furthermore, future versions of surface assembly can leverage the use of components derived from ISRU-based materials in combination with Earth sourced components. Specifically, it is envisioned that the ISRU-based components can range from simple shapes such as trusses, beams, and panels, to more complex 3D manufactured joints, connections, mounting features, and will enable the transition from Earth-sourced to lunar-sourced components as they become available.

Outfitting is the process by which a structure is transformed into a useable system by in-situ installation of subsystems, such as the routing and integration of wiring, connections, and outlets for power and data transmission, lighting, sensor systems, pressurized gas/fluid systems, and Environmental Control and Life Support Systems (ECLSS), which includes water, hydraulics, coolants. Outfitting also requires in-situ inspection, testing, maintenance, and repair of these integrated subsystems. To the extent reasonable, some of these subsystems can be pre-assembled into modules and the modules integrated in situ (e.g., integrated power subsystem and wiring harness). To the extent reasonable, outfitting should be accomplished using autonomous robotic agents to minimize crew time expended; however, the specific agents (robotic or human) performing the outfitting need to be considered as part of the co-design of the overall excavation, construction, and outfitting (ECO) system.

The first applications of lunar surface assembly and outfitting are likely to be simple structures such as a communications tower, a vertical solar power tower, lander plume containment shields, or a small shelter for surface asset protection with limited outfitting requirements.

Scope Title: Implements for In-Situ Resource Utilization (ISRU) Regolith Excavation, Tailings Removal and Regolith Manipulation to Support Lunar Infrastructure Development

Scope Description:

NASA is seeking implements that can be automatically attached to a standard "quick-attach" interface via remote operations without human intervention. An implement is defined here as a modular and detachable tool, or piece of equipment that is used to carry out a specific task or function. These implements will be used on a multi-purpose robotic mobility platform that will be provided by NASA, or its partners, on the lunar surface. The mass and dimensions of this robotic mobility platform are not known yet, so proposers should suggest appropriate mobility platform metrics and related rationale. Reduced mass and dimensions are preferred if mining excavation feasibility can be established.

Proposals should be submitted in the context of the following reference concept of operations:

An In-Situ Resource Utilization (ISRU) surface regolith mining operation that will produce 10,000 kg of oxygen per year. Therefore, approximately 155,039 kg of surface lunar regolith needs to be mined per year to produce 10,000 kg of oxygen with an assumed extraction efficiency of 15% using the Carbothermal reduction process. This regolith shall be delivered to an ISRU plant as shown in Figure 2: Lunar ISRU System and Concept of Operations of reference [14].

The proposed implement(s) shall also be capable of removing ISRU mining tailings from the resource processor and delivering them to a waste dump site. The mining tailings will be in the form of expelled solidified melted regolith "pucks" from a carbothermal resource processor. The size of an expelled regolith puck from the Carbothermal ISRU plant typically measures around 10 cm in diameter and 1 cm thick. These pucks are the byproduct of the carbothermal reduction process, which extracts oxygen from lunar regolith by heating it with a carbon source at high temperatures. The remaining regolith material, primarily composed of slag and unreacted regolith, is disposed from the reactor without being compacted into pucks and requires handling and disposal.

There are many applications for using lunar regolith as a feedstock for creating lunar infrastructure by either using it in bulk granular material form or by processing the regolith to create useful structures in the lunar surface architecture. In a recent Space Technology Mission Directorate (STMD) analysis the following relevant shortfalls were recognized as being of high priority:

- Overall Priority #1, 1618: Survive and operate through the lunar night
- Overall Priority #15, 1527: Radiation Countermeasures (Crew and Habitat)
- Overall Priority #46, 361: Surface Mating Mechanisms

By storing thermal energy in densified regolith (such as by sintering or melting), then lunar assets placed on it can benefit from the slow radiant heat transfer throughout the lunar night or transient shadowed periods. This concept has previously been proposed as a "Thermal Wadi", [15].

Radiation shielding can be achieved with in-situ lunar regolith in bulk form or processed form. For example, lunar regolith could be emplaced on a structural shell hangar at a depth of at least 3 meters to create a sufficient radiation shield for lunar assets parked inside this hangar. An example of processed regolith radiation shielding is creating structural elements out of hydrocarbon polymer regolith concrete where thermoplastic polymers are used as the binder material, [16].

Proposals for relevant regolith manipulation implements only should be submitted in the context of one or both of the following reference use cases:

A thermal wadi pad structure on the lunar surface created out of sintered or melted regolith with a circular shape and a depth to be determined by the environmental conditions at a selected site which may be any one of the Artemis designated candidate landing zones [18]. The thermal wadi pad shall be of a sufficient diameter and depth to ensure survival through the lunar night of the lunar mobility platform concept that was specified by the proposer for the regolith manipulation implements.

A structural shell hangar that is constructed out of structural elements or in-situ regolith concrete with sufficient strength in the lunar environment to hold the load of a 3 meter regolith overburden that has been placed on top of these hangars for radiation shielding. The hangar shall be large enough to house a habitation module for 4 crew or 2 pressurized lunar rover for crew excursions that can support 2 astronauts each. The implement(s) shall be used to transport and emplace the regolith for hangar radiation shielding.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:

- Level 1: TX 07 Exploration Destination Systems
- Level 2: TX 07.1 In-Situ Resource Utilization

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

This solicitation is seeking the following regolith excavation and tailings removal implement deliverables:

• Research
• Analysis
• Prototype
• Hardware
• Software

In Phase I, a prototype is not required but research, analysis and a prototype concept design should be produced and delivered to NASA. Phase I deliverables may be a conceptual design or development plan with analysis to show feasibility at relevant scales and/or a small demonstration of the concept.

If selected, it would be expected that a fully functional implement(s) shall be delivered to NASA, including hardware, sensors, and software, for a specified interface that will be coordinated with NASA prior to a Phase II follow on contract. Phase II deliverables should be hardware demonstrations at a relevant scale.

A potential Phase III deliverable might include a long-term test campaign (>1 year) in a lunar analogous terrestrial environment in order to subject equipment to realistic work conditions.

State of the Art and Critical Gaps:

The state of the art consists of terrestrial prototypes at TRL 3 or 4 that have been previously built and tested for SBIR/STTR, NASA Centennial Challenge, NASA competitions for universities, and in-house NASA technology development such as the Regolith Advanced Surface Systems Operations Robot (RASSOR) 2.0. In-Situ Resource Utilization (ISRU) Pilot Excavator (IPEX) and the Advanced Planetary EXcavator (APEX). The NASA "Chariot' mobility platform demonstrated a modular quick attach system for a lunar bulldozer blade prototype. Very few dedicated regolith excavation modular implement have been prototyped by NASA.

Civil Space Shortfall Ranking https://www.nasa.gov/spacetechpriorities/

- 369 – Excavation of granular (surface) regolith for ISRU commodities production
- 384 - Excavation of hard/compacted/icy regolith material
- 385 - Regolith and resource delivery system
- 662 - Robotic regolith manipulation and site preparation
- 617 – On-surface robotic assembly of vertical structures
- 1400 - On-surface robotic assembly of horizontal structures
- 425 - On-Surface ISRU-based Construction of Vertical Structures
- 666 - On-Surface ISRU-based Construction of Horizontal Structures
- 1480 - On-surface Outfitting of Lunar Structures

Relevance / Science Traceability:

The work desired applies to Technology Taxonomy area 7 (TX07): Exploration Destination Systems. It applies to Strategic Goal 2: Extend Human Presence Deeper into Space and to the Moon for Sustainable Long-Term Exploration and Utilization, from the 2018 NASA Strategic Plan. It also applies to the Plan's Strategic Objective 3.1: Develop and Transfer Revolutionary Technologies to Enable Exploration Capabilities for NASA and the Nation. It also applies to TX04: Robotic Systems, as the excavation equipment will need to operate without a human crew present during some periods.

References:

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19. https://www.nasa.gov/news-release/nasa-identifies-candidate-regions-for-landing-next-americans-on-moon/
20. NASA STMD National Space Technology Priority Shortfall List https://www.spacetechpriorities.org/

Scope Title: Robotic Assembly Systems and Outfitting for Lunar Surface Construction

Scope Description:

Robotic assembly of structures is one of the leading candidates for establishing some of the critical early lunar surface infrastructure—for example, tall towers (>50-m total height) for solar power generation and communications, lander plume containment shields for launch and landing pads, and shelters for crew and surface asset protection, etc. It is envisioned that these structures could be assembled from basic structural elements such as trusses and panels (e.g., truss-based tower [Refs. 1-3], or shelter [Ref. 5]), prefabricated truss-based and panel-based subassemblies (e.g., voxels [Ref. 4], truss-beams), or other hybrid or novel structural elements/concepts [Ref. 5]. While structural assembly on Earth is a well-established construction approach, many technology gaps exist for the automated assembly of structures on the lunar surface. Specifically, robotic agents and robotic tools are required to enable efficient and reliable autonomous/automated assembly, inspection, and repair of these structures.

To this end, proposals are invited for the development of robotic assembly system concepts, robotic assembly tool designs, and structural element and joint designs for the assembly of lunar surface structures such as those examples mentioned above. Joining methods can include, but are not limited to, interlocking joints, mechanical fastening (e.g., rivets), welding, and bonding (both reversible and nonreversible). Proposals are free to use any structural element geometry (e.g., trusses, panels, voxels, other) and material (e.g., composite, metallic). However, any design choices should have a clear path to flight hardware and benefits of a particular structural element configuration should be justified (e.g., structural efficiency, assembly efficiency, cost, etc.). In addition, over time, it is expected that ISRU-based structural elements will replace Earth-sourced elements for large-scale infrastructure development. Thus, concepts that support the transition from Earth-sourced elements to ISRU-based elements are of particular interest.

Proposers are also free to select a structural application of their choice as the focus of their assembly system development. Specific geometries for candidate structural applications are not specified herein, however, example geometries and load cases can be found in the literature including the references given herein.

Offerors can propose the use of commercially available general-purpose space-capable robotic manipulating arms and concentrate on the development and integration of specialized robotic end-effectors and tooling required for assembly; or they can propose the design and use of special-purpose assembly robots (e.g., Ref. 4); or a combination of both. However, it is desirable for proposers to specify any commercial robot capabilities and other support equipment assumed in their concept, if used (e.g., reach, payload capacity, power consumption, etc.). Additionally, it is desirable for proposers to justify the robot agents selected and/or designed. Assembly concepts that maximize structural efficiency, minimize power requirements and complexity, and maintain suitable construction tolerances are desired. Justification of all design decisions shall be included.

Note: joining approach, robotic assembly system, and tools are not expected to be flight qualified, however, they should have a clear path to flight.

Phase I efforts are expected to focus primarily on system design and feasibility studies and proof of concept tests to identify and demonstrate key technology functions such as robotic structural element manipulation, joint design, joining, etc.; Phase II efforts will be used to mature these technologies and concepts and to conduct a ground demonstration to robotically assemble a representative structure.

Outfitting is the process by which a structure is transformed into a useable system by in-situ installation of subsystems, such as the routing and integration of wiring, connections, and outlets for power and data transmission, lighting, sensor systems, pressurized gas/fluid systems, and Environmental Control and Life Support Systems (ECLSS). Outfitting also requires in-situ inspection, testing, maintenance, and repair of these integrated subsystems. While manual structural outfitting on Earth is a well-established construction approach, many technology gaps exist for the automated outfitting of infrastructure on the Moon. Specifically, robotic tools and attachment concepts that enable autonomous/automated routing and securing cables and tubing to a structure; robotic tools and attachment concepts to install equipment such as communication packages, cameras, lights and antenna and join connectors; and autonomous systems for in-situ inspection, maintenance, and repair.

To focus efforts, this solicitation seeks solutions for the outfitting of structures with cables, wiring harnesses, equipment/payloads, and connectors necessary for power distribution and/or communications. Of particular interest is the outfitting of structures assembled from trusses or truss-like elements including truss-based power and communication towers, environmental shields, and shelters (see example assembly concepts in Refs. 1-5). However, concepts for the outfitting of other types of construction will also be considered. To this end, proposals are invited for the development of concepts to outfit truss-based structures including: routing of electrical cables, securing cables along the truss structure, connection of equipment such as communication packages, cameras, lights and antenna, and making and testing connections. Proposals should include concept of operations and associated robotic tools required to outfit the structure.

Proposers are free to select a structural application of their choice as the focus of their outfitting system development. Specific geometries for candidate structural applications are not specified herein, however, example geometries and load cases can be found in the literature including the references given herein.

Finally, offerors can propose the use of commercially available general-purpose space-capable robotic manipulating arms and concentrate on the development and integration of specialized robotic end-effectors and tooling required for outfitting applications; or they can propose the design and use of special-purpose outfitting robots; or some combination of both. However, it is desirable for proposers to note any commercial robot capabilities and other support equipment assumed in their concept, if used (e.g., reach, payload capacity, power consumption, etc.). Additionally, it is desirable for proposers to justify the robot agents selected and/or designed. Outfitting concepts that maximize efficiency, minimize power requirements and complexity are desired. Justification of all design decisions should be included.

Note: the robotic outfitting system, tools, and outfitting hardware, are not expected to be flight qualified, however, they should have an obvious development path to flight.

Phase I efforts are expected to focus primarily on system design and feasibility studies and proof of concept tests to identify and demonstrate key technology functions such as robotic manipulation, cable/wire attachment, connections, etc.; Phase II efforts will be used to mature these technologies and concepts and to conduct a ground demonstration to robotically outfit a representative structure.

Proposal elements of interest for Assembly Systems & Outfitting include, but are not limited to, the following:

- Robotic agents and/or tools for outfitting.
- Concepts for cable routing and securing to an assembled structure.
- Securing equipment such as communication packages (50 cm 50 cm x 100 cm 20 kg boxes), cameras, lights and antenna (in the 10 kg class).
- Making and securing electrical connection of equipment including strain relief.
- Robotic outfitting considerations for repair, and inspection.
- Concept of operations describing process to outfit one or more structural concepts of choice using the robotic tools and joining methods developed.
- In-situ verification and functional testing.
- Description of the assumed robotic system(s), tools, and infrastructure necessary for the proposed outfitting approach, including reach, payload, power consumption, communications, etc., of the individual robotic agents.
- Considerations for operating in lunar daytime environment (1/6 gravity, temperature, radiation, vacuum, lighting, power requirements). Note: Proposal does not have to produce space-rated equipment; however, the concept and processes shall be extensible to the lunar environment.
- Preliminary proof-of-concept demonstrations, methods, and equipment.
- Discuss application of technology to the outfitting of other structures outside the focused application, e.g., shelters, habitats.

Expected TRL or TRL Range at completion of the Project: 4 to 6

Primary Technology Taxonomy:

- Level 1: TX 07 Exploration Destination Systems
- Level 2: TX 07.X Other Exploration Destination Systems

Desired Deliverables of Phase I and Phase II:

- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Phase I hardware development is desired including but not limited to efforts that emphasize robotic tools and/or system designs for the manipulation and assembly of structural elements (e.g., trusses, panels, voxels, or other subassemblies); feasibility studies and assembly and outfitting concepts of operation; and proof of concept tests to demonstrate key technology functions.

Phase I software development is desired including but not limited to efforts that emphasize initial software framework for structural design and planning (a.k.a., building information model (BIM)), or proof of concept simulations or digital engineering.

Phase II hardware development efforts likely include maturation of Phase I concepts and integrated system test to demonstrate end-to-end assembly and/or outfitting processes.

Phase II software development efforts will include advanced versions of Phase I structural design and planning software that can address a variety of assemblies, assembly approaches, and selected outfitting concepts and approaches, and achieve some level of validation via case study.

State of the Art and Critical Gaps:

The state of the art is contained in concept studies only.

Applicable shortfalls:

Civil Space Shortfall Ranking https://www.nasa.gov/spacetechpriorities/

- 617 – On-surface robotic assembly of vertical structures
- 790 – Tall (>30m) Inexpensive Self-Erecting Communications Towers
- 1214 - Habitat outfitting approaches for inflatable habitat structures and/or vertically constructed habitats
- 1480 – On-surface Outfitting of Lunar Structures
- 1527 – Radiation countermeasures (Crew and habitat) (e.g., assembled radiation shelters for crew, habitats, and surface assets)
- 1538 – General-purpose robotic manipulation to perform human-scale logistics, maintenance, outfitting, and utilization
- 1540 – Intelligent robots for the servicing, assembly, and outfitting of in-space assets and industrial-scale surface infrastructure

- 1558 – High rate communications across the lunar surface (includes reference to 790 – Tall (>30m) Inexpensive Self-Erecting Communications Towers, 617 - assembly of vertical structures, 1480 - Outfitting)
- 1596 – High power energy generation on moon and Mars surfaces (includes reference to 504 – Photovoltaic Arrays up to 50 kWe Increments, 617 - assembly of vertical structures, 1480 - Outfitting)

Relevance / Science Traceability:

The work desired applies to Technology Taxonomy area 7 (TX07): Exploration Destination Systems. It applies to Strategic Goal 2: Extend Human Presence Deeper into Space and to the Moon for Sustainable Long-Term Exploration and Utilization, from the 2018 NASA Strategic Plan. It also applies to the Plan's Strategic Objective 3.1: Develop and Transfer Revolutionary Technologies to Enable Exploration Capabilities for NASA and the Nation. It also applies to TX04: Robotic Systems, as the assembly equipment will need to operate without a human crew present during some periods.

References:

See the following references for recent NASA projects and example assembled structures for consideration:

1. Tall Lunar Tower Project page: https://techport.nasa.gov/view/116431
2. Tall Lunar Tower animation: https://ntrs.nasa.gov/citations/20230007930
3. Towers: Critical Initial Infrastructure for the Moon, Such as a Power Module Support: https://techport.nasa.gov/view/116431?lib=310810
4. Automated Reconfigurable Mission Adaptive Digital Assembly Systems (ARMADAS): https://www.nasa.gov/general/robot-team-builds-high-performance-digital-structure-for-nasa/
5. Design Analysis for Lunar Safe Haven Concepts: https://ntrs.nasa.gov/api/citations/20210024725/downloads/FINAL-BlueTeam-AIAA%20Editing%20version%20for%20presentation%20in%20January.pdf
6. NASA STMD National Space Technology Priority Shortfall List https://www.spacetechpriorities.org/

Scope Title: Software for Structural Design, Robotic Assembly and Outfitting Planning Optimization

Scope Description:

Planning the construction and outfitting of lunar surface infrastructure by robotic agents will be critical for establishing a permanent human and robotic lunar presence and robust lunar economy. It is envisioned that this infrastructure will be built using a combination of structural types including deployable structures, assembled structures, and in-situ derived structures (e.g., ISRU-based additive construction). Additionally, the emplacement of infrastructure will require the use of autonomous/automated robotic systems for activities including site preparation, surface construction, and outfitting (i.e., in-situ installation of subsystems), inspection, maintenance, and repair. The robotic systems must be thoughtfully employed due to limited power, reach, load capabilities, and little to no spare parts. Typical terrestrial construction activities involve many steps over the life of the construction effort including site selection, structural design, construction planning, cost estimates, and management, physical construction, and post-construction inspection, verification/certification. Successful terrestrial construction activities often rely on software such as computer aided design (CAD) and Building Information Models (BIM) to aid in the design, construction planning, coordination and management. It is desirable to have similar software for the robotic construction of lunar surface infrastructure.

To this end, NASA seeks proposals for the development of software that can aid in the design of assembled structures (e.g., power and communication towers, radiation protection shelters, etc.) and the outfitting of these structures with mechanical, electrical, and plumbing (MEP), as well as perform design trades and make decisions related to assembly and outfitting approaches and sequence.

In Phase I, software development is desired including but not limited to efforts that emphasize initial software framework for structural design and planning of assembled structures (particular structures and assembly concepts of interest are described in Refs. 1-5), assembly process optimization (including variables such as number and types of robotic agents, structural element types, assembly and outfitting methods, power consumption, cost, other design considerations), building information model (BIM) that link 3D CAD models of the structural assembly and MEP with time or sequencing information, or proof of concept simulations or digital engineering.

Follow-on Phase II software development efforts will likely include advanced versions of Phase I structural design and planning software that can address a variety of assemblies, assembly approaches, and selected outfitting concepts and approaches, and achieve some level of validation via case study.

Proposal elements of interest include, but are not limited to, the following:

- Description of a software framework for structural design and planning of assembled lunar surface structures.
- Describe approach to assembly and outfitting process optimization (including variables such as number and types of robotic agents, structural element types, assembly and outfitting methods, power consumption, cost, other design considerations).
- Description of a building information model (BIM) framework that links 3D CAD models of the structural assembly and MEP with time or sequencing information for lunar surface structures.
- Preliminary proof-of-concept simulations and/or software demonstration.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:

- Level 1: TX 11 Software, Modeling, Simulation, and Information Processing
- Level 2: TX 11.1 Software Development, Engineering, and Integrity

Desired Deliverables of Phase I and Phase II:

- Research
- Prototype
- Software

Desired Deliverables Description:

Phase I software development is desired including but not limited to efforts that emphasize initial software framework for structural design and planning (a.k.a., building information model (BIM)), or proof of concept simulations or digital engineering.

Phase II software development efforts will include advanced versions of Phase I structural design and planning software that can address a variety of assemblies, assembly approaches, and selected outfitting concepts and approaches, and achieve some level of validation via case study.

State of the Art and Critical Gaps:

The state of the art for this software is terrestrial applications and Earth orbiting satellites.

Applicable shortfalls:

Civil Space Shortfall Ranking https://www.nasa.gov/spacetechpriorities/

- 617 – On-surface robotic assembly of vertical structures
- 790 – Tall (>30m) Inexpensive Self-Erecting Communications Towers
- 1214 - Habitat outfitting approaches for inflatable habitat structures and/or vertically constructed habitats
- 1480 – On-surface Outfitting of Lunar Structures
- 1527 – Radiation countermeasures (Crew and habitat) (e.g., assembled radiation shelters for crew, habitats, and surface assets)
- 1538 – General-purpose robotic manipulation to perform human-scale logistics, maintenance, outfitting, and utilization
- 1540 – Intelligent robots for the servicing, assembly, and outfitting of in-space assets and industrial-scale surface infrastructure
- 1558 – High rate communications across the lunar surface (includes reference to 790 – Tall (>30m) Inexpensive Self-Erecting Communications Towers, 617 - assembly of vertical structures, 1480 - Outfitting)
- 1596 – High power energy generation on moon and Mars surfaces (includes reference to 504 – Photovoltaic Arrays up to 50 kWe Increments, 617 - assembly of vertical structures, 1480 - Outfitting)

Relevance / Science Traceability:

The work desired applies to Technology Taxonomy area 7 (TX07): Exploration Destination Systems. It applies to Strategic Goal 2: Extend Human Presence Deeper into Space and to the Moon for Sustainable Long-Term Exploration and Utilization, from the 2018 NASA Strategic Plan. It also applies to the Plan’s Strategic Objective 3.1: Develop and Transfer Revolutionary Technologies to Enable Exploration Capabilities for NASA and the Nation. It also applies to TX04: Robotic Systems, as the assembly equipment will need to operate without a human crew present during some periods.

References:

See the following references for recent NASA projects and example assembled structures for consideration:

1. Tall Lunar Tower Project page: https://techport.nasa.gov/view/116431
2. Tall Lunar Tower animation: https://ntrs.nasa.gov/citations/20230007930
3. Towers: Critical Initial Infrastructure for the Moon, Such as a Power Module Support: https://techport.nasa.gov/view/116431?lib=310810
4. Automated Reconfigurable Mission Adaptive Digital Assembly Systems (ARMADAS): https://www.nasa.gov/general/robot-team-builds-high-performance-digital-structure-for-nasa/
5. Design Analysis for Lunar Safe Haven Concepts: https://ntrs.nasa.gov/api/citations/20210024725/downloads/FINAL-BlueTeam-AIAA%20Editing%20version%20for%20presentation%20in%20January.pdf
6. NASA STMD National Space Technology Priority Shortfall List https://www.spacetechpriorities.org/

Z-EXPAND.01: Servicing and Assembly Applications (SBIR) (Previously Z5.06)

Lead Center: GSFC
Participating Center(s): JPL, KSC

Subtopic Introduction:

Technology development efforts are required to enable in-space servicing for commercial satellites and robotic and human exploration. In-space servicing, assembly, and manufacturing (ISAM) 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. This subtopic addresses key servicing gaps / shortfalls in the Space Technology Mission Directorate (STMD) roadmap.

Scope Title: Clean Robotics for Highly Sensitive Systems

Scope Description:

NASA requests demonstration apparatus and procedures to quantify the cleanliness of robotic components to enable significant improvements in cleanliness of robotic systems. Future development can address conceptual designs for significant improvements in cleanliness of robotic systems that will enable in-space servicing and assembly of highly sensitive spacecraft and platforms, such as the Habitable Worlds Observatory and other future telescopes. With increasing inclusion of in-space servicing, assembly, and manufacturing in future architectures, there is a need to reduce contamination for operations around highly sensitive platforms. The current state of the art for robot systems poses risks for servicing of platforms with ultraviolet (UV) systems that may be susceptible to contamination which could dramatically reduce instrument performance. As an example, future ultraviolet observatories are seeking 1,000 times more stability than the James Webb Space Telescope and contamination levels that do not degrade wavefront stability needed for coronograph performance.

NASA STMD Shortfall 379 for Upgrade or Install Instruments on Large Space Observatories is directly applicable.

Moving parts, lubrication, thermal management systems, harnesses, sensors, and other arm subsystems are likely to result in outgassing, particulate ejection, and other forms of contamination. Specific missions set contamination budgets and deploy verification and validation approaches for mission assurance. This scope seeks methods and equipment that can form a future standard for quantifying contamination ranges to be expected.

Approaches to understand the cleanliness characterization of current robotic arm offerings and new means, incremental or otherwise, to improve the same. Engineering estimates of the impact of improving the overall cleanliness on design complexity, schedule, cost, and risk are encouraged.

Expected TRL or TRL Range at completion of the Project: 1 to 4

Primary Technology Taxonomy:

- Level 1: TX 04 Robotics Systems
- Level 2: TX 04.6 Robotics Integration

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis

Desired Deliverables Description:

Phase I deliverables include:

- Background research and feasibility studies.
- Modeling to demonstrate feasibility.
- Conceptual design, trade studies, and description of proposed solution.
- Concept for environmental characterization of improved performance.

Phase II deliverables include:

- Validation of current contamination budget/estimates.
- Validation of methods to improve contamination performance at system or subsystem level.

State of the Art and Critical Gaps:

The current state of the art includes robot arms systems such as Canadarm2; Japanese Module Remote Manipulator System; On-Orbit Servicing, Assembly, and Manufacturing 1 (OSAM-1); and Robotic Servicing of Geosynchronous Satellites (RSGS) robot arms, which have primarily been used in low Earth orbit (LEO). Future servicing and assembly applications require expanded capabilities in multiple orbital domains, including LEO, geostationary orbit (GEO), Lagrange points, and beyond.

This scope provides a potentially enabling capability for planetary science mission concepts that implement robotics for instrument upgrades and/or assembly, and improved robotics for minimizing contamination risk for sample return.

Civil Space Shortfall Ranking https://www.nasa.gov/spacetechpriorities/

- 379: Upgrade or install instruments on large space observatories
- 1480: On-surface Outfitting of Lunar Structures
- 1506: In-Space & Surface Transfer of High-Pressure Pneumatic Fluids
- 1612: Surface-based fluid management for near/mid-term missions

Relevance / Science Traceability:

NASA is evaluating architectures that involve upgrade and modernization of instruments or subsystems on multiple platforms. An improved-cleanliness robotic system provides additional options for science instrument modernization at optimized costs.

References:

1. On-Orbit Satellite Servicing Study Project Report. October 2010. https://sspd.gsfc.nasa.gov/images/NASA_Satellite%20Servicing_Project_Report_0511.pdf
2. Contamination and Cleanliness of UV and EUV space instruments. https://www2.mps.mpg.de/homes/schuehle/documents/Presentations/Schuehle_SRI-WS_SpaceDegradation.pdf

Scope Title: In-Space Helium Transfer Compressor for In-space Vehicle to Vehicle Transfer

Scope Description:

NASA requests novel conceptual designs for the transfer of high pressure helium gases, along with other gases for future space missions.

The transfer of high-pressure helium gas (GHe) along with other gases such as gaseous oxygen (GO2), gaseous nitrogen (GN2), air, gaseous hydrogen (GH2), gaseous methane (CH4), and carbon dioxide (CO2) are required for future space missions for outlet pressures up to 4000 or possibly as high as 6000 psi with an inlet pressure as low as 500 psia. The average power consumptions should be less than 800 Watts. A prototype design able to survive the launch environment and operate in the space environment is of interest to enable highly mass-efficient and timely fluid transfers up to dozens or as high as hundreds of kilograms over the life of the component. The current state of the art for efficient and timely on-orbit transfer of gaseous fluids, specifically helium, in large quantities is nonexistent. Previous attempts such as a scroll concept have been made to design and build hardware for mechanically assisted subsystem-level transfer, but to date, none have been successful for high cycle/highly reliable use in a microgravity space environment.

Lessons learned can be leveraged from these past efforts to make improvements for efficiency, reliability, size, mass, and power needs for an advanced prototype for testing. The Phase I effort should focus on the conceptual design and supporting analyses.

Expected TRL or TRL Range at completion of the Project: 2 to 4

Primary Technology Taxonomy:

- Level 1: TX 01 Propulsion Systems
- Level 2: TX 01.X Other Propulsion Systems

Desired Deliverables of Phase I and Phase II:

- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Phase I deliverables include:

- Background research and feasibility studies.
- Modeling to demonstrate feasibility.
- Conceptual design, trade studies, and description of proposed solution.
- Demonstrations of subsystems or key technologies.
- Pathfinder technology demonstrations.
- Prototype tank-venting device.

Phase II deliverables include:

- Advancement of the design to a flight engineering development unit.
- Demonstration using the tank-venting prototype on a microgravity flight.
- Environmental testing of key components.
- Further advancement of the unit for the spaceflight and launch environments (vibration, shock, thermal vacuum, electromagnetic interference, and emissions, etc.).

State of the Art and Critical Gaps:

The current state of the art for efficient and timely on-orbit transfer of gaseous fluids, specifically helium, in large quantities is nonexistent. Previous attempts have been made to design and build hardware for mechanically assisted subsystem-level transfer, but to date, none have been successful for high cycle/highly reliable use in a microgravity space environment. Lessons learned can be leveraged from these past efforts to make improvements for efficiency, reliability, size, mass, and power needs for an advanced prototype for testing.

Civil Space Shortfall Ranking https://www.nasa.gov/spacetechpriorities/

- 1480: On-surface Outfitting of Lunar Structures
- 1506: In-Space & Surface Transfer of High-Pressure Pneumatic Fluids
- 1612: Surface-based fluid management for near/mid-term missions

Parent Shortfalls: 1480, 1506, and 1612

Child shortfalls: 357 (O_2), 371 (GHe), 443 (CO_2), 462 (GHe), 555 (GN_2), 570 (O_2 & CO_2), 571 (CH_4), 578 (CO_2), 579 (H_2 & CH_4), 857 (GHe & GN_2), 1226 (O_2, H_2, & CH_4), and 1372 (surface gas transfers)

Relevance / Science Traceability:

In-space helium transfer is relevant to missions including propellant transfer technology demonstrations, in-space commercial stations, sample return missions, Gateway, Artemis, Human Landing System, and future Moon to Mars missions. Spin off capabilities for innovative methods for high pressure transfer of gases such as GHe breathing air, O_2, GN_2, and GH_2 for ECCLS logistics supply and/or transfer applications.

References:

1. NASA’s Exploration & In-Space Services (NExIS). Propellant Transfer Technologies. https://nexis.gsfc.nasa.gov/propellant_transfer_technologies.html
2. https://www.nasa.gov/spacetechpriorities/

Scope Title: Precision Instrument Latches for Large Space Observatory Servicing and Upgrade

Scope Description:

NASA requests novel conceptual design for precision instrument latches that will enable robotic upgrade and installation of science instrument on large space observatories.

Ultra-stable robotically actuated latches for observatories like HabWorlds is vitally important, especially for coronagraph measurements. Telescope and replaceable instrument design that is 1,000 more stable than James Webb

Space Telescope and 1-2 orders of magnitude leap in sensitivity compared to Hubble Space Telescope is desired. 10 picometer wavefront error stability over 10 minute measurements is desired for advanced coronagraph performance.

NASA STMD Shortfall 379 Upgrade or Install Instruments on Large Space Observatories is directly applicable for this technology development scope. The need for ultra-stable robotically actuated latches for HWO is vitally important, especially for coronagraph measurements. We cannot replace instruments on HWO without closing shortfalls for mechanical and electrical ultra-stable interfaces.

Expected TRL or TRL Range at completion of the Project: 2 to 4

Primary Technology Taxonomy:

- Level 1: TX 04 Robotics Systems
- Level 2: TX 04.X Other Robotic Systems

Desired Deliverables of Phase I and Phase II:

- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Phase I deliverables include:

- Background research and feasibility studies.
- Modeling to demonstrate feasibility.
- Conceptual design, trade studies, and description of proposed solution.
- Demonstrations of subsystems or key technologies.
- Pathfinder technology demonstrations.
- Brassboard interface.
- Concept for low-cost flight demonstration.

Phase II deliverables include:

- Demonstration using the brassboard interface.
- Environmental testing of key components.

State of the Art and Critical Gaps:

The current state of the art for in-space precision latches that can be actuated during servicing are Hubble Space Telescope instrument and spacecraft interfaces, as well as modular instrument interfaces on International Space Station.

Improvements in precision alignment are required to enable the required performance for instruments like coronagraphs. 10 picometer wavefront error stability over 10 minutes is needed for future instrument performance and transformative astrophysics.

Technology development addresses gaps and shortfalls such as 379, Upgrade or Install of Instruments on Large Space Observatories.

Civil Space Shortfall Ranking https://www.nasa.gov/spacetechpriorities/

- 379: Upgrade or install instruments on large space observatories
- 1480: On-surface Outfitting of Lunar Structures
- 1506: In-Space & Surface Transfer of High-Pressure Pneumatic Fluids
- 1612: Surface-based fluid management for near/mid-term missions

Relevance / Science Traceability:

NASA is studying mission concepts for assembly of spacecraft components in space, and upgrade of science instruments on spacecraft.

References:

1. On-Orbit Satellite Servicing Study Project Report. October 2010. https://sspd.gsfc.nasa.gov/images/NASA_Satellite%20Servicing_Project_Report_0511.pdf
2. The Large UV/Optical/Infrared Surveyor (LUVOIR): Decadal Mission Study Update. https://ntrs.nasa.gov/api/citations/20180006451/downloads/20180006451.pdf
3. When is it Worth Assembling Observatories in Space? Astro2020 APC Whitepaper. https://baas.aas.org/pub/2020n7i050/release/1

Z-EXPAND.02: Orbital Infrastructure Assembly (SBIR)

Related Subtopic Pointers: Z-LIVE.05
Lead Center: ARC
Participating Center(s): GSFC, JSC, LaRC, MSFC

Subtopic Introduction:

NASA is investing in robotic assembly and construction capabilities that will help establish infrastructure and science assets such as persistent platforms, space stations, space based solar power, space stations, large aperture observatories, large fuel depots, and more. Current robotic assembly architectures are also designed to facilitate multi-mission (re)use, modularization, and leverage economies of scale to help facilitate a growing and robust ecosystem. This technology is envisioned to help usher in a paradigm where each mission isn't a bespoke multi-billion-dollar mission, but a system where developers can leverage a robust infrastructure network and build upon what has already been done, instead of starting from the ground up each time. A paradigm where space operations such as robotic assembly, servicing, upgrades, and repairs are commonplace and well-integrated. Robotic assembly is an inherently cross cutting technology that can interface between the full lifecycle of a mission from design, manufacturing, operations, to end of life.

Robotic assembly technologies typically consist of 3 core subsystems: The structural elements, the robotic agents, and control software. A fourth outfitting system is needed to install and enable functionality within the assembled structure. Core outfitting capabilities include functional module installation, cable routing and connections, and fluid routing and connections, and more. Systems are co-designed together to build complexity and capability into the structure to reduce robotic requirements.

Development of this technology in a sustainable and reusable manner will enhance LEO, cislunar, and lunar economy development and help address M2M Lunar Infrastructure and Science objectives. These systems could also be designed to facilitate M2M recurring tenants of collaboration, maintainability, reuse, and interoperability.

Development of reusable robotic assembly technologies could help enable orbital applications such as the following:

- Evolvable Persistent Platforms
- Refueling Stations
- Regional Hubs
- Observation Platforms
- Space Based Solar Power
- On Demand Satellites
- Space Stations
- More

Robotic assembly has a long research history, with current trends towards enabling lower cost missions, increased reliability, and scalability. NASA is also working on assembly of backbone array truss structures, modular high performance building block 3d tiling structures, solar panels, and thermal radiators to help address science, infrastructure, and operational objectives.

This subtopic seeks proposals in the following areas:

- Scope 1: Structures and Outfitting for Orbital Robotic Assembly
- Scope 2: Robotic Agents for Orbital Robotic Assembly
- Scope 3: Mission Analysis and Software Tools for Orbital Robotic Assembly

Relevant Shortfalls:

- 376 - Modular design for in-space installation
- 379 - Upgrade or Install Instruments on Large Space Observatories
- 498 - Broad and dependable supply chain for space qualified robotic hardware, electronics, and associated software
- 512 - Cooperative interfaces, aids, and standards
- 513 - Robotic Assembly and Construction of Modular Systems for Sustained In-Space Infrastructure
- 1540 - Intelligent Robots for the Servicing, Assembly, and Outfitting of In Space Assets and Industrial Scale Surface Infrastructure
- 1543 - Multi Agent Robotic Coordination and Interoperability for Cooperative Task Planning and Performance
- 1545 - Robotic Actuation, Subsystem Components, and System Architectures for Long Duration and Extreme Environment Operation

Scope Title: Structures and Outfitting for Orbital Robotic Assembly

Scope Description:

Structural elements are the basic building blocks of robotic assembly with many different geometries, types of connections, and decompositions. Various designs ranging from strut and node decompositions to integrated modules enable assembled structures to address dynamic mission needs and requirements. These structures can be designed to serve as a framework for future missions and applications to be built upon. Co-design of the structures along with robotic agents ensure ease of manipulation and joining to create highly efficient and scalable architectures. Co-design of the structures and robotics allow designers to build complexity into the structure to reduce the robotic requirements and increase reliability.

Structures in traditional mission designs are highly tailored and optimized for the specific mission need due to launch constraints, but assembled structures for general applications will need to be optimized for multi-mission, scalability, and ecosystem, tunability. Lower the cost and risk of conducting robotic assembly missions. Foundational technologies for that are enabling and can be built upon for future mission and add capability.

Proposals are invited to develop structural elements that are suitable for the space environment and are designed to be robotically manipulated and joined. Characteristics such as high packing efficiency, stability, light weight, low parasitic mass are desirable for structural elements. Joints should be designed for robotic actuation with low parasitic mass, and low activation energy. Element variations could be applied and tuned for various applications. Interfaces to adjoining structures, robotic grapple points, and other payload modules should be considered. Plans for environmental testing and flight operation of development is crucial.

A successful solution example would be the development of a cost effective and adaptable structural system that can be leveraged in multiple types of missions and applications with a clear path to flight certification.

Proposal topics of interest include, but are not limited to, the following:

- Structural elements
  - High packing efficiency reconfigurable structural element designs
  - High performance, stable structures
  - Mechanical metamaterials
  - Tunable structures
  - Manufacturing methods
  - Functional structures - EM structures, curved structures, deployable
  - Autonomous health monitoring, inspection, and repair
  - Interfaces & standardization
  - Fractionated spacecraft
  - Analysis tools
- In-Space Robotic Joining
  - Reversible fasteners and robotic end effectors
  - Stable robotically activated joints
  - Low activation energy and parasitic mass joints
- Outfitting
  - Wire routing and connections
  - Fluid routing and connections
  - Payload and functional module installation, upgrade, and repair
  - Paneling elements

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:

- Level 1: TX 07 Exploration Destination Systems
- Level 2: TX 07.2 Mission Infrastructure, Sustainability, and Supportability

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Phase I efforts are expected to focus primarily on system design and feasibility studies and proof of concept tests to identify and demonstrate key technology functions such as structural element design, manipulation, joint design, joining, etc.

Phase II efforts will be used to mature these technologies and concepts and to conduct a ground demonstration to robotically assemble a representative structure.

State of the Art and Critical Gaps:

Robotic assembly of structures in space is an active area of research for NASA and will help push towards a paradigm of sustainable and scalable space exploration. This technology is essential for establishing critical long-term orbital infrastructure. Recent efforts within NASA's Robotic Assembly Community (e.g., Automated Reconfigurable Mission Adaptive Digital Assembly Systems (ARMADAS), NASA's Precision Assembled Space Structure (PASS), Tall Lunar Tower (TLT)) have developed modular structural elements and multi-agent robot systems for building complex lightweight structures, telescope array backbones, and tall towers in space. The teams have demonstrated the potential of these construction methods by building various structures with assembly agents ranging in complexity from astronaut assembly to teleoperated robotic arms to fully autonomous multi-agent systems. Previous work at JPL have also developed truss modules for observatories.

Commercial developers have also developed various assembly systems demonstrating structural beam assembly, tower assembly, and telescope element assembly.

Gaps in technology development include development of flight rated components and integration of robotic systems to enable assembly capabilities.

Civil Space Shortfall Ranking: https://www.nasa.gov/spacetechpriorities/

- 376 - Modular design for in-space installation
- 379 - Upgrade or Install Instruments on Large Space Observatories
- 498 - Broad and dependable supply chain for space qualified robotic hardware, electronics, and associated software
- 512 - Cooperative interfaces, aids, and standards
- 513 - Robotic Assembly and Construction of Modular Systems for Sustained In-Space Infrastructure
- 1540 - Intelligent Robots for the Servicing, Assembly, and Outfitting of In Space Assets and Industrial Scale Surface Infrastructure
- 1543 - Multi Agent Robotic Coordination and Interoperability for Cooperative Task Planning and Performance
- 1545 - Robotic Actuation, Subsystem Components, and System Architectures for Long Duration and Extreme Environment Operation

Relevance / Science Traceability:

Programs and Projects - NASA Robotic Assembly Missions, Artemis, ISAM, ARMADAS, TLT, PASS

References:

1. PASS - https://ntrs.nasa.gov/api/citations/20230013537/downloads/main.pdf
2. ARMADAS - https://ntrs.nasa.gov/api/citations/20230005194/downloads/SciRobotics-ARMADAS_System_Paper_Distribution.pdf
3. https://ntrs.nasa.gov/api/citations/20190004967/downloads/20190004967.pdf
4. TLT - https://ntrs.nasa.gov/citations/20230007930
5. RAMST - https://www.spiedigitallibrary.org/journals/Journal-of-Astronomical-Telescopes-Instruments-and-Systems/volume-2/issue-4/041207/Architecture-for-in-space-robotic-assembly-of-a-modular-space/10.1117/1.JATIS.2.4.041207.full

6. Novawurks - Priestley, Kory J., William Crandall, and Talbot Jaeger. "A Building Block Approach to Satellites and its Impact on Changes in Late AI&T Athena–A Case Study." (2024).
7. DARPA Phoenix - Melroy, Pamela, et al. "DARPA phoenix satlets: Progress towards satellite cellularization." *AIAA SPACE 2015 Conference and Exposition*. 2015.
8. EU Pulsar - Roa Garzon, Máximo Alejandro, et al. "PULSAR: Testing the technologies for on-orbit assembly of a large telescope." *16th Symposium on Advanced Space Technologies in Robotics and Automation, ASTRA 2022*. ESA, 2022.

Scope Title: Robotic Agents for Orbital Robotic Assembly

Scope Description:

Robotic agents are needed to perform robotic assembly tasks such as material manipulation, transport, joining, payload installation, cable routing and connections, inspection, repair and many other assembly and maintenance tasks. Complexity of agents can range from humans to dexterous robots, to robotic arm architectures, to simple task specific mechanisms for assembly. Research interest include flexible robotic systems to address various tasks as well as lower cost, task specific robots designed for robust assembly operations. The co-design of the agents with the structure being built will enable reliable new robotic architectures that can scale and are cost effective.

Various robotic assembly architecture used include fixed robotic platforms, mobile platforms, as well as hybrid variations. Mobile robots allow for repositioning and allow for much larger work envelopes. Recent work investigates multi-agent teams and swarms of light weight (~10 kg) robots working together to perform assembly tasks.

Proposals are invited to develop robotic systems and components for completing assembly tasks.

Proposal elements of interest include, but are not limited to, the following:

- Integrated Robotic Agents
    - Climbing robots
    - Free flyers
    - Fixed robots
    - Task specific robots
    - Multi-mission assets
- Robotic Components
    - End Effectors
    - Robotic Components
    - Actuators
    - Interfaces, Grapple Fixtures
    - Power systems charging, battery swap
    - Software and Control systems
    - Swarm and multi-agent robot systems
    - Standardized motions

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:

- Level 1: TX 07 Exploration Destination Systems
- Level 2: TX 07.2 Mission Infrastructure, Sustainability, and Supportability

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Phase I efforts are expected to focus primarily on system design and feasibility studies and proof of concept tests to identify and demonstrate key technology functions such as robotic locomotion, payload operations, robustness, and reliability.

Phase II efforts will be used to mature these technologies and concepts and to conduct a ground demonstration to robotically assemble a representative structure, as well as further characterization.

State of the Art and Critical Gaps:

Robotic assembly of structures in space is an active area of research for NASA and will help push towards a paradigm of sustainable and scalable space exploration. This technology is essential for establishing critical long-term orbital infrastructure. Recent efforts within NASA’s Robotic Assembly Community (e.g., ARMADAS, PASS, TLT) have developed modular structural elements and multi-agent robot systems for building complex lightweight structures, telescope array backbones, and tall towers in space. The teams have demonstrated the potential of these construction methods by building various structures with assembly agents ranging in complexity from astronaut assembly to teleoperated robotic arms to fully autonomous multi-agent systems. Previous work at JPL have also developed truss modules for observatories.

Commercial developers have also developed various assembly systems demonstrating structural beam assembly, tower assembly, and telescope element assembly.

Gaps in technology development include development of flight rated components and integration of robotic systems to enable assembly capabilities.

Civil Space Shortfall Ranking: https://www.nasa.gov/spacetechpriorities/

- 376 - Modular design for in-space installation
- 379 - Upgrade or Install Instruments on Large Space Observatories
- 498 - Broad and dependable supply chain for space qualified robotic hardware, electronics, and associated software
- 512 - Cooperative interfaces, aids, and standards
- 513 - Robotic Assembly and Construction of Modular Systems for Sustained In-Space Infrastructure
- 1540 - Intelligent Robots for the Servicing, Assembly, and Outfitting of In Space Assets and Industrial Scale Surface Infrastructure
- 1543 - Multi Agent Robotic Coordination and Interoperability for Cooperative Task Planning and Performance
- 1545 - Robotic Actuation, Subsystem Components, and System Architectures for Long Duration and Extreme Environment Operation

Relevance / Science Traceability:

Programs and Projects - NASA Robotic Assembly Missions, Artemis, ISAM, ARMADAS, TLT, PASS

References:

1. PASS - https://ntrs.nasa.gov/api/citations/20230013537/downloads/main.pdf
2. ARMADAS - https://ntrs.nasa.gov/api/citations/20230005194/downloads/SciRobotics-ARMADAS_System_Paper_Distribution.pdf
3. https://ntrs.nasa.gov/api/citations/20190004967/downloads/20190004967.pdf
4. https://ntrs.nasa.gov/api/citations/20230011353/downloads/IEEE_IROS_2023_SOLLE_Final.pdf
5. https://ieeexplore.ieee.org/document/10161263
6. TLT - https://ntrs.nasa.gov/citations/20230007930
7. RAMST - https://www.spiedigitallibrary.org/journals/Journal-of-Astronomical-Telescopes-Instruments-and-Systems/volume-2/issue-4/041207/Architecture-for-in-space-robotic-assembly-of-a-modular-space/10.1117/1.JATIS.2.4.041207.full
8. EU Robotic Assembly - Roa, Máximo A., et al. "Robotic technologies for in-space assembly operations." *Proc. Symp. Adv. Space Technol. Robot. Automat.(ASTRA)*. 2017.

Scope Title: Mission Analysis and Software Tools for Orbital Robotic Assembly

Scope Description:

Mission analysis and operational software tools are important to enable a robust robotic assembly ecosystem. These tools could be used to plan missions, estimate costs, and simulate environments and run operations needed to achieve robotic assembly goals. Successful products will help augment existing mission design and analysis studies to increase fidelity and reduce time to implement such missions.

Proposal elements of interest include, but are not limited to, the following:

- Mission Analysis
  - Mission ConOps and analysis
  - Requirements development
  - Cost modeling
- Software Tools
  - Multi-agent/swarm control software
  - Robotic assembly operational software
  - Path planning algorithms
  - Autonomy/Autonomous control architectures, software, and algorithms
  - Fault tolerance
  - Contingency planning

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:

- Level 1: TX 07 Exploration Destination Systems
- Level 2: TX 07.2 Mission Infrastructure, Sustainability, and Supportability

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis

- Prototype
- Hardware
- Software

Desired Deliverables Description:

Phase I efforts are expected to focus primarily on system design and feasibility studies and proof of concept tests to identify and demonstrate key technology functions.

Phase II efforts will be used to mature these technologies and concepts and to integrated into ground demonstrations or mission analysis.

State of the Art and Critical Gaps:

Robotic assembly of structures in space is an active area of research for NASA and will help push towards a paradigm of sustainable and scalable space exploration. This technology is essential for establishing critical long-term orbital infrastructure. Recent efforts within NASA's Robotic Assembly Community (e.g., ARMADAS, PASS, TLT) have developed modular structural elements and multi-agent robot systems for building complex lightweight structures, telescope array backbones, and tall towers in space. The teams have demonstrated the potential of these construction methods by building various structures with assembly agents ranging in complexity from astronaut assembly to teleoperated robotic arms to fully autonomous multi-agent systems. Previous work at JPL have also developed truss modules for observatories.

Commercial developers have also developed various assembly systems demonstrating structural beam assembly, tower assembly, and telescope element assembly.

Gaps in technology development include development of flight rated components and integration of robotic systems to enable assembly capabilities.

Civil Space Shortfall Ranking: https://www.nasa.gov/spacetechpriorities/

- 376 - Modular design for in-space installation
- 379 - Upgrade or Install Instruments on Large Space Observatories
- 498 - Broad and dependable supply chain for space qualified robotic hardware, electronics, and associated software
- 512 - Cooperative interfaces, aids, and standards
- 513 - Robotic Assembly and Construction of Modular Systems for Sustained In-Space Infrastructure
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- 1543 - Multi Agent Robotic Coordination and Interoperability for Cooperative Task Planning and Performance
- 1545 - Robotic Actuation, Subsystem Components, and System Architectures for Long Duration and Extreme Environment Operation

Relevance / Science Traceability:

Programs and Projects - NASA Robotic Assembly Missions, Artemis, ISAM, ARMADAS, TLT, PASS

References:

1. https://ntrs.nasa.gov/api/citations/20170009114/downloads/20170009114.pdf
2. PASS - https://ntrs.nasa.gov/api/citations/20230013537/downloads/main.pdf
3. ARMADAS - https://ntrs.nasa.gov/api/citations/20230005194/downloads/SciRobotics-ARMADAS_System_Paper_Distribution.pdf
4. TLT - https://ntrs.nasa.gov/citations/20230007930
5. RAMST - https://www.spiedigitallibrary.org/journals/Journal-of-Astronomical-Telescopes-Instruments-and-Systems/volume-2/issue-4/041207/Architecture-for-in-space-robotic-assembly-of-a-modular-space/10.1117/1.JATIS.2.4.041207.full

Z-EXPAND.03: Space Debris Prevention for Small Spacecraft (SBIR) (Previously Z8.13)

Related Subtopic Pointers: H9.03
Lead Center: MSFC
Participating Center(s): ARC, GSFC

Subtopic Introduction:

The rise in small spacecraft launches, including swarms, is causing congestion in low Earth orbit (LEO) and higher orbits. From 2013 to 2022, small spacecraft accounted for over 87% of all launches by number and 25% by mass, becoming a key method for space access across commercial, government, private, and academic sectors [Ref. 1]. In 2013, 247 CubeSats and 105 other small spacecraft under 50 kilograms (kg) were launched globally, representing less than 2% of launched mass over several years. In that year, 60% of launched spacecraft had a mass under 600 kg, with 83% under 200 kg, and 37% were nanosatellites [Ref. 2]. By 2021, 94% of the 1,849 spacecraft launched were under 600 kg, with 40% under 200 kg, and 11% were nanosatellites [Ref. 2]. In the last decade, 5,681 spacecraft were launched, 45% of which were under 200 kg [Ref. 2]. The number continues to grow, with plans for swarms and constellations of thousands, even tens of thousands, of small spacecraft.

The U.S. National Space Policy has focused on orbital debris prevention since 1988, with its 2020 update stating: “The United States shall … limit the creation of new debris, consistent with mission requirements and cost-effectiveness” [Refs. 3-5].

Space debris is categorized by size, affecting risk and detectability:

- Small Debris: Less than 1 cm in diameter, includes particles like paint flecks and metal fragments. Difficult to track but can cause damage due to high velocity.
- Medium Debris: Between 1 cm and 10 cm in diameter, includes fragments from collisions or explosions. Can penetrate spacecraft shields and pose significant risks.
- Large Debris: Greater than 10 cm in diameter, includes defunct satellites, spent rocket stages, and large fragments. Easier to track but can cause catastrophic collisions.

These categories help assess threat levels and inform mitigation strategies. Concerns about increasing debris, small spacecraft mobility (both propulsive and non-propulsive), and operational monitoring in congested space have risen as “the number of objects orbiting the Earth has grown substantially in recent years, with well over 90% being dead objects (inoperative satellites, spent upper stages, and fragmentation debris)” [Ref. 5]. Studies from NASA and other agencies predict severe outcomes and potential “runaway debris situations” under “business-as-usual” scenarios [Ref. 5], as well as strain on current space traffic management systems [Ref. 7].

The growth of small satellite (SmallSat) technologies and plans for deploying thousands of satellites in LEO by companies like SpaceX, OneWeb, Theia, Boeing, Amazon Kuiper, and Inmarsat raise significant concerns. As discussed in Reference 6, “if these plans materialize, the population of operational satellites in LEO would increase over tenfold, from ~1,000 today to over 16,000 within the next 10 to 20 years,” which could strain space traffic management systems and affect the space environment for generations. This increase might lead to numerous conjunction alerts and collisions with spacecraft and debris.

Beyond LEO, the use of small satellites in higher orbits, especially cislunar space, presents both opportunities and challenges. Small satellites are increasingly used for cislunar missions, including demonstrations, communication relays, navigation, scientific exploration, and space situational awareness. These missions are critical for supporting larger lunar exploration efforts, such as NASA's Artemis missions. However, increasing lunar activities heighten the risk of congestion and debris, necessitating coordinated policies and advanced technologies for sustainable space traffic management and debris mitigation in cislunar space. Communication latency between Earth and cislunar space also demands enhanced autonomous operations. Small satellites must make quick decisions without direct human intervention to avoid collisions or other hazards, highlighting the need for high onboard autonomy.

To address these challenges, improving the mobility and autonomy of small satellites is essential. Better mobility would enable effective maneuvering, reducing collision risks, while enhanced autonomy would allow independent operation in congested environments, minimizing additional debris. This is particularly crucial in cislunar space, where communication delays complicate real-time human control. Advanced propulsion systems, especially during deorbit or disposal, could offer greater flexibility in orbit management and repositioning, reducing conjunction risks. Advancing mobility and autonomous decision-making can improve space traffic coordination, ensure safer operations, and enhance mission effectiveness in LEO, cislunar, and other space environments. Focused enhancements in these areas are key to adapting to the complexities of space operations as human and robotic activities expand beyond Earth’s vicinity.

Scope Title: Enhanced Orbit Insertion, Avoidance Mobility, Deorbit and/or Disposal of Single Small Spacecraft

Scope Description:

Objective: Develop low size, weight, power, and cost (SWaP-C) active and/or passive onboard propulsive and non-propulsive devices for enhanced orbit insertion, avoidance mobility, deorbit or disposal of single spacecraft while also efficiently and effectively minimizing the probability of new orbital debris creation during various mission phases.

Both propellant and non-propellant approaches are utilized for small spacecraft mobility, depending on mission requirements and operation phases. Propellant methods typically include traditional chemical, electric, or hybrid propulsion systems. Non-propellant approaches often use natural forces or external aids, such as atmospheric drag, electrodynamic forces, and pressure exerted by solar photons. The increasing challenges of space debris and the management of large swarms and constellations present a complex, multidimensional problem that requires diverse solutions. This discussion specifically focuses on technical approaches for enhanced orbit insertion, avoidance mobility, deorbit, or disposal to ensure safe mission operations and effective end-of-life management for small satellite swarms and constellations.

The threats posed by space debris are increasing, particularly with the launch of multiple-satellite missions in LEO. Previously, the guideline for satellites in LEO was to deorbit or move to a graveyard orbit within 25 years after mission completion. However, as of September 29, 2022, the Federal Communications Commission (FCC) adopted a new rule reducing this requirement to 5 years for U.S.-licensed satellites and those from other countries seeking access to the U.S. market. Spacecraft under 2,000 km in altitude must now deorbit as soon as possible, and no later than 5 years after mission end; this requirement applies to spacecraft launched 2 years after the rule's approval. As of the publication date of this report, this rule does not specifically apply to NASA satellites not licensed through the FCC, and discussions at the Agency and federal levels are ongoing to determine the final policies.

With increased use of higher and more diverse orbital regimes by small spacecraft and growing regulatory attention on long-term debris concerns, it is critical for the small spacecraft community to responsibly manage enhanced orbital insertion, avoidance mobility, deorbiting, and disposal. This should be done in a way that preserves both the orbital environment and the efficiency of small missions. The development and demonstration of both active and passive technology approaches with low SWaP-C deorbit capabilities, compatible with common small spacecraft form factors, are necessary to maintain the agility of Earth and cislunar small spacecraft missions while complying with regulatory requirements. These low SWaP-C technologies for enhanced orbit insertion, avoidance mobility, deorbit, or disposal are being solicited here, including both propulsive and non-propulsive systems.

Highly desired technologies include those based on fueled propulsion systems using nontoxic fuels, "green technologies," and propellants. These technologies reduce complexity in the spacecraft vehicle integration process, maximize launch opportunities, and encourage a more sustainable space domain. Enhanced orbit insertion, avoidance mobility, deorbit, and disposal technologies are needed not only for near-Earth space domain missions but also for other operational missions, such as in the cislunar space domain. Technologies that actively or passively enable various phases of mission mobility are also desired, with careful consideration of potential risks for creating additional debris or increasing conjunction risk. Such technologies should provide active or passive management throughout the enhanced orbital insertion, avoidance mobility, deorbit, or disposal process to further protect against collisions and interferences with both active and inactive spacecraft and debris.

Offerors should clearly define key performance parameters for the appropriate space domain region and the applicable mission phase of the technology. These performance parameters (e.g., SWaP-C) should be quantified for any applicable mission phases, compared to the state of the art (SOA), and contextualized within a planned, proposed, or hypothetical mission. Offerors should also clearly define any unique operational attributes that should be considered during deployment. As an example, deployed tether conjunction assessments are often performed assuming the swept area of the tether. This will help highlight the advantages and disadvantages of the offered technology over SOA and other proposed solutions.

Expected TRL or TRL Range at completion of the Project: 2 to 5

Primary Technology Taxonomy:

- Level 1: TX 09 Entry, Descent, and Landing
- Level 2: TX 09.5 Flight Mechanics and GN&C for Entry, Descent, and Safe Precise Landing

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

In Phase I, a contextual study to further understand the feasibility of the proposed solution is desired. Ideally, Phase I would conclude with a basic proof-of-concept prototype (hardware or software as appropriate). Critical requirements and interfaces should be defined alongside refinements of the proposed key performance parameters in Phase I. The Phase I effort should provide evidence of the feasibility of key elements such as cost, assembly, integration, and operations. The concept should reach sufficient maturity to show strong feasibility for the defined mission environments and performance requirements. The prototype system design should reach sufficient maturity to define test objectives and map key performance parameters (mass, power, cost, etc.) from the prototype to the flight design. Hardware development during the Phase I effort should provide confidence in the design maturity and execution of the Phase II effort. Last, the Phase I effort should identify potential opportunities for mission infusion and initiate partnerships or cooperative agreements necessary for mission execution.

In Phase II, further development and technology maturation is desired. Ideally, Phase II would culminate with Technology Readiness Level (TRL) 5+ and include demonstration of the proposed solution. Both Phase I and Phase II should be approached with focus on infusion, ensuring solutions are being developed with the proper requirements, interfaces, performance parameters, partnerships, etc., such that they, through a Phase III award or otherwise, could be directly applied to real spacecraft and real missions.

State of the Art and Critical Gaps:

The 2022 NASA State of the Art of Small Spacecraft Technology report [Ref. 9], Section 13.0, Deorbit Systems, gives a comprehensive overview of the SOA for both passive and active deorbit systems. The report details drag systems, including tethers, the Exo-Brake, and others. Drag sails have been the primary deorbit technology to date and have been developed, demonstrated, and even commercialized/sold for mission use. However, capability needs to continue to grow, especially for higher orbital applications with considerations to minimize the risk of new debris creation during the disposal phase of missions, as well as for more controlled deorbit and disposal. This subtopic, in the context of SmallSats, is of high importance to the Small Spacecraft Technology (SST) Program, the Agency, and the Nation in helping avoid a world that lives under the threat of the Kessler syndrome (i.e., exponential, catastrophic production of debris in orbit).

Previous instances of this subtopic were focused on drag sails, but more investment is needed to help build and expand the ecosystem to include other onboard deorbit and disposal devices, as well as swarm/constellation management technologies, to help mitigate the risks (including considerations minimizing the probability of new space debris creation during the disposal phase of the mission) raised by the anticipated launch of many thousands more satellites in the years to come, most of which will be SmallSats. As a result of most nontraditional deorbit devices, uncertainties exist related to when and where space objects will come out of their established orbit due to natural causes (e.g., atmospheric drag, solar pressure) or when deorbit is initiated. To achieve precise prediction of deorbit trajectories and satellite behavior in that phase, improved methods of prediction and control are desired, possibly including real-time, closed-loop modeling and/or control, and deorbit initiation systems.

Civil Space Shortfall Ranking https://www.nasa.gov/spacetechpriorities/

- 1430: Small Spacecraft Propulsion
- 1431: Access Beyond LEO for Small Spacecraft

Relevance / Science Traceability:

With increased use of higher orbital regimes by small spacecraft and regulatory attention on short- and long-term debris concerns, it is critical that the small spacecraft community responsibly manage deorbiting and disposal in a way that preserves both the orbital environment and the efficiency of small missions. Solutions are relevant to commercial space, national defense, and Earth science missions.

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Scope Title: Enhanced Space Traffic Management Technologies for Small Spacecraft Swarms and Constellations

Scope Description:

Objective: Develop advanced technological solutions that enhance the safe operation of SmallSat swarms and constellations, specifically aimed at reducing the strain on currently available space traffic management (STM) architectures and space traffic coordination capabilities. The challenges posed by space debris and the management of large constellations and swarms are complex and require diverse solutions. This subtopic focuses on innovative technical solutions for autonomous and safe operations of SmallSat swarms and constellations. The goal is to alleviate the burden on existing STM frameworks by significantly reducing or eliminating the need for human intervention ("human in the loop") and replacing it with faster, decision-making autonomous onboard systems capabilities when feasible. These systems should improve the tracking coordination capabilities and overall management of small spacecraft, particularly just after launch, in LEO and in areas beyond LEO, ultimately reducing the risk of collisions and the subsequent generation of orbital debris from such collisions.

As part of this scope, the following technologies are being solicited:

1. Low Size, Weight, Power, and Cost (SWaP-C) Small Spacecraft Systems for Cooperative Identification and Tracking:
    - Develop and demonstrate low SWaP-C identification and tracking systems that can be integrated into small spacecraft. These systems should be scalable, manufacturable, and easily standardized for small spacecraft ecosystems, including CubeSats and other small spacecraft classes. Given the increased demand on existing space situational awareness (SSA) capabilities and regulatory concerns regarding unidentified or misidentified spacecraft—especially those too small to be tracked reliably—there is a critical need for onboard technologies that enable immediate tracking and identification right after launch and throughout their mission life, including beyond LEO.

    - The technologies should include passive tracking options that do not depend on the functionality of the spacecraft's main systems, allowing continuous tracking even after the spacecraft's operational life has ended. This minimizes the need for human intervention, which is often limited after the spacecraft's primary mission phase.

2. Low SWaP-C Spacecraft Systems for Autonomous Reactive Operations of Small Spacecraft Swarms and Constellations:
    - Develop and demonstrate low SWaP-C technologies, such as advanced onboard sensors and coupled maneuvering systems, designed for small spacecraft. These systems should enable autonomous operation of swarms and constellations in formation, close proximity to other objects (whether cooperative or uncooperative), or in scenarios that exceed the capabilities of traditional human-in-the-loop control. Autonomous systems onboard each spacecraft should be capable of processing sensor data and executing appropriate responses in real time, ensuring both spacecraft safety and compliance with STM protocols.

    - These solutions must incorporate existing conjunction assessment processes, such as those defined by the 19th Space Defense Squadron (19 SDS) on Space-Track.org, to prevent collisions by executing avoidance maneuvers based on real-time data without requiring ground-based operator input.

3. Advanced Onboard Software Modules for Autonomous Operations and Tracking:
    - Develop and demonstrate onboard software solutions that enhance cooperative identification, tracking, and autonomous reactive operations. The software should be capable of operating either on individual spacecraft or across a swarm/constellation, leveraging onboard processing capabilities. The focus should be on developing software that can perform its primary functions within the budget of standard NASA Phase I and II Small Business Innovation Research (SBIR) awards.

    - The software should include artificial intelligence and machine learning (AI/ML) techniques that enable autonomous orbit adjustment and collision avoidance maneuvers, using real-time data from onboard sensors. These software solutions should also facilitate efficient data exchange between spacecraft, reduce dependency on ground-based commands, optimize the use of space-qualified computing resources, and support high-precision swarm navigation and control.

4. Supporting Ground Systems for Autonomous Operations:
    - Develop and demonstrate ground systems that complement the onboard technologies for cooperative identification, tracking, and autonomous reactive operations. These ground systems should support the operational capabilities of the small spacecraft swarms and constellations and be compatible with NASA's SBIR budgetary constraints.

In this context, "SmallSat" and "small spacecraft" are defined as interchangeable terms referring to spacecraft in the Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA)-class and below typically less than 500 kg, including the CubeSats class with masses up to 180 kg. Technologies applicable to CubeSats class are particularly desirable due to their potential for broader adoption across the small spacecraft community.

Key Performance Parameters:

- Proposals should clearly define key performance parameters (e.g., SWaP-C metrics) that are quantifiable, benchmarked against the current state of the art, and contextualized within the framework of a planned or hypothetical mission. Technologies are highly desirable that can be adapted for use in LEO, cislunar and deep space environments, thus enabling new scientific and exploratory missions using SmallSat swarms or constellations.

Please note that this scope does not solicit trajectory prediction algorithms. Proposals focused on such algorithms should be submitted through subtopic H9.03.

Expected TRL or TRL Range at completion of the Project: 2 to 5

Primary Technology Taxonomy:

- Level 1: TX 17 Guidance, Navigation, and Control (GN&C)
- Level 2: TX 17.2 Navigation Technologies

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

In Phase I, a contextual study to further understand the feasibility of the proposed solution is desired. Ideally, Phase I would conclude with a basic proof-of-concept prototype (hardware or software as appropriate). Critical requirements and interfaces should be defined alongside refinements of the proposed key performance parameters in Phase I. The Phase I effort should provide evidence of the feasibility of key elements such as cost, assembly, integration, and operations. The concept should reach sufficient maturity to show strong feasibility for the defined mission environments and performance requirements. The prototype system design should reach sufficient maturity to define test objectives and map key performance parameters (mass, power, cost, etc.) from the prototype to the flight design. Hardware development during the Phase I effort should provide confidence in the design maturity and execution of the Phase II effort. Lastly, the Phase I effort should identify potential opportunities for mission infusion and initiate partnerships or cooperative agreements necessary for mission execution.

In Phase II, further development and technology maturation is desired. Ideally, Phase II would culminate with TRL 5+ and include demonstration of the proposed solution. Both Phase I and Phase II should be approached with a focus on infusion, ensuring solutions are being developed with the proper requirements, interfaces, performance parameters, partnerships, etc., such that they, through a Phase III award or otherwise, could be directly applied to real spacecraft and real missions.

State of the Art and Critical Gaps:

Current space traffic coordination architectures typically have a significant involvement of “humans in the loop” for identifying conjunction threats, making decisions on whether and how to respond, and implementing responses.

Currently, the U.S. Air Force 19th Space Control Squadron provides conjunction data messages (CDMs) to virtually all space operators worldwide following tracking measurements taken with its assets. CDMs are used to create orbit determination solutions that comprise the space object catalog. Operators then assess and weigh the risks to their assets posed by the event described by the CDM against the resources to be expended to mitigate those risks, as well as consider the non-close-approach risks of taking mitigating action. This process is time-consuming, typically on timescales that do not allow for rapid reaction to a rapidly evolving threat.

To help address such situations, various stakeholders have been implementing solutions of their own, but these solutions are likely to run into limitations, particularly as more spacecraft are deployed, and systems need to be scaled further and interact with each other.

- For example, to help protect its nonhuman spaceflight assets, NASA established its Conjunction Assessment and Risk Analysis (CARA) program, with operational interfaces with the 18th Space Control Squadron to receive close-approach information in support of NASA mission teams. However, the system still features humans in the loop, and if further investments are not made, this approach may run into combined scalability and time-responsiveness issues as more commercial and/or noncooperative foreign assets deploy and/or pass through the operational orbits of NASA spacecraft. While regulatory solutions are part of the mix to help resolve the issues encountered, such as the Space Act Agreement between NASA and SpaceX to identify how each party will respond [Ref. 7], those solutions are slow to implement and have legislative limitations. Technical solutions will inevitably be necessary to address gaps posed by regulatory means.

- Deployers of SmallSat swarms and constellations are increasingly implementing software solutions for spacecraft to autonomously decide and implement collision-avoidance maneuvers. However, given the large capital and labor-intensive investment required to implement them, such systems may not be within the reach of all spacecraft operators, especially startup or single-spacecraft mission operators. Furthermore, with such technologies in their infancy, and with commercial operators racing to deploy and scale their spacecraft constellations to achieve market dominance, there is a very real risk that such systems may struggle to interface adequately with other autonomous and nonautonomous constellations, as was experienced by OneWeb and SpaceX [Ref. 8]. There may even be an enhanced collision risk as each autonomous system independently takes evasive action that, unbeknownst to the other, increases the risk of collision, much like two persons unsuccessfully trying to avoid each other in a corridor.

Civil Space Shortfall Ranking https://www.nasa.gov/spacetechpriorities/

- 1589: Space Situational Awareness
- 1477: Mitigation of New Orbital Debris Generation

Relevance / Science Traceability:

- Low-SWaP-C small spacecraft systems for cooperative identification and tracking: With increased demands on existing space situational awareness capabilities, and with regulatory attention on the threat of spacecraft that are unidentified, misidentified, or too small to track, the small spacecraft community needs low-SWaP-C identification and tracking aids. Employing such methods would allow the community to operate with lower risk to all spacecraft in orbit without negatively impacting the efficiency of small missions. There is a clear need to develop and demonstrate low-cost and low-complexity identification and tracking aids that can be scaled, produced, and readily standardized under the paradigm of small spacecraft ecosystems.
    - Technologies used for identification and tracking aids are needed in all orbit regimes, including the rapidly growing cislunar environment.

- Low-SWaP-C spacecraft systems for autonomous reactive operations of small spacecraft swarms and constellations: Small spacecraft operating in formation, in close proximity to other objects, or beyond the capacity of human-in-the-loop control will be required to process input onboard and execute correct responses autonomously.

- These sensor-driven operations will be enabling for safe proximity operations with spacecraft or small bodies as well as the detection and reaction to transient events for observation, such as would be required for sampling a plume from Enceladus. Furthermore, enabling multiple small spacecraft operating in coordinated orbital geometries or performing relative station-keeping can further expand human knowledge deeper into the universe by performing coordinated occultation, acting as virtual telescopes, and forming distributed apertures that would be prohibitively complex and expensive to launch into space as monolithic structures. Small spacecraft formation flight can also enable swarm gravimetry, synchronized observation of transient phenomena, and proximity operations for inspection of other assets.
- Autonomous maneuvering is not synonymous with real-time maneuvering. All autonomous maneuvering solutions must allow time and capability to screen planned maneuvers via existing close-approach screening methods at 19 SDS (see Space-Track.org for more information) to share planned information with other operators and prevent collisions.

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Z-EXPAND.04: Low Earth Orbit (LEO) Sustainability (SBIR)

Related Subtopic Pointers: S14.01
Lead Center: ARC
Participating Center(s): GSFC

Subtopic Introduction:

This subtopic addresses NASA's technology objectives for LEO sustainability. Volume 1 of NASA's Space Sustainability Strategy focuses on advancing the Agency's responsibilities in space sustainability in Earth's orbit, aligned with its mission to innovate, explore, and inspire humanity.

The space operating environment is undergoing rapid changes with the emergence of new commercial capabilities that NASA has championed, including increased satellite activity and novel space capabilities such as satellite constellations, autonomous spacecraft, and commercial space destinations. Understanding the associated risks and benefits of new and existing capabilities is crucial for space sustainability.

The first volume of the strategy focuses on operations in Earth's orbit, especially in LEO, which present highly visible challenges to space sustainability. This domain includes topics such as space situational awareness, space traffic coordination, space environment (weather) awareness, orbital debris management, and spacecraft servicing. The domain emphasizes the health and safety of human spaceflight. Space situational awareness refers to the knowledge and characterization of space objects and their operational environment to support safe, stable, and sustainable space activities. Space traffic coordination refers to planning, coordinating, and synchronizing on-orbit activities to enhance the safety, stability, and sustainability of operations in space. NASA views orbital debris management as the ability to mitigate the creation of new debris through design and operations, implement operational procedures for spacecraft to avoid collisions with debris, protect missions from damage due to strikes of orbital debris, limit reentry casualty risks, to characterize the populations of debris that are not currently tracked, and clean up debris through various remediation methods. Space weather awareness regards obtaining knowledge of and predicting the varying natural environment in response to changing solar conditions.

Scope Title: Small Debris Tracking to Support Debris Removal

Scope Description:

The purpose of this scope is to develop a ground-based solution that can maintain custody of a piece of small debris from the time it rises above the horizon to the time it descends below the horizon. This solution is primarily intended to support laser removal of orbital debris and to provide near-term improvements to existing space situational awareness (SSA) capabilities.

The U.S. economy depends on space for critical infrastructure, from communications and financial exchanges to national security, transportation, and climate monitoring. Orbital debris such as abandoned vehicle stages, non-functional satellites, and fragments of launched materials impedes our ability to use space by increasing the cost of space operations. More than 23,000 pieces of orbital debris are larger than a softball (about 10 cm) and tracked by the Department of Defense's global Space Surveillance Network (SSN) sensors. Because the debris is tracked, spacecraft operators can predict conjunctions with this debris and maneuver to avoid potential collisions. However, less than 1 percent of debris objects that could cause damage to a spacecraft are currently tracked and can damage satellites and crewed spacecraft without warning. In the space environment, there are approximately half a million pieces of debris larger than the size of a pea (1 cm) and approximately 100 million pieces of debris larger than the size of a grain of sand (1 mm).

Spacecraft cannot feasibly be shielded from debris that are larger than a few millimeters. Thus, the only feasible approaches to protect spacecraft from this risk are to track them well enough to enable spacecraft to maneuver to avoid them or to remove them altogether. Both approaches require the ability to maintain custody of small debris as they pass overhead. NASA seeks innovative technologies that could be used to provide the following level of custody:

- Addresses debris as small as 1 cm, in orbits from 350 to 800 kilometers altitude.
- Acquires custody of the debris as it rises above the horizon, possibly by being tipped with an externally provided orbital solution.
- Maintains custody of the debris at least until it is directly overhead, but ideally also until it descends below the horizon.

Relevant technologies for this topic include, but are not limited to:

- Light Detection and Ranging (LiDAR) systems that could maintain custody of such debris.
- Adaptive optics capabilities for observing and/or delivering pre-compensated beams to fast-moving objects in LEO.
- Phased-array radar systems that could detect, rapidly do orbit determination, and maintain custody of such debris.
- Passive optical or IR systems if they can maintain custody of such debris throughout the night and not just near sunset.

Expected TRL or TRL Range at completion of the Project: 2 to 4

Primary Technology Taxonomy:

- Level 1: TX 05 Communications, Navigation, and Orbital Debris Tracking and Characterization Systems
- Level 2: TX 05.6 Networking and Ground Based Orbital Debris Tracking and Management

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

At the end of Phase I, the performer should provide (1) a preliminary analysis of the trades and requirements that would be placed on the sensor, (2) an early design or prototype (of the system or a subsystem) that is analyzed to show that it meets a reasonable set of requirements, and (3) an implementation plan for maturation of the technology in Phase II, including technical risks and mitigations. If testing of the technology will require access to equipment or facilities beyond those owned by the performer, the Phase II plan should include a letter of support from a entity that can provide access to such facilities.

At the end of Phase II, a prototype of the technology (at system or subsystem level) should be completed that is capable of being tested in a laboratory or relevant environment. Ideally, the performer will also have been able to test the prototype with their own laboratory equipment. A final report, including relevant analytical and test data should be delivered to NASA. Likewise, the prototype should be made available to NASA for further testing.

State of the Art and Critical Gaps:

Challenges associated with maintaining custody of 1 cm debris:

- This debris is not currently tracked. To maintain custody of the debris, it must first be discovered and its orbit rapidly determined.
- The uncertainties are high in tracking objects and propagating orbits. The uncertainty tends to grow with time due to the compounding effects of atmospheric drag, space weather, and other nongravitational perturbations that may be difficult to predict.
- The debris is small and thus the signal it reflects from a laser or radar will be much less than larger debris. Solutions may require higher power and higher frequency emitters.
- To correct for atmospheric turbulence and tip-tilt errors with beam pre-compensation requires a consistent return of photons from the atmosphere and likely also the debris itself to close the adaptive optics loop. Getting sufficient returns from such a small object is very difficult even at night. Further, the debris is traveling so quickly across the sky that the adaptive optics system experiences an artificial wind; this exacerbates the challenge correcting for turbulence. Likewise, this rapid motion also exacerbates the tip-tilt challenges and the look-ahead problem.
- Radar systems in the X-band (or smaller wavelengths) can detect 1 cm debris; however, it is unclear whether any such systems have ever demonstrated the ability to track such debris. Phased-array radar systems in these wavelengths could likely perform the task but are prohibitively expensive.
- It is difficult to integrate heterogeneous data in real time. Many different types of systems are used for object tracking, with different uncertainties, data formats, and possible proprietary restrictions.

NASA has identified the following as the likely state of the art for the relevant capabilities.
LIDAR Systems:

- Researchers from Electro Optic Systems (EOS) working at the Space Environment Research Centre (SERC) in Australia demonstrated laser ranging to debris smaller than 10 cm debris during project Razor View in 2014.
- Beam Pre-Compensation. In 2024, the French national aerospace research center (ONERA) demonstrated a bidirectional laser link pre-compensated by adaptive optics between its FEELINGS ground station (FEEder LINks Ground Station) the TELecoms on all Earth Orbits (TELEO) payload in geostationary orbit (GEO)**.**
- Fugate (2003) demonstrated pre-compensation of beams to an asset in LEO. Solar reflections and natural guide stars were used to deliver a beam that was pre-compensated for tip/tilt and turbulence to a satellite at 800 km altitude—no laser guide stars or Rayleigh beacons were used.
- Phased Array Radar: Recent advancements have significantly reduced the costs of phased array radars in frequency bands that are potentially attractive for tracking centimeter-size debris. For example, Leolabs has developed a low-cost phased-array S-band radar. Similarly, SpaceX Starlink user terminals are phased-array in the Ka band and affordable enough for end users to purchase.

Civil Space Shortfall Ranking https://www.nasa.gov/spacetechpriorities/

- 1262: Small Debris Remediation
- 1476: Large Debris Remediation
- 1477: Debris Mitigation
- 1432: Rendezvous, Proximity Operations, and Debris Remediation using Small Spacecraft mentions

Relevance / Science Traceability:

Each of these technologies requested (LIDAR, adaptive optics, and phased-array radar) may be required for a ground-based system to perform laser debris removal. Two recent NASA studies have identified laser debris remediation as the most cost-effective form of debris remediation (Colvin 2023, Locke 2024). A distributed network of space-observation nodes using these technologies, albeit at much lower power levels, could develop a catalog of 1-10 cm debris and support collision avoidance maneuvers for active spacecraft. Further, low-cost commercial development of these sensors can be used by existing SSA providers to augment their existing services, such as by using these systems to reduce the uncertainties associated with predicted high-threat conjunctions involving large debris; this application was identified as the most cost-effective method for improving SSA in a recent NASA study (Locke 2024). Finally, enhancements to LIDAR systems and beam pre-compensation capabilities to LEO are also highly germane to future optical communications systems.

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Scope Title: Commercial Development of Active Debris Remediation (ADR) Services

Scope Description:

NASA is supporting the development of commercial services that can reduce the risks associated with orbital debris. Specifically, we are seeking innovative systems or subsystems that can enable low-cost services to perform: (1) controlled reentry of large debris, greater than 1,000 kg; or (2) just-in-time collision avoidance—maneuvering or nudging of debris objects via contact or non-contact means to avoid collisions detected *a priori* (this approach was ranked as most cost-effective approach to debris remediation in the recent NASA "Cost and Benefit Analysis of Mitigating, Tracking, and Remediating Orbital Debris").

Preference will be given to proposals that do one or more of the following:

- Solutions providing an end-to-end capability that detects, approaches, detumbles (if necessary), grasps or otherwise captures, and de-orbits the debris in a controlled manner (controlled reentry); or solutions providing the capability to nudge a piece of debris to avoid a collision.
- Solutions that can scale to provide bulk removal services.
- Systems for de-tumbling and gaining positive control of large objects with uncertain dynamical properties and high rotation rates.
- Novel methods for performing controlled reentry, such as those that do not need chemical propulsion to perform the reentry or enable a single vehicle to perform multiple controlled reentries.

The U.S. economy depends on space for critical infrastructure, from communications and financial exchanges to national security, transportation, and climate monitoring. Orbital debris such as abandoned vehicle stages, non-functional satellites, and fragments of launched materials impedes our ability to use space by increasing the cost of space operations; operators must monitor conjunctions with debris and maneuver to avoid potential collisions. These pieces of debris are mostly trackable and can be avoided; however, they may also collide with each other to generate many pieces of smaller debris that are not tracked by our current methods of space situational awareness (SSA). These smaller pieces of debris can damage satellites and crewed spacecraft without warning. As described in the 2022 National Orbital Debris Implementation Plan, there are three broad methods to reduce the risks associated with debris: (1) limit the generation of new debris, (2) better track and characterize debris, (3) and remediate debris that has already been created.

Debris remediation services are those that move, remove, or reuse extant debris to reduce the risks associated with it. While the risks associated with most trackable debris may be remediated by techniques such as just-in-time collision avoidance or removal via uncontrolled reentry, an important subset of large debris will need to be disposed of through a controlled reentry; this will reduce the risks posed to people and property on the ground for debris that does not fully disintegrate during reentry. However, there are a few major challenges with making this service cost-effective, such as the debris may be rotating in such a way that precludes contact or effective control of the object; electric propulsion may not be able to perform a controlled reentry due to its thrust being overpowered by aerodynamic drag; and difficulties associated with creating a system that can perform controlled reentries of multiple pieces of debris per mission (which likely requires a rapid reentry avoidance maneuver by the servicer/remover after the final deorbit burn and release of the debris object).

Expected TRL or TRL Range at completion of the Project: 2 to 5

Primary Technology Taxonomy:

- Level 1: TX 05 Communications, Navigation, and Orbital Debris Tracking and Characterization Systems
- Level 2: TX 05.X Other Communications, Navigation, and Orbital Debris Tracking and Characterization Systems

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype

Desired Deliverables Description:

At the end of Phase I, the performer should provide (1) a preliminary analysis of the trades and requirements that would be placed on the ADR solution, (2) an early design or prototype (at system or subsystem level) that is analyzed to show that it meets a reasonable set of requirements, and (3) an implementation plan for maturation of the technology in Phase II, including technical risks and mitigations. If testing of the technology will require access to equipment or facilities beyond those owned by the performer, the Phase II plan should include a letter of support from a entity that can provide access to such facilities.

At the end of Phase II, analysis that supports the feasibility of the ADR technology should be completed. Ideally, a prototype of at least a subsystem of the technology should be completed that is capable of being tested in a laboratory or relevant environment. Ideally, the performer will also have been able to test the prototype with their own laboratory equipment. A final report, including relevant analytical and test data should be delivered to NASA. Likewise, the prototype should be made available to NASA for further testing.

State of the Art and Critical Gaps:

Space debris poses a risk for current and future missions. ADR or just-in-time collision avoidance solutions would help remediating the environment and are currently not commercially available.

Civil Space Shortfall Ranking https://www.nasa.gov/spacetechpriorities/

- 1262: Small Debris Remediation
- 1476: Large Debris Remediation
- 1477: Debris Mitigation
- 1432: Rendezvous, Proximity Operations, and Debris Remediation using Small Spacecraft mentions

Relevance / Science Traceability:

An increasing debris population is a threat to all space operations. Remediation efforts support the space sustainability goals.

References:

1. “2021 National Orbital Debris Research and Development Plan” - Available at https://trumpwhitehouse.archives.gov/wp-content/uploads/2021/01/National-Orbital-Debris-RD-Plan-2021.pdf
2. “Cost and Benefit Analysis of Mitigating, Tracking, and Remediating Orbital Debris” - available at https://ntrs.nasa.gov/api/citations/20240003484/downloads/2024%20-%20OTPS%20-%20CBA%20of%20Orbital%20Debris%20Phase%202%20v3.pdf

Scope Title: Space Environmental Monitoring Sensor

Scope Description:

The space environment in Earth orbit is complex and dynamic, and while larger objects in Earth orbit are generally well tracked, due to its vast size, much of the other areas of the space environment are not effectively monitored. Two of the prime areas of interest for space environmental monitoring are space weather and small debris.

NASA is interested in developing a low Size, Weight, and Power (SWAP) device that is independent power and communications that can (1) provide consistent GPS tracking, (2) provide indications and possible forensics on small micrometeoroid and orbital debris strikes, and (3) monitor the space weather environment. The goal is to provide a commercial device that can be hosted on a variety of small and large spacecraft to provide for dispersed sampling of the space environment.

A distributed network of these devices will provide data across the space environment to provide better hazard predictions and perhaps operational safety information.

The following provides additional background:

- Spaceflight Safety GPS Transponder
    - Device must have a GNSS receiver (primary sensor).
    - Device must calculate GPS/GNSS navigation solutions (fixes) and record them at a regular cadence.
- MMOD Strike Detection and Forensics

  - Device must be able to detect and measure benign impacts on the spacecraft with energy of 1 to 65 millijoules (mJ), which corresponds sub-1mm debris.
  - Expected rates are zero to 25 strikes per day per square meter of spacecraft area, depending on orbital parameters.
  - Device must record detector orientation when strikes occur (for example, using a 9-axis MEMS IMU (accelerometer, gyroscope, magnetometer))
- Space Weather Data
  - Other ancillary sensors are highly encouraged and could include radiation dosimeter, light/horizon sensor, thermometer, and any other space environment or safety sensors.
- Supporting features
  - Device must be self-powered or have a self-powered default should optional host power become unavailable.
  - Device should operate for months/years under an independent power mode.
  - Device should have an option for power and communication with the host. The host should have the option to notify the device of critical spaceflight safety events or intents.
  - Device should be as small as possible, ideally no larger than 10 x 10 x 3 cm, < 300 grams, and consume no more than 1.5 Watts (orbit averaged) from the host.
  - Device should have an independent means of communication from its host.

An example for a potential solution for a MMOD impact sensor is an acoustic sensor placed on a solar panel.

Expected TRL or TRL Range at completion of the Project: 1 to 6

Primary Technology Taxonomy:

- Level 1: TX 05 Communications, Navigation, and Orbital Debris Tracking and Characterization Systems
- Level 2: TX 05.X Other Communications, Navigation, and Orbital Debris Tracking and Characterization Systems

Desired Deliverables of Phase I and Phase II:

- Software
- Hardware
- Prototype
- Analysis
- Research

Desired Deliverables Description:

Phase I research should demonstrate technical feasibility, with preliminary hardware system requirements being delivered to NASA, as well as show a plan toward Phase II sensor design. Phase II new technology development efforts shall deliver components at the TRL 5 to 6 level to NASA, with mature algorithms and software components complete and preliminary integration and testing in a quasi-operational environment.

State of the Art and Critical Gaps:

This is technology currently not available commercially. This leads to a gap in understanding of the current sub-mm debris, and results in an uncertainty for shielding requirements and potentially too high or too low shielding mass.

Civil Space Shortfall Ranking https://www.nasa.gov/spacetechpriorities/

- 1262: Small Debris Remediation
- 1476: Large Debris Remediation
- 1477: Debris Mitigation
- 1432: Rendezvous, Proximity Operations, and Debris Remediation using Small Spacecraft mentions

Relevance / Science Traceability:

This technology is relevant and needed for all human spaceflight and robotic missions in the near-Earth space environment. The ability to accurately understand the holistic near-space environment will improve space safety for all operations involving orbiting spacecraft, improve operational support by providing more accurate and longer-term predictions, and reduce propellant usage for collision avoidance maneuvers.

References:

1. Christiansen & Lear, "Micrometeoroid and Orbital Debris Environment & Hypervelocity Shields", NASA 2012, https://ntrs.nasa.gov/api/citations/20120002584/downloads/20120002584.pdf

Z-EXPAND.05: Beyond LEO Sustainability (SBIR)

Lead Center: GSFC
Participating Center(s): LaRC

Subtopic Introduction:

This subtopic addresses NASA's technology objectives for space sustainability beyond Low Earth Orbit (LEO). Volume I of NASA's Space Sustainability Strategy focuses on advancing the agency's responsibilities in space sustainability in Earth Orbit, aligned with its mission to innovate, explore, and inspire humanity. Future volumes will address the other domains including: on Earth; in Earth's orbit; in cislunar space, including the Lagrange points and the lunar surface; and in deep space, including other celestial bodies. This subtopic addresses the portion of Earth's orbit above LEO, as well as the cislunar space domain.

The space operating environment is undergoing rapid changes with the emergence of new commercial capabilities that NASA has championed, including increased satellite activity and novel space capabilities such as satellite constellations, autonomous spacecraft, and commercial space destinations. Understanding the associated risks and benefits of new and existing capabilities is crucial for space sustainability.

Many of the challenges regarding sustainability in cislunar space (including the Earth-Moon Lagrange points) and the lunar surface are similar to those regarding sustainability in Earth's orbit. However, the challenges regarding cislunar space and the lunar surface are magnified because there are fewer historical precedents and norms to follow. Also, the world may not yet have the operational capabilities needed to support sustainable operations. For example, capabilities for situational navigation awareness, navigation, and communications are currently insufficient to support robust space traffic coordination and to monitor the sustainability of the operating environment. Similarly, when the mission of lunar surface assets ends, they must be properly disposed of to reduce the risks to other space operators; however, there are no guidelines for performing this disposal. Post mission disposal of orbiting assets is complicated by the Moon's lack of an atmosphere to accelerate the reentry of debris and the chaotic nature of cislunar orbits. Further, preserving scientifically or culturally valuable sites is an important consideration.

Scope Title: Low Lunar Orbit Space Object Sensing for Conjunction Assessment

Scope Description:

As the interest and investment in lunar missions increases from commercial and government entities both domestic and abroad, the number of objects entering lunar orbit is also quickly increasing. With a higher population of spacecraft dwelling about the Moon, these high-risk missions are facing an ever-rising danger of collision. The regimes that these objects will occupy range from distant, and extremely difficult to currently impossible to observe using traditional Earth-based sensors. Spacecraft collisions in these regimes are not currently well understood, putting an elevated risk on low lunar orbit missions themselves and potentially lunar surface operations as well.

Challenges:

- Lunar and Solar exclusion zones create large temporal and spatial gaps for existing sensors.
- Few steps have been taken to deploy sensors to solve this problem.
- Detectability of distant, small objects creates a sensitivity challenge.
- Lunar gravity creates challenging dynamics, making the orbit propagation highly variable.

This subtopic seeks innovative technologies to improve the close approach risk assessment process, including the following specific areas:

- Models to simulate the dynamics and observability of non-transmitting spacecraft in Low Lunar Orbit and their expected evolution over the next several decades. This includes the novel analysis of the long-term propagation of uncontrolled spacecraft orbiting within the lunar gravitational environment, the number of spacecraft (both active and inactive) likely to be deployed to this environment, requirements for the accuracy of metric observations of these spacecraft that allow sufficient conjunction assessment to be performed, and the types and locations of the sensors that are required to provide that information.
- Novel sensor design that could provide metric observations of low-lunar orbit non-transmitting spacecraft capable of being deployed to the lunar-surface via the Commercial Lunar Payload program or other similar lunar landers. Challenges to be considered include but are not limited to lunar regolith mitigation, power generation (both general and through lunar night), communications, and cost of proposed solutions.
- Analysis of a lunar-based SSA system comprised of sensors solely located at projected Commercial Lunar Payload program sites.
- The design of novel sensors that could provide metric observations of low-lunar orbit non-transmitting objects capable of operating as a hosted payload on spacecraft in an orbit within the lunar environment.
- Analysis of the position, navigation, and timing requirements for a sensor to obtain relevant metric observations of non-transmitting low-lunar spacecraft.
- Development of Low-lunar orbit space debris environmental models capable of modeling the long-term impacts of spacecraft ceasing their operational lifetime while still in low-lunar orbit.
- Development of debris mitigation strategies for spacecraft operators' end-of-life design.
- Analysis of the unique challenges associated with calculating the probability of collision for spacecraft or debris in low-lunar orbit.

Expected TRL or TRL Range at completion of the Project: 2 to 5

Primary Technology Taxonomy:

- Level 1: TX 05 Communications, Navigation, and Orbital Debris Tracking and Characterization Systems
- Level 2: TX 05.4 Network Provided Position, Navigation, and Timing

Desired Deliverables of Phase I and Phase II:

- Software
- Hardware
- Prototype
- Analysis
- Research

Desired Deliverables Description:

Phase I research should demonstrate technical feasibility, with preliminary software/hardware being delivered to NASA, as well as show a plan toward Phase II integration. Phase II new technology development efforts shall deliver components at the TRL 5 to 6 level to NASA, with mature algorithms and software/hardware components complete and preliminary integration and testing in a quasi-operational environment.

State of the Art and Critical Gaps:

The number of conjunction events is expected to continually increase with the rising international interest in exploring and creating settlements on the Moon. The inability to track smaller objects, the increasing numbers of CubeSat/SmallSats, and the proliferation of space debris within the low-lunar environment pose a risk to human and robotic spaceflight. Thus, NASA has identified the following challenges for which they are actively seeking solutions: modeling of the long-term man-made lunar environment, sensor technologies capable of providing relevant information for use in conjunction risk assessment about the Moon, improved understanding of any unique conjunction assessment requirements while operating in the lunar gravitational field, and the lack of maturity of the current position, navigation, and timing resources for sensors taking measurements near the Moon. The decision space for collision avoidance relies on not only the quality of the data (state and covariance) but also the tools and techniques.

Relevance / Science Traceability:

This technology is relevant and needed for all human spaceflight and robotic missions in the cislunar, lunar, and potentially other solar system body environments. The ability to understand the environment and accurately observe potentially hazardous spacecraft or debris will improve space safety for all operations involving orbiting spacecraft, improve operational support by providing more accurate and longer-term predictions, and reduce propellant usage for collision avoidance maneuvers. The development of robust conjunction risk assessment and mitigation processes about the Moon will further extend the heredity of NASA as an international touchpoint of spaceflight safety. This technology will ultimately support safer, more prudent, and conscious operations for all lunar space missions to come.

References:

1. 2020 NASA Technology Taxonomy: https://www3.nasa.gov/sites/default/files/atoms/files/2020_nasa_technology_taxonomy_lowres.pdf
2. Alfano, Salvatore. "A numerical implementation of spherical object collision probability." The Journal of the Astronautical Sciences 53, no. 1 (2005): 103-109.
3. Balch, Michael Scott, Martin, Ryan, and Ferson, Scott, "Satellite conjunction analysis and the false confidence theorem." Proceedings of the Royal Society A 475, no. 2227 (2019): 20180565.
4. Frigm, Ryan C., Hejduk,Matthew D., Johnson, Lauren C., and Plakalovic, Dragan, "Total probability of collision as a metric for finite conjunction assessment and collision risk management." Proceedings of

the Advanced Maui Optical and Space Surveillance Technologies Conference, Wailea, Maui, Hawaii. 2015.
5. NASA Conjunction Assessment Risk Analysis (CARA) Office: https://www.nasa.gov/conjunction-assessment
6. NASA Orbital Debris Program Office: https://www.orbitaldebris.jsc.nasa.gov/
7. 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
8. 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
9. Newman, Lauri K., et al., "NASA Conjunction Assessment Risk Analysis Updated Requirements Architecture," AIAA/AAS Astrodynamics Specialist Conference, Portland, ME, AAS 19-668, (2019).
10. Office of Safety and Mission Assurance, "NASA Procedural Requirements for Limiting Orbital Debris and Evaluating the Meteoroid and Orbital Debris Environments," NPR 8715.6, https://nodis3.gsfc.nasa.gov/displayDir.cfm?t=NPR&c=8715&s=6B
11. NASA Interim Directive (NID) 7120.132: Collision Avoidance for Space Environment Protection: NID_7120_132_.pdf (nasa.gov)
12. NASA Spacecraft Conjunction Assessment and Collision Avoidance Best Practices Handbook: OCE_50.pdf (nasa.gov)
13. Consultative Committee for Space Data Systems (CCSDS) Recommended Standard for Conjunction Data Messages: https://public.ccsds.org/Pubs/508x0b1e2c2.pdf

Scope Title: Highly Elliptical Orbit Tracking

Scope Description:

The U.S. Space Surveillance Network (SSN) currently tracks more than 45,000 objects larger than 10 cm (Ref: https://www.space-track.org), and the number of objects in orbit is steadily increasing, which causes an increasing threat to spacecraft in the near-Earth environment. Some of the objects in Highly Elliptical Orbits (HEOs) are not tracked well due to the nature of the orbits and the configuration of the SSN. NASA has a need to place scientific spacecraft in HEO; those spacecrafts need to be tracked well to meet orbital safety requirements.

NASA is interested in determining if commercial Space Situational Awareness (SSA) data might be an effective tracking solution for HEO spacecraft. If there is an effective commercial solution, NASA would like to develop and evaluate this solution so that it may then be available as a commercial service that can be ordered in the future as needed.

This subtopic seeks innovative technologies to improve the risk assessment process, including the following specific areas (see Reference 1 for the 2020 NASA Technology Taxonomy (TX) areas TX05.6.1, TX10.1.4, TX10.1.5, and TX10.1.6):

- Repeatable routine tracking and custody in HEO orbits of:
    - Object sizes ranging from 1U (10 cm x 10 cm x 10 cm) and larger.
    - Orbits flow inclination.
    - Tracking augmentations that persist beyond spacecraft operational lifetime.
- Methods for improved HEO ephemeris generation with sparse sensor observations, incorporating:
    - Sensor observability during a narrow angular range of the orbit (e.g., only around perigee or apogee).

- Improved predicted position and velocity accuracy.
- Covariance realism in prediction such that errors in prediction are appropriately contained within the propagated covariance.

Expected TRL or TRL Range at completion of the Project: 2 to 6

Primary Technology Taxonomy:

- Level 1: TX 05 Communications, Navigation, and Orbital Debris Tracking and Characterization Systems
- Level 2: TX 05.X Other Communications, Navigation, and Orbital Debris Tracking and Characterization Systems

Desired Deliverables of Phase I and Phase II:

- Software
- Analysis
- Research
- Hardware
- Prototype

Desired Deliverables Description:

Phase I research should assess technical feasibility and data/track quality, as well as show a plan toward Phase II, demonstration of the system. Overall objective should be to establish a path towards commercially available data service on an accessible marketplace.

Phase II new technology development efforts shall deliver components at the TRL 5 to 6 level to NASA, 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 tracking systems are not optimized for HEO object tracking.

Relevance / Science Traceability:

This technology is relevant and needed for all missions in the near-Earth space environment. The ability to perform conjunction risk assessment more accurately will improve space safety for all operations involving orbiting spacecraft, improve operational support by providing more accurate and longer-term predictions, and reduce propellant usage for collision avoidance maneuvers.

References:

1. https://www.space-track.org
2. https://www.nasa.gov/otps/2020-nasa-technology-taxonomy/

Scope Title: Micrometeoroid Damage Mitigation for Large Telescopes

Scope Description:

Building on discoveries of exoplanets made in the last decade [1], the latest astrophysics decadal plan [2] recommends that a priority area for scientific study is the search for worlds that could resemble Earth. Of great interest is understanding potentially habitable planets, especially those orbiting more Sun-like stars, to answer profound questions about the existence of life beyond Earth. These discoveries will be made by the Habitable Worlds Observatory, the next telescope which will orbit at Sun-Earth L2, where the James Webb Space Telescope (JWST) is positioned.

Although JWST was designed to operate for five years, there is uncertainty in its long-term optical performance due to degradation resulting from micrometeoroid impacts on its mirrors [3,4]. Since the flux of micrometeorites in L2 is not well characterized, the risk mitigation method for JWST is to point the telescope in the wake direction to avoid higher energy micrometeoroid impacts known to occur in the ram direction [4]. Previous generations of telescopes overcome this risk with the use of heavy protective baffles integral to the telescope.

The Habitable Worlds Observatory is envisioned to have optics with diameters in the range of 6 to 6.5 meters [5,6]. This solicitation seeks innovative, lightweight risk mitigation solutions to prevent micrometeoroid damage to optical components in the next generation large telescope without causing a cascading effect on optical performance from shield damage.

Expected TRL or TRL Range at completion of the Project: 2 to 5

Primary Technology Taxonomy:

- Level 1: TX 12 Materials, Structures, Mechanical Systems, and Manufacturing
- Level 2: TX 12.1 Materials

Desired Deliverables of Phase I and Phase II:

- Research
- Prototype

Desired Deliverables Description:

In this solicitation, proposals are invited for approaches to shield the optical components of the Habitable Worlds Observatory. Proposed solutions shall be:

- Lightweight
- Integral to the telescope and must not interfere with telescope operations.
- Perform micrometeoroid damage shielding without causing cascading damage to the optical components.

Proposal elements of interest include but are not limited to:

- Identification of material systems that can survive the thermal environment at L2.
- Design concepts to overcome micrometeoroid damage and extend the optical performance of telescope mirrors.
- Proof of concept for performance of proposed technology solution.

Phase I will provide design concepts for micrometeoroid damage mitigation. The concept will include the material choices for the telescope environment, employment mechanism integral to the telescope structure.

Phase II would look at prototyping a damage mitigation system.

State of the Art and Critical Gaps:

Although JWST was designed to operate for five years, there is uncertainty in its long-term optical performance due to degradation resulting from micrometeoroid impacts on its mirrors [3,4]. Since the flux of micrometeorites in L2 is not well characterized, the risk mitigation method for JWST is to point the telescope in the wake direction to avoid higher energy micrometeoroid impacts known to occur in the ram direction [4]. Previous generations of telescopes overcome this risk with the use of heavy protective baffles integral to the telescope.

The Habitable Worlds Observatory is envisioned to have optics with diameters in the range of 6 to 6.5 meters [5,6]. This solicitation seeks innovative, lightweight risk mitigation solutions to prevent micrometeoroid damage to optical components in the next generation large telescope without causing a cascading effect on optical performance from shield damage.

SoA and Critical Gaps:

- Current mitigation approaches include meteoroid avoidance for JWST which may reduce its instantaneous field of regard [4].
- Deployable shields integral to the telescope that are heavy.

Relevance / Science Traceability:

Astro2020 [1,2]
JWST Reports [3,4]
Habitable World Observatory Concepts [5,6]
Provides solution for shortfall ID 1576

References:

1. National Academies of Sciences, Division on Engineering and Physical Sciences, Board on Physics, Space Studies Board and Committee on Exoplanet Science Strategy, *Exoplanet Science Strategy*, 2019, https://nap.nationalacademies.org/catalog/25187/exoplanet-science-strategy, https://doi.org/10.17226/25187 .
2. National Academies of Sciences, Engineering, and Medicine, *Pathways to Discovery in Astronomy and Astrophysics for the 2020s*, 2021, https://nap.nationalacademies.org/catalog/26141/pathways-to-discovery-in-astronomy-and-astrophysics-for-the-2020s?ref=space-news.io, https://doi.org/10.17226/26141
3. Rigby, J., et al., "The Science Performance of JWST as Characterized in Commissioning," Publications of the Astronomical Society of the Pacific, 135:048001, 2023, https://doi.org/10.1088/1538-3873/acb293.
4. McElwain, M. W., et al., "The James Webb Space Telescope Mission: Optical Telescope Element Design, Development, and Performance," Publications of the Astronomical Society of the Pacific, 135:058001, 2023, https://doi.org/10.1088/1538-3873/acada0.
5. LUVOIR Team, The LUVOIR Mission Concept Study Final Report, arXiv:1912.06219v1 [astro-ph.IM], 2019, https://doi.org/10.48550/arXiv.1912.06219.
6. Stark, C. C., et al., "Paths to Robust Exoplanet Science Yield Margin for the Habitable Worlds Observatory," arXiv:2405.19418v1 [astro-ph.EP], 2024, https://doi.org/10.48550/arXiv.2405.19418.

Z-ENABLE.01: Enabling Power and Thermal Technologies (SBIR)

Related Subtopic Pointers: S13.06
Lead Center: GRC
Participating Center(s): N/A

Subtopic Introduction:

This is a proposed new sub-topic to cover the STMD Foundational (Enable) Capability Portfolio in the area of Advanced Power and Thermal technology development. Because STMD has significant investments in the Surface Infrastructure and Exploration (Live) Capability in Surface Power Technologies, this subtopic will be seeking mainly Advanced Power and Thermal technologies that are needed for missions that are primarily in-space missions.

The high priority "shortfalls" that this subtopic is meant to address are:

- 709 - Nuclear Electric Propulsion for Human Missions
- 1597 - Power for Non-Solar Illuminated Small Systems
- 610 - Solar Electric Propulsion
- 1430 - Small Spacecraft Propulsion
- 611 - Sub-kW and kW Class Electric Propulsion Systems
- 1619: High Temperature Heat Rejection for Nuclear Applications

Three scopes will be sought focusing on advancements that small businesses can advance in the areas of high-performance electrical power systems for kilowatt-class nuclear propulsion, advanced technologies for photovoltaic solar arrays in extreme environments, and advanced thermal transport technologies for space missions.

Scope Title: Kilowatt-Class Thermal Energy Conversion Technologies

Scope Description:

NASA is considering the use of kilowatt class nuclear reactor fission power systems for small in-space nuclear electric propulsion (NEP) and surface missions to the moon and Mars. Studies have shown the benefits of 10 to 40 kW fission power systems providing power to high-TRL electric thrusters for science missions to the outer planets. The analysis shows that kilowatt-class nuclear electric propulsion (NEP) can deliver larger payloads and provide greater power for science at the destination than conventional spacecraft power and propulsion approaches, with comparable trip times. Candidate mission applications include Titan/Enceladus, Neptune/Triton, Centaurs, Saturn, Uranus, and Pluto. In addition, NASA is currently funding the Fission Surface Power (FSP) project to deliver 40 kW of continuous, sun-independent power on the surface of the Moon and Mars. Fission power systems are likely to generate AC power, either single-phase AC at relatively low frequency with Stirling conversion (50 to 100 Hz) or three-phase AC at higher frequency with Brayton conversion (500 to 2000 Hz).

These technologies directly align with the Space Technology Mission Directorate (STMD) roadmap for space power and energy storage. Future reactor designs will include shielding to reduce gamma rays and neutrons to the power conversion system, control electronics, payload, and habitat. Heat could be removed from the reactor core using heat pipes, liquid metal loops, or gas loops and delivered to the Power Conversion Systems (PCS). Waste heat would be removed from the PCS and delivered to radiators. High performance and radiation tolerant power electronics are needed to bolster convertor, controller and PMAD robustness.

Needed Technologies:

Robust, radiation hardened power conversion systems

- Capable of long-life (>10 years), and high efficiency (>30%).
- Demonstrating relevant Free-Piston Stirling cycle convertors and Closed Brayton Cycle convertors supporting the 40 kW FSP target and scalable to support future 50 kW-100 kW for larger surface power and NEP systems. There is an interest in higher power convertors, and it is anticipated all systems will contain more than one convertor for the purpose of redundancy. Balancing fault tolerance and complexity, past concepts have explored two to four convertors.
- High power density convertor alternator designs are sought to survive combined temperature and radiation environments, with robust organic and magnet materials. Alternators should be able to survive 200°C+ at radiation levels over 5E14 n/cm2 + 1E4 krad.

Radiation hardened electronic controllers and power processing

- Electronic controller hardware for Stirling and Brayton systems with a credible path to flight, able to control one or more dynamic convertors.
- Increasing the radiation tolerance of electronic components found in PCS controllers and accompanying power processing systems to values greater than 5E11 n/cm2 + 3E2 krad + 40 MeV-cm2/mg (LET). Higher tolerance will enable a reduction in shielding mass and is strongly desired.
- Increasing voltage capability of radiation hardened systems beyond the 120 Vdc typically used for space power. Focus on 300V+ capability.
- Increasing specific power density (w/kg) of controllers with high density capacitive and magnetic filtering and buffering.
- Sensors, control algorithms and data processing to enable robust, autonomous operation.

Radiation hardened sensing and sensor signal processing systems for reactor operation

- Radiation hardness of 5E14 n/cm2 + 1E4 krad + 40 MeV-cm2/mg (LET) and higher.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:

- Level 1: TX 03 Aerospace Power and Energy Storage
- Level 2: TX 03.1 Power Generation and Energy Conservation

Desired Deliverables of Phase I and Phase II:

- Research
- Prototype
- Hardware
- Analysis

Desired Deliverables Description:

NASA seeks advanced technology concepts that small businesses can turn into prototypes to prove feasibility of the concept, a well-defined path to flight, and an ability to manufacture flight-ready prototypes for potential NASA mission use.

Successful Phase I proposals would propose detailed studies, research, and/or prototype development and testing that would be able to prove the feasibility of key factors of the overall concept.

Successful Phase II proposals would improve upon the fidelity of the hardware and testing and would prove a mission benefit to NASA. At the same time, the company and their partners would demonstrate to NASA an ability to further develop and manufacture the technology into a high-fidelity space simulation ground test and/or a demonstration flight mission.

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 40 kWe power system level using a Uranium-based reactor core. Shielding is used to the power conversion system, control electronics, payload, and habitat from gamma rays and neutrons. Heat is removed from the core at approximately 800°C using heat pipes, liquid metal loops, or gas loops and delivered to the power conversion system. Waste heat is removed from the power conversion system at approximately ~100 to 300°C using water, water mixtures, and hydrocarbons and coupled to aluminum or composite radiator panels that deploy prior to startup.

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.

Civil Space Shortfall Ranking: https://www.nasa.gov/spacetechpriorities/

- 709 - Nuclear Electric Propulsion for Human Missions
- 1597 - Power for Non-Solar Illuminated Small Systems
- 610 - Solar Electric Propulsion
- 1430 - Small Spacecraft Propulsion
- 611 - Sub-kW and kW Class Electric Propulsion Systems

Relevance / Science Traceability:

This technology directly aligns with the STMD roadmap for space power and energy storage. Sustainable Living and Working Farther from Earth is a major NASA Strategic Capability need and part of this is the development of sustainable power and energy storage systems and other surface utilities to enable continuous lunar and Mars surface operations.

References:

1. Kilopower–Nuclear Electric Propulsion for Outer Solar System Exploration, JPL D-103385, April 2019
2. Kilopower (https://www.nasa.gov/directorates/spacetech/kilopower)
3. Gibson, M.A., et al., "The Kilopower Reactor Using Stirling Technology (KRUSTY) Nuclear Ground Test Results and Lessons Learned," AIAA P&E 2018, AIAA-2018-4973.
4. Mason, Lee S., "A Comparison of Energy Conversion Technologies for Space Nuclear Power Systems," AIAA P&E 2018, AIAA-2018-4977.
5. 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.
6. 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.
7. Mason, Lee S., et al., "A Small Fission Power System for NASA Planetary Science Missions," NASA/TM--2011-217099.

Scope Title: Advanced Photovoltaics

Scope Description:

Photovoltaics have been proven as a reliable in-space power generation technology for decades, supporting missions ranging from watts to 10s of kilowatts with lifetimes of over 20 years in well understood conditions and environments. As NASA and the commercial space industry continue to push the boundaries of traditional spacecraft, the solar array and its component technologies are changing from the well tested and characterized to novel (and in many cases terrestrial) technologies. Additionally, solar powered spacecraft are being used in and considered for missions that push extremes in terms of temperature ranges and cycles and radiation fluence. The scope of this subtopic is seeking photovoltaic cell, module, and blanket technologies that lead to significant improvements in overall solar array and related power system component system performance with novel technologies in traditional and extreme environments The subtopic goal is to demonstrate a significant improvement of performance versus state-of-the-art solar cell and array technologies.

Expected TRL or TRL Range at completion of the Project: 2 to 4

Primary Technology Taxonomy:

- Level 1: TX 03 Aerospace Power and Energy Storage
- Level 2: TX 03.1 Power Generation and Energy Conservation

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware

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 (SOA) photovoltaic array technology consists of high efficiency, multijunction cell technology on thick honeycomb panels and, as of late, lightweight blanket deployable systems. A current solution for high-radiation intensity involves adding thick cover glass to the cells, which increases the overall system mass.

Significant improvements in overall performance are needed to address the current gaps between the SOA and many mission requirements for photovoltaic cell efficiency >30%, array mass specific power >200 W/kg, decreased stowed volume, long-term operation in radiation environments, high-power and high voltage arrays, and a wide range of environmental operating conditions.

Civil Space Shortfall Ranking: https://www.nasa.gov/spacetechpriorities/

- 709 - Nuclear Electric Propulsion for Human Missions
- 1597 - Power for Non-Solar Illuminated Small Systems
- 610 - Solar Electric Propulsion
- 1430 - Small Spacecraft Propulsion
- 611 - Sub-kW and kW Class Electric Propulsion Systems

Relevance / Science Traceability:

This scope directly addresses the high priority STMD Shortfalls (https://www.nasa.gov/spacetechpriorities/) as follows:

- #610 - Solar Electric Propulsion - High Specific Impulse
- #1430 - Small Spacecraft Propulsion

References:

1. Brophy, John, et al. Non-Nuclear Exploration of the Solar System Study. Tech. rep., WM Keck Institute for Space Studies, Pasadena, California, 2022. doi: 10.7907/h62p-6328, 2022.
2. Shearer, C. K., et al. "Results of the lunar exploration analysis group (LEAG) gap review: Specific action team (SAT), examination of strategic knowledge gaps (SKGs) for human exploration of the moon." 2016 Annual Meeting of the Lunar Exploration Analysis Group (# LEAG16). No. JSC-CN-37602. 2016.
3. Cohen, Barbara A. "Lunar Mission Priorities for the Decade 2023-2033." (2020).
4. Kirmani, Ahmad R., et al. "Countdown to perovskite space launch: Guidelines to performing relevant radiation-hardness experiments." Joule 6.5 (2022): 1015-1031.
5. McMillon-Brown, Lyndsey, Joseph M. Luther, and Timothy J. Peshek. "What would it take to manufacture perovskite solar cells in space?." (2022): 1040-1042.

Scope Title: Advanced Thermal Transport Technologies for Space Missions

Scope Description:

NASA is seeking the development of thermal transport systems for space applications which require the transfer of large amounts of thermal energy from a nuclear reactor to a Stirling or Brayton cycle power conversion system, and transport to a high temperature radiator. The resultant thermal management systems may support multi-kilowatt class fission power systems for Fission Surface Power (FSP) or future hundreds of kW to MW-scale Nuclear Electric Propulsion (NEP) Systems.

The goals of this subtopic scope are derived from the STMD Technology Maturation Plan for LIVE: Thermal Management Systems and GO: Space Nuclear Propulsion. The ultimate goal is to advance the state of the art in high temperature heat transport and radiator systems in the areas of reduced weight, increased heat transport capability, higher temperature capability, robustness to anticipated environments and reliability.

Proposals may address one, multiple, or all of the following sub-systems of interest. Technology advancement of specific subcomponents being sought in this solicitation include:

Heat Rejection: Radiators

- 500 to 600 K heat rejection temperature
- Targeting < 3 kg/m2 double-sided areal density and < 1 kg/kW specific heat rejection
  - < 6 kg/m2 considering total deployment assembly mass
  - Deployable panels with ≥ 1 m2 per panel
- Scalable and/or modular in a way to support the total heat load required for the target FSP/NEP application.

Power Conversion System (PCS) Heat Transport

- Reactor to the power conversion system.
  - Heat must be transported from the reactor to the hot side of the power conversion system.
  - The target heat flux that the heat transport subsystem must accept from the reactor is dependent on the number of convertors planned for a system design, where two to four convertors are anticipated at a conversion efficiency of 25 to 30%. The target supply temperature is 1,000 to 1,400 K.
  - System thermal interfaces optimized to result in a system temperature drop of no more than 150 K from the reactor interface to power conversion working fluid.
  - The target distance for the PCS is 5 m from the reactor, but transport distances up to 10 m may be required. There is a special interest in heat pipe designs.
- Power Conversion System to Radiators
  - Heat must be rejected from the power conversion system and transported to the radiators at a target temperature range of 400 to 600 K. There is a special interest in maturing high performance, robust, long-life designs.
  - This may be an integral solution with the radiators, e.g., pumped-loop radiators.
- Advanced Heat Exchangers at power conversation system interfaces are also desired.

Possible environmental challenges among these components include:

- Dust-tolerance
- Gamma and neutron-radiation tolerance
- Design life of 8 to 15 years
- Solutions must address coefficient of thermal expansion (CTE) mismatch at interfaces, if applicable

- For surface missions, designed for Lunar missions with Mars extensibility, capable of day and night operation, robust deployment mechanism
- Solutions should be single-fault tolerant
- While small scale demonstrations in the SBIR proposal stage are acceptable, solutions should show a feasible path for scalability to multiple kW scale for FSP systems and MW scale for NEP systems

Proposals that include a hardware demonstration in Phase I or Phase II are highly desired. While these hardware demonstrations need not be at the scale or exact requirements described in the solicitation goals, the prototypes should be clearly relevant to and demonstrate scalability to the application goals.

Example solutions include, but are not limited to, liquid metal heat pipes, pumped fluid loops, heat exchangers, lightweight high temperature space radiators, and stable radiator optical coatings. Special consideration should be given to interfaces (at the reactor, power conversion system, or radiator) to maximize heat transfer. Integration with the reactor may include solutions that run through the reactor core. For integration with the power conversion system, a helium-xenon working fluid in a Brayton cycle system may be assumed but is not required.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:

- Level 1: TX 14 Thermal Management Systems
- Level 2: TX 14.2 Thermal Control Components and Systems

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware
- Analysis
- Software

Desired Deliverables Description:

Phase I awards in this area are expected to demonstrate analytical and/or empirical proof-of-concept results that demonstrate the ability of the organization to meet the goals stated in the solicitation.

At the conclusion of a Phase II contract, deliverables are expected to include a functioning prototype (or better) that demonstrates the potential to meet the performance goals of the technology or software. Any delivered math models should include supporting data that validate the assumptions used within the model.

State of the Art and Critical Gaps:

This scope strives to reduce mass, volume, and power of a thermal control system in the next generation of robotic and human-class spacecraft and to enable long-term missions to the Moon. The current state of the art in thermal control systems is vehicle power and mass impact of greater than 25 to 30% due to old technologies still in use. Furthermore, as missions become more variable (dormancy, environments, etc.), the need for intelligent design and control (both actively and passively) within the thermal control system becomes more apparent. Namely, the need to provide variable heat rejection through the complex lunar temperature profile has provided the opportunity from any novel heat rejection system technologies to be developed and evaluated. However, among the most significant challenges associated with modulating radiator efforts is the ability to provide the desired optical properties in the solar spectra while achieving the desired IR transmission for tunable products. An engineerable solar reflective coating with high transmission in the IR spectra is expected to address this gap while also providing a general tool capability to tune solar and IR properties of static coatings. This scope also acknowledges the need to improve system robustness while minimizing impact to other systems.

Civil Space Shortfall Ranking: https://www.nasa.gov/spacetechpriorities/

- 1619: High Temperature Heat Rejection for Nuclear Applications
- 709: Nuclear Electric Propulsion for Human Exploration

Relevance / Science Traceability:

This technology directly aligns with the STMD roadmap for space power and energy storage. Sustainable Living and Working Farther from Earth is a major NASA Strategic Capability need and part of this is the development of thermal management technologies that enable surviving the extreme lunar and Mars environments.

The NASA missions that would benefit from advancements in thermal transport technologies include:

- Deep space habitats and crewed vehicles (Moon, Mars, etc.) i.e., Orion, Gateway, Human Landing System (HLS)
- Mars transit vehicles
- SmallSats/CubeSats
- Rovers and surface mobility

References:

1. Stephan, R. Overview of the Altair Lunar Lander Thermal Control System Design, and the Impacts of Global Access. AIAA 2011-5001. 2011.
2. Ewert, M.K. Investigation of Lunar Base Thermal Control System Options. SAE Transactions. J. of Aerospace.102(1). 829-840. 1993.
3. Kauder, L. Spacecraft Thermal Control Coatings References. NASA/TP-2005-212792. 2005.
4. Dudon, J.P., et al. Development of Variable Emissivity Coatings for Thermal Radiator. ICES-2021-063. 50thInternational Conference on Environmental Systems. July 2021.
5. Wetch, J.R., et al. Megawatt Class Nuclear Space Power Systems (MCNSPS) Conceptual Design and Evaluation Report, Volumes I-IV. NASA-CR-179614. September 1988.
6. General Atomics Project 3450. Thermionic Fuel Element Performance Final Test Report, TFE Verification Program. GA-A21596 (UC-224). Prepared under Contract DE-AC03-86SF16298. Department of Energy. 1994.
7. Ashcroft, J. and Eshelman, C. Summary of NR Program Prometheus Efforts. LM-05K188. 2006.
8. Aerojet. SNAP-8 Performance Potential Study, Final Report. NASA-CR-72254. 1967.
9. Horner-Richardson, K., et al. Fabrication and Testing of Thermionic Heat Pipe Modules for Space Nuclear Power Systems. 27th IECEC, San Diego, CA. Paper Number 929075. 1992.
10. Ernst, D.M. and Eastman, G.Y. High Temperature Heat Pipe Technology at Thermacore – An Overview. AIAA-85-0981. 1985.
11. Voss, S.S. and Rodriguez, E.A. Russian System Test Program (1970-1989). American Institute of Physics Conference Paper 94-0101. 1994.
12. Stone, J.R. Alkali Metal Rankine Cycle Boiler Technology Challenges and Some Potential Solutions for Space Nuclear Power and Propulsion Applications. NASA-TM-106593. July 1994.
13. Demuth, S.F. SP 100 Space Reactor Design. Progress in Nuclear Energy. 42(3). 2003.
14. Ashcroft, J. and Eshelman, C. Summary of NR Program Prometheus Efforts. LM-05K188. 2006.
15. Davis, J.E. Design and Fabrication of the Brayton Rotating Unit. NASA-CR-1870. March 1972.
16. Richardson-Hartenstein, K., et al. Fabrication and Testing of Thermionic Heat Pipe Modules for Space Nuclear Power Systems. 27th IECEC, Paper Number 929075. 1992.

Z-ENABLE.02: High-Performance Space Computing Technology (SBIR) (Previously Z2.02)

Lead Center: JPL
Participating Center(s): GSFC, JSC

Subtopic Introduction:

In order to meet the foreseeable needs of future NASA missions, it is apparent that an evolution in general-purpose computing is required from the current state of the art used in space applications. A 100X increase in computational capability for the same power utilization of current space-based processors is envisioned for the next generation of computation capability. Potential use cases include crewed exploration missions in cislunar and Mars environments, robotic science missions destined to outer planets, and science observatories in Earth orbit. The qualities that NASA needs that might not naturally be provided by commercially available solutions are:

- Radiation tolerance
- Fault tolerance
- Mechanical robustness
- Energy management combined with scalable power efficiency

Scope Title: Coprocessors for Digital Signal Processing (DSP) and Artificial Intelligence (AI)

Scope Description:

Create a proof-of-concept (POC) end-to-end software/firmware/hardware demonstration using an open-source framework (like OpenCL) to enable heterogeneous compute offload for space-grade Reduced Instruction Set Computer-V (RISC-V) processors. Coprocessors to (a) accelerate onboard AI applications, (b) perform DSP functions, or (c) computer vision functions. Specifically, technologies are sought that either enable the reliable use of commercial off-the-shelf (COTS) coprocessors in space systems, or fault-tolerant design intellectual property (IP) cores that can be implemented in a radiation-hardened field programmable gate array (FPGA). Co-processors may include Processing in Memory (PIM) memory modules and Processing Near Memory (PNM) or Processing Using Memory (PUM) variants. Preferred processor interface is Compute Express Link (CXL) or, alternatively, Peripheral Component Interconnect Express (PCIe).

Expected TRL or TRL Range at completion of the Project: 1 to 4

Primary Technology Taxonomy:

- Level 1: TX 02 Flight Computing and Avionics
- Level 2: TX 02.1 Avionics Component Technologies

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Phase I Deliverables:

For software and hardware elements, a solid conceptual design, plan for full-scale prototyping, and simulations, testing, and benchmarking results to justify prototyping approach. Detailed specifications for intended Phase II deliverables.

Phase II Deliverables:

For software and hardware elements, a prototype that demonstrates sufficient performance and capability and is ready for future development and commercialization.

State of the Art and Critical Gaps:

Commercial coprocessor/accelerator devices and design IP are continuously being developed to support heterogeneous computing systems for use in self-driving cars, data centers, and modern smartphones. State-of-the-art heterogeneous computing systems use field programmable gate arrays (FPGAs), graphics processing units (GPUs), tensor processing units (TPUs), and neuromorphic processors, and Processing in Memory (PIM) as accelerators to offload specialized tasks like machine learning or image processing. Accelerator programming models include a variety of different programming models, such as OpenCL, Compute Unified Device Architecture (CUDA), and TensorFlow. These programming models make it easier to develop and deploy applications for accelerators in heterogeneous computing systems. General programming models for PIM systems are yet to be developed and are specific to the implementation. Critical technology gaps include:

- Performance - Existing space-grade coprocessor/accelerator devices are not yet powerful enough to meet the performance requirements of NASA's next-generation systems for future missions. Next-generation autonomous systems need to be able to process a large amount of sensor data in real time to make safe decisions.
- Energy Efficiency - Existing accelerator devices are not yet efficient enough to meet NASA's power and thermal constraints. Next-generation systems need to be able to operate under solar-array-with-a-battery power constraints (no radioisotope thermoelectric generators (RTGs)).
- Scalability/Versatility - Existing accelerator devices are often designed for specific workloads, such as machine learning or image processing. Next-generation autonomous systems need to be used for a variety of different workloads, such as perception, planning, and control. These needs will be mission specific.
- Resilience - NASA systems need to self-heal due to harsh environmental conditions. Commercial accelerator devices can be leveraged, but a redundant system design with health monitoring is needed.

Civil Space Shortfall Ranking https://www.nasa.gov/spacetechpriorities/

- 1554: High Performance Onboard Computing to Enable Increasingly Complex Operations
- 1555: Next Generation Avionics Architectures

Relevance / Science Traceability:

The high-performance spaceflight computing (HPSC) ecosystem is enhancing to most major programs in the Exploration Systems Development Mission Directorate (ESDMD) and the Space Operations Mission Directorate (SOMD). It is also enabling for key Space Technology Mission Directorate (STMD) technologies that are needed by ESDMD-SOMD. Within the Science Mission Directorate (SMD), strong mission pull exists to enable onboard autonomy across Earth science, astrophysics, heliophysics, and planetary science missions. There is also relevance to other high-bandwidth processing applications within SMD, including adaptive optics for astrophysics missions and science data reduction for hyperspectral Earth science missions.

References:

Possible existing open-source projects for consideration, in order of relevance:

1. nVDLA: http://nvdla.org. Open-source deep learning accelerator successfully implemented in FPGAs (Xilinx). See also https://github.com/nvdla/hw
2. nVDLA on RISC/V - SiFive sponsored work. Details in this codebase: https://github.com/CSL-KU/firesim-nvdla
3. Miaow: https://github.com/VerticalResearchGroup/miaow. Open-source GPU.
4. FlexGrip: https://github.com/Jerc007/Open-GPGPU-FlexGrip-. Open-source GPU from the University of Turin and U MASS. See also http://www.ecs.umass.edu/ece/tessier/andryc-fpt13.pdf
5. VeriGPU: https://github.com/hughperkins/VeriGPU. Open source - Amateur project with plans to use SYCL.

Alternately, license a GPU, TPU (tensor processing unit), or DSP core from a vendor and prototype it in the FPGA:

1. https://www.design-reuse.com/sip/?q=GPU
2. https://www.xilinx.com/products/technology/dsp.html
3. https://www.microsemi.com/product-directory/technology/1742-dsp

Experience of Qualcomm enabling code generation for their Hexagon DSP with LLVM:

1. https://www.llvm.org/devmtg/2011-11/Simpson_PortingLLVMToADSP.pdf

Companies producing PIM memory modules and processors

1. https://gsitechnology.com/hpc-overview/
2. https://semiconductor.samsung.com/us/solutions/technology/pim/
3. https://news.skhynix.com/sk-hynix-develops-pim-next-generation-ai-accelerator/
4. https://www.upmem.com/

Other PIM references

1. https://events.safari.ethz.ch/real-pim-tutorial/lib/exe/fetch.php?media=realpimtutorial-hpca23-processingnearmemory-juan-slides.pd
2. https://arxiv.org/abs/2012.03112
3. https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=9567191

Scope Title: Reduced Instruction Set Computer-V (RISC-V) Software Tools

Scope Description:

NASA is seeking software enhancements that would enable leading application programming interfaces (APIs) and operating systems to maximize the capabilities of emerging multicore RISC-V architectures. Specific areas of interest are:

- Verification and Validation tools for Interference Analysis in multi-core safety-critical applications.
- Graphics processing unit (GPU) computation (e.g., OpenCL, OpenCV on Nvidia).
- Enhancing AI/ML compliers (e.g., OpenXLA) with Safety-Critical features for resilience.
- Machine learning libraries (e.g., Dlib).
- Deterministic graphics (e.g., VulkanSC).

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:

- Level 1: TX 11 Software, Modeling, Simulation, and Information Processing
- Level 2: TX 11.1 Software Development, Engineering, and Integrity

Desired Deliverables of Phase I and Phase II:

- Software

Desired Deliverables Description:

Phase I Deliverables:

- Market research.
- Conceptual design.
- Use case analysis.
- Detailed plan for porting to RISC-V.
- Business case, including any plans for providing and supporting open-source.

Phase II Deliverables:

- Prototype software operating on representative RISC-V platform.

State of the Art and Critical Gaps:

The current state of the art (SOA) in RISC-V software tools for the specified domains (Interference Analysis, GPU Computation, AI/ML Compilers, Machine Learning) involves predominantly using proprietary architectures like x86 and ARM. These architectures have well-established ecosystems and support from major vendors and software developers.

- Multi-core interference analysis and mitigation: There is a need for innovative software tools for measuring, quantifying, and mitigating interference on multi-core processors and System-on-Chip (SoC) architectures with a specific focus on safety-critical applications. The goal is to enhance the reliability and predictability of multi-core RISC-V systems in space applications by addressing the challenges of inter-core, shared memory, and peripheral-induced interference.
- GPU Computation (e.g., OpenCL, OpenCV on Nvidia): GPU computation libraries like OpenCL and OpenCV are primarily designed for x86 and Nvidia GPUs. RISC-V support for such libraries is underdeveloped, resulting in limited access to GPU acceleration on RISC-V platforms.
- Enhancing AI/ML compilers with resilience techniques: Current compilers (e.g., OpenXLA) lack safety-critical features to be resilient to errors for critical space applications while leveraging the benefits of open-source ML compiler infrastructure.
- Machine learning libraries (e.g., Dlib): Machine learning libraries like Dlib are well-established on x86 and ARM, with hardware acceleration support from major GPU manufacturers. RISC-V lacks comprehensive support in this domain, hindering the development of machine learning applications on RISC-V platforms.
- Deterministic graphics (e.g., VulkanSC): At the SOA, graphics APIs like Vulkan have limited support for RISC-V architectures. Most graphics-intensive applications and games are optimized for x86 and ARM platforms, and RISC-V support is in its early stages.

Critical Gaps:

1. Lack of Optimization: The critical gap lies in the absence of optimized software and libraries for RISC-V architectures in these domains. Existing software is primarily tailored for x86 and ARM, resulting in suboptimal performance on RISC-V platforms.
2. Limited Ecosystem: RISC-V lacks a mature software ecosystem compared to x86 and ARM. This includes development tools, libraries, and a robust community of developers, which is crucial for rapid software development and adoption.
3. GPU Support: The absence of comprehensive GPU support for RISC-V hinders the acceleration of graphics and computation-intensive workloads, making RISC-V less attractive for applications that rely on GPU power.
4. Compatibility: Many existing applications and systems are not compatible with RISC-V, making it challenging for organizations to transition to RISC-V platforms without significant software redevelopment efforts.
5. Community Engagement: Building a vibrant open-source community around RISC-V software is essential but currently lacking. This gap affects collaborative development and support for RISC-V software projects.

Addressing these critical gaps is essential to unlock the full potential of RISC-V architectures in the specified domains, enabling their widespread adoption in various applications, including those relevant to NASA's needs. The proposed RISC-V software tool enhancements aim to bridge these gaps and make RISC-V a competitive choice for developers and organizations.

Civil Space Shortfall Ranking https://www.nasa.gov/spacetechpriorities/

- 1304: Robust, High-Progress-Rate, and Long-Distance Autonomous Surface Mobility
- 1531: Autonomous Guidance and Navigation for Deep Space Missions
- 1558: High-Rate Communications Across The Lunar Surface
- 1573: Terrain Mapping Capabilities for Precision Landing and Hazard Avoidance
- 1562: Advanced Algorithms and Computing for Precision Landing
- 1560: High-Rate Deep Space Communications
- 1438: Autonomy, Edge Computation, and Interoperable Networking for Small Spacecraft

Relevance / Science Traceability:

The Science Mission Directorate's (SMD's) missions involve collecting and analyzing vast amounts of scientific data from space, Earth, and beyond. Efficient data processing and computation are essential for achieving scientific objectives. Enhancing RISC-V software tools can be directly relevant to SMD by improving the computational capabilities of spacecraft and instruments, leading to more effective data analysis and scientific discoveries.

List of Missions, Programs, or Projects:

1. Astrophysics: Future astrophysics missions concepts require starlight nulling to allow imaging of exoplanets. These RISC-V software tools can enable the high-bandwidth processing needed for adaptive wavefront sensing and control approaches for starlight nulling.
2. Endurance: NASA's lunar rovers are equipped with advanced scientific instruments for exploring the Moon. Improved software tools can enhance the autonomy of these rovers, enabling more sophisticated data analysis and decision-making during missions.
3. Mass Change: Many Earth science instruments, including multispectral/hyperspectral imagers and synthetic aperture radars, gather high volumes of data. These RISC-V software tools can improve data processing efficiency, allowing onboard data classification and intelligent data compression to maximize science return and provide time-critical alerts to users.

Benefits for Identified Mission/Program/Project:

- Data Processing Efficiency: RISC-V software optimizations can significantly reduce the time required for data processing, allowing scientists to receive and analyze mission data more quickly.
- Enhanced Autonomy: Improved software can enhance the autonomy of spacecraft and rovers, enabling them to make real-time decisions based on scientific objectives and mission priorities.
- Reduced Computational Resource Demands: Efficient RISC-V software can reduce the computational resource demands on spacecraft, leading to reduced power consumption and increased mission longevity.

Potential Advocates to Contact:

When seeking advocates within NASA's Science Mission Directorate for this technology; consider reaching out to the following individuals or groups:

1. SMD Chief Scientist: The Chief Scientist of SMD can be a key advocate, as they have a deep understanding of the scientific priorities and data processing needs of SMD missions.
2. Mission Project Scientists/Principal Investigators: The scientists leading specific missions or projects can advocate for technology enhancements that directly impact their scientific objectives.
3. Mission Managers: Mission managers responsible for overseeing SMD missions can be supportive advocates for technology improvements that enhance mission efficiency and data quality.
4. SMD Technology and Data Systems Division: This division within SMD is responsible for managing technology investments. They can provide guidance on technology adoption and potential advocacy.
5. SMD Data Centers: SMD operates data centers that support various missions. Contacting the heads of these centers can lead to advocacy within the data management community.

Engaging with these advocates can help align RISC-V software enhancements with SMD's mission goals and priorities, ultimately benefiting NASA's scientific endeavors in space and Earth sciences.

References:

1. High-Performance Spaceflight Computing (HPSC) Processor: https://www.microchip.com/en-us/products/microprocessors/64-bit-mpus/pic64-hpsc
2. Rapita Systems: https://www.rapitasystems.com/products/mach178 , https://www.rapitasystems.com/services/multicore-timing
3. GPU Computation: https://opencv.org/
4. OpenXLA: https://openxla.org
5. Machine Learning: http://dlib.net/
6. VulkanSC: https://www.vulkan.org/

Z-ENABLE.03: Advanced In-Space Laser Welding and Nondestructive Evaluation (SBIR) (Previously Z4.05)

Lead Center: LaRC
Participating Center(s): GSFC, MSFC

Subtopic Introduction:

This subtopic has two scopes:

1. Inspection Methods for Condition Based Maintenance of Vehicles for Lunar Excavation
2. Space-Capable Laser Beam Welding Component and Subsystem Development

Nondestructive Evaluation (NDE):

- Lunar Transport Vehicles (LTV) will have to be able to handle the extreme conditions at the Moon's South Pole and will feature advanced technologies for power management, autonomous driving, and state of the art communications and navigation systems. Crews will use the LTV to explore, transport scientific equipment, and collect samples of the lunar surface, much farther than they could on foot, enabling increased science returns.
- Maintenance and remote inspection of these LTV's will be critical to keeping the lunar mission operational. Within this subtopic we will be developing technologies that can monitor the health of the vehicles and alert personnel or systems that inspection is required. Additionally within this subtopic we are developing technologies that will be able to remotely perform these direct inspections.

Laser Welding:

- In-space laser beam welding is a capability that once obtained, will enable off-planet construction of structures on scales orders of magnitude larger than what is possible with current launch payload-maximizing efforts today. Repair, servicing, reclamation, and recycling of existing structures, as well as incorporation of materials sourced from extra-planetary sources will also be enabled, realizing a paradigm shift in space operations, simultaneously increasing capability for science, exploration, and economic missions.
- However, while laser welding itself is a burgeoning terrestrial technology, there has been little in-space testing of laser welding needed to drive the development of the ruggedization, instrumentation, and operational methods necessary for implementing this technology in space. Innovative solutions and carefully considered studies are required to understand how components and sub-systems of laser welding can be prepared to survive and to operate in space environments. Despite the relevant lack of maturity for in-space laser welding, successful solution of these issues is technologically feasible at a relatively low cost to the larger projects and efforts which they would enable and provide significant cost savings for.

Scope Title: Inspection Methods for Condition Based Maintenance of Vehicles for Lunar Excavation

Scope Description:

Inspection methods for condition-based maintenance of vehicles for lunar excavation activities consists of two separate focus areas, both are addressed in this scope. It is suggested that to meet the requirements of a Phase I SBIR, one focus area should be addressed for final production. The two focus areas are structural health monitoring (SHM) and direct remote inspection (DRI).

SHM systems capable of operating in a lunar environment should be targeted. SHM systems should be low power and capable of detecting anomalous behavior of Lunar Vehicles. SHM systems should also be capable of producing a general location of the anomalous behavior for DRI. It is also highly desirable for the SHM system to be easily integrated into a lunar vehicle. SHM systems should also be able to provide varying levels of feedback on the health of the parent system. An example of this would be the system is healthy, the system is experiencing an issue but is operational, the system is in need of DRI, the system is critical.

DRI systems should be capable of inspecting a range of material systems that will be used for lunar vehicles and characterization of structural anomalies on a lunar vehicle. Direct characterization should include the ability to locate and size structural anomalies. Structural anomalies can include characterization of engineering properties, strain, stress, load verification, cracks, voids, inclusions, disbonds, delaminations, bonding, corrosion, erosion, constitutive components, volume fraction, orientation, impact damage, age, pressure, mass loss, mass gain, thinning, alignment, thermal diffusivity, emissivity, leaks, signature, and contamination. DRI system should have the ability during Phase II to be made to operate autonomously.

In support of autonomous inspection techniques that can dynamically and accurately determine position and orientation of the NDE sensor are needed to register NDE results to precise locations on the structure with little to no human intervention. Additionally advanced processing and displays are needed to reduce the complexity of operation and interpretation for astronaut crews who need to make important assessments quickly. 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.

Special attention should be made to address the effect of lunar regolith on mechanical structures. Lunar regolith is made up of rock chips, mineral fragments, impact and volcanic glasses and a peculiar component only found on the Moon called “agglutinates.” The ratio of these various components varies widely from one soil to the next [Ref. 1]. Most of the lunar vehicle concepts will be battery, fuel cell or solar powered, SHM and DRI systems that can help determine the health of these system will be highly encouraged. Many of these concepts can be found on the NASA website or in the historical Apollo Logistics Support systems report by Marshal Space Flight Center report [Ref. 2]. Additional consideration will be given to SHM/DRI systems that can determine damage from thermal cycling or impact damage.

It is also strongly encouraged that proposals provide an explanation of how the proposed techniques a can support integrated SHM and DRI. Additionally, techniques for quantitative analysis of sensor data are also desired.

Expected TRL or TRL Range at completion of the Project: 1 to 5

Primary Technology Taxonomy:

- Level 1: TX 12 Materials, Structures, Mechanical Systems, and Manufacturing
- Level 2: TX 12.1 Materials

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Phase I Deliverables:

- For proposals focusing on NDE and SHM sensors: Laboratory prototype and feasibility study or software package, including applicable data or observation of a measurable phenomenon on which the prototype will be built.
- All Phase I proposals will include a proposed approach to develop a given methodology to a TRL of 2 to 4. All Phase I proposals will include minimum of short description for Phase II prototype/software. It will be highly favorable to include a 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 TRL 5 to 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:

Currently there is no path for monitoring and inspection of lunar vehicles. These systems will be required to continually safely operate lunar vehicles. It is acceptable to address metallic components, but the current focus considers regolith inspections a higher priority. These gaps have been identified in the STMD Strategic Framework under Advanced Materials.

Civil Space Shortfall Ranking https://www.nasa.gov/spacetechpriorities/

- 1486: In-Space and On-Surface NDE and Qualification of Components for Manufacturing, Assembly, and Construction
- 1490: Additive Manufacturing for New and High Performance Materials
- 1537: Free-Flying Systems for Robotic Inspection, Data Collection, and Servicing of In-Space Assets
- 1487: In-Space and On-Surface Welding Technologies for Manufacturing, Assembly, and Construction

Relevance / Science Traceability:

Many of NASA's current programs involving spaceflight are looking to use lunar vechiles. These programs include, but are not limited to, Space Launch System, Artemis, and NASA Transformational Tools and Technologies (TTT). This also includes many NASA commercial crew partners. Developments in this critical area will support future operations in ISRU as well as advanced in-space manufacturing.

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Scope Title: Space-Capable Laser Beam Welding Component and Subsystem Development

Scope Description:

Many areas of interest exist that must be addressed before implementation of laser beam welding (LBW) in space can be realized. These include but are not limited to:

- Ruggedization of LBW system components, (e.g., power supply, diodes, gain fiber, delivery fiber, optics, wire feed, etc.) for space (or space analog) environments, including factors such as thermal vacuum, radiation, dust, micro-meteoroid and orbit debris, vibe/shock, etc.
- Development/hardening of in-situ instrumentation to support ground-based TVAC testing, such as in-line laser beam diagnostics, spectrometry, non-contact NDE, thermography, etc. in which the effectiveness of specific components and subsystems may be studied.
- Addressing and/or mitigating metal vaporization/plating onto optical components in vacuum; may include cleaning methods, design solutions, physical or electrical preventative measures, etc.
- The benchmark for successful improvement of a component or sub-subsystem shall be performance in a space analog environment comparable to that of existing systems designed and used in terrestrial applications. For improvement or implementation of in-situ instrumentation, reliable data collection should be possible over sufficient time lengths to prove out the performance criteria stated above.

Expected TRL or TRL Range at completion of the Project: 4 to 6

Primary Technology Taxonomy:

- Level 1: TX 12 Materials, Structures, Mechanical Systems, and Manufacturing
- Level 2: TX 12.4 Manufacturing

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

Phase I Deliverables:

- Testable ruggedized components, in-situ instrumentation, and/or protection of optics shall be proven out at least in a laboratory environment, ideally being tested in a relevant environment (e.g., TVAC).
- Phase I success would produce components ready to integrate into subsystems and advanced in TRL for Phase II.

Phase II Deliverables:

- Testable ruggedized subsystems, in-situ instrumentation prototypes, and/or protection of optics methods/subsystems shall be proven out in a relevant environment (e.g., TVAC).
- Phase II success would produce subsystems in a state ready for integration into a suborbital flight or other method of testing in a true space environment.

State of the Art and Critical Gaps:

Currently, there are no deployable or manufacturing technologies ready to emplace scalable Lunar infrastructure. A long-term Lunar base will be enabled by the assembly, joining, and repair of surface structures, such as the power/communication tower of STMD super gap 629 via an "autonomous robotic structure maintenance and repair system" (1411) that uses in-space welding (646).

ISAM is currently limited by joining and repair techniques. Mechanical fasteners & rivets have strength, reliability, hermiticity, and mass concerns; in-space welding alleviates these concerns and also enables repair [Ref. 1]. High-energy density welding has been explored for space applications as these processes are non-contact, have precise heat control leading to lower distortion & deleterious effects, and are readily automated [Ref. 2]. While electron beam welding (EBW) was demonstrated in space during Skylab in 1973, LBW has greatly advanced since it was first investigated for space use in the early 1990s and is now ripe for development for ISAM [Refs. 1-4]. Substantial advantages of LBW over EBW include: operation in atmosphere and vacuum as EBW only operates in vacuum; adaptability to more processes, geometries, and materials through control over output power and beam rasterization; easier integration onto robotic fixtures with in situ inspection equipment due to reduced electromagnetic interference (EMI); and separation of the power and heat source via a low efficiency loss optical fiber rather than a copper wire. While LBW still has higher power requirements and lower energy efficiency compared to EBW, the gap has been greatly ameliorated in recent years to make LBW viable; the versatility of LBW makes it ideal for further development now that it is technically feasible in space [Refs. 2-3]. LBW is also extensible to additional ISAM techniques such as bending/forming, cleaning, cutting, drilling, and even additive manufacturing.

Beyond thermal vacuum and microgravity ruggedization of laser welding equipment, there is a need to understand and mitigate the combined effects of space radiation, thermal cycling, atomic oxygen, MMOD, and vacuum on such equipment. For instance, the rare earth-doped optical gain fibers of fiber lasers have been shown already to be susceptible to thermo-mechanical damage and space environmental effects simulated on Earth, such as assessments of gamma and neutron radiation [Ref. 5]. Previous on-orbit exposures have largely focused on low-power, undoped optical delivery fibers for communications and the like [Refs. 6-7]. Experiments have not been performed that assess simultaneous damage of combined space effects of temperature and the space environment on high-power laser welding components such as doped optical gain fibers. It is imperative that space environmental effects are evaluated and mitigated through ruggedization or otherwise so that laser welding systems have robust performance for deployment during in-space manufacturing and assembly operations under expected in-space environmental conditions.

Civil Space Shortfall Ranking https://www.nasa.gov/spacetechpriorities/

- 1486: In-Space and On-Surface NDE and Qualification of Components for Manufacturing, Assembly, and Construction
- 1490: Additive Manufacturing for New and High Performance Materials
- 1537: Free-Flying Systems for Robotic Inspection, Data Collection, and Servicing of In-Space Assets
- 1487: In-Space and On-Surface Welding Technologies for Manufacturing, Assembly, and Construction

Relevance / Science Traceability:

This technology would potentially benefit any craft or payload that must be launched from a gravity well, including existing craft and payloads whose life could be extended by servicing and repair. Internal MSFC TIP (Technology Investment Program) funds supported in-space laser welding for FY23 and FY24. STMD Flight Opportunities, Biological & Physical Sciences, and SNP program funded a parabolic flight test of laser beam welding. There is the upcoming LASAR FY25 start ECI (STMD HQ funded) for thermal vacuum-rated laser welding. NASA/MSFC recently partnered with the DARPA NOM4D program on laser forming, which has substantial synergy with laser welding. To mature beyond benchmark cases during flight experiments and infuse into NASA's Lunar exploration plans, laser welding equipment must be ruggedized to survive and to operate in the harsh environments of space such as the Lunar surface.

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Z-ENABLE.04: Robotic Hardware for In-Space Manipulation (SBIR) (Previously Z5.09)

Related Subtopic Pointers: S13.01
Lead Center: JSC
Participating Center(s): ARC, GSFC, JPL

Subtopic Introduction:

The growth of commercial operations, whether in Earth orbit, in cislunar space, or on the lunar surface, is contingent upon affordable, readily available robotic assets capable of projecting robust manipulation capability into these challenging environments. The objectives of maximizing science return and establishing a sustainable exploration infrastructure, highlighted in NASA's Moon-to-Mars objectives, are directly impacted by the availability of robust, capable robotic manipulation. In-space servicing and assembly, the outfitting of lunar surface infrastructure, and science sample collection in extreme environmental conditions are just a few of the many example applications enabled by robotic manipulators. The commercial availability, cost-effectiveness, environmental survivability, and performance capability of existing flight-worthy robotic manipulation hardware is limited, however, and novel advancements in these areas will significantly impact the degree to which robotics can be leveraged by NASA and commercial entities in future space operations.

To foster the expansion of U.S. industry and innovation beyond Earth orbit and establish long-term sustainability of deep space and lunar operations, as outlined in the foundational recurring tenets of the Agency's Moon-to-Mars Objectives, novel advancements in manipulator dexterity, strength-to-weight performance, power efficiency, robustness, and sensing are needed. Additionally, cost must be driven down, and innovation is needed to translate current successes in the terrestrial marketplace to the challenging constraints of spaceflight application.

This subtopic seeks to encourage new approaches and novel design adaptations to in-space robotic manipulation to enable the broad set of tasks required in remote deep space and lunar surface settings.

Scope Title: End Effectors for Manipulation Task Performance

Scope Description:

Establishing a sustainable exploration infrastructure (on the lunar surface, in lunar orbit, in cislunar space, and on to Mars) requires extensive robotic operations. Much of this work will be performed during uncrewed periods, highlighting the need for broader manipulation capabilities to perform a wider range of autonomous tasks, many of which would typically be reserved for human hands or handheld tools terrestrially. Initial deployment, assembly, and outfitting of lunar surface infrastructure will need to be done robotically, as will maintenance, logistics management, and sustained utilization of equipment, instruments, and experiments (both internal and external to vehicles and habitats). The ability to interact with tools, interfaces, and components not expressly designed for robotic manipulation is highly desirable, as this expands the range of design solutions that mission planners, architects, and the science community can adopt for their space systems.

Robotic hardware robust to the space environment yet still capable of human-scale, unrehearsed, unstructured tasks must be developed to enable operation with limited human oversight & intervention. Novel end-effector designs with improved dexterity, versatility, and overall task performance in the space environment are specifically sought for a range of intravehicular, lunar surface, and in-space servicing tasks, including:

- Logistics management (e.g., payload handling; packing/unpacking bags; kitting items).
- Assembly, maintenance, and outfitting (e.g., mating/demating power, data, and fluid connections; opening/closing panels; installation, stowage, and handling of cables and fluid lines; manipulation of softgoods).
- Science utilization (e.g., moving samples between cold storage and instruments; experiment monitoring and caretaking; small tool use; manipulation of buttons, switches, levers, etc.).
- Habitat mobility (e.g., hatch opening/closing; handrail and seat track grasping).
- Sample collection (particularly cold samples in cryogenic conditions).

Technology areas of interest include, but are not limited to:

- Robust fine dexterity for human-hand-like tasks and tool/interface manipulation.
- Multipurpose and adaptable grasping.
- Modularity.
- Lightweight, low-volume, and/or low-power actuation solutions.
- Novel strength-to-weight or force/torque density improvements.
- End effectors suitable for environmental extremes (e.g., long-duration use in permanently shadowed lunar regions, cryo-sample interaction).
- Compact integrated sensing approaches (improving, for example, tactile sensitivity or controllability).

All technologies must provide a demonstrable advance over current state-of-the-art solutions and present a viable path toward use in intravehicular or extravehicular space applications. Dual-use technologies with broad applicability to both space and terrestrial applications are encouraged, as are both system-level and component-level technology proposals, but a clear infusion path to NASA mission applications must be demonstrated.

To facilitate infusion, proposals are encouraged, but not required, to:

- Use industry-standard hardware and software interfaces, architectures, and frameworks that align with relevant NASA robotic development efforts to reduce future integration effort (e.g., Robot Operating System (ROS)/ROS2/SpaceROS).
- Limit dependence on third-party proprietary technologies that might complicate NASA adoption of the technology.
- Target near-term integration and testing on relevant NASA robots (e.g., NASA JSC iMETRO or ISS Astrobee) and/or flight manipulators, with existing spaceflight interfaces, or in coordination with ongoing spaceflight development efforts (Government or commercial).
- Demonstrate technology advances in the context of relevant manipulation or utilization task performance.
- Trace proposal relevance to high-priority shortfalls from the NASA STMD National Space Technology Priority shortfall list.

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:

- Level 1: TX 04 Robotics Systems
- Level 2: TX 04.3 Manipulation

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

Phase I deliverables include:

- Background research and feasibility studies.
- Conceptual design, trade studies, and description of proposed solution.
- Initial concept of operation and demonstrated progress toward a significant improvement over state-of-the-art robotic solutions, rather than just an incremental enhancement.

Phase II deliverables include:

- Hardware prototype with supporting software, design information, and documentation.
- Test and/or performance data.
- Demonstration of robot hardware performing a relevant task.

State of the Art and Critical Gaps:

State-of-the-art robotic end effectors are found in terrestrial-industry-targeted applications (e.g., factory floor manipulation), early-TRL dexterous robots, and new advanced prosthetic devices. Each suffers shortcomings that, to date, have limited infusion into spaceflight applications. Industrial manipulators typically rely on end effectors that have limited dexterity and less integrated sensing, or grippers that are purpose-built for specific structured tasks. More complex dexterous robotic hands have, in theory, greater versatility but are also less robust and more sensitive to environmental extremes. Achieving high force/torque capability and adequate sensing in a compact volume for these high-degree-of-freedom systems is also difficult. A new generation of prosthetic robotic hands offers promise, but force range and sensing are still limited, as is the suitability of these designs to the challenging space environment and more rigorous use cases.

Existing flight systems are limited in dexterity and significantly larger than fine manipulation tasks require. Transitioning terrestrial advances to challenging spaceflight applications is needed. Critical gaps exist in the demonstrated performance of key use cases, particularly fine manipulation tasks such as mating/demating connectors designed for human-hand manipulation, and low size and mass solutions are needed that can nevertheless withstand human-scale forces and offer long operational life.

Civil Space Shortfall Ranking https://www.nasa.gov/spacetechpriorities/

- 1545: Robotic Actuation, Subsystem Components, and System Architectures for Long-Duration and Extreme Environment Operation
- 1546: Robotic Mobile Manipulation for Autonomous Large-Scale Logistics, Payload Handling, and Surface Transport
- 1538: General-Purpose Robotic Manipulation to Perform Human-Scale Logistics, Maintenance, Outfitting, and Utilization

Relevance / Science Traceability:

This scope represents an enabling technology for remote robotic manipulation on the lunar surface in support of infrastructure outfitting and asset utilization and maintenance. Intravehicular robot (IVR) operations on Gateway and other future vehicles/habitats require improved manipulation for science utilization, logistics management, payload handling, etc., and in-space servicing and assembly activities across NASA and commercial mission portfolios are significantly expanded by more capable flight-worthy robotic end effectors.

Manipulation leveraging the novel hardware technologies targeted directly supports NASA's Moon-to-Mars objectives to: "(LI-4) Demonstrate technologies supporting cislunar orbital/surface depots … and support systems needed for continuous human/robotic presence," and "(OP-9) Demonstrate the capability of integrated robotic systems to support and augment the work of crewmembers on the lunar surface, and in orbit around the Moon."

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Scope Title: Efficient Production of Space Robotic Manipulators and Related Actuation Components

Scope Description:

Currently, flight robotic arms and their drive electronics are bespoke systems carefully designed for custom applications with significant emphasis on mass efficiency and life. The robotic arms also undergo detailed sensitivity analyses, characterization, calibration, and testing over a large range of joint positions and load conditions at both the system and individual actuator level. The overall cost of these systems reflects the uniqueness of each arm. Similarly, motor controllers and other drive electronics needed for the robot arm are typically customized and tuned for specific robot characteristics. The need for high reliability over years of performance life in the challenging environmental conditions of space drive this level of rigor (and its associated cost), but the availability and selection of space-qualified robotic manipulators is highly limited as a result.

Conversely, mass-produced, standard components with specific, short-duration applications typically have a lower cost than bespoke systems. Recent progress in terrestrial robotic actuators, for example, has led to cost-effective, high-performance integrated robotic actuator modules used across academia and industry (e.g., the Massachusetts Institute of Technology (MIT) Cheetah robot actuators and similar drives in other commercially available quadrupeds). Fully integrated collaborative robot manipulators are ubiquitous in academic labs and commercial robotic applications. Availability of comparable spaceflight manipulators, by comparison, is significantly limited, with few vendors (and even fewer domestic suppliers), few flight-proven solutions, and much higher costs.

The goal of this scope is to characterize and subsequently validate opportunities for cost saving, time saving and other efficiency improvements to providing robotic manipulators and constituent actuation components for space applications; to present novel design approaches to robotic manipulators suitable for in-space use; and, in so doing, to broaden the availability and reduce the cost of capable flight robotic manipulators. Cost, manufacturability, and overall availability in the marketplace would ideally not come at the cost of performance in spaceflight use cases, however. In fact, achieving new levels of manipulator performance is a driving need. Specifically, the overall manipulator performance needs to be considered for sustainable lunar surface infrastructure construction outfitting, utilization, and maintenance; the manipulation of in-space assets during deep space servicing and assembly; and accomplishing challenging science objectives on the Moon, Mars, and distant destinations throughout the solar system. This performance, though, must be achieved hand-in-hand with attainable cost and multi-mission versatility to effectively expand commercial activities beyond Earth orbit and deploy robotic capabilities at greater scale across NASA's entire mission portfolio.

Technology areas of interest include, but are not limited to:

- Novel adaptation or translation of terrestrial robot manipulators, actuation modules, or other subsystem components for robust use in relevant space environments (e.g., lunar surface, cislunar space, Earth orbit).
- Efficient space qualification of power-dense actuation, motor drive and control electronics.
- Unique design improvements to drive down the cost of previous flight-proven or flight-targeted manipulators.
- Unique design improvements to increase flight manipulator performance without increased cost.
- Expanding the use-case environments of existing manipulators (e.g., novel adaptation of Earth-orbit manipulators for use in lunar surface permanently shadowed regions).
- Novel robot arm design that achieves cost-effective multi-mission versatility.
- Cost-effective approaches to robustness, reliability, and fault tolerance.

Specific applications of interest include:

- Lunar surface manipulation, including: infrastructure assembly, maintenance, and repair; excavation, construction, and outfitting; and logistics management and equipment utilization.
- Robust, large-scale robotic manipulation of equipment, interfaces, and items in the surrounding environment.
- Robotic payload offloading, relocation, and precision placement.
- Cold-temperature sample collection and curation.

Parameters typically used in robotic arm acquisition, such as precision, accuracy, configuration, overall mass allocation, margins, etc., are expected to be treated as free variables in the interest of bringing down overall cost or introducing novel capabilities. Production lot sizes should be assumed small (e.g., 1, 10, or 25 units) in any cost analysis to reasonably project infusion potential. And while target arm length and degrees of freedom are not specified, dexterous manipulation at the 1- to 2.5-m scale is expected to have the most immediate impact on operational scenarios. Additional capabilities are necessary for large scale robotic manipulation listed above.

Dual-use technologies with broad applicability to both space and terrestrial applications are encouraged, but all technologies must provide a viable path to flight use and demonstrate advances that will lead to likely mission infusion and adoption by NASA and/or the broader commercial space community.

Expected TRL or TRL Range at completion of the Project: 2 to 6

Primary Technology Taxonomy:

- Level 1: TX 04 Robotics Systems
- Level 2: TX 04.3 Manipulation

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

Phase I deliverables include:

- Background research and feasibility studies.
- Modeling to demonstrate feasibility.
- Conceptual design, trade studies, and description of proposed solution.
- Concept for low-cost flight demonstration.

Phase II deliverables include:

- Validation of concept and cost range.
- Prototyping with viable path toward production.

State of the Art and Critical Gaps:

Agile space missions for emerging new space use cases are likely to require low-cost robotic arms that fit within the budget ranges of Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA)-based or SmallSat-based missions. The current costs and other factors driven by reusability, reconfigurability, commonality, supply chain, and certifiability associated with space robotic manipulators are unfavorable for easy adoption of robotics in such mission classes. Industrial applications, however, are seeing increased adoption of robotic manipulation and widespread growth in cost-effective collaborative robots for human-scale tasks. A general heuristic used for early-stage cost modeling is that a 1-degree-of-freedom actuator subsystem costs on the order of a million dollars for a class-B type mission. There is very little data, and very few models, to characterize cost of robotic arms designed for use cases described in this topic. The translation of similar capabilities to flight-use cases is needed.

Further, current practice does not typically include standardization of components or even joints across specific arms or manipulator product lines, and very few standard products are available for use in space robotic manipulation. Low-cost, high-reliability robotic manipulators with performance capabilities suitable for the challenging use cases of sustained lunar presence and reuse across cislunar operations are needed.

Civil Space Shortfall Ranking https://www.nasa.gov/spacetechpriorities/

- 1545: Robotic Actuation, Subsystem Components, and System Architectures for Long-Duration and Extreme Environment Operation
- 1546: Robotic Mobile Manipulation for Autonomous Large-Scale Logistics, Payload Handling, and Surface Transport
- 1538: General-Purpose Robotic Manipulation to Perform Human-Scale Logistics, Maintenance, Outfitting, and Utilization

Relevance / Science Traceability:

Infusion of robotic in-space servicing, assembly, and manufacturing (ISAM) missions or demonstrations for science, commerce, exploration, and national interest are challenging due to the high cost of overall systems and related logistics. Ability to fly low-cost, short-duration missions and demonstrations would lower the threshold for access to space and encourage infusion of ISAM.

Current programmatic and architectural decisions are often driven by cost constraints, putting the integration of needed robotic capability at risk and potentially sacrificing long-term success toward Moon-to-Mars objectives.

References:

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2. Ingenuity: https://www.jpl.nasa.gov/news/press_kits/ingenuity/landing/mission/spacecraft/
3. NASA's Plans for Commercial LEO Development: https://ieeexplore.ieee.org/document/9172512
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6. Automated Multi-Agent Assembly System (ARMADAS): https://www.nasa.gov/general/robot-team-builds-high-performance-digital-structure-for-nasa/
7. NASA STMD National Space Technology Priority Shortfall List https://www.spacetechpriorities.org/

Scope Title: Sensors for Robotic Manipulation

Scope Description:

Autonomous robotic manipulation is contingent on a robot's ability to safely sense and interact with equipment, interfaces, and natural features in the environment. Supervisory control, and remote operations more generally, are enabled by rich sensor feedback that relays situational awareness to remote operators. Robust sensing is a challenge in robotics, and even more so in the harsh space environment. This scope aims to improve sensor hardware and the integration of sensors into robotic manipulators for the difficult tasks required on the lunar surface, in cislunar space, and in the rapidly expanding marketplace of Earth orbit.

All new sensor technology should address envisioned robustness to radiation, temperature extremes, and other environmental factors relevant to the targeted space application. Space-qualified, environmentally tested, or otherwise environmentally robust sensor systems applicable to use in lunar and cislunar environments are desired in addition to improvements in sensor performance or novel sensing methodologies.

Dual-use technologies with broad applicability to both space and terrestrial applications are encouraged, but new sensor development should have a clear path to flight readiness and targeted spaceflight use cases.

To facilitate infusion, proposals are encouraged, but not required, to:

- Use industry-standard interfaces (hardware and software) to reduce future integration effort.
- Limit dependence on third-party proprietary technologies that might complicate NASA adoption of the technology.
- Demonstrate sensor performance in the context of relevant spaceflight manipulation or utilization task performance as described throughout this subtopic, including by collaborating with a NASA center (e.g., iMETRO).
- Demonstrate operation of the sensor system within a space-relevant environment.

Specific sensors or sensor systems of interest include, but are not limited to:

- Low-mass, low-volume, high-dynamic-range force/torque sensors.
- Distributed sensor systems that provide unique manipulation feedback.
- Integrated perception sensors addressing challenges unique to manipulation.
- Active perception sensors that do not require artificial illumination.
- Integrated tactile sensors for manipulation.
- Novel sensors for task completion monitoring.

Note: Sensing and perception systems targeted for lunar surface mobility, on-orbit servicing, assembly and manufacturing (OSAM) and/or other use cases and environments should be addressed to other subtopics.)

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:

- Level 1: TX 04 Robotics Systems
- Level 2: TX 04.1 Sensing and Perception

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Phase I deliverables include:

- Background research and feasibility studies.
- Conceptual design, trade studies, and description of proposed solution.
- Initial concept of operation and demonstrated progress toward a significant improvement over state-of-the-art sensor solutions, rather than just an incremental enhancement.

Phase II deliverables include:

- Hardware prototype with supporting software, design information, and documentation.
- Test and/or performance data.

State of the Art and Critical Gaps:

Many sensors currently used in terrestrial robotic manipulation cannot survive or effectively perform in the space environment. State of the art varies across sensor type, but a lack of robustness to radiation and thermal extremes is common. Compact, low-mass sensing integrated into robot arms and/or end effectors is needed to reduce robot size and eliminate the need for external support equipment during manipulation tasks, as current solutions do not offer the high dynamic range required for more dexterous tasks.

Civil Space Shortfall Ranking https://www.nasa.gov/spacetechpriorities/

- 1545: Robotic Actuation, Subsystem Components, and System Architectures for Long-Duration and Extreme Environment Operation
- 1546: Robotic Mobile Manipulation for Autonomous Large-Scale Logistics, Payload Handling, and Surface Transport
- 1538: General-Purpose Robotic Manipulation to Perform Human-Scale Logistics, Maintenance, Outfitting, and Utilization

Relevance / Science Traceability:

Autonomous manipulation and utilization enabled by novel sensors for robotic manipulation directly supports NASA's Moon-to-Mars objectives to: "(LI-4) Demonstrate technologies supporting cislunar orbital/surface depots and support systems needed for continuous human/robotic presence," and "(OP-9) Demonstrate the capability of integrated robotic systems to support and augment the work of crewmembers on the lunar surface, and in orbit around the Moon."

Manipulation for in-space servicing and assembly, sustained lunar surface operations, and science exploration and utilization require robust sensing.

References:

1. EtherCAT Technology Group: https://www.ethercat.org/default.htm
2. EtherCAT In-Space Robotics: https://www.ethercat.org/download/documents/EtherCAT-in-Space-Robotics.pdf
3. Robot Operating System (ROS): https://www.ros.org/
4. Space Robot Operating System: https://space.ros.org/ and https://techport.nasa.gov/view/116403
5. NASA's Plans for Commercial LEO Development: https://ieeexplore.ieee.org/document/9172512
6. N. Radford, et al. 2015. "Valkyrie: NASA's First Bipedal Humanoid Robot." In Journal of Field Robotics, vol. 32, no. 3, pp. 397-419, 2015. https://onlinelibrary.wiley.com/doi/abs/10.1002/rob.21560
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8. "State-of-the-Art: Small Spacecraft Technology." https://ntrs.nasa.gov/api/citations/20220018058/downloads/_2022_SOA_full--.pdf
9. S. Frishman et al., "A Multi-Axis FBG-Based Tactile Sensor for Gripping in Space," 2021 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Prague, Czech Republic, 2021, pp. 1794-1799, doi:10.1109/IROS51168.2021.9635998.
10. T. Smith et al., 2021. "ISAAC: An Integrated System for Autonomous and Adaptive Caretaking (ISAAC)." Presentation, ISS Research and Development Conference. https://ntrs.nasa.gov/citations/20210020134
11. JSC iMETRO (Integrated Mobile Evaluation Testbed for Robotics Operations) Facility, https://ntrs.nasa.gov/citations/20230015485
12. NASA STMD National Space Technology Priority Shortfall List https://www.spacetechpriorities.org/

Z-ENABLE.05: Extensible Perception, Manipulation, and Interoperability for Autonomous Robotic Systems (SBIR) (Previously Z5.10)

Related Subtopic Pointers: A2.01, S17.02, T11.05
Lead Center: ARC
Participating Center(s): JSC, LaRC

Subtopic Introduction:

NASA's Moon-to-Mars objectives highlight the need to develop and demonstrate robotic and autonomous systems capable of supporting sustained operations on the lunar surface and in cislunar space. The following scopes highlight key challenges toward:

- Advancing remote robotic perception and manipulation technologies to enable autonomous robots to assess environment state, detect changes and anomalies, interact with their environment, and perform utilization, maintenance, logistics management, infrastructure outfitting, and in-space assembly tasks.
- Software interoperability for sustained collaborative operations, mission extensibility, improving software quality by streamlining reuse of heritage software components, and the accelerated integration and advancement of autonomy across these assets, so that multiple lunar surface and deep space robotic systems can more easily leverage rapidly evolving and maturing autonomous capabilities while a broad and dependable supply chain of commercial involvement and growth of a sustainable lunar surface and cislunar ecosystem is facilitated.

Scope Title: Sensing and Perception Software for Autonomous Manipulation and Utilization Tasks

Scope Description:

Accurate sensing and perception are critical for achieving the autonomous manipulation and task performance capabilities required for future lunar missions (both on Gateway and the lunar surface). Limited situational awareness, time delay, data latencies, etc., prevent direct, real-time, human-in-the-loop control from the ground at efficient operational cadences and necessitate greater autonomy on board remote robots in situ. Like those developed for terrestrial applications, perception algorithms and approaches for in-space manipulation require improvements in a variety of technical areas, but with the added challenge of being compatible with current-generation space-rated computing, sensors, etc. Solutions must also be suitable for use within the intravehicular or extravehicular space environment and relevant mission operation constraints.

Technology areas of interest include, but are not limited to:

- Semantic simultaneous localization and mapping (SLAM).
- Affordance recognition.
- Object/obstacle detection and segmentation.
- Object classification and/or registration.
- Pose estimation.
- Grasp detection and planning.
- Perceiving the shape of flexible or articulated objects such as jointed booms, cables, hoses, blankets, fabric cargo bags, etc.

Proposals to improve performance and advance current capabilities in areas of interest are encouraged, but technologies must also present a viable path to deployment on board space robots using current-generation computers and sensing suitable for the environment. Improving the speed and efficiency of sensor data processing and perception algorithm performance is desired, and novel techniques to translate state-of-the-art (or better) terrestrial performance to flight robotic manipulation are specifically sought. Novel approaches to leveraging machine learning for manipulation in the space environment (i.e., without reliance on significant cloud computing resources or large prior datasets) is also of potential interest.

Technologies must be applicable to intravehicular robotics, lunar surface, or other in-space manipulation use cases, such as:

- Assembly and maintenance (e.g., mating/de-mating power, data, and fluid connections; opening/closing panels; installation, stowage, and handling of cables and fluid lines; manipulation of soft goods).
- Science utilization (e.g., moving samples between cold storage and instruments; experiment monitoring and caretaking; small tool use; manipulation of buttons, switches, levers, etc.).
- Habitat mobility (e.g., hatch opening/closing; handrail and seat track grasping).
- Logistics management (e.g., payload handling; packing/unpacking bags; kitting items).
- Intravehicular robot (IVR) spacecraft inspection, monitoring, and anomaly detection.

Dual-use technologies with broad applicability to both space and terrestrial applications are encouraged, but a clear infusion path to NASA missions must be demonstrated. To facilitate infusion, proposals are encouraged, but not required, to:

- Address challenges that are particularly relevant in the space environment, such as ability to run on a radiation-tolerant computing platform, robustness to the high-dynamic-range lighting conditions present both in orbit and at the lunar surface, robustness to sensor radiation damage like hot pixels, adherence to relevant aerospace flight software quality assurance standards, etc.
- Trace proposal relevance to high-priority shortfalls from the NASA STMD National Space Technology Priority shortfall list. In particular, the following shortfalls may be relevant:
    - 1548: Sensing for Autonomous Robotic Operations in Challenging Environmental Conditions
    - 1538: General-Purpose Robotic Manipulation to Perform Human-Scale Logistics, Maintenance, Outfitting, and Utilization
    - 1535: Autonomous Vehicle, System, Habitat, and Infrastructure Health Monitoring and Management
    - 680: Robust Robotic Intelligence for High-Tempo Autonomous Operations in Dynamic Mission Conditions
- Target near-term integration and testing on relevant NASA robots (e.g., International Space Station Astrobee Facility, NASA JSC iMETRO facility, Valkyrie) or in coordination with ongoing NASA development efforts.
- Limit dependence on third-party proprietary technologies that might complicate NASA adoption of the technology.
- Use industry-standard hardware and software interfaces, architectures, and frameworks that align with relevant NASA robotic development efforts to reduce future integration effort (e.g., ROS/ROS2/SpaceROS).
- Demonstrate technology advances in the context of relevant manipulation or utilization task performance.

Expected TRL or TRL Range at completion of the Project: 4 to 6

Primary Technology Taxonomy:

- Level 1: TX 04 Robotics Systems
- Level 2: TX 04.1 Sensing and Perception

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Software

Desired Deliverables Description:

Phase I deliverables include:

- Background research and feasibility studies.
- Conceptual design, trade studies, and description of proposed solution.
- In some instances, an initial proof-of-concept implementation and/or testing (using either hardware or simulation).

Phase II deliverables include:

- Software source code, user manual/instructions, documentation.
- Test and/or performance data.
- Demonstration of software prototype on robot hardware.

State of the Art and Critical Gaps:

Current state-of-the-art approaches rely on computing performance far greater than current space-rated systems; external equipment or sensors not suitable for the internal habitat or in-space environments; significant cloud computing resources; or large external datasets and training time. Increased accuracy and speed are needed for improved reliability during task performance and to expand the range of manipulation and utilization tasks possible with autonomous robots. Perception suitable for fine dexterous manipulation is limited in the field. Improved processing efficiency and a reduced reliance on external resources is needed to facilitate deployment of onboard space robotic systems and mitigate the lack of direct user interaction during remote operations.

Civil Space Shortfall Ranking https://www.nasa.gov/spacetechpriorities/

- 1548: Sensing for Autonomous Robotic Operations in Challenging Environmental Conditions
- 1538: General-Purpose Robotic Manipulation to Perform Human-Scale Logistics, Maintenance, Outfitting, and Utilization
- 1535: Autonomous Vehicle, System, Habitat, and Infrastructure Health Monitoring and Management
- 680: Robust Robotic Intelligence for High-Tempo Autonomous Operations in Dynamic Mission Conditions
- 1542: Metrics and Processes for Establishing Trust and Certifying the Trustworthiness of Autonomous Systems
- 498: Broad and dependable supply chain for space-qualified robotic hardware, electronics, and associated software

Relevance / Science Traceability:

This scope represents an enabling technology for IVR operations on Gateway (science utilization, logistics management, payload handling, maintenance, etc.) and remote robotic manipulation, more generally, in support of lunar surface infrastructure assembly and robotic in-space servicing.

Autonomous manipulation, inspection, and utilization supported by the perception technologies in scope directly support NASA's Moon-to-Mars objectives to: "(LI-4) Demonstrate technologies supporting cislunar orbital/surface depots and support systems needed for continuous human/robotic presence," and "(OP-9) Demonstrate the capability of integrated robotic systems to support and augment the work of crewmembers on the lunar surface, and in orbit around the Moon."

Greater robotic autonomy for infrastructure-related manipulation tasks on the lunar surface and in cislunar space is needed: (1) to prevent an undue burden on crew time to perform many of these tasks, and (2) to address the communication limitations (time delay, latency, loss of communications, etc.) that prevent direct ground control from Earth in many of the target use cases.

References:

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3. NASA Outlines Lunar Surface Sustainability Concept: https://www.nasa.gov/feature/nasa-outlines-lunar-surface-sustainability-concept
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7. A. Katterhagen, et al. "Astrobee: A New Tool for ISS Operations." Presentation, International Conference on Space Operations (SpaceOps 2018). https://ntrs.nasa.gov/citations/20190006684
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9. iMETRO (Integrated Mobile Evaluation Testbed for Robotics Operations) Facility: https://ntrs.nasa.gov/api/citations/20230015485/downloads/iMETRO_Azimi_Poster_v5.pdf
10. NASA's Plans for Commercial LEO Development: https://ieeexplore.ieee.org/document/9172512
11. N. Radford et al. 2015. "Valkyrie: NASA's First Bipedal Humanoid Robot." In Journal of Field Robotics, vol. 32, no. 3, pp. 397-419. https://onlinelibrary.wiley.com/doi/abs/10.1002/rob.21560
12. NASA STMD National Space Technology Priority Shortfall List https://www.spacetechpriorities.org/
13. Examples of potentially relevant software quality assurance standards:
    - NPR 7150.2 NASA Software Engineering Requirements https://nodis3.gsfc.nasa.gov/displayDir.cfm?t=NPR&c=7150&s=2D
    - DO-178C Software Considerations in Airborne Systems and Equipment Certification https://en.wikipedia.org/wiki/DO-178C

Scope Title: Modular, Interoperable, and Extensible Flight Software Frameworks

Scope Description:

With multiple lunar surface assets from various vendors representing a core component of NASA's strategy to build a sustainable lunar surface ecosystem, software interoperability is critical for sustained collaborative operations, mission extensibility, enhancing software quality by streamlining reuse of heritage software components, rapid evolution and integration of autonomy between robotic assets, and maintaining a broad and dependable supply chain for robot software. Infusion of commercial robotic capabilities is slowed, however, by the lack of a fully matured flight software framework compatible with the widespread terrestrial commercial standards (e.g., Robot Operating System (ROS)). Robust robot control software and infrastructure developed to the rigors of spaceflight verification and validation standards is needed.

This includes, but is not limited to:

- Spaceflight versions of ROS, core packages, middleware, and oft-used components (e.g., Space ROS).
- Innovative approaches to continuous integration along with easily reusable and reproducible tools and processes targeted to satisfying spaceflight software standards.
- Integration of improved software quality tools such as static code analyzers into spaceflight software frameworks, enabling easier use of the tools to improve trust for future missions.
- Methods to apply code quality standards automatically to ground-focused software to enable use in spaceflight.
- Standardized interfaces and software bridges between robot software frameworks such as ROS and existing spaceflight software architectures (e.g., core Flight System (cFS), F Prime).
- New build/compiler improvements to enable use of existing software tools in resource-constrained applications.

- Novel run-time monitoring, deployment, and management approaches for non-spaceflight software that enables its use in lieu of certification of the frameworks themselves.
- Adapting, modifying, extending, and/or certifying existing open-source robotic software tools for spaceflight computer architectures (e.g., Reduced Instruction Set Computer-V (ISC-V)).

It is desirable to see relevant robotic task capabilities tested and demonstrated using these new software architectures and robotic autonomy/control frameworks. To accelerate development of needed advances beyond individual contributions, offerors are encouraged to contribute improvements and processes to upstream open-source projects, maintain or support continuous integration tools/processes, and/or provide support to foster communities around spaceflight-focused robotics software.

A clear infusion path to NASA mission use cases must be demonstrated, but an open-source business model that enables reuse and interoperability of software components (e.g., open-core) to benefit many potential hardware and software providers and applications is encouraged. Such a model would maximize utility across flight applications while enabling a revenue stream for the offeror, serving to bolster both flight software development efforts and the growth of commercial space and autonomy small businesses.

Proposals are encouraged, but not required, to trace proposal relevance to high-priority shortfalls from the NASA STMD National Space Technology Priority shortfall list. In particular, the following shortfalls may be relevant:

- 1542: Metrics and Processes for Establishing Trust and Certifying the Trustworthiness of Autonomous Systems
- 498: Broad and dependable supply chain for space-qualified robotic hardware, electronics, and associated software
- Some of the shortfalls listed in scope 1 are also likely to be relevant depending on the targeted applications.

Expected TRL or TRL Range at completion of the Project: 2 to 6

Primary Technology Taxonomy:

- Level 1: TX 04 Robotics Systems
- Level 2: .TX 04.6 Robotics Integration

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Software

Desired Deliverables Description:

Phase I deliverables include:

- Background research and feasibility studies.
- Conceptual design, trade studies, description of proposed solutions, references to contributions made to upstream projects.
- In some instances, an initial proof-of-concept implementation and/or testing (using either hardware or simulation).

Phase II deliverables include:

- Software source code, user manual/instructions, documentation, contributions to upstream projects.
- Test and/or performance data.
- Demonstration of software prototype on robot hardware.

State of the Art and Critical Gaps:

State of the art consists of terrestrial standards like ROS that are not fully matured for robust spaceflight use, and existing spaceflight software frameworks like cFS that do not address the specific challenges of robotic control and robot task development and performance.

Innovative approaches to code quality verification and validation, new software architecture designs, and novel software interfaces are needed to accelerate infusion of autonomous robotic capabilities into flight applications. The lack of such solutions has led to a dramatic underutilization of terrestrial robotic and autonomy technologies in space. Recent work toward developing SpaceROS and ROS-cFS bridge software has exposed multiple gaps in existing technology that must be addressed to successfully field such software frameworks and realize the desired benefits of interoperability and extensibility called for within NASA's Moon-to-Mars recurring tenets.

Civil Space Shortfall Ranking https://www.nasa.gov/spacetechpriorities/

- 1548: Sensing for Autonomous Robotic Operations in Challenging Environmental Conditions
- 1538: General-Purpose Robotic Manipulation to Perform Human-Scale Logistics, Maintenance, Outfitting, and Utilization
- 1535: Autonomous Vehicle, System, Habitat, and Infrastructure Health Monitoring and Management
- 680: Robust Robotic Intelligence for High-Tempo Autonomous Operations in Dynamic Mission Conditions
- 1542: Metrics and Processes for Establishing Trust and Certifying the Trustworthiness of Autonomous Systems
- 498: Broad and dependable supply chain for space-qualified robotic hardware, electronics, and associated software

Relevance / Science Traceability:

This scope represents an enabling capability for rapid software infusion for advanced robotic capabilities across a broad range of potential missions. The needs for interoperability, common interfaces, and extensibility are explicitly highlighted in NASA's Moon-to-Mars objectives, and the pursuit of such software tools and frameworks would serve to broaden industry collaboration and commercial access to lunar surface and deep space applications (again, in support of Agency recurring tenets).

Producing software frameworks and standard interfaces specifically geared toward autonomous and robotic capabilities is highlighted as a need in the current Extravehicular Activity (EVA) and Human Surface Mobility (HSM) Program (EHP) Autonomous Mobility and Operations Roadmap, and technologies within this scope would enable rapid integration of terrestrial technology in support of lunar surface infrastructure and cislunar in-space servicing, assembly, and manufacturing (ISAM) needs.

References:

1. Space Robot Operating System: https://space.ros.org/ and https://techport.nasa.gov/view/116403
2. FreeRTOS: https://www.freertos.org/RTOS.html
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4. ROS-Industrial: https://rosindustrial.org/
5. NASA STMD National Space Technology Priority Shortfall List https://www.spacetechpriorities.org/
6. Examples of potentially relevant software quality assurance standards:
    - NPR 7150.2 NASA Software Engineering Requirements https://nodis3.gsfc.nasa.gov/displayDir.cfm?t=NPR&c=7150&s=2D
    - DO-178C Software Considerations in Airborne Systems and Equipment Certification https://en.wikipedia.org/wiki/DO-178C

Scope Title: Integrated Mission Planning and Execution Software for Earth-Independent Robotic Missions

Scope Description:

Accurate sensing and perception are critical for achieving the autonomous manipulation and task performance capabilities required for future lunar missions (both on Gateway and the lunar surface). Limited situational awareness, time delay, data latencies, etc., prevent direct, real-time, human-in-the-loop control from the ground at efficient operational cadences and necessitate greater autonomy on board remote robots in situ. Like those developed for terrestrial applications, perception algorithms and approaches for in-space manipulation require improvements in a variety of technical areas, but with the added challenge of being compatible with current-generation space-rated computing, sensors, etc. Solutions must also be suitable for use within the intravehicular or extravehicular space environment and relevant mission operation constraints.

Technology areas of interest include, but are not limited to:

- Semantic simultaneous localization and mapping (SLAM).
- Affordance recognition.
- Object/obstacle detection and segmentation.
- Object classification and/or registration.
- Pose estimation.
- Grasp detection and planning.
- Perceiving the shape of flexible or articulated objects such as jointed booms, cables, hoses, blankets, fabric cargo bags, etc.

Proposals to improve performance and advance current capabilities in areas of interest are encouraged, but technologies must also present a viable path to deployment on board space robots using current-generation computers and sensing suitable for the environment. Improving the speed and efficiency of sensor data processing and perception algorithm performance is desired, and novel techniques to translate state-of-the-art (or better) terrestrial performance to flight robotic manipulation are specifically sought. Novel approaches to leveraging machine learning for manipulation in the space environment (i.e., without reliance on significant cloud computing resources or large prior datasets) is also of potential interest.

Technologies must be applicable to intravehicular robotics, lunar surface, or other in-space manipulation use cases, such as:

- Assembly and maintenance (e.g., mating/de-mating power, data, and fluid connections; opening/closing panels; installation, stowage, and handling of cables and fluid lines; manipulation of soft goods).
- Science utilization (e.g., moving samples between cold storage and instruments; experiment monitoring and caretaking; small tool use; manipulation of buttons, switches, levers, etc.).
- Habitat mobility (e.g., hatch opening/closing; handrail and seat track grasping).
- Logistics management (e.g., payload handling; packing/unpacking bags; kitting items).
- Intravehicular robot (IVR) spacecraft inspection, monitoring, and anomaly detection.

Dual-use technologies with broad applicability to both space and terrestrial applications are encouraged, but a clear infusion path to NASA missions must be demonstrated.

To facilitate infusion, proposals are encouraged, but not required, to:

- Address challenges that are particularly relevant in the space environment, such as an ability to run on a radiation-tolerant computing platform, robustness to the high-dynamic-range lighting conditions present both in orbit and at the lunar surface, robustness to sensor radiation damage like hot pixels, adherence to relevant aerospace flight software quality assurance standards, etc.
- Trace proposal relevance to high-priority shortfalls from the NASA STMD National Space Technology Priority shortfall list. In particular, the following shortfalls may be relevant:
    - 1548: Sensing for Autonomous Robotic Operations in Challenging Environmental Conditions
    - 1538: General-Purpose Robotic Manipulation to Perform Human-Scale Logistics, Maintenance, Outfitting, and Utilization
    - 1535: Autonomous Vehicle, System, Habitat, and Infrastructure Health Monitoring and Management
    - 680: Robust Robotic Intelligence for High-Tempo Autonomous Operations in Dynamic Mission Conditions
- Target near-term integration and testing on relevant NASA robots (e.g., International Space Station Astrobee Facility, NASA JSC iMETRO facility, Valkyrie) or in coordination with ongoing NASA development efforts.
- Limit dependence on third-party proprietary technologies that might complicate NASA adoption of the technology.
- Use industry-standard hardware and software interfaces, architectures, and frameworks that align with relevant NASA robotic development efforts to reduce future integration effort (e.g., ROS/ROS2/SpaceROS).
- Demonstrate technology advances in the context of relevant manipulation or utilization task performance.

Expected TRL or TRL Range at completion of the Project: 4 to 6

Primary Technology Taxonomy:

- Level 1: TX 10 Autonomous Systems
- Level 2: TX 10.X Other Autonomous Systems

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Software

Desired Deliverables Description:

Desired Deliverables Description (provide deliverable description for both Phase I & Phase II):

Phase I deliverables include:

- Background research and feasibility studies.
- Conceptual design, trade studies, and description of proposed solution.
- In some instances, an initial proof-of-concept implementation and/or testing (using either hardware or simulation).

Phase II deliverables include:

- Software source code, user manual/instructions, documentation.
- Test and/or performance data.
- Demonstration of software prototype on robot hardware.

State of the Art and Critical Gaps:

Current state-of-the-art approaches rely on computing performance far greater than current space-rated systems; external equipment or sensors not suitable for the internal habitat or in-space environments; significant cloud computing resources; or large external datasets and training time. Increased accuracy and speed are needed for improved reliability during task performance and to expand the range of manipulation and utilization tasks possible with autonomous robots. Perception suitable for fine dexterous manipulation is limited in the field. Improved processing efficiency and a reduced reliance on external resources is needed to facilitate deployment of onboard space robotic systems and mitigate the lack of direct user interaction during remote operations.

Civil Space Shortfall Ranking https://www.nasa.gov/spacetechpriorities/

- 1548: Sensing for Autonomous Robotic Operations in Challenging Environmental Conditions
- 1538: General-Purpose Robotic Manipulation to Perform Human-Scale Logistics, Maintenance, Outfitting, and Utilization
- 1535: Autonomous Vehicle, System, Habitat, and Infrastructure Health Monitoring and Management
- 680: Robust Robotic Intelligence for High-Tempo Autonomous Operations in Dynamic Mission Conditions
- 1542: Metrics and Processes for Establishing Trust and Certifying the Trustworthiness of Autonomous Systems
- 498: Broad and dependable supply chain for space-qualified robotic hardware, electronics, and associated software

Relevance / Science Traceability:

This scope represents an enabling technology for IVR operations on Gateway (science utilization, logistics management, payload handling, maintenance, etc.) and remote robotic manipulation, more generally, in support of lunar surface infrastructure assembly and robotic in-space servicing.

Autonomous manipulation, inspection, and utilization supported by the perception technologies in scope directly support NASA's Moon-to-Mars objectives to: "(LI-4) Demonstrate technologies supporting cislunar orbital/surface depots and support systems needed for continuous human/robotic presence," and "(OP-9) Demonstrate the capability of integrated robotic systems to support and augment the work of crewmembers on the lunar surface, and in orbit around the Moon."

Greater robotic autonomy for infrastructure-related manipulation tasks on the lunar surface and in cislunar space is needed: (1) to prevent an undue burden on crew time to perform many of these tasks, and (2) to address the communication limitations (time delay, latency, loss of communications, etc.) that prevent direct ground control from Earth in many of the target use cases.

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9. iMETRO (Integrated Mobile Evaluation Testbed for Robotics Operations) Facility: https://ntrs.nasa.gov/api/citations/20230015485/downloads/iMETRO_Azimi_Poster_v5.pdf
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12. NASA STMD National Space Technology Priority Shortfall List https://www.spacetechpriorities.org/
13. Examples of potentially relevant software quality assurance standards:
    - NPR 7150.2 NASA Software Engineering Requirements https://nodis3.gsfc.nasa.gov/displayDir.cfm?t=NPR&c=7150&s=2D
    - DO-178C Software Considerations in Airborne Systems and Equipment Certification https://en.wikipedia.org/wiki/DO-178CZ99.01

Appendix B: SBIR and the Technology Taxonomy

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. 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 2024 NASA Technology Taxonomy is an evolution of the technology roadmaps developed in 2015 and 2020. The 2024 NASA Technology Taxonomy provides a structure for articulating the technology development disciplines needed to enable future space missions and support commercial air travel. The 2024 revision is composed 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 that is the title of that area. Level 2 is a list of the subareas 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 2024 NASA Technology Taxonomy can be found at: https://techport.nasa.gov/view/taxonomy

2024 TX Mapping Level 1	2024 TX Mapping Level 2	SBIR/STTR Subtopic Number	Subtopic Title
TX01 - Propulsion Systems	TX01.3 - Aero Propulsion	A1.04	Novel Aircraft Configurations for Electrified Aircraft Propulsion
		A1.09	Zero-Emissions Technologies for Aircraft
	TX01.4 - Advanced Propulsion	Z-GO.02	Space Nuclear Propulsion
		Z-GO.03	Solar Photon Sails Research and Technology Development
	TX01.X - Other Propulsion Systems	Z-EXPAND.01	Servicing and Assembly Applications
TX02 - Flight Computing and Avionics	TX02.1 - Avionics Component Technologies	Z-ENABLE.02	High-Performance Space Computing Technology
	TX02.3 - Avionics Tools, Models, and Analysis	A2.04	Aviation Cybersecurity
TX03 - Aerospace Power and Energy Storage	TX03.1 - Power Generation and Energy Conservation	S13.06	Dynamic Power Conversion
		Z-ENABLE.01	Enabling Power and Thermal Technologies
	TX03.2 - Energy Storage	Z-LIVE.01	Surface Power Technologies
	TX03.3 - Power Management and Distribution	Z-LIVE.01	Surface Power Technologies
		T3.05	Lunar Orbital Power Beaming Technology Development

TX04 - Robotics Systems	TX04.1 - Sensing and Perception	H15.01	Autonomous Capabilities for Lunar Surface Mobility Systems
		Z-ENABLE.04	Robotic Hardware for In-Space Manipulation
		Z-ENABLE.05	Extensible Perception, Manipulation, and Interoperability for Autonomous Robotic Systems
	TX04.2 - Mobility	H15.02	Simulation and Modeling of Lunar Mobility System Interaction with Lunar Regolith
	TX04.3 - Manipulation	S13.01	Robotic Mobility, Manipulation, and Sampling
		Z-ENABLE.04	Robotic Hardware for In-Space Manipulation
	TX04.4 - Human-Robot Interaction	H6.25	Trusted Autonomy in Space Systems
		H15.01	Autonomous Capabilities for Lunar Surface Mobility Systems
	TX04.6 - Robotics Integration	Z-EXPAND.01	Servicing and Assembly Applications
		Z-ENABLE.05	Extensible Perception, Manipulation, and Interoperability for Autonomous Robotic Systems
	TX04.X - Other Robotic Systems	Z-EXPAND.01	Servicing and Assembly Applications
TX05 - Communications, Navigation, and Orbital Debris Tracking and Characterization Systems	TX05.1 - Optical Communications	S16.04	Suborbital Platform Technologies
	TX05.3 - Internetworking	H9.08	Lunar 3GPP Technologies
		T5.07	Communications Quality of Service (QoS) Optimization Through Network Autonomy
	TX05.4 - Network Provided Position, Navigation, and Timing	Z-EXPAND.05	Beyond LEO Sustainability
	TX05.5 - Revolutionary Communications Technologies	T8.06	Quantum Sensing/Measurement and Communication
	TX05.6 - Networking and Ground Based Orbital Debris Tracking and Management	H9.03	Flight Dynamics and Navigation Technologies
		Z-EXPAND.04	Low Earth Orbit (LEO) Sustainability
		T5.06	Non-Earth Orbit Conjunction Risk Analysis
	TX05.X - Other Communications, Navigation, and Orbital Debris Tracking and Characterization Systems	A2.01	Flight Test and Measurement Technologies
		Z-EXPAND.04	Low Earth Orbit (LEO) Sustainability
		Z-EXPAND.05	Beyond LEO Sustainability
	TX06.1 - Environmental Control & Life Support	H3.13	Oxygen Compatible Habitation Solutions for Exploration Environments

TX06 - Human Health, Life Support, and Habitation Systems	Systems (ECLSS) and Habitation Systems	H3.14	Nanobubble Facilitated Hydrogen Peroxide Production In Space
	TX06.2 - Extravehicular Activity Systems	H4.09	Long-Duration Exploration Portable Life Support System (PLSS) Capabilities
		H4.11	Advanced Materials for Durable Space Suits for the Moon and Mars
		H12.09	In-Suit Detection of Venous Gas Emboli
TX07 - Exploration Destination Systems	TX07.1 - In-Situ Resource Utilization	Z-LIVE.03	Space Resource Processing for Consumables, Manufacturing, Construction, and Energy
		Z-LIVE.05	Regolith Excavation and Manipulation for Surface Operations and Infrastructure with Assembly and Outfitting of Lunar Surface Structures
	TX07.2 - Mission Infrastructure, Sustainability, and Supportability	Z-EXPAND.02	Orbital Infrastructure Assembly
		Z-LIVE.04	Components for Extreme Environments
		Z-LIVE.05	Regolith Excavation and Manipulation for Surface Operations and Infrastructure with Assembly and Outfitting of Lunar Surface Structures
		T7.04	Lunar Surface Site Preparation
	TX07.3 - Mission Operations and Safety	S13.04	Contamination Control and Planetary Protection
	TX07.X - Other Exploration Destination Systems	Z-LIVE.05	Regolith Excavation and Manipulation for Surface Operations and Infrastructure with Assembly and Outfitting of Lunar Surface Structures
TX08 - Sensors and Instruments	TX08.1 - Remote Sensing Instruments/Sensors	A2.01	Flight Test and Measurement Technologies
		S11.01	Lidar Remote-Sensing Technologies
		S11.02	Technologies for Active Microwave Remote Sensing
		S11.03	Technologies for Passive Microwave Remote Sensing
		S11.04	Sensor and Detector Technologies for Visible, Infrared (IR), Far-IR, and Submillimeter
		S12.06	Detector Technologies for Ultraviolet (UV), X-Ray, and Gamma-Ray Instruments
		S14.02	In Situ Particles and Fields and Remote-Sensing-Enabling Technologies for Heliophysics Instruments
		S16.04	Suborbital Platform Technologies
		S16.07	Cryogenic Systems for Sensors and Detectors
		S16.08	Quantum Sensing: Atomic sensors, optical atomic clocks, and solid-state systems
		T8.07	Photonic Integrated Circuits
		T8.08	Lunar Imagery

	TX08.2 - Observatories	S12.01	Exoplanet Detection and Characterization Technologies
		S12.02	Precision Deployable Optical Structures and Metrology
		S12.03	Advanced Optical Systems and Fabrication/Testing/Control Technologies for Extended-Ultraviolet/Optical to Mid-/Far-Infrared Telescopes
		S12.04	X-Ray Mirror Systems Technology, Coating Technology for X-Ray-UVOIR (Ultraviolet-Optical-Infrared), and Free-Form Optics
	TX08.3 - In-Situ Instruments/Sensor	S11.05	Suborbital Instruments and Sensor Systems for Earth Science Measurements
		S13.05	In Situ Instruments and Instrument Components for Lunar and Planetary Science
		S14.02	In Situ Particles and Fields and Remote-Sensing-Enabling Technologies for Heliophysics Instruments
		S15.02	In Situ Sample Preparation and Analysis for Biological and Physical Sciences in a Microgravity Environment
		S15.03	Environmental Monitoring for Micro-G and Partial-G Experiments
		S16.08	Quantum Sensing: Atomic sensors, optical atomic clocks, and solid-state systems
	TX08.X - Other Sensors and Instruments	A3.05	Advanced Air Mobility (AAM) Integration
		S11.02	Technologies for Active Microwave Remote Sensing
		S13.03	Extreme Environments Technology
		S14.01	Space Weather Research-to-Operations and Operations-to-Research (R2O2R)
		T8.06	Quantum Sensing/Measurement and Communication
TX09 - Entry, Descent, and Landing	TX09.1 - Aeroassist and Atmospheric Entry	Z-LAND.02	Entry and Descent System Technologies
	TX09.2 - Descent	S16.04	Suborbital Platform Technologies
		Z-LAND.01	Parachute Systems for Maneuverability and Wireless Data Acquisition
	TX09.3 - Landing	Z-LAND.03	Plume-Surface Interaction (PSI) Technologies
	TX09.5 - Flight Mechanics and GN&C for Entry, Descent, and Safe Precise Landing	Z-LAND.01	Parachute Systems for Maneuverability and Wireless Data Acquisition
		Z-EXPAND.03	Space Debris Prevention for Small Spacecraft
TX10 - Autonomous Systems	TX10.1 - Situational and Self Awareness	H15.01	Autonomous Capabilities for Lunar Surface Mobility Systems
		A1.11	Health Management and Sensing Technologies For Sustainable Aviation Vehicles
	TX10.2 - Reasoning and Acting	A2.02	Enabling Aircraft Autonomy

		H6.25	Trusted Autonomy in Space Systems
		S17.03	Fault Management Technologies
	TX10.3 - Collaboration and Interaction	T6.09	Human-Autonomous System Integration for Deep Space Tactical Anomaly Response in Smart Habitats
	TX10.4 - Engineering and Integrity	A2.04	Aviation Cybersecurity
	TX10.X - Other Autonomous Systems	A2.02	Enabling Aircraft Autonomy
		Z-ENABLE.05	Extensible Perception, Manipulation, and Interoperability for Autonomous Robotic Systems
TX11 - Software, Modeling, Simulation, and Information Processing	TX11.1 - Software Development, Engineering, and Integrity	Z-ENABLE.02	High-Performance Space Computing Technology
		Z-LIVE.05	Regolith Excavation and Manipulation for Surface Operations and Infrastructure with Assembly and Outfitting of Lunar Surface Structures
	TX11.2 - Modeling	A1.06	Vertical Takeoff and Landing (VTOL) Vehicle Technologies - Vehicle Design Tool & Electric Powertrain Test Capability
		S17.02	Integrated Campaign and System Modeling
	TX11.3 - Simulation	S17.02	Integrated Campaign and System Modeling
	TX11.5 - Mission Architecture, Systems Analysis and Concept Development	A3.05	Advanced Air Mobility (AAM) Integration
	TX11.6 - Ground Computing	S17.01	Technologies for Large-Scale Numerical Simulation
	TX11.X - Other Software, Modeling, Simulation, and Information Processing	S14.01	Space Weather Research-to-Operations and Operations-to-Research (R2O2R)
		T11.05	Model-Based Enterprise
TX12 - Materials, Structures, Mechanical Systems, and Manufacturing	TX12.1 - Materials	A1.03	Propulsion Efficiency - Propulsion Materials and Structures
		Z-ENABLE.03	Advanced In-Space Laser Welding and Nondestructive Evaluation
		Z-LIVE.04	Components for Extreme Environments
		Z-EXPAND.05	Beyond LEO Sustainability
		T12.01	Additively Manufactured Electronics for Space Applications
		T12.10	Low-Cost Manufacturing and Integration of Reusable Thermal Protection Systems (TPS)
		T12.12	Spray Processing of Oxide Dispersion Strengthened (ODS) Alloy GRX-810

	TX12.2 - Structures	H5.01	Modular, Multi-Use 50 kW Lunar Solar Array Structures
		S12.02	Precision Deployable Optical Structures and Metrology
		Z-LIVE.05	Regolith Excavation and Manipulation for Surface Operations and Infrastructure with Assembly and Outfitting of Lunar Surface Structures
	TX12.4 - Manufacturing	H8.01	In Space Production Applications (InSPA) Flight Development and Demonstrations on ISS
		Z-ENABLE.03	Advanced In-Space Laser Welding and Nondestructive Evaluation
		T12.01	Additively Manufactured Electronics for Space Applications
	TX12.X - Other Manufacturing, Materials, and Structures	T12.11	Biomanufacturing for Space Missions: Harnessing Microbial Communities for Sustainable Production in Moon and Mars Environments
TX13 - Ground, Test, and Surface Systems	TX13.1 - Infrastructure Optimization	H10.04	In-line Commodity Purity Analysis
		T13.02	High-Efficiency, Reliable Electrical Subsystems for Cryogenic Pumps
	TX13.2 - Test and Qualification	A1.06	Vertical Takeoff and Landing (VTOL) Vehicle Technologies - Vehicle Design Tool & Electric Powertrain Test Capability
		A1.08	Aeronautics Ground Test and Measurement Technologies: Diagnostic Systems for High-Speed Flows and Icing
	TX13.5 - Surface Systems Technologies	A1.08	Aeronautics Ground Test and Measurement Technologies: Diagnostic Systems for High-Speed Flows and Icing
TX14 - Thermal Management Systems	TX14.1 - Cryogenic Systems	Z-GO.01	Cryogenic Fluid Management
	TX14.2 - Thermal Control Components and Systems	S16.05	Thermal Control Systems
		Z-ENABLE.01	Enabling Power and Thermal Technologies
		Z-LIVE.02	Spacecraft Thermal Management
		Z-LIVE.04	Components for Extreme Environments
	TX14.3 - Thermal Protection Components and Systems	S16.05	Thermal Control Systems
	TX14.X - Other Thermal Management Systems	S16.04	Suborbital Platform Technologies
		S16.05	Thermal Control Systems
		Z-LIVE.02	Spacecraft Thermal Management
TX15 - Flight Vehicle Systems	TX15.1 - Aerosciences	A1.02	Quiet Performance - Airframe Noise
		T15.04	Full-Scale (Passenger/Cargo) Electric Vertical Takeoff and Landing (eVTOL) Scaling, Propulsion, Aerodynamics, and Acoustics Investigations

	TX15.2 - Flight Mechanics	H9.03	Flight Dynamics and Navigation Technologies
		T15.04	Full-Scale (Passenger/Cargo) Electric Vertical Takeoff and Landing (eVTOL) Scaling, Propulsion, Aerodynamics, and Acoustics Investigations
TX16 - Air Traffic Management and Range Tracking Systems	TX16.1 - Safe All Vehicle Access	A2.04	Aviation Cybersecurity
		A3.03	Future Aviation Systems Safety
	TX16.3 - Traffic Management Concepts	A3.02	Advanced Air Traffic Management for Nontraditional Airspace Missions
TX17 - Guidance, Navigation, and Control (GN&C)	TX17.2 - Navigation Technologies	H9.03	Flight Dynamics and Navigation Technologies
		Z-EXPAND.03	Space Debris Prevention for Small Spacecraft
	TX17.X - Other Guidance, Navigation, and Control	S16.03	Guidance, Navigation, and Control