Quantum Interferometry and Signal Systems for Spacecraft and Telescopes

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T5
X08.1.3

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James Ruel Niere (Deputy Project Manager, Engineering Lead, and Electrical Engineer)
John Philip Slope (Financial Lead and Mechanical Engineer)
Hillary Sim (Record Keeper and Quantum Physicist)
Charlotte Gorgemans (Outreach Coordinator)
Kiah May (Radiation Specialist)
Alvin Hang (Astrophysicist)
Kevin Harry (Aerospace Engineer)
Bhargavi Datye (Computer Engineer)z
Lauren Christenson (Aerospace Engineer)

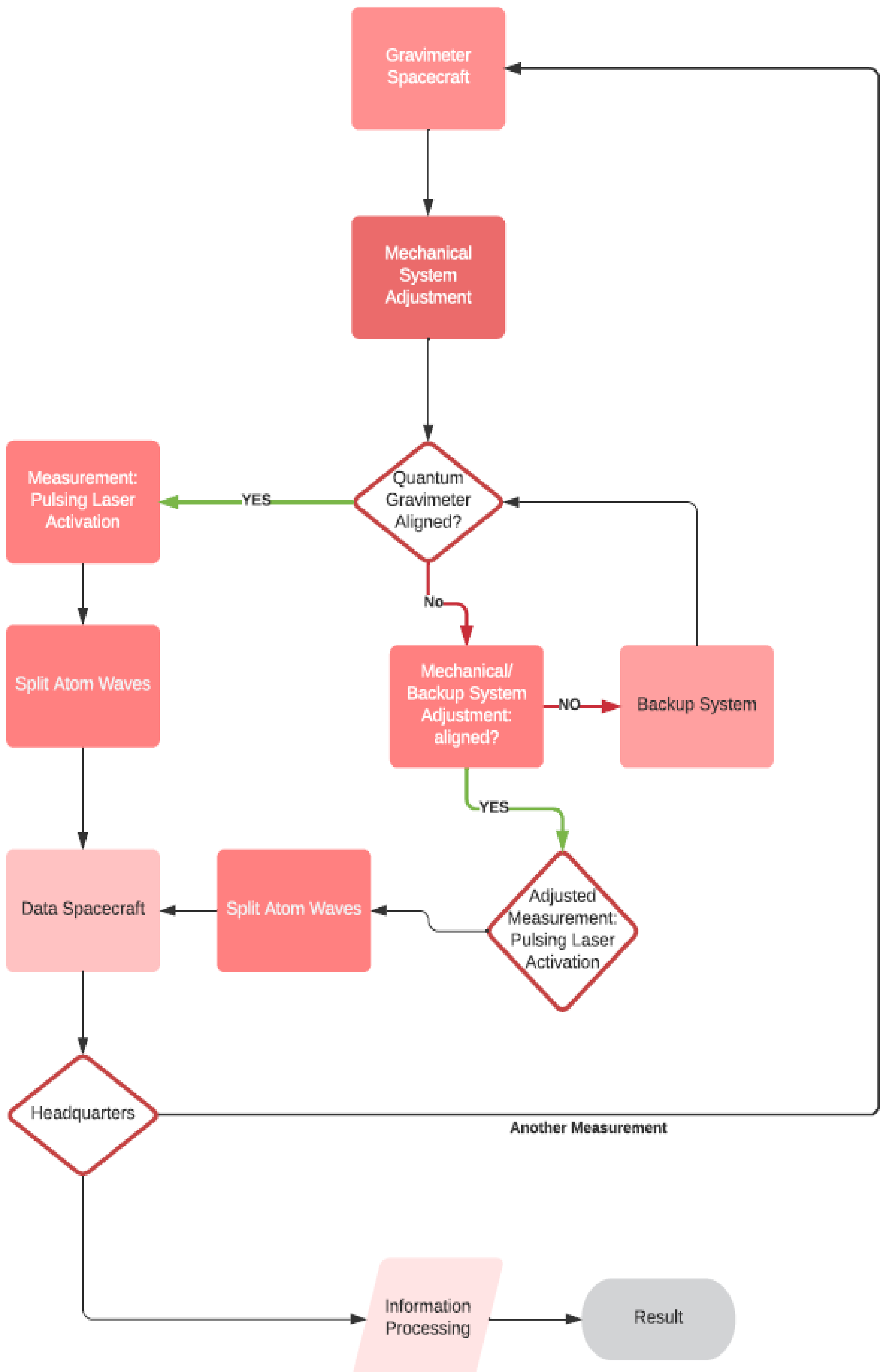
Abstract

The use of quantum sensors, more specifically Quantum-based Gravimeters, will lead to more accurate measurements of gravitational fields in comparison to classical sensors. This has uses in telescopes and satellites, and space probes, with the potential to increase accuracy and precision in a variety of measurements across the space industry. The increase in accuracy through the use of these sensors has been found to be up to 100,000,000 times more sensitive than classical sensors. Quantum sensors in space will be able to determine the density and seismic status and change of the global environment, climate, and bodies in space that may be of significance to NASA's missions through the use of Quantum Interferometry. Considerations for the use of quantum sensors in space are protection from damage while in space, as well as the methods for data collection and transfer, and the processing of data. Global needs for quantum sensors consist of climate change, seismic scanning for earthquakes, and density analysis for future NASA missions to other planets or celestial bodies. In order to optimize the sensor, it must be able to make remote measurements without much loss in accuracy—a mechanical hatch system that works alongside an electronic receiver and transmitter would help with the measurement and collection of quantum sensor data sets. This project will attempt to synthesize current knowledge of technology and modern physics into a prototype that can be extended to uses in space and a proof of concept final paper that contains the efforts and detailed steps of the project.

Concept and Technology Merit

The main technology used is quantum interferometry: a technique that utilizes a split in an atomic beam and their changes in optical path length to measure an external field through an interference pattern. Atomic beams are affected by a gravitational field, and the changes in their path length can be shown in such an interference pattern. Analysis of the patterns will return precise data about what it is meant to measure. Its applications are in detecting changes in a certain mass, an example being water or oil. It is used for the analysis of density and the gravitational field, and when applied in space, could potentially provide essential information about the moon or other bodies. With the addition of cryogenic low noise amplifiers, as well as onboarded computers, a mechanical system, and radiation-safe spacecraft, such analysis in space is made possible. Specifically, there will be two spacecraft implemented: one that will use a pulsing laser to scatter the atom waves for quantum measurements (the measurement spacecraft), and one that will receive the data and deliver it to earth (receiving and data spacecraft). Both spacecraft will be put in orbit or spaced accurately apart for the atomic waves to detect gravitational fields. A test could be done with one measurement spacecraft, and the proper receiving angles and materials on earth in order to measure densities in between the earth and the measurement spacecraft. There must be a minimum of 3 computers, one Gyro Suspension System (GSS) computer, a SQUID Readout Electronics (SRE) computer, and a Telescope Readout Electronics (TRE) computer. They will have approximately 10-year old IBM RS6000 Central Processing Units (CPUs), coupled with 4 MB of radiation-hardened RAM memory. These computers, along with ruggedized power supplies will be encased in sturdy aluminum boxes, with sides up to 1/4" thick. In addition, there will be amplifiers in the receiving and data transferring spacecraft. The mechanical hatch system will be developed in the measurement spacecraft, with optimization of the pulsing laser and its distances, quantum sensor, and the safest materials and configurations. A counterpart would then be installed in the data spacecraft that would collect the interference pattern. While current sensing technology is precise, there may be offsets to its accuracy due to external factors. To account for this, the team will attempt to research and optimize the system.

Block Diagram



Gravimeter Spacecraft
Mechanical System Adjustment
Quantum Gravimeter Aligned?
YES
Measurement: Pulsing Laser Activation
No
Split Atom Waves
Mechanical/ Backup System Adjustment: aligned?
NO
Backup System
YES
Data Spacecraft
Split Atom Waves
Adjusted Measurement: Pulsing Laser Activation
Headquarters
Another Measurement
Information Processing
Result

Work Plan

There already exists a prototype of a quantum sensor that was made in the late 1980s. The state-of-the-art technology has a sensitivity of approximately 100 million times more than its classical counterparts—its current limitations, however, has its roots in its versatility. Being able to take measurements in space would allow for the sensor to be used in measuring different parameters for supporting future NASA missions. The project will take place over a course of 5 months and will address the possibilities of taking a quantum interferometry measurement from within a spacecraft through a mechanical system that will collect data and transfer it to Earth. The key challenge is finding an environment where the measurement can be made and the best materials that would be used around it accordingly. The first month will be devoted to understanding the best materials used in parallel for a safe measurement. There will be an initial design element—using Computer-Aided Design (CAD) we will construct a mechanical system in which the quantum sensor may reside or work alongside. The next two months, months 2 and 3, will be spent revising the current data and constructing an improved model. It will be compatible with low noise amplifiers and software that will send the data. The final two months, months 4 and 5, will be used to develop a prototype of the system and its backups that work on earth and can be used in space and a proof of concept paper based on experimentation.

Calendar

- Month 1 (Materials Research)
    - Weeks 1-2
        - Research materials compatible with quantum sensing and error reduction.
        - Radiation safety will also be a researched topic.
        - Ideas will be developed for the general structure and form of the prototype mechanical device for quantum sensing.
    - Weeks 3-4
        - Finalization of materials research is the goal.
        - Record keepers will begin note-taking and engineers will be paired up with a scientist for further optimization.
        - Scientists will begin individual research in their respective specializations with the help and involvement of members of finance roles.
        - Admin and outreach will contact outside experts for additional support and reference.

- Month 2 (Model Construction Part 1)
    - Weeks 1-2
        - The design project will begin using Computer-Aided Design and will be done by the engineering group.
        - Science team will continue research with outside experts in order to recognize new potential dangers or performance enhancements.
        - Record keeper will continue to log progress with the Principal Investigator for future reference.
    - Weeks 3-4
        - Begin ordering the necessary electronics to simulate a signal.
        - Design team of engineers will have a model ready by the end of this stage.

        - Further development in design will incorporate any new findings by the science team.

- Month 3 (Model Construction Part 2)
    - Weeks 1-2
        - 3D printed prototype of the system that will work alongside the electronics.
        - Team will begin troubleshooting and improving the model.
        - Record keeper and Principal investigator (1st author) will continue the write-up, including all the processes and errors.
    - Weeks 3-4
        - Records will be synthesized into a proof of concept paper that will act as a second product.
        - Further investigation by the science and engineering groups, who will both work towards efficiency and compatibility.
        - The 3D printing process will continue, with trial and error in the design element.
        - Models for a Backup mechanical system will be developed.

- Month 4 (Experimentation)
    - Weeks 1-2
        - The entire team will experiment with signals and the prototype
        - Specific materials will be purchased in an effort to experiment with radiation.
        - Outreach Coordinator will continue to arrange meetings with professionals in radiation, data transfer, quantum mechanics, and electrical engineering for progress.
        - We will test the efficiencies for both the prototype and the backup model.
    - Weeks 3-4
        - Principal Investigator will complete the proof of concept along with the lead engineer along with the science team.
        - Record keeper will continue to log progress for reference in the paper.
        - The last of the experiments will take place, and if there are no further objections or discoveries, the project will come to a conclusion, with the final goals of a prototype and proof of concept met.

- Month 5 (Adjustment in the Case of New Discoveries)
    - Weeks 1-2
        - The science team will investigate the parameters which must be addressed.
        - The engineering team along with the finance team will use the reserves in order to print, if needed, a new prototype.
        - The Outreach Coordinator will contact professionals who have experience in the newly discovered area(s) that the team must work towards addressing.
    - Weeks 3-4
        - Revisions will be made to the Proof of Concept.
        - Final experiments will take place, and if there are no further objections or discoveries, the project will finally come to a conclusion, with the final goals of a prototype and proof of concept met.

Project Management Approach

The project will allow for different sections of the group to work concurrently with each other. This will allow for greater efficiency in particularly research-oriented tasks. For example, deeper research will be a major aspect of the project and also covers a variety of topics. Therefore, we will have a science team, consisting of a radiation specialist, a quantum physicist, and an astrophysicist each conducting separate independent research. The main goal of conducting this research will be to provide the engineers with tangible parameters for performance, safety, reliability, and accuracy. The science team will also research potential needs for this technology. It is expected that this process will take approximately 3 months to complete. Engineers will work concurrently with the scientists once the scientists have provided basic design parameters; the engineering team consisting of Computer, Aerospace, Mechanical, and Electrical engineers will use CAD to design a mechanical system that would allow for quantum sensors to be used in space while meeting all parameters relating to performance, safety, reliability, and accuracy. Each engineer will work with a scientist to determine the best fit in modeling. This design phase will also include the testing of the designs, as well as an estimate of the cost of a prototype. The initial design is expected to take a combined 240 hours of work to complete over a 2 month period. Additional crucial findings and ideas from the science team may increase the hours and timeframe. 3D printing will be imperative for experimentation—the average cost for an hour of 3D printing is around $1, and 2000 printing hours, our expected time, would cost $2000.

Teaming and Workforce Development

- Hong Joo Ryoo (UC Berkeley, Junior):
  - Principal Investigator (PI)
  - Project Manager
  - Lead Scientist
  - In charge of project, research, development, and investigation.
  - Responsible for contacting/consulting with the SME for scientific concepts and applications.
  - Research Experience: PI2 program Stage 2 (Supernova Host Galaxy Mass Step research proposal with Dr. Antonella Palmese), Unification and Black Hole Information Honors Senior thesis under theoretical physicist Dr. Yasunori Nomura, BPURS UC Berkeley Research Scholar Stipend, PDRP Quantum Field Theory mentorship and presentation, AIAA Quantum Mechanics Conference Research Paper and presentation, Research Internship in Dr. Orebi Gann’s Experimental Neutrino Physics Group
  - Programming experiences: Python, Mathematica, LaTeX, LabView, MATLAB
  - Will lead the science group and make executive decisions

- James Ruel Niere (UC Berkeley, Freshman):
  - Deputy Project Manager
  - Engineering Lead

- Electrical Engineer
- Second in command, responsible for development and progress in absence of Principal Investigator
- Research experience: Quantum Cascade Lasers, Environmental Engineering, Artificial Intelligence, Economics
- Programming experience: Python, MATLAB, Scheme, SQL
- Tiger (Earl) Woods Scholar, UC Berkeley Computer Science Scholar
- Will lead the Engineering Team for the development of mechanical systems

- John Slope (UC Irvine, Sophomore): Admin Lead, Financial Planner, Mechanical Engineer
  - In charge of managing logistics/finances as well as assisting in the development and testing of CAD designs
  - Computer-aided design: Solidworks
  - Programming Languages: MATLAB
  - Will work with Engineering and Science teams to keep track of material costs

- Alvin Hang (Long Beach City College, Sophomore):
  - Astrophysicist
  - Will assist lead scientist in research and development
  - Programming languages: C++, Python, Java
  - Computer-aided design: Fusion 360

- Kiah May (CU Boulder, Freshman):
  - Radiation Scientist
  - Responsible for research in radiation and spacecraft/mechanical systems materials
  - Will work alongside aerospace engineers for efficiency and safety in the spacecraft
  - Will work with Quantum Physicist for development and design of safety modifications

- Hillary Sim (UC Berkeley, Junior):
  - Record Keeper
  - Quantum Physicist
  - Responsible for progress reports and research in quantum sensors
  - Will work with Principal investigator to create extensions to current design plan
  - Will work with Admin lead and Science and Engineering teams to keep records of progress
  - Responsible for assisting Principal Investigator with Proof of Concept Paper

- Charlotte Gorgemans (CU Boulder, Freshman):
  - Outreach Coordinator
  - In charge of outreach and communications with Subject Matter Experts Along with Principal Investigator
  - Programming Languages: C++, C, Python

- Kevin Harry (UC Irvine, Sophomore):

- Aerospace Engineer
- Will work with Engineering Team alongside Astrophysicist for efficient mechanical systems

- Bhargavi Datye (San Jose State, Junior)
    - Computer Engineer
    - Programming Languages: C, C++
    - Will work with Financial Planner for long-term expenses and planning
    - Will work with Engineering Team for the development of mechanical systems

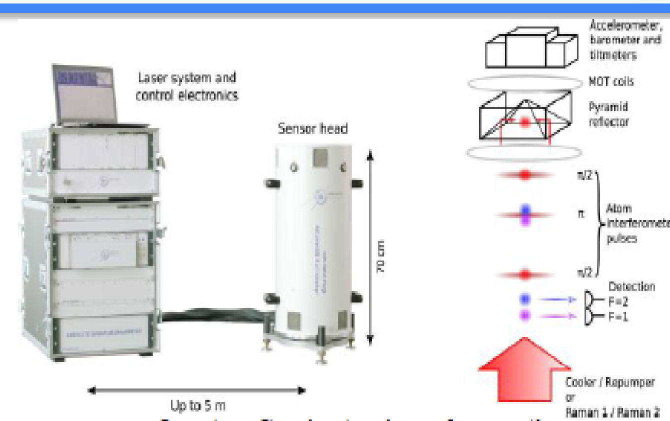
- Lauren Christenson (CU Boulder, Freshman):
    - Aerospace Engineer
    - Will work alongside Radiation Specialist for development and design of safety modifications
    - Programming Languages: C++, MATLAB

Appendix
Quad Chart

Atom Interferometry and Signal Systems for Spacecraft and Telescopes
PI: Hong Joo Ryoo, Team 6

Goal / Objective

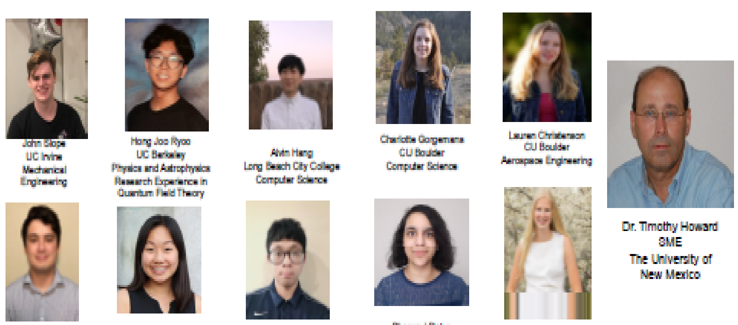
- **Goal**
- Achieve more precise measurements of Gravitational Fields and to use them to determine the density and seismic status and change of the global environment, climate, and bodies in space that may be of significance to NASA's missions through the use of Quantum Interferometry on spacecraft and telescopes that contain a data transferring method (electromagnetic waves and hatch systems) to deliver and activate measurements remotely in space.
- The final product will be a mechanical system prototype that effectively communicates on land that will potentially allow for taking quantum measurements in space. Accordingly, a final paper will be produced by the Principal investigator that address the Proof of Concept.
- **Objectives**
- Using quantum interferometry, determine other global needs/problems and get the necessary information for solutions
- Extend quantum sensors to telescope based remote spacecrafts for future measurements and missions
- Develop an effective communication system to take measurements



Quantum Gravimeter size and properties

Team Overview TX08.1.3

- Qualifies for NTR



John Slope, UC Irvine, Mechanical Engineering
Hong Joo Ryoo, UC Berkeley, Physics and Astrophysics, Research Experience in Quantum Field Theory
Alvin Hang, Long Beach City College, Computer Science
Charlotte Gorgemans, CU Boulder, Computer Science
Lauren Christenson, CU Boulder, Aerospace Engineering
Dr. Timothy Howard, SME, The University of New Mexico
Kevin Harry UC Irvine, Mechanical Engineering
Hillary Sim, UC Berkeley, Data Science, Experience in Health and Data
James Ruel Neire, UC Berkeley, Electrical Engineering and Computer Science, Research Experience in Quantum Optics
Bhargavi Datye, San José State, Computer Engineering
Kiah May, CU Boulder, Aerospace Engineering, Experience in Atomic Physics and Nuclear Engineering

Metrics and Key Performance Parameters

- **Metrics**
- Greater sensitivity than any other sensing technology by a factor of around 100,000,000.
- Effective measurements of density and seismic waves within celestial bodies as well as geography and shifts in bodies of water from warming
- **Parameters**
- Electromagnetic waves require efficient and accurate antennas (70-meter (230-foot) diameter)
- Must have activation functions that are reliable and do not take up much space
- Data sets must be stored and transferred precisely through signals and the process must be able to be repeated after a single measurement for concreteness

Nasa 1679 Form

National Aeronautics and Space Administration

Disclosure of Invention and New Technology (Including Software)

Form Approved O.M.B. NO. 2700-0009	DATE 3/14/2022
CONTRACTOR CASE NO.	
NASA CASE NO. (OFFICIAL USE ONLY)	

This is an important legal document. Carefully complete and forward to the Patent Representative (NASA in-house innovation) or New Technology Representative (contractor/grantee innovation) at NASA. Use of this report form by contractor/grantee is optional; however, an alternative format must at a minimum contain the information required herein. NASA in-house disclosures should be read, understood and signed by a technically competent witness in the witness signature block at the end of this form. In completing each section, use whatever detail deemed appropriate for a "full and complete disclosure." Contractors/Grantees please refer to the New Technology or Patent Rights – Retention by the Contractor clauses. When necessary, attach additional documentation to provide a full, detailed description.

1. DESCRIPTIVE TITLE
Quantum Interferometry and Signal Systems for Spacecraft and Telescopes

2. INNOVATOR(S) *(For each innovator provide: Name, Title, Work Address, Work Phone Number, and Work E-mail Address. If multiple innovators, number each to match Box 5.)*
Hong Joo Ryoo:
Phone Number: (909)-219-0502
Email Address: lyuhongju1@berkeley.edu

3. INNOVATOR'S EMPLOYER WHEN INNOVATION WAS MADE *(For each innovator provide: Name, Division and Address of Employer, Organizational Code/Mail Code, and Contract/Grant Number if applicable. If multiple innovators, number each to match Box 5.)*
Location: University of California, Berkeley
Address: 110 Sproul Hall #5800, Berkeley, California, 94720

4. PLACE OF PERFORMANCE *(Address(es) where innovation made)*
110 Sproul Hall #5800, Berkeley, California, 94720

5. EMPLOYER STATUS *(choose one for each innovator)*

Innovator #1	Innovator #2
CU	

Innovator #3	Innovator #4

GE = Government
CU = College or University
NP = Non-Profit Organization
SB = Small Business Firm
LE = Large Entity

6. ORIGIN *(Check all that apply and provide all applicable numbers. If multiple Contracts/Grants, etc., list Contract/Grant Numbers in Box 3 with applicable employer information.)*

- ☐ NASA In-house Org. Mail Code ____ — WBS ____
- ☒ Grant/Cooperative Agreement No. 80NSSC19M0186 — WBS ____
- ☐ Prime Contract No. ____ — WBS ____
  Task No. ____ Report No. ____
- ☐ Subcontractor; Subcontract Tier ____ — WBS ____
- ☐ Joint Effort *(contractor, subcontractor and/or grantee contribution(s), and NASA in-house contribution)*
- ☐ Multiple Effort *(multiple contractor, subcontractor and/or grantee contributions, no NASA in-house contribution)*
- ☐ Other (e.g., Space Act Agreement, MOA) No. ____ — WBS ____

7. NASA CONTRACTING OFFICER'S TECHNICAL REPRESENTATIVE *(COTR)*
John Dankanich

8. CONTRACTOR/GRANTEE NEW TECHNOLOGY REPRESENTATIVE *(POC)*

9. BRIEF ABSTRACT *(A general description of the innovation which describes its capabilities, but does not reveal details that would enable duplication or imitation of the innovation.)*
The technology is a mechanical system that will allow for the use of sensors utilizing quantum interferometry in spacecraft. The system will allow the sensor to survive in a high radiation and zero gravity environment.

SECTION I – DESCRIPTION OF THE PROBLEM OR OBJECTIVE THAT MOTIVATED THE INNOVATION'S DEVELOPMENT *(Enter as appropriate: A. – General description of problem/objective; B. – Key or unique problem characteristics; C. – Prior art, i.e., prior techniques, methods, materials, or devices performing function of the innovation, or previous means for performing function of software; and D. – Disadvantages or limitation of prior art.)*

Quantum sensors/gradiometers have an accuracy of approximately 100,000,000 times greater than their conventional counterparts and have been utilized on the ground to image and collect data on the interior of Earth.. The incorporation of quantum sensors into spacecrafts will allow for better measurements of several aspects of bodies in the solar system. This enables better planning of future missions as a better understanding of the body will allow for more control over variables that may affect the mission.

SECTION II – TECHNICALLY COMPLETE AND EASILY UNDERSTANDABLE DESCRIPTION OF INNOVATION DEVELOPED TO SOLVE THE PROBLEM OR MEET THE OBJECTIVE *(Enter as appropriate; existing reports, if available, may form a part of the disclosure, and reference thereto can be made to complete this description: A. – Purpose and description of innovation/software; B. – Identification of component parts or steps, and explanation of mode of operation of innovation/software preferably referring to drawings, sketches, photographs, graphs, flow charts, and/or parts or ingredient lists illustrating the components; C. – Functional operation; D. – Alternate embodiments of the innovation/software; E. – Supportive theory; F. – Engineering specifications; G. – Peripheral equipment; and H. – Maintenance, reliability, safety factors.)*

The use of quantum sensors in spacecrafts will require a mechanical system that will protect the sensitive instruments from higher levels of radiation in comparison to Earth. It will also protect the sensor from potential damage due to high g-forces during launch as well as a zero gravity environment.

SECTION III – UNIQUE OR NOVEL FEATURES OF THE INNOVATION AND THE RESULTS OR BENEFITS OF ITS APPLICATION *(Enter as appropriate: A. – Novel or unique features; B. – Advantages of innovation/software; C. – Development or new conceptual problems; D. – Test data and source of error; E. – Analysis of capabilities; and F. – For software, any re-use or re-engineering of existing code, use of shareware, or use of code owned by a non-federal entity.)*

The use of quantum sensors in space with adequate protection will allow for vastly improved accuracy and sensitivity in a wide variety of measurements in bodies in the solar system. Far greater than any current current sensor used in spacecrafts.

SECTION IV – SPECULATION REGARDING POTENTIAL COMMERCIAL APPLICATIONS AND POINTS OF CONTACT (*Including names of companies producing or using similar products.)*

The technology has potential uses in a wide variety of private space endeavors including the mining of solar system bodies, private space exploration, and earth based endeavors such as mining, and the modeling of climate and geological trends.

10. ADDITIONAL DOCUMENTATION *(Include copies or list below any pertinent documentation which aids in the understanding or application of the innovation (e.g., articles, contractor reports, engineering specs, assembly/manufacturing drawings, parts or ingredients list, operating manuals, test data, assembly/manufacturing procedures, etc.).)*

TITLE	PAGE	DATE

11. DEGREE OF TECHNOLOGY SIGNIFICANCE (*Which best expresses the degree of technological significance of this innovation?)*

☒ Modification to Existing Technology ☐ Substantial Advancement in the Art ☐ Major Breakthrough

12. STATE OF DEVELOPMENT

☒ Concept Only ☐ Design ☐ Prototype ☐ Modification ☐ Production Model ☐ Used in Current Work

13. PATENT STATUS (Prior patent on/or related to this innovation.)

☐ Application Filed Application No. Application Date

☐ Patent Issued Patent No. Issue Date

14. INDICATE THE DATE OR THE APPROXIMATE TIME PERIOD WHICH THIS INNOVATION WAS DEVELOPED (*i.e., conceived, constructed, tested, etc.)*

February 2022

15. PREVIOUS OR CONTEMPLATED PUBLICATION OR PUBLIC DISCLOSURE INCLUDING DATES *(Provide as applicable: A. – Type of publication or disclosure, e.g., report, conference or seminar, oral presentation; B. – Disclosure by NASA or Contractor/Grantee; and C. – Title, volume no., page no., and date of publication.)*

16. QUESTIONS FOR SOFTWARE ONLY

(a) Using non-NASA employees to beta-test the program? ☒ YES ☐ NO If Yes, done under a beta-test agreement? ☐ YES ☐ NO
(b) Modification of this program continued by civil servant and/or contractual agreement? ☐ YES ☐ NO
(c) Copyright registered? ☐ YES ☐ NO ☐ UNKNOWN If Yes, then by whom?
(d) Has the latest version been distributed outside of NASA or contractor? ☐ YES ☐ NO ☐ UNKNOWN
If Yes, date of first disclosure:
(e) Were prior versions distributed outside of NASA or Contractor? ☐ YES ☐ NO If Yes, supply NASA or contractor contract:
(f) Contains or based on code not owned by U.S. Government or its contractors? ☐ YES ☐ NO ☐ UNKNOWN
If Yes, name of code and code's owner:
Has a license for use been obtained? ☐ YES ☐ NO ☐ UNKNOWN

17. DEVELOPMENT HISTORY

STAGE OF DEVELOPMENT	DATE (MM/YYYY)	LOCATION	IDENTIFY SUPPORTING WITNESSES (NASA in-house only)
a. First disclosure to others	02/2022		
b. First sketch, drawing, logic chart or code			
c. First written description	03/2022		
d. Completion of first model of full size device *(invention)* or beta version *(software)*			
e. First successful operational test *(invention)* or alpha version *(software)*			

f. Contribution of innovators *(if jointly developed, provide the contribution of each innovator)*
Hong Joo Ryoo: Created the initial concept and researched basic parameters.

g. Indicate any past, present, or contemplated government use of the innovation

18. SIGNATURES OF INNOVATOR(S), WITNESS(ES), AND NASA APPROVAL

TYPED NAME AND SIGNATURE	DATE	TYPED NAME AND SIGNATURE	DATE
TYPED NAME AND SIGNATURE *(Innovator #1)* Hong Joo Ryoo	DATE 3/14/2022	TYPED NAME AND SIGNATURE *(Innovator #2)*	DATE
TYPED NAME AND SIGNATURE *(Innovator #3)*	DATE	TYPED NAME AND SIGNATURE *(Innovator #4)*	DATE
TYPED NAME AND SIGNATURE *(Witness #1)*	DATE	TYPED NAME AND SIGNATURE *(Witness #2)*	DATE
NASA APPROVED	TYPED NAME	SIGNATURE	DATE

References:

Sensitivity of sensor
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NASA quantum sensor prototype
https://www.nasa.gov/feature/goddard/2018/nasa-industry-team-creates-and-demonstrates-first-quantum-sensor-for-satellite-gravimetry

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SME Dr. Timothy L Howard AIAA paper

Timothy L. Howard, "Aspects of Quantum Sensing for Aerospace Systems", AIAA paper no.2020-0711, presented at AIAA SciTech 2020, Orlando, FL, Jan. 6 – 10, 2020.