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. 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, the Moon, and other planetary bodies will be considered under this subtopic. Compact, high-efficiency lidar instruments for deployment on unconventional platforms, such as unmanned aerial vehicles, SmallSats, and CubeSats are also considered and encouraged. Proposals must show relevance to the development of lidar instruments that can be used for NASA science-focused measurements or to support current technology programs. Meeting science needs leads to four primary instrument types:

- Backscatter: Measures beam reflection from aerosols and clouds to retrieve the optical and microphysical properties of suspended particulates.
- Laser spectral absorption: Measures laser absorption by trace gases from atmospheric or surface backscatter and volatiles on surfaces of airless planetary bodies at multiple laser wavelengths to retrieve concentration of gas within measurement volume.
- Ranging: Measures the return beam’s time of flight to retrieve distance.
- Doppler: Measures wavelength changes in the return beam to retrieve relative velocity

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
Desired Deliverables Description:

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 often require follow on programs such as Phase III SBIR to evaluate and optimize performance in relevant environment.

State of the Art and Critical Gaps:

- Compact, efficient, and rugged narrow-linewidth continuous-wave and pulsed lasers operating between ultraviolet and infrared wavelengths suitable for lidar. Specific wavelengths are of interest to match absorption lines or atmospheric transmission: 290 to 320 nm (ozone absorption), 450 to 490 nm (ocean sensing), 532 nm, 817 nm (water vapor line), 935 nm (water vapor line), 1064 nm, 1550 nm (Doppler wind), 1645 to 1650 nm (methane line), and 3000 to 4000 nm (hydrocarbon lines and ice measurement).
  
  Architectures involving new developments in high-efficiency diode laser, quantum cascade laser, and fiber laser technologies are especially encouraged. 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 spectral absorption applications such as Differential Absorption Lidar or Integrated Path Absorption Lidar a frequency-agile source is required to tune >100 pm on a shot-by-shot basis while maintaining high spectral purity of >1000:1. Laser sources of wavelength at or around 780 nm are not sought this year. Also, laser sources of wavelength at or near 2050 nm are not sought this year. Laser sources for lidar measurements of carbon dioxide are not sought this year.

- Novel approaches and components for lidar receivers such as: integrated optical/photonic circuitry, frequency-agile ultra-narrow-band solar blocking filters at 817 and/or 935 nm, and phased-array or electro-optical beam scanners for large (>10 cm) apertures. Development of telescopes should be submitted to a different subtopic within S2 “Advanced Telescope Technologies,” unless the design is specifically a lidar component, such as a telescope integrated with other optics. Infrared photodetectors involving new semiconductor materials/architectures should be submitted to a different subtopic, S1.04 “Sensor and Detector Technologies for Visible, IR, Far-IR, and Submillimeter,” unless the design is specifically a lidar component, such as a photodetector combined with electronics or optics for lidar application that match wavelength ranges listed for lasers in the above bullet. Receivers for direct-detection wind lidar are not sought this year.

- New 3D mapping and hazard detection lidar with compact and high-efficiency diode and fiber lasers to measure range and surface reflectance of planets or asteroids from >100 km altitude during mapping to <1 m during landing or sample collection, within size, weight, and power fit into a 4U CubeSat or smaller. New lidar technologies 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.

- Transformative technologies and architectures are sought to vastly reduce the cost, size, and complexity of lidar instruments. Advances are needed in generation of high-efficiency and high-pulse energy (>>1 mJ) from compact (SmallSat to CubeSat size) packages, avoiding the long cavity lengths associated with current solid-state laser transmitter designs. Mass-producible laser designs, perhaps by a hybrid diode/fiber/crystal architecture, are desirable for affordable sensor solutions and reducing parts count. Heat removal from lasers is a persistent problem, requiring new technologies for thermal management of laser transmitters. New materials concepts could be of interest for the reduction of weight for optical benches and subcomponents. Novel low-SWaP (size, weight, and power) electrical systems are of interest for data acquisition from multipixel linear mode photon detector arrays in future multichannel lidar receivers, capable of fast waveform capturing, onboard signal processing, and data compression.

Relevance / Science Traceability:

The proposed subtopic addresses missions, programs, and projects identified by the Science Mission Directorate,
including:

- Atmospheric Water Vapor—Profiling of tropospheric water vapor supports studies in weather and dynamics, radiation budget, clouds, and aerosols 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.
- Automated Landing, Hazard Avoidance, and Docking—Technologies to aid spacecraft and lander maneuvering and safe operations.

References:

- NASA missions are aligned with the National Research Council's decadal surveys, with the latest survey on earth science published in 2018 under the title “Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space”: http://sites.nationalacademies.org/DEPS/esas2017/index.htm [1]
- Description of NASA lidar instruments and applications can be found at: https://science.larc.nasa.gov/lidar/ [3]  

S1.02 Technologies for Active Microwave Remote Sensing

Lead Center: GSFC

Participating Center(s): GSFC

Scope Title:

High-Efficiency Solid-State Power Amplifiers

Scope Description:

This subtopic supports technologies to aid NASA in its active microwave sensing missions. 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.
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.

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: Provide research and analysis to advance scope concept as a final report.

Phase II: Design and simulation of 1-kW S-/L-band amplifiers with >50% PAE, with prototype.

State of the Art and Critical Gaps:

Surface Deformation and Change is strongly desired for Earth remote sensing, for land use, natural hazards, and disaster response. NASA-ISRO Synthetic Aperture Radar (NISAR) is a Flagship-class mission, but 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 postrelaxation. 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.

Relevance / Science Traceability:

Surface Deformation and Change science is a continuing Decadal Survey topic, and follow-ons to the science desired for NISAR mission are already in planning. Cloud, water, and precipitation measurements increase capability of measurements to smaller particles and enable much more compact instruments.

References:

Scope Title:

Deployable Antenna Technologies

Scope Description:

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, an approximately 5- to 6-MHz band, with an approximately 85- to 95-MHz band. Designs need to be temperature tolerant; that is, not changing performance parameters drastically over flight temperature ranges of ~100 °C.

High-frequency (V-band) deployable antennas for SmallSats and CubeSats: Small format, deployable antennas are desired (for 65 to 70 GHz) with an aperture size of ~1 m² 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 at 70 GHz are 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

Desired Deliverables Description:

For both antenna types (low and high frequency) a paper design is desired for Phase I, and a prototype for Phase II. Concepts and prototypes for targeted advances in deployment technologies are welcome and do not need to address every need for mission-ready hardware.

State of the Art and Critical Gaps:

Low-frequency antennas, per physics, are large, and so are deployable, even for large spacecraft. For Small/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 Small/CubeSat form factors.

High-frequency antennas can often be hosted without deployment, but a ~1-m²-diameter
antenna on a Small/CubeSat is required to be deployable. 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.

Relevance / Science Traceability:

Low-frequency-band 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 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, [9]

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

References:

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

- MARSIS: [https://mars.nasa.gov/express/mission/sc_science_marsis01.html](https://mars.nasa.gov/express/mission/sc_science_marsis01.html) [11]

For high-frequency deployable, see similar, but lower frequency mission:


Scope Title:

Steerable Aperture Technologies

Scope Description:

Technologies enabling low-mass steerable technologies, especially for L or S bands—including, but not limited to—antenna or radio-frequency (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/m² (or less) with a minimum aperture of 12 m².

Examples of different electronics solutions include completely integrated TR (transmit/receive) 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:

Phase I: A paper study with analysis.
Phase II: Prototype of subcomponent.

State of the Art and Critical Gaps:

No technology currently exists for such low mass density for steerable arrays.

Relevance / Science Traceability:

Surface Deformation and Change science is a key Earth Science Decadal Survey topic.

References:

NISAR follow-on and Surface Deformation:

- [https://science.nasa.gov/earth-science/decadal-sdc](https://science.nasa.gov/earth-science/decadal-sdc) [5]

Scope Title:

Low-Power W-Band Transceiver

Scope Description:

Require 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 for 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 until later. For ocean worlds around Jupiter, bounding (worse 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 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:
Desired Deliverables Description:

Phase I: Paper study/design.
Phase II: Prototype.

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.

Relevance / Science Traceability:

- [https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19710011019.pdf](https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19710011019.pdf) [14]

References:

Missions for atmospheric science and altimetry applications:

• Low-noise receivers at frequencies up to 1 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.

**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
- Research
- Analysis
- Software

**Desired Deliverables Description:**

Research, analysis, software, or hardware prototyping of novel components or methods to improve the performance of passive microwave remote sensing.

- Depending on the complexity of the proposed work, Phase I deliverables may include a prototype system or a study.
- Phase II deliverables should include a prototype component or system with test data verifying functionality.

**State of the Art and Critical Gaps:**

Depending on frequency, current passive microwave remote-sensing instrumentation is limited in sensitivity (as through system noise, 1/f noise, or calibration uncertainty), resolution, or in SWaP. Critical gaps depend on specific frequency and application.

**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.

**References:**


**Scope Title:**

**Photonic Systems for Microwave Remote Sensing**

**Scope Description:**

Photonic systems are an emerging technology for passive microwave remote sensing. This topic solicits photonic systems and subsystems to process microwave signals for passive remote sensing applications. Example applications include spectrometers, beam-forming arrays, correlation arrays, oscillators, noise sources, and other active or passive microwave instruments. Proposals should compare predicted performance and size, weight, and power (SWaP) to conventional radio frequency and digital processing methods. Proposers for specific Photonic
Integrated Circuit (PIC) technology should instead see related STTR subtopic T8.02.

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:
Photonic systems to enable increased capability in passive microwave remote sensing instruments. This is a low-TRL emerging technology, so offerors are encouraged to identify and propose designs where photonic technology would be most beneficial.

- Depending on the complexity of the proposed work, Phase I deliverables may include a prototype system or a study.
- Phase II deliverables should include a prototype component or system with test data verifying functionality.

State of the Art and Critical Gaps:
The state of the art is currently the use of conventional microwave electronics for frequency conversion and filtering. Photonic systems for microwave remote sensing are an emerging technology not used in current NASA microwave missions, but they may enable significant increases in bandwidth or reduction in SWaP.

Relevance / Science Traceability:
Photonic systems may enable significantly increased bandwidth of Earth viewing, astrophysics, and planetary science missions. In particular, this may allow for increased bandwidth or resolution receivers, with applications such as hyperspectral radiometry.

References:

- Ulaby, Fawwaz; and Long, David: Microwave radar and radiometric remote sensing, Artech House, 2015.

Scope Title:
Spectrometer Processing Technology for Microwave Radiometers

Scope Description:
Microwave spectrometry is used for characterizing radiances over absorption spectra and for mitigating radio-frequency interference (RFI). NASA requires technology for low-power, rad-tolerant broad-band microwave spectrometers. Possible Implementations could include:

- Digitizers starting at 20 Gsps, 20 GHz bandwidth, 4 or more bit. and simple interface to a field-programmable gate array (FPGA).
- Application-specific integrated circuit (ASIC) implementations of polyphase spectrometer digital signal processing with ~1 W/GHz; 10 GHz bandwidth polarimetric-spectrometer with 1,024 channels; Radiation-
hardened and minimized power dissipation.

- Analog or photonic spectrum processors with size, weight, and power (SWaP) or performance advantages over digital technology.

**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:**

- Analysis
- Prototype
- Hardware

**Desired Deliverables Description:**

The desired deliverable of this Subtopic Scope is a low-power spectrometer for application-specific integrated circuit (ASIC) or other component that can be incorporated into multiple NASA radiometers.

- Depending on the complexity of the proposed work, Phase I deliverables may include a prototype system or a study.
- Phase II deliverables should include a prototype component or system with test data verifying functionality.

**State of the Art and Critical Gaps:**

Current FPGA-based spectrometers require ~10 W/GHz and are not flight qualifiable. High-speed digitizers exist but have poorly designed output interfaces. Specifically designed ASICs could reduce this power by a factor of 10, but pose challenges in design and radiation tolerance. A low-power solution could be used in a wide range of NASA remote-sensing applications.

**Relevance / Science Traceability:**

Broadband spectrometers are required for Earth-observing, planetary, and astrophysics missions. Improved digital spectrometer capability is directly applicable to planetary science and enables radio-frequency interference (RFI) mitigation for Earth science.

**References:**


**Scope Title:**

**Deployable Antenna Apertures at Frequencies up to Millimeter-Wave**

**Scope Description:**

Deployable antenna apertures are required for a wide range of NASA passive remote-sensing applications from SmallSat platforms. Current deployable antenna technology is extremely limited above Ka-band. NASA requires low-loss deployable antenna apertures at frequencies up to 200 GHz. Deployed aperture diameters of 0.5 m or larger are desired, but proposers are invited to propose concepts for smaller apertures at higher frequencies.

NASA also requires low-loss broad-band deployable or compact antenna feeds with bandwidths of two octaves.
Frequencies of interest start at 500 MHz. Loss should be as low as possible (less than 1%). The possibility of active thermal control is desired to improve system calibration stability.

**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:**

- Analysis
- Prototype
- Hardware

**Desired Deliverables Description:**

Phase I deliverables should consist of analysis and potential prototyping of key enabling technologies.

Phase II deliverables should include a deployable antenna prototype.

**State of the Art and Critical Gaps:**

Current low-loss deployable antennas are limited to Ka-band. Deployable apertures at higher frequencies are required for a wide range of applications, as aperture size is currently a instrument size, weight, and power (SWaP) driver for many applications up to 200 GHz.

**Relevance / Science Traceability:**

Antennas at these frequencies are used for a wide range of passive and active microwave remote sensing, including measurements of water vapor and temperature.

**References:**

- Passive remote sensing such as performed by the Global Precipitation Mission (GPM) Microwave Imager (GMI): [https://gpm.nasa.gov/missions/GPM/GMI](https://gpm.nasa.gov/missions/GPM/GMI) [17]

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**S1.04 Sensor and Detector Technologies for Visible, Infrared (IR), Far-IR, and Submillimeter**

**Lead Center:** GSFC

**Participating Center(s):** ARC, GSFC, LaRC

**Scope Title:**

**Sensor and Detector Technologies for Visible, Infrared (IR), Far-IR, and Submillimeter**

**Scope Description:**

NASA is seeking new technologies or improvements to existing technologies to meet the detector needs of future missions, as described in the most recent decadal surveys:
• Earth Science and Applications from Space: http://www.nap.edu/catalog/11820.html (link is external) [18]
• New Frontiers in the Solar System: http://www.nap.edu/catalog/10432.html (link is external) [19]
• Astronomy and Astrophysics in the New Millennium: http://www.nap.edu/books/0309070317/html/(link is external) [20]

Please note:

1. Technologies for visible detectors are not being solicited this year.

2. Proposers should direct proposals to S1.01 for technologies that don’t address fundamental photodetection process improvements, (i.e., improvement in detection efficiency, excess noise, dark count rate, gain characteristics, afterpulsing, etc.), but instead focus on lidar-only solutions for detection and readout technologies not widely applicable to other fields. Please see the S1.01 scope for further clarification on what is being solicited.

LOW-POWER AND LOW-COST READOUT INTEGRATED ELECTRONICS

• Photodiode Arrays: In-pixel Digital Readout 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 Detector/Transition-Edge Sensor (MKID/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 TESs per pixel within a 1 mm² spacing. The wafer-scale readout of interest will be capable of being indium-bump bonded directly to 2D arrays of membrane bolometers. We require row and column readout with very low crosstalk, low read noise \( \lambda \), and low detector noise-equivalent power degradation.

• Thermopile Detector Arrays: Mars Climate Sounder (MCS), the Diviner Lunar Radiometer Experiment (DLRE), and the Polar Radiant Energy in the Far Infrared Experiment (PREFIRE) are NASA space-borne radiometers that utilize custom thermopile detector arrays. Next-generation radiometers will use larger format thermopile detector arrays, indium bump bonding to hybridize the detector arrays to the Readout Integrated Circuits (ROICs), low input-referred noise, and low power consumption. ROICs compatible with 128×64 element Bi-Sb-Te thermopile arrays with low 1/f noise, an operating temperature between 200 and 300 K, radiation hardness to 300 krad, and on-ROIC analog-to-digital converter (ADC) will be desirable.

LIDAR DETECTORS

• Enhanced photon detection efficiency (PDE), low excess noise, low dark noise, radiation-tolerant detectors for space-based 1.064-µm cloud profiling lidar applications. Detector should operate at a noncryogenic temperature. Solutions could include patterned/black silicon and III-V materials, but should optimize for signal-to-noise ratio in the ~3.7 fW to 190 nW optical power range (~2×10⁴ to 1×10¹² photons/sec) at 1.064 µm. Architectures might include massively parallel, fast-photon counting arrays of diodes operated in Geiger mode, or avalanche photodiodes (APDs) operated in linear mode with higher PDE than existing silicon APDs (PDE > 40%), but with a comparable or lower excess noise factor (ENF < 3). Improved absorption of
1.064 µm than bulk silicon is desired for better radiation tolerance and lower noise. A timing resolution of 67 ns (~10 m) is desired for atmospheric profiling, but resolutions of 1 ns (~15 cm) or better would make this detector more widely applicable to hard target ranging in areas such as planetary surface mapping, and vegetation/canopy lidar. Sensitivity of such a detector to the near-IR from 800 to 950 nm would also enable high-precision atmospheric profiling of key trace gases such as water vapor.

IR & Far-IR/SUBMILLIMETER-WAVE DETECTORS

- **Novel Materials and Devices:** New or improved technologies leading to measurement of trace atmospheric species (e.g., CO, CH₄, N₂O) or broadband energy balance in the IR and far-IR from geostationary and low-Earth orbital platforms. Of particular interest are new direct detector or heterodyne detector technologies made using high-temperature superconducting films (YBCO, MgB₂) or engineered semiconductor materials, especially 2D electron gas (2DEG) and quantum wells (QW).

- **Array Receivers:** Development of a robust wafer-level packaging/integration technology that will allow high-frequency-capable interconnects and allow two dissimilar substrates (i.e., silicon and GaAs) to be aligned and mechanically 'welded' together. Specially develop ball grid and/or through-silicon via (TSV) technology that can support submillimeter-wave (frequency above 300 GHz) arrays. Compact and efficient systems for array receiver calibration and control are also needed.

- **Receiver Components:** Local oscillators capable of spectral coverage 2 to 5 THz; Output power up to >2 mW; frequency agility with >1 GHz near chosen THz frequency; 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) will be needed. Components and devices such as mixers, isolators, and orthomode transducers, working in the terahertz range, that enable future heterodyne array receivers are also desired. GaN-based power amplifiers at frequencies above 100 GHz and with power-added efficiency (PAE) > 25% are also needed. 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.

**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:**
For Phase I activities the deliverables are nominally feasibility studies, detailed design, or determination of the trade space and detailed optimization of the design, as described in a final report. In some circumstances simple prototype models for the hardware can be demonstrated and tested.

For Phase II studies a working prototype that can be tested at one of the NASA centers is highly desirable.

**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 ROICs available on the market. Without these, high-density, large-format IR arrays such as quantum well infrared photodetectors, HgCdTe, and strained-layer superlattice would not exist. The Moore's Law corollary for pixel count describes the number of pixels for the digital camera industry as growing in an exponential manner over the past several decades, and the trend is continuing. The future of long-wave detectors is moving toward tens of thousands of pixels and beyond. Readout circuits capable of addressing their needs do not exist, and without them the astronomical community will not be able to keep up with the needs of the future. These technology needs must be addressed now, or we are at risk of being unable to meet the science requirements of the future.
Commercially available 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 5x to 10x the quantum limit in the submillimeter-wave range while operating at 30 to 77 K are an improvement in the state of the art due to 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. Novel superconducting material such a MgB_2 can provide significant enhancement of up to 9 GHz intermediate frequency (IF) bandwidth.

Cryogenic Low Noise Amplifiers (LNAs) in the 4 to 8 GHz bandwidth with thermal stability are needed for focal plane arrays, Origins Space Telescope (OST) instruments, Origins Survey Spectrometers (OSS), MKIDs, far-IR imager and polarimeters (FIPs), Heterodyne Instrument on OST (HERO), and the Lynx Telescope. 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.

Cryogenic readout circuits are analogous to semiconductor ROICs operating at much higher temperatures. We can produce millions-of-pixel detector arrays 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 quantum well infrared photodiode, HgCdTe, and strained-layer superlattice would not exist.

For lidar detectors, extended-wavelength InGaAs detector/preamplifier packages operating at 2- to 2.1-μm wavelengths with high quantum efficiency (>90%) operating up to about 1 GHz bandwidth are available, as are packages operating up to about 10 GHz with lower quantum efficiency. Detectors that have >90% quantum efficiency over the full bandwidth from near DC to >5 GHz and capable of achieving near-shot-noise limited operation are not currently available.

Relevance / Science Traceability:

- Future short-, 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).
- Aerosol spaceborne lidar as identified by 2017 decadal survey to reduce uncertainty about climate forcing in aerosol-cloud interactions and ocean ecosystem carbon dioxide uptake. Additional applications in planetary surface mapping, vegetation, and trace-gas lidar.
- Earth radiation budget measurement per 2007 decadal survey Clouds and Earth’s Radiant Energy System (CERES) Tier-1 designation to maintain the continuous radiation budget measurement for climate modeling and better understand radiative forcings.
- Astrophysical missions such as 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.
- Current science missions utilizing 2D, large-format cryogenic readout circuits:
  1. HAWC + (High Resolution Airborne Wideband Camera Upgrade) for SOFIA (Stratospheric Observatory for Infrared Astronomy) future missions:
     - PIPER (Primordial Inflation Polarization Experiment), balloon-borne.
     - PICO (Probe of Inflation and Cosmic Origins), a probe-class cosmic microwave background mission
concept.

- Lidar detectors are needed for 3D wind measurements from space.

References:

- Characterization of Kilopixel TES detector arrays for PIPPER," Bibliographic link: http://adsabs.harvard.edu/abs/2018AAS...23115219D [22]

S1.05 Detector Technologies for Ultraviolet (UV), X-Ray, Gamma-Ray Instruments

Lead Center: GSFC

Participating Center(s): GSFC, MSFC

Scope Title:

Detectors

Scope Description:

This subtopic covers detector requirements for a broad range of wavelengths.
from UV through to gamma ray for applications in Astrophysics, Earth Science, Heliophysics, and Planetary Science. Requirements across the board are for greater numbers of readout pixels, lower power, faster readout rates, greater quantum efficiency, single photon counting, and enhanced energy resolution. The proposed efforts must be directly linked to a requirement for a NASA mission. These include Explorers, Discovery, Cosmic Origins, Physics of the Cosmos, Solar-Terrestrial Probes, Vision Missions, and Earth Science Decadal Survey missions. Proposals should reference current NASA missions and mission concepts where relevant. Specific technology areas are:

- **Large-format, solid-state single-photon-counting radiation-tolerant detectors in charge-coupled device (CCD) or complementary metal-oxide-semiconductor (CMOS) architecture—including 3D stacked architecture—for astrophysics, planetary, and UV heliophysics missions.**
- **Solid-state detectors with polarization sensitivity relevant to astrophysics as well as planetary and Earth science applications, for example, in spectropolarimetry as well as air quality and aerosol monitoring.**
- **UV detectors for \( \text{O}_3, \text{NO}_2, \text{SO}_2, \text{H}_2\text{S}, \text{and ash detection. Refer to National Research Council's Earth Science Decadal Survey (2018).} \)**
- **Significant improvement in wide-band-gap semiconductor materials (such as AlGaN, ZnMgO, and SiC), individual detectors, and detector arrays for astrophysics missions and planetary science composition measurements. For example, SiC avalanche photodiodes (APDs) must show:**
  - Extreme-UV (EUV) photon counting, a linear mode gain >10×10\(^6\) at a breakdown reverse voltage between 80 and 100 V;
  - Detection capability of better than 6 photons/pixel/s down to 135 nm wavelength.
- **Solar-blind (visible-blind) UV, far-UV (80 to 200 nm), and 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.**
- **UV detectors suitable for upcoming ultra-high-energy cosmic ray (UHECR) mission concepts.**
- **Solar x-ray detectors with small independent pixels (10,000 count/s/pixel) over an energy range from <5 to 300 keV.**
- **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 to 100 \(\mu\)m, and ways to read out the signals. For example, modular superconducting magnetic shielding is sought that can be extended to enclose a full-scale focal plane array. All joints between segments of the shielding enclosure must also be superconducting. Improved long-wavelength blocking filters are needed for large-area, x-ray microcalorimeters.**
- **Filters with supporting grids are sought that, in addition to increasing filter strength, also enhance 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 infrared transmissions less than 0.01% and**
ultraviolet transmission of less than 5% per filter. A means of producing filter diameters as large as 10 cm should be considered.

- Detectors with fast readout that can support high count rates and large incident flux from the EUV and x-rays for heliophysics applications, especially solar-flare measurements.

**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 deliverables: results of tests and analysis of designs, as described in a final report.

Phase II deliverables: prototype hardware or hardware for further testing and evaluation is desired.

**State of the Art and Critical Gaps:**

This subtopic aims to develop and advance detector technologies focused on UV, x-ray, and gamma ray spectral ranges. The science needs in this range span a number of fields, focusing on astrophysics, planetary science, and UV heliophysics. A number of solid-state detector technologies promise to surpass the traditional image-tube-based detectors. Silicon-based detectors leverage enormous investments and promise high-performance detectors, while more complex material such as gallium nitride and silicon carbide offer intrinsic solar blind response. This subtopic supports efforts to advance technologies that significantly improve the efficiency, dynamic range, noise, radiation tolerance, spectral selectivity, reliability, and manufacturability in detectors.

**Relevance / Science Traceability:**

Missions under study: Large Ultraviolet Optical Infrared Surveyor (LUVOIR), Habitable Exoplanet Observatory (HabEx), Lynx, New Frontier-IO, Discovery-IVO

- Habitable Exoplanet Observatory (HabEx): [https://www.jpl.nasa.gov/habex/](https://www.jpl.nasa.gov/habex/) [27]
- The LYNX Mission Concept: [https://wwwastro.msfc.nasa.gov/lynx/](https://wwwastro.msfc.nasa.gov/lynx/) [28]
- NASA Astrophysics: [https://science.nasa.gov/astrophysics/](https://science.nasa.gov/astrophysics/) [29]

**References:**
S1.06 Particles and Fields Sensors and Instrument Enabling Technologies

Lead Center: GSFC

Participating Center(s): JPL, MSFC

Scope Title:

Particles and Fields Sensors and Instrument Enabling Technologies

Scope Description:

The 2013 National Research Council’s "Solar and Space Physics: A Science for a Technological Society" motivates this subtopic: “Deliberate investment in new instrument concepts is necessary to acquire the data needed to further solar and space physics science goals, reduce mission risk, and maintain an active and innovative hardware development community.” This subtopic solicits development of advanced in-situ instrument technologies and components suitable for deployment on heliophysics missions. Advanced sensors for the detection of elementary particles (atoms, molecules, and their ions) and electric and magnetic fields in space 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 atmospheric composition of the planets and their moons. These technologies must be capable of withstanding operation in space environments, including the expected pressures, radiation levels, launch and impact stresses, and range of survival and operational temperatures. Technology developments that result in a reduction of mass, power, volume, and data rates for instruments and instrument components without loss of scientific capability are of particular importance.
In addition, technologies that can increase instrument resolution and sensitivity or achieve new and innovative scientific measurements are solicited.

Improvements in particles and fields sensors and associated instrument technologies enable further scientific advancement for upcoming NASA missions such as CubeSats, Explorers, Solar Terrestrial Probe (STP), Living With a Star (LWS), and planetary exploration missions. Specifically, this year the subtopic solicits instrument development that provides significant advances in the following areas:

- Faraday cup: 2-kHz alternating-current (AC) power supply with direct-current (DC) offset up to 40 kV and AC peak-to-peak at 10% of DC offset, operating temperature range -35 to +55 °C, and radiation hardness >1 ~ 200 krad.
- Magnetically clean >2 m compact deployable booms for CubeSats.
- Innovative high-efficiency neutral particle ionizers based on thermionic, cold electron emission, or ultraviolet (UV) ionization.
- Direct neutral particle detectors to energies <1 eV.

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.

**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  

**Desired Deliverables Description:**

**Phase I deliverables:** Concept study report, preliminary design, and test results.  
**Phase II deliverables:** Detailed design, prototype test results, and a prototype deliverable with guidelines for in-house integration and test (I&T).

**State of the Art and Critical Gaps:**

**High-Voltage Power Supplies DC and AC:**

Low-energy particle instruments often require significant high-voltage DC power supplies up to 40 kV. Some applications such as Faraday cups require sine wave power supplies with a DC offset 0 to 40 kV and AC peak-to-peak at 10% of DC offset at oscillating frequency of 2 kHz, an operating temperature range from -35 to +55 °C, and radiation hardness >1 ~ 200 krad.

Importance: – Critical need for next-generation Faraday cups in order to extend the upper limit of solar wind speed measurement to >2,500 km/sec. Current Faraday cup high-voltage (HV) power supplies support maximum solar wind speeds of up to 1,500 km/sec. Very important for future space weather missions.

Existing direct neutral particle detectors are not capable of detecting, without ionization, neutral particles with energy <1 eV.
There is a need for nonthermionic ionizers to reduce power dissipation.

There is a need for magnetically clean, small booms for CubeSat magnetometers.

**Relevance / Science Traceability:**

Particles and fields instruments and technologies are essential bases to achieve SMD's Heliophysics goals summarized in the National Research Council’s, Solar and Space Physics: A Science for a Technological Society. In situ instruments and technologies play indispensable roles for NASA’s LWS and STP mission programs, as well as a host of smaller spacecraft in the Explorers Program. In addition, there is growing demand for particles and fields technologies amenable to CubeSats and SmallSats. NASA SMD has two excellent programs to bring this subtopic technologies to higher level: Heliophysics Instrument Development for Science (H-TIDeS) and Heliophysics Flight Opportunities for Research and Technology (H-FORT). H-TIDeS seeks to advance the development of technologies and their application to enable investigation of key heliophysics science questions. This is done through incubating innovative concepts and development of prototype technologies. It is intended that Page 2 of 3 technologies developed through H-TIDeS would then be proposed to H-FORT to mature by demonstration in a relevant environment. The H-TIDeS and H-FORT programs are in addition to Phase III opportunities. Further opportunities through SMD include Explorer Missions, New Frontiers Missions, and the upcoming Geospace Dynamic Constellation.

**References:**

- For example missions, see: [http://science.nasa.gov/missions](http://science.nasa.gov/missions) [38] (e.g., NASA Magnetospheric Multiscale (MMS) mission, Fast Plasma Instrument).
- For details of the specific requirements, see the National Research Council’s Solar and Space Physics: A Science for a Technological Society, [http://nap.edu/13060](http://nap.edu/13060) [39]

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**S1.07 In Situ Instruments/Technologies for Lunar and Planetary Science**

Lead Center: GSFC

Participating Center(s): ARC, GRC, GSFC, MSFC

**Scope Title:**

In Situ Instruments/Technologies for Planetary Science

**Scope Description:**

This subtopic solicits development of advanced instrument technologies and components suitable for deployment on in situ planetary and lunar missions. These technologies must be capable of withstanding operation in space and planetary
environments, including the expected pressures, radiation levels, launch and impact stresses, and range of survival and operational temperatures. Technologies that reduce mass, power, volume, and data rates for instruments and instrument components without loss of scientific capability are of particular importance—for both conventional missions as well as for small-satellite missions. In addition, technologies that can increase instrument resolution and sensitivity or achieve new and innovative scientific measurements are solicited. For examples of NASA science missions, see [https://science.nasa.gov/missions-page](https://science.nasa.gov/missions-page) [40]. For details of the specific requirements see the National Research Council report “Vision and Voyages for Planetary Science in the Decade 2013-2022” ([http://solarsystem.nasa.gov/2013decadal/](http://solarsystem.nasa.gov/2013decadal/)), hereafter referred to as the Planetary Decadal Survey. Of particular interest are technologies to support future missions under the New Frontiers and Discovery programs.

Specifically, this subtopic solicits instrument development that provides significant advances in the following areas, broken out by planetary body:

- **Mars:**
  - Subsystems relevant to current in situ instrument needs (e.g., lasers and other light sources from UV to microwave, x-ray and ion sources, detectors, mixers, mass analyzers, and front-end ion/neutrals separation/transport technologies, etc.) or electronics technologies (e.g., field-programmable gate array (FPGA) and application-specific integrated circuit (ASIC) implementations, advanced array readouts, miniature high-voltage power supplies).
  - Technologies that support high-precision in situ measurements of the elemental, mineralogical, and organic composition of planetary materials.
  - Conceptually simple, low-risk technologies for in situ sample extraction and/or manipulation including fluid and gas storage, pumping, and chemical labeling to support analytical instrumentation.
  - Seismometers, mass analyzers, technologies for heat flow probes, and atmospheric trace gas detectors. Improved robustness and g-force survivability for instrument components, especially for geophysical network sensors, seismometers, and advanced detectors (intensified charge-coupled devices (iCCDs), photomultiplier tube (PMT) arrays, etc.).
  - Instruments geared towards rock/sample interrogation prior to sample return. Sensors to measure dimensions of laser ablation pits in natural rock samples with unprepared rough surfaces to support geochronology measurements on rock samples collected by a rover (spatial and depth resolution of 10 µm or better from a working distance of tens of centimeters desired to characterize ~1-mm-deep by ~0.5-mm-wide pits).

- **Venus:**
  - Sensors, mechanisms, and environmental chamber technologies for operation in Venus's high-temperature, high-pressure environment with its unique atmospheric composition.
  - Approaches that can enable precision measurements of surface mineralogy and elemental composition and precision measurements of trace species, noble gases, and isotopes in the atmosphere.
• Small bodies:
  - Technologies that can enable sampling from asteroids and from depth in a comet nucleus, improved in situ analysis of comets.
  - Imagers and spectrometers that provide high performance in low light environments.
  - Dust environment measurements and particle analysis, small body resource identification, and/or quantification of potential small-body resources (e.g., oxygen, water, and other volatiles; hydrated minerals; carbon compounds; fuels; metals; etc.).
  - Advancements geared towards instruments that enable elemental or mineralogy analysis (such as high-sensitivity x-ray and UV-fluorescence spectrometers, UV/fluorescence systems, scanning electron microscopy with chemical analysis capability, mass spectrometry, gas chromatography and tunable diode laser sensors, calorimetry, imaging spectroscopy, and laser-induced breakdown spectroscopy (LIBS).

• Saturn, Uranus, and Neptune and their moons:
  - Components, sample acquisition, and instrument systems that can enhance mission science return and withstand the low temperatures/high pressures of the atmospheric probes during entry. Note that in situ instruments and components focused on ocean worlds life detection are specifically solicited in S1.11 and are encouraged to be submitted to S1.11.

• The Moon:
  - This topic seeks advancement of concepts and components to develop a Lunar Geophysical Network as envisioned in the Planetary Decadal Survey. Understanding the distribution and origin of both shallow and deep moonquakes will provide insights into the current dynamics of the lunar interior and its interplay with external phenomena (e.g., tidal interactions with Earth). The network is envisioned to comprise multiple free-standing seismic stations that would operate over many years in even the most extreme lunar temperature environments.
  - Technologies to advance all aspects of the network including sensor emplacement, power, and communications in addition to seismic, heat flow, magnetic field and electromagnetic sounding sensors are desired.
  - This topic also seeks technologies for quantifying lunar water and measuring the D/H ratio in lunar water. Several evidences point to the presence of water ice at cold spots in the permanently shadowed regions at the lunar poles, with estimated abundance of ~5 to 10 wt%.

Novel instrument concepts are encouraged particularly if they enable a new class of scientific discovery. Technology developments relevant to multiple environments and platforms are also desired. Proposers should show an understanding of relevant space science needs and present a feasible plan to fully develop a technology and infuse it into a NASA mission.

**Expected TRL or TRL Range at completion of the Project:** 3 to 5  
**Primary Technology Taxonomy:** 
Level 1: TX 08 Sensors and Instruments
Desired Deliverables of Phase I and Phase II:

- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

The Phase I project should focus on feasibility and proof-of-concept demonstration (TRL 2-3). The required Phase I deliverable is a report documenting 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. The report can include a feasibility assessment and concept of operations, simulations and/or measurements, and a plan for further development to be performed in Phase II.

The Phase II project should focus on component and/or breadboard development with the delivery of specific hardware for NASA (TRL 4-5). Phase II deliverables include a working prototype of the proposed hardware, along with documentation of development, capabilities, and measurements.

State of the Art and Critical Gaps:

In situ instruments and technologies are essential bases to achieve Science Mission Directorate's (SMD's) planetary science goals summarized in the Planetary Decadal Survey. In situ instruments and technologies play an indispensable role for NASA's New Frontiers and Discovery missions to various planetary bodies (Mars, Venus, small bodies, Saturn, Uranus, Neptune, Moon, etc.).

There are currently various in situ instruments for diverse planetary bodies. However, there are ever-increasing science and exploration requirements and challenges for diverse planetary bodies. For example, there is urgent need for exploring RSL (recurring slope lineae) on Mars and plumes from planetary bodies, as well as a growing demand for in situ technologies amenable to small spacecraft.

To narrow the critical gaps between the current state of art and the technology needed for the ever-increasing science/exploration requirements, in situ technologies are being sought to achieve much higher resolution and sensitivity with significant improvements over existing capabilities with lower mass, power, and volume.

Relevance / Science Traceability:

In situ instruments and technologies are essential bases to achieve SMD's planetary science goals summarized in the Planetary Decadal Survey. In situ instruments and technologies play an indispensable role for NASA's New Frontiers and Discovery missions to various planetary bodies.

In addition to Phase III opportunities, SMD offers several instrument development
programs as paths to further development and maturity. These include the Planetary Instrument Concepts for the Advancement of Solar System Observations (PICASSO) Program, which invests in low-TRL technologies and funds instrument feasibility studies, concept formation, proof-of-concept instruments, and advanced component technology, as well as the Maturation of Instruments for Solar System Exploration (MatISSE) Program and the Development and Advancement of Lunar Instrumentation (DALI) Program, which invest in mid-TRL technologies and enable timely and efficient infusion of technology into planetary science missions.

References:

- Li et al.: “Direct evidence of surface exposed water ice in the lunar polar regions,” *PNAS* 115 (2018), 8907-8912, [https://www.pnas.org/content/pnas/115/36/8907.full.pdf](https://www.pnas.org/content/pnas/115/36/8907.full.pdf) [41]

S1.08 Suborbital Instruments and Sensor Systems for Earth Science Measurements

Lead Center: GSFC

Participating Center(s): ARC, GSFC, JPL

Scope Title:

**Sensors and Sensor Systems Targeting Aerosols and Clouds**

Scope Description:

Earth science measurements from space are considerably enhanced by observations from generally far less costly suborbital instruments and sensor systems. These instruments and sensors support NASA’s Earth Science Division (ESD) science, calibration/validation, and environmental monitoring activities by providing ancillary data for satellite calibration and validation, algorithm development/refinement, and finer scale process studies. NASA seeks measurement capabilities that support current satellite and model validation, advancement of surface-based remote-sensing networks, and targeted Airborne Science Program and ship-based field campaign activities as discussed in the Research Opportunities in Space and Earth Science (ROSES) solicitation. Data from such sensors also inform process studies to improve our scientific understanding of the Earth System. In situ sensor systems (airborne, land, and water-based) can comprise stand-alone instrument and data packages; instrument systems configured for integration on ship-based (or alternate surface-based platform) and in-water deployments, NASA’s Airborne Science aircraft fleet or commercial providers, UAS, balloons, ground networks; or end-to-end solutions providing needed data products from mated sensor and airborne/surface/subsurface platforms. An important goal is to create sustainable measurement capabilities to support NASA’s Earth science objectives, with infusion of new technologies and systems into current/future NASA research programs. Instrument prototypes as a
deliverable in Phase II proposals and/or field demonstrations are highly encouraged.

Complete instrument systems are generally desired, including features such as remote/unattended operation and data acquisition as well as minimum size, weight, and power consumption. All proposals must summarize the current state of the art and demonstrate how the proposed sensor or sensor system represents a significant improvement over the state.

Specific desired sensors or mated platform/sensors include:

- Combined aerosol absorption and scattering/extinction of atmospheric aerosols with calibrated accuracy and a particular emphasis on the ultraviolet (UV) or near-UV wavelengths.
- Spectrally resolved aerosol absorption, scattering, or extinction (UV to near-infrared (NIR) wavelengths).
- Aerosol scattering as a function of scattering angle (phase function or, preferably, phase matrix).
- Aerosol complex refractive index.
- Aerosols and cloud particle number and size distribution covering the diameter size range of 0.01 to 200 µm with 10% accuracy. Probes targeting cloud particles in the lower end of this size range (0.01 to 5 µm) are particularly encouraged.
- Cloud probes able to differentiate and quantify nonsphericity and phase of cloud particles.
- Liquid and ice water content in clouds with calibrated accuracy and precision.
- Liquid and ice water path in relevant tropical, midlatitude, and/or polar environments, including data inversion and analysis software.
- Spectrally resolved cloud extinction.
- Static air temperature measured from aircraft to better than 0.1 ºC accuracy.
- A well-calibrated airborne hyperspectral imager with spectral sensitivity in the UV to visible (VIS) (340 to 900 nm; preferably 320 to 1,080 nm) with spectral sampling of at least 2.5 nm, spectral resolution of at least 5 nm, and a wide dynamic range and sensitivity spanning from ocean radiances to cloud radiances for use in comparison to the PACE Ocean Color Instrument and other sensors.
- Portable hyperspectral UV-VIS-NIR (340 to 900 nm; preferably 320 to 1,100 nm) radiometric calibration system with a stabilized optical light source for verification of field radiometer stability by traceable National Institute of Standards and Technology (NIST) standards with variable flux levels. System must include thermal stabilization for the instrument to be independent of the ambient temperature for evaluation of radiometric stability as a function of time.
- Innovative, high-value sensors directly targeting a stated NASA need (including trace gases and ocean) may also be considered. Proposals responding to this specific bullet are strongly encouraged to identify at least one relevant NASA subject matter expert.

**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:

The ideal Phase I proposal would 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 then 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.

The ideal Phase II effort would build, characterize, and deliver a prototype instrument to NASA including necessary hardware and operating software. The prototype would be fully functional, but the packaging may be more utilitarian (i.e., less polished) than a commercial model.

State of the Art and Critical Gaps:

The S1.08 subtopic is and remains highly relevant to NASA Science Mission Directorate (SMD) and Earth Science research programs, in particular the Earth Science Atmospheric Composition, Climate Variability & Change, and Carbon Cycle and Ecosystems focus areas. Suborbital in situ and remote sensors inform NASA ground, ship, and airborne science campaigns led by these programs and provide important validation of the current and next generation of satellite-based sensors (e.g., PACE, OCO-2, TEMPO, SGB, and A-CCP; see links in References). The solicited measurements will be highly relevant to current and future NASA campaigns with objectives and observing strategies similar to past campaigns; e.g., 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).
Relevant Programs and Program Officers include:

- NASA ESD Ocean Biology and Biogeochemistry Program (Paula Bontempi and Laura Lorenzoni, HQ Program Managers)
- NASA ESD Tropospheric Composition Program (Barry Lefer, HQ Program Manager)
- NASA ESD Radiation Sciences Program (Hal Maring, HQ Program Manager)
- NASA ESD Airborne Science Program (Bruce Tagg, HQ Program Manager)

References:

Relevant current and past satellite missions and field campaigns include:

- Decadal Survey Recommended ACCP Mission focusing on aerosols, clouds, convection, and precipitation: [https://science.nasa.gov/earth-science/decadal-surveys](https://science.nasa.gov/earth-science/decadal-surveys) [37]
- TEMPO Satellite Mission focusing on geostationary observations of air quality over North America: [http://tempo.si.edu/overview.html](http://tempo.si.edu/overview.html) [42]
- CAMP2Ex airborne field campaign focusing on tropical meteorology and aerosol science: [https://espo.nasa.gov/camp2ex](https://espo.nasa.gov/camp2ex) [43]
- FIREX-AQ airborne and ground-based field campaign targeting wildfire and agricultural burning emissions in the United States: [https://www.esrl.noaa.gov/csd/projects/firex-aq/](https://www.esrl.noaa.gov/csd/projects/firex-aq/) [44]
- KORUS-AQ airborne and ground-based field campaign focusing on pollution and air quality in the vicinity of the Korean Peninsula: [https://espo.nasa.gov/korus-aq/content/KORUS-AQ](https://espo.nasa.gov/korus-aq/content/KORUS-AQ) [45]
- DISCOVER-AQ airborne and ground-based campaign targeting pollution and air quality in four areas of the United States: [https://discover-aq.larc.nasa.gov/](https://discover-aq.larc.nasa.gov/) [46]
- NAAMES Earth Venture Suborbital field campaign targeting the North Atlantic phytoplankton bloom cycle and impacts on atmospheric aerosols, trace gases, and clouds: [https://naames.larc.nasa.gov](https://naames.larc.nasa.gov) [47]
- ATOM airborne field campaign mapping the global distribution of aerosols and trace gases from pole-to-pole: [https://espo.nasa.gov/atom/content/ATOM](https://espo.nasa.gov/atom/content/ATOM) [48]
- PACE Satellite Mission, scheduled to launch in 2022, that focuses on observations of ocean biology, aerosols, and clouds: [https://pace.gsfc.nasa.gov/](https://pace.gsfc.nasa.gov/) [49]
- EXPORTS field campaign targeting the export and fate of upper ocean net primary production using satellite observations and surface-based measurements: [https://oceanexports.org](https://oceanexports.org) [50]
S1.09 Cryogenic Systems for Sensors and Detectors

Lead Center: GSFC

Participating Center(s): JPL

Scope Title:

Low-Temperature/High-Efficiency Cryocoolers

Scope Description:

NASA seeks improvements to multistage low-temperature spaceflight cryocoolers. Coolers are sought with the lowest temperature stage typically in the range of 4 to 10 K, with cooling power at the coldest stage larger than currently available, and high efficiency. The desired cooling power is application specific, but an example is 0.2 W at 4 K. Devices that produce extremely low vibration, particularly at frequencies below a few hundred hertz, are of special interest. System- or component-level improvements that improve efficiency and reduce complexity and cost are desirable. In addition to the large coolers, there has recently been interest in small, low-power (~10-mW) 4 K coolers. For example, the Origins Space Telescope mission concept includes a cold telescope, requiring cooling to 4 K; and the Lynx X-ray Observatory mission concept requires a state-of-the-art cryogenic system to enable high-precision and high-resolution x-ray spectroscopy.

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: Functioning hardware ready for functional and possibly environmental testing.

State of the Art and Critical Gaps:

Current spaceflight cryocoolers for this temperature range include linear piston-driven Stirling cycle or pulse tube cryocoolers with Joule-Thompson low-temperature stages. One such state-of-the-art cryocooler provides 0.09 W of cooling at 6 K. For large future space observatories, large cooling power and much greater efficiency will be needed. For cryogenic instruments or detectors on instruments with tight point requirements, orders-of-magnitude improvement in the levels of exported vibration will be required. Some of these requirements are laid out in the "Advanced cryocoolers" Technology gap in the latest (2017) Cosmic Origins Program Annual Technology Report.

Relevance / Science Traceability:

Science traceability: Goal 1 and Objective 1.6 of NASA’s Strategic Plan: Goal 1: Expand the frontiers of knowledge, capability, and opportunity in space Objective 1.6: Discover how the universe works, explore how it began and evolved, and search for life on planets around other stars. Low-temperature cryocoolers are listed as a "Technology Gap" in the latest (2017) Cosmic Origins Program Annual Technology Report. Future missions that would benefit from this technology include two of the large missions under study for the 2020 Astrophysics Decadal Survey: Origins Space Telescope and Lynx microcalorimeter instrument.

References:
For more information on the Origins Space Telescope, see: https://asd.gsfc.nasa.gov/firs/ [52]

For more information on LYNX, see: https://wwwastro.msfc.nasa.gov/lynx/docs/science/observatory.html [53]

Scope Title:

Actuators and Other Cryogenic Devices

Scope Description:

NASA seeks devices for cryogenic instruments, including:

- Small, precise motors and actuators, preferably with superconducting windings, that operate with extremely low power dissipation. Devices using standard NbTi conductors, as well as devices using higher temperature superconductors that can operate above 5 K, are of interest.
- Cryogenic heat pipes for heat transport within instruments. Heat pipes using hydrogen, neon, oxygen, argon, and methane are of interest. Length should be at least 0.3 m. Devices that have reduced gravitational dependence and that can be made low profile, or integrated into structures such as radiators, are of particular interest.

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.

State of the Art and Critical Gaps:

Motors and actuators: Instruments often have 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. While heat generation is naturally dependent on the application, an example of a recent case is 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× smaller.

Cryogenic heat pipes: Heat transport in cryogenic instruments is typically handled with solid thermal straps, which do not scale well for larger heat loads. Currently available heat pipes are optimized for temperatures above ~ 20 K. They have limited capacity to operate against a gravitational potential.

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, dissipation in actuators can be a significant design problem.
References:

For more information on earlier low-temperature heat pipes, see:


Scope Title:

Ultra-Lightweight Dewars

Scope Description:

NASA seeks extremely lightweight thermal isolation systems for scientific instruments. An important example is a large cylindrical, open-top dewar to enable large, cold balloon telescopes. In one scenario, such a dewar would be launched warm and so would not need to function at ambient pressure, but at altitude, under ~4 mbar external pressure, it would need to contain cold helium vapor. The ability to rapidly pump and hold a vacuum at altitude is necessary. An alternative concept is that the dewar would be launched at operating temperature, with some or all of the needed liquid helium. In both cases, heat flux through the walls should be less than 0.5 W/m², and the internal surfaces must be leak tight against superfluid helium. Initial demonstration units of greater than 1 m inner diameter and height are desired, but the technology must be scalable to an inner diameter of 3 to 4 m with a mass that is a small fraction of the net lift capability of a scientific balloon (~2,000 kg).

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: Subscale prototypes that demonstrate critical properties of the concept, including scalability and leak-free containment of superfluid helium

Phase II: A working prototype of the scale described is desired.

State of the Art and Critical Gaps:

Currently available liquid helium dewars have heavy vacuum shells that allow them to be operated in ambient pressure. Such dewars have been used for balloon-based astronomy, as in the Absolute Radiometer for Cosmology, Astrophysics, and Diffuse Emission (ARCADE) experiment. However, the current dewars are already near the limit of balloon lift capacity and cannot be scaled up to the required size for future astrophysics measurements.

Relevance / Science Traceability:


The potential for ground-based far-infrared astronomy is extremely limited. Even in airborne observatories, such as SOFIA, observations are limited by the brightness of the atmosphere and the warm telescope itself. However, high-altitude scientific balloons are above enough of the atmosphere that, with a telescope large enough and cold...
enough, background-limited observations are possible. The ARCADE project demonstrated that at high altitudes, it is possible to cool instruments in helium vapor. Development of ultra-lightweight dewars that could be scaled up to large size, yet still be liftable by a balloon would enable ground-breaking observational capability.

References:

For a description of a state-of-the-art balloon cryostat, see:


Scope Title:

Miniaturized/Efficient Cryocooler Systems

Scope Description:

NASA seeks miniature, highly efficient cryocoolers for instruments on Earth and planetary missions. A range of cooling capabilities 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 ?5 W and a total mass of ?400 g is desired. The ability to fit within the volume and power limitations of a SmallSat platform would be highly advantageous. Cryocooler electronics are also sought in two general categories: (1) low-cost devices that are sufficiently radiation hard for lunar or planetary missions, and (2) very low cost devices for a relatively short term (~1 year) in low Earth orbit. The latter category could include controllers for very small coolers, such as tactical and rotary coolers.

For many infrared (IR) spectrometer instrument systems, the spectrometer can operate at a temperature more than 60 K higher than the focal plane array. A miniature two-stage cryocooler is ideal for this type of application to minimize the cooler input power. Therefore, NASA is seeking an innovative miniature two-stage cryocooler technology with low-exported vibrations. The lowest cooling temperature of interest for the lower stage is 80 K, and the maximum cooling power is about 1 W. The cooling temperature of the second stage should be 60 to 80 K higher than the lower stage, and the cooling power should be about 2 W. 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 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 demonstration.

Phase II: Desired deliverables include miniature coolers and components, such as electronics, that are ready for functional and environmental testing.

State of the Art and Critical Gaps:

Present state-of-the-art capabilities provide 0.1 W of cooling capacity with heat rejection at 300 K at approximately 5 W input power with a system mass of 400 g.

Cryocoolers enable the use of highly sensitive detectors, but current coolers cannot operate within the tight power
constraints of outer planetary missions. Cryocooler power could be greatly reduced by lowering the heat rejection temperature, but presently there are no spaceflight systems that can operate with a heat rejection temperature significantly below ambient.

**Relevance / Science Traceability:**


NASA is moving toward the use of small, low-cost satellites to achieve many of its Earth science—and some of its planetary—science goals. The development of cryocoolers that fit within the size and power constraints of these platforms will greatly expand their capability, for example, by enabling the use of infrared detectors.

In planetary science, progress on cryogenic coolers will enable the use of far- to mid-infrared sensors with orders-of-magnitude improvement in sensitivity for outer planetary missions. These will allow thermal mapping of outer planets and their moons.

**References:**

- An example of CubeSat mission using cryocoolers is given at: [https://www.jpl.nasa.gov/cubesat/missions/ciras.php](https://www.jpl.nasa.gov/cubesat/missions/ciras.php) [57]

**Scope Title:**

Sub-Kelvin Cooling Systems

**Scope Description:**

Future NASA missions will require requiring sub-Kelvin coolers for extremely low temperature detectors. Systems are sought that will provide continuous cooling with high cooling power (>5 mW at 50 mK), low operating 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:

1) 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/mm².
- A field/current ratio of >0.33 T/A, and preferably >0.66 T/A.
- Low hysteresis heating.
- Bore size between 22 and 60 mm, depending on the application.

2) Lightweight active/passive magnetic shielding (for use with 4-T magnets) with low hysteresis and eddy current losses as well as low remanence. Also needed are lightweight, highly effective outer shields that reduce the field outside an entire multistage device to <5 µT. Outer shields must operate at 4 to 10 K and must have penetrations for low-temperature, noncontacting heat straps.

3) Heat switches with on/off conductance ratio >30,000 and actuation time of <10 s. Materials are also sought for gas gap heat switch shells: these are tubes with extremely low thermal conductance below 1 K; they must be impermeable to helium gas, have high strength, have stability against buckling, and have an inner diameter >20 mm.

4) High cooling power density magnetocaloric materials. Examples of desired materials include GdLiF₄, Yb₃Ga₅O₁₂, GdF₃, 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. Volume must be >40 cm³.
5) 10 to 300 mK high-resolution thermometry.

6) Suspensions with the strength and stiffness, 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.

**State of the Art and Critical Gaps:**

The adiabatic demagnetization refrigerator in the Soft X-ray Spectrometer instrument on the Hitomi mission represents the state of the art in spaceflight sub-Kelvin cooling systems. The system is a 3-stage, dual-mode device. In the more challenging mode, it provides 650 µW of cooling at 1.625 K, while simultaneously absorbing 0.35 µW from a small detector array at 0.050 K. It rejects heat at 4.5 K. In this mode, the detector is held at temperature for 15.1-h periods, with a 95% duty cycle. Future missions with much larger pixel count will require much higher cooling power at 0.050 K or lower, higher cooling power at intermediate stages, and 100% duty cycle. Heat rejection at a higher temperature is also needed to enable the use of a wider range of more efficient cryocoolers.

**Relevance / Science Traceability:**

Science traceability: NASA Strategic plan 2018, Objective 1.1: Understand The Sun, Earth, Solar System, And Universe


Future missions that would benefit from this technology include two of the large missions under study for the 2020 Astrophysics Decadal Survey:
- Origins Space Telescope (contact: michael.j.dipirro@nasa.gov [58])
- LYNX (microcalorimeter instrument) (contact: simon.r.bandler@nasa.gov [59])

Also: Probe of Inflation and Cosmic Origins, POC: Shaul Hanany, University of Minnesota

**References:**

For a description of the state-of-the-art sub-Kelvin cooler in the Hitomi mission, see:


For articles describing magnetic sub-Kelvin coolers and their components, see the July 2014 special issue of Cryogenics:
S1.10 Atomic Quantum Sensor and Clocks

Lead Center: GSFC

Participating Center(s): GSFC

Scope Title:

Atomic Quantum Sensor and Clocks

Scope Description:

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, Rydberg atom sensors, and artificial-atom-based sensors such as nitrogen-vacancy (NV) center point-defect sensors, etc.).

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 $10^{18}$. These optical clocks can be used, in turn, as precision sensors; for example, sensitivity to the fundamental physics constants have been explored for detection of dark matter and time variations in those fundamental constants. These approaches, when made Doppler sensitive, become exquisite inertial sensors, mostly in the form of 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.

The gaps to be filled and technologies to be matured include, but are not limited to, the following:

1. Optical atomic clocks

   - 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.

- Space-qualifiable small-size low-power clock lasers at, or subsystems that can lead to, better than $3 \times 10^{-15} \text{ Hz/} \Delta \tau$ near 0.1 to 10 s (wavelengths for Yb+, Yb, and Sr clock transitions are of special interest).
- Technical approaches and methods for beyond state-of-the-art compact and miniature clocks for space with emphasis on the performance per size, power, and mass.

(2) Atom interferometers

- Space-qualifiable high-flux ultra-cold atom sources, related components, and methods: e.g., $>1 \times 10^6$ total atoms near the point at <1 nK: Rb, K, Cs, Yb, and Sr.
- Ultra-high vacuum technologies and approaches for atom interferometer applications that allow small-size and low-power, completely sealed, nonmagnetic enclosures with high-quality optical access and are capable of maintaining $<1 \times 10^{-9}$ 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.
- Beyond the state-of-the-art photonic components at wavelengths for atomic species of interest, particularly visible and ultraviolet (UV):
  - Efficient acousto-optic modulators: e.g., low radio-frequency (RF) power ~200 mW, low thermal distortion, ~80% or greater diffraction efficiency.
  - Efficient electro-optic modulators: e.g., low bias drift, residual AM, and return loss; fiber-coupled preferred.
  - Miniature optical isolators: e.g., ~30 dB isolation or greater, ~ -2 dB loss or less.
  - Robust high-speed high-extinction shutters: e.g., switching time <1 ms and extinction >60 dB are highly desired.
- Flight qualifiable: i.e., 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;
  Also, 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.
  - Analysis and simulation tool of a cold atom system in trapped and freefall states relevant to atom interferometer and clock measurements in space.

(3) Other atomic and artificial atomic sensors

- Rydberg sensors or their subsystems/components for electric field or microwave measurements.
- Space qualifiable NV diamond or chip-scale atomic magnetometers.
High-performance, miniaturized or chip-scale optical frequency combs.

Other innovative atomic quantum sensors for high-fidelity field measurements that have space applications and can be developed into a space-quantifiable instrument.

Because of the breath and diversity of the portfolio, performers are expected to be aware of specific gaps for specific application scenarios. All proposed system performances may be defined by offeror with clear justifications. Subsystem technology development proposals should clearly state the relevance to the anticipated system-level implementation and performance; define requirements, relevant atomic species, and working laser wavelengths; and indicate its path to a space-borne instrument. Finally, for proposals interested in quantum sensing methodologies for achieving the optimal collection of light for photon-starved astronomical observations, it is suggested to consider the STTR subtopic T8.06.

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
- Software

Desired Deliverables Description:

Phase I deliverables: results of a feasibility study, analysis, and preliminary laboratory demonstration, as described in a final report.

Phase II deliverables: prototype or demonstration hardware; summary of performance analysis; and applicable supporting documentation, data, and/or test reports.

State of the Art and Critical Gaps:

Many technology gaps exist in the development state of atomic sensors and clocks intended for NASA space applications. These gaps are mainly in the areas of reducing size, mass, and power, while increasing their performance and advancing them towards space qualification. These gaps may pertain to components, subsystems, instruments/devices, novel approaches and/or theoretical analysis tools. Most of the needed improvements are elements which are beyond current state-of-the art. These needed improvements include high-flux ultra-cold atom sources, atomic physics packages and atomic vacuum cell technology specific for clock and atom interferometer applications, miniature optical isolators, efficient modulators, active wave front and polarization devices, fast high-extension-ratio switches, efficient detectors, and novel frequency conversion methods/devices. Also needed are lasers and laser-optics system
approaches with a high degree of integration and robustness, and suitable for atomic devices; small ultra-stabilized laser systems, and miniature self-referenced optical frequency combs. These are examples and not an exhaustive list.

Relevance / Science Traceability:

Currently, no technology exists that can compete with the (potential) sensitivity, (potential) compactness, and robustness of atom optical-based gravity and time measurement devices. Earth science, planetary science, and astrophysics all benefit from unprecedented improvements in gravity and time measurement. Specific roadmap items supporting science instrumentation include, but are not limited to:

- TX07.1.1: Destination Reconnaissance, Prospecting, and Mapping (gravimetry)
- TX08.1.2: Electronics (reliable control electronics for laser systems)
- TX08.1.3: Optical Components (reliable laser systems)
- TX08.1.4: Microwave, Millimeter, and Submillimeter-Waves (ultra-low noise microwave output when coupled w/ optical frequency comb)
- TX08.1.5: Lasers (reliable laser system w/ long lifetime)

References:

- 2020 NASA Technology Taxonomy: [https://go.nasa.gov/3hGhFJf](https://go.nasa.gov/3hGhFJf) [60]
- 2017 NASA Strategic Technology Investment Plan: [https://go.usa.gov/xU7sE](https://go.usa.gov/xU7sE) [61]

S1.11 In Situ Instruments/Technologies and Plume Sampling Systems for Ocean Worlds Life Detection

Lead Center: GSFC

Participating Center(s): ARC, GRC, GSFC

Scope Title:

In Situ Instruments/Technologies and Plume Sampling Systems for Ocean Worlds Life Detection

Scope Description:

This subtopic solicits development of in situ instrument technologies and components to advance the maturity of science instruments and plume sample collection systems focused on the detection of evidence of life, especially extant life, in the ocean worlds (e.g., Europa, Enceladus, Titan, Ganymede, Callisto, Ceres, etc.). Technologies that can increase instrument resolution and sensitivity or achieve new and innovative scientific measurements are of particular interest. Technologies that allow collection during high-speed (>1 km/sec) passes through a plume are solicited as are technologies that can maximize total sample mass collected while passing through tenuous plumes. This fly-through sampling focus is distinct from S4.02, which solicits sample collection technologies from surface platforms.

These technologies must be capable of withstanding operation in space and planetary environments, including the expected pressures, radiation levels, launch and impact stresses, and range of survival and operational
temperatures. Technologies that reduce mass, power, volume, and data rates for instruments and instrument components without loss of scientific capability are of particular importance.

Specifically, this subtopic solicits instrument technologies and components that provide significant advances in the following areas, broken out by planetary body:

- **General to Europa, Enceladus, Titan, and other ocean worlds:** Technologies and components relevant to life detection instruments (e.g., microfluidic analyzer, microelectromechanical systems (MEMS) chromatography/mass spectrometers, laser-ablation mass spectrometer, fluorescence microscopic imager, Raman spectrometer, tunable laser system, liquid chromatography/mass spectrometer, X-ray fluorescence, digital holographic microscope-fluorescence microscope, antibody microarray biosensor, nanocantilever biodetector, etc.). Technologies for high-radiation environments (e.g., radiation mitigation strategies, radiation-tolerant detectors, and readout electronic components), which enable orbiting instruments to be both radiation hard and undergo the planetary protection requirements of sterilization (or equivalent).
  - Collecting samples for a variety of science purposes is also sought. These include samples that allow for determination of the chemical and physical properties of the source ocean, samples for detailed characterization of the organics present in the gas and particle phases, and samples for analysis for biomarkers indicative of life. Front-end system technologies include sample collection systems and subsystems capable of capture, containment, and/or transfer of gas, liquid, ice, and/or mineral phases from plumes to sample processing and/or instrument interfaces.
  - Technologies for characterization of collected sample parameters including mass, volume, total dissolved solids in liquid samples, and insoluble solids. Sample collection and sample capture for in situ imaging. Systems capable of high-velocity sample collection with minimal sample alteration to allow for habitability and life detection analyses. Microfluidic sample collection systems that enable sample concentration and other manipulations. Plume material collection technologies that minimize risk of terrestrial contamination, including organic chemical and microbial contaminates. These technologies would enable high-priority sampling and potential sample return from the plumes of Enceladus with a fly-by mission. This would be a substantial cost savings over a landed mission.

- **Europa:** Life detection approaches optimized for evaluating and analyzing the composition of ice matrices with unknown pH and salt content. Instruments capable of detecting and identifying organic molecules (in particular biomolecules), salts and/or minerals important to understanding the present conditions of Europa's ocean are sought (such as high resolution gas chromatograph or laser desorption mass spectrometers, dust detectors, organic analysis instruments with chiral discrimination, etc.). These developments should be geared towards analyzing and handling very small sample sizes (µg to mg) and/or low column densities/abundances. Also of interest are imagers and spectrometers that provide high performance in low-light environments (visible and near-infrared (NIR) imaging spectrometers, thermal imagers, etc.), as well as instruments capable of improving our understanding of Europa's habitability by characterizing the ice, ocean, and deeper interior and monitoring ongoing geological activity such as plumes, ice fractures, and fluid motion (e.g., seismometers, magnetometers). Improvements to instruments capable of gravity (or other) measurements that might constrain properties such as ocean and ice shell thickness will also be considered.

- **Enceladus (including plume material and E-ring particles):** Life detection approaches optimized for analyzing plume particles as well as for determining the chemical state of Enceladus icy surface materials (particularly near plume sites). Instruments capable of detecting and identifying organic molecules (in particular biomolecules), salts and/or minerals important to understand the present conditions of the Enceladus ocean are sought (such as high resolution gas chromatograph or laser desorption mass spectrometers, dust detectors, organic analysis instruments with chiral discrimination, etc.). These developments should be geared towards analyzing and handling very small sample sizes (µg to mg) and/or low column densities/abundances. Also of interest are imagers and spectrometers that provide high performance in low-light environments (visible and NIR imaging spectrometers, thermal imagers, etc.), as well as instruments capable of monitoring the bulk chemical composition and physical characteristics of the plume (density, velocity, variation with time, etc.). Improvements to instruments capable of gravity (or other) measurements that might constrain properties such as ocean and ice shell thickness will also be considered.

- **Titan:** Life detection approaches optimized for searching for biosignatures and biologically relevant compounds in Titan's lakes, including the presence of diagnostic trace organic species, and also for
analyzing Titan’s complex aerosols and surface materials. Mechanical and electrical components and subsystems that work in cryogenic (95 K) environments; sample extraction from liquid methane/ethane, sampling from organic “dunes” at 95 K, and robust sample preparation and handling mechanisms that feed into mass analyzers are sought. Balloon instruments, such as IR spectrometers; imagers; meteorological instruments; radar sounders; solid, liquid, and air sampling mechanisms for mass analyzers; and aerosol detectors are also solicited. Low-mass and low-power sensors, mechanisms and concepts for converting terrestrial instruments such as turbidimeters and echo sounders for lake measurements, weather stations, surface (lake and solid) properties packages, etc. to cryogenic environments (95 K). Other ocean worlds targets may include Ganymede, Callisto, Ceres, etc.

Proposers are strongly encouraged to relate their proposed development to:

- NASA’s future ocean worlds exploration goals (see references).
- Existing flight instrument capability, to provide a comparison metric for assessing proposed improvements.

Proposed instrument architectures should be as simple, reliable, and low risk as possible while enabling compelling science. Novel instrument concepts are encouraged, particularly if they enable a new class of scientific discovery. Technology developments relevant to multiple environments and platforms are also desired.

Proposers should show an understanding of relevant space science needs, and present a feasible plan to fully develop a technology and infuse it into a NASA program.

**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:**

- Analysis
- Prototype
- Hardware
- Software

**Desired Deliverables Description:**

The Phase I project should focus on feasibility and proof-of-concept demonstration (TRL 2-3). The required Phase I deliverable is a report documenting 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. The report can include a feasibility assessment and concept of operations, simulations and/or measurements, and a plan for further development to be performed in Phase II.

The Phase II project should focus on component and/or breadboard development with the delivery of specific hardware for NASA (TRL 4-5). Phase II deliverables include a working prototype of the proposed hardware, along with documentation of development, capabilities, and measurements.

**State of the Art and Critical Gaps:**

In situ instruments and technologies are essential bases to achieve NASA’s ocean worlds exploration goals. There are currently some in situ instruments for diverse ocean worlds bodies. However, there are ever increasing science and exploration requirements and challenges for diverse ocean worlds bodies. For example, there are urgent needs for the exploration of icy or liquid surface on Europa, Enceladus, Titan, Ganymede, Callisto, etc., and plumes from planetary bodies such as Enceladus.

To narrow the critical gaps between the current state of art and the technology needed for the ever-increasing science/exploration requirements, in situ technologies are being sought to achieve much higher resolution and sensitivity with significant improvements over existing capabilities, and at the same time with lower resource (mass, power, and volume) requirements.
Relevance / Science Traceability:

In situ instruments and technologies are essential bases to achieve Science Mission Directorate’s (SMD) planetary science goals summarized in Decadal Study (National Research Council’s Vision and Voyages for Planetary Science in the Decade 2013-2022.) In situ instruments and technologies play indispensable role for NASA’s New Frontiers and Discovery missions to various planetary bodies.

NASA SMD has two programs to bring this subtopic technologies to higher level: PICASSO and MatISSE. The Planetary Instrument Concepts for the Advancement of Solar System Observations (PICASSO) Program invests in low-TRL technologies and funds instrument feasibility studies, concept formation, proof-of-concept instruments, and advanced component technology. The Maturation of Instruments for Solar System Exploration (MatISSE) Program invests in mid-TRL technologies and enables timely and efficient infusion of technology into planetary science missions. The PICASSO and MatISSE are in addition to Phase III opportunities.

References:

- For the NASA Roadmap for Ocean World Exploration see: [http://www.lpi.usra.edu/opag/ROW](http://www.lpi.usra.edu/opag/ROW) [62]
- In situ instruments and technologies for NASA's ocean worlds exploration goals see: [https://www.nasa.gov/specials/ocean-worlds/](https://www.nasa.gov/specials/ocean-worlds/) [63]
- NASA technology solicitation, see ROSES 2016/C.20 Concepts for Ocean worlds Life Detection Technology (COLDTECH) call: [https://nspires.nasa.gov/external/solicitations/summary.do?method=init&solId=5C43865B-0C93-6ECA BCD2-A3783CB1AAC8]&path=init [64]

S1.12 Remote Sensing Instrument Technologies for Heliophysics

Lead Center: GSFC

Participating Center(s): HQ

Scope Title:

Remote-Sensing Instruments/Technologies for Heliophysics

Scope Description:

The 2013 National Research Council’s, Solar and Space Physics: A Science for a Technological Society [http://nap.edu/13060](http://nap.edu/13060) [39]) motivates this subtopic: “Deliberate investment in new instrument concepts is necessary to acquire the data needed to further solar and space physics science goals, reduce mission risk, and maintain an active and innovative hardware development community.” This subtopic solicits development of advanced remote-sensing instrument technologies and components suitable for deployment on heliophysics missions. These technologies must be capable of withstanding operation in space environments, including the expected pressures, radiation levels, launch and impact stresses, and range of survival and operational temperatures. Technologies that reduce mass, power, volume, and data rates for instruments and instrument components without loss of scientific capability are of particular importance. In addition, technologies that can increase instrument resolution and sensitivity or achieve new and innovative scientific measurements are solicited. For example missions, see [https://science.nasa.gov/missions-page?field_division_tid=5&field_phase_tid=All](https://science.nasa.gov/missions-page?field_division_tid=5&field_phase_tid=All) [66]. For details of the specific requirements see the Heliophysics Decadal Survey. Technologies that support science
aspects of missions in NASA’s Living With a Star and Solar-Terrestrial Probe programs are of top priority, including long-term missions like Interstellar Probe mission (as called out in the Decadal Survey).

Remote-sensing technologies are being sought to achieve much higher resolution and sensitivity with significant improvements over existing capabilities. Remote-sensing technologies amenable to CubeSats and SmallSats are also encouraged. Specifically, this subtopic solicits instrument development that provides significant advances in the following areas:

- Light detection and ranging (LIDAR) systems for high-power, high-frequency geospace remote sensing, such as sodium and helium lasers.
- Technologies or components enabling auroral, airglow, geospace, and solar imaging 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, diffractive and metamaterial optics).
- Electromagnetic sounding of ionospheric or magnetospheric plasma density structure at radio-frequencies from kHz to >10 MHz.
- Passive sensing of ionospheric and magnetospheric plasma density structure using transmitters of opportunity (e.g., global navigation satellite system (GNSS) or ground-based transmissions).
- Technologies that enable the development of dedicated solar flare sensors with intrinsic ion suppression and sufficient angular resolution in the EUV to soft x-ray wavelength range such as fast cadence charge-coupled devices and complementary metal-oxide semiconductor devices.
- Technologies that enable x-ray detectors to observe bright solar flares in x-ray from 1 to hundreds of keV without saturation.
- Technologies that attenuate solar x-ray fluences by flattening the observed spectrum by a factor of 100 to 1,000 across the energy range encompassing both low- and high-energy x-rays—preferably flight programmable.
- X-ray optics technologies to either reduce the size, complexity, or mass or to improve the point spread function of solar telescopes used for imaging solar x-rays in the ~1 to 300 keV range.
- Technologies, including metamaterials and micro-electro-mechanical systems (MEMS) that enable polarization, wavelength, or spatial discrimination without macroscale moving parts.

Proposers are strongly encouraged to relate their proposed development to NASA’s future heliophysics goals as set out in the Heliophysics Decadal Survey (2013-2022) and the NASA Heliophysics Roadmap (2014-2033). Proposed instrument components and/or architectures should be as simple, reliable, and low risk as possible, while enabling compelling science. Novel instrument concepts are encouraged, particularly if they enable a new class of scientific discovery. Technology developments relevant to multiple environments and platforms are also desired. Proposers should show an understanding of relevant space science needs, and present a feasible plan to fully develop a technology and infuse it into a NASA program. Detector technology proposals should be referred to the S116 subtopic.

**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:**

- Analysis  
- Prototype  
- Hardware  
- Software  

**Desired Deliverables Description:**
Phase I deliverables may include an analysis or test report, a prototype of an instrument subcomponent, or a full working instrument prototype.

Phase II deliverables must include a prototype or demonstration of a working instrument or subcomponent and may also include analysis or test reports.

State of the Art and Critical Gaps:

Remote-sensing instruments and technologies are essential bases to achieve Science Mission Directorate’s (SMD) Heliophysics goals summarized in National Research Council’s, Solar and Space Physics: A Science for a Technological Society. These instruments and technologies play indispensable roles for NASA’s Living With a Star (LWS) and Solar Terrestrial Probe (STP) mission programs as well as a host of smaller spacecraft in the Explorers Program. In addition, there is growing demand for remote-sensing technologies amenable to CubeSats and SmallSats. To narrow the critical gaps between the current state of art and the technology needed for the ever increasing science/exploration requirements, remote-sensing technologies are being sought to achieve much higher resolution and sensitivity with significant improvements over existing capabilities—and at the same time with lower mass, power, and volume.

Relevance / Science Traceability:

Remote-sensing instruments and technologies are essential bases to achieve SMD's Heliophysics goals summarized in National Research Council's, Solar and Space Physics: A Science for a Technological Society. These instruments and technologies play indispensable roles for NASA’s LWS and STP mission programs, as well as a host of smaller spacecraft in the Explorers Program. In addition, there is growing demand for remote-sensing technologies amenable to CubeSats and SmallSats. NASA SMD has two excellent programs to bring this subtopic technologies to a higher level: Heliophysics Technology and Instrument Development for Science (H-TIDEs) and Heliophysics Flight Opportunities for Research and Technology (HFORT). H-TIDEs seeks to advance the development of technologies and their application to enable investigation of key heliophysics science questions. This is done through incubating innovative concepts and development of prototype technologies. It is intended that technologies developed through H-TIDEs would then be proposed to HFORT to mature by demonstration in a relevant environment. The H-TIDEs and H-FORT programs are in addition to Phase III opportunities.

References:

- For example missions, see: https://science.nasa.gov/missions [67]
- For details of the specific requirements, see the National Research Council's, Solar and Space Physics: A Science for a Technological Society: http://nap.edu/13060 [39]
- For details of NASA's Heliophysics roadmap, see the NASA Heliophysics Roadmap: https://explorers.larc.nasa.gov/HPSMEX/MO/pdf_files/2014_HelioRoadmap_Final_Reduced_0.pdf [68]

S2.01 Proximity Glare Suppression for Astronomical Direct Detection of Exoplanets

Lead Center: GSFC

Participating Center(s): GSFC

Scope Title:

Control of scattered starlight with coronagraphs and starshades
Scope Description:

The goal of this subtopic is to address the unique problem of imaging and spectroscopic characterization of faint astrophysical objects that are located within the obscuring glare of much brighter stellar sources. Examples include planetary systems beyond our own, the detailed inner structure of galaxies with very bright nuclei, binary star formation, and stellar evolution. Contrast ratios of one million to ten billion over an angular spatial scale of 0.05 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 innovative research focuses on advances in coronagraphic instruments, starlight cancellation instruments, and potential occulting technologies that operate at visible and near-infrared wavelengths. The ultimate application of these instruments is to operate in space as part of a future observatory mission concepts such as the Habitable Exoplanet Observatory (HabEx) and Large Ultraviolet Optical Infrared Surveyor (LUVOIR). Measurement techniques include imaging, photometry, spectroscopy, and polarimetry. There is interest in component development and innovative instrument design, as well as in the fabrication of subsystem devices to include, but not limited to, the following areas:

Starlight Suppression Technologies:

- Hybrid metal/dielectric and polarization apodization masks for diffraction control of phase and amplitude for coronagraph-scaled starshade experiments.
- Low-scatter, low-reflectivity, sharp, flexible edges for control of solar scatter in starshades.
- Low-reflectivity coatings for flexible starshade optical shields.
- Methods to distinguish the coherent and incoherent scatter in a broadband speckle field.

Wavefront Measurement and Control Technologies:

- Small-stroke, high-precision, deformable mirrors and associated driving electronics scalable to 10,000 or more actuators (both to further the state of the art towards flightlike hardware and to explore novel concepts). Multiple deformable mirror technologies in various phases of development and processes are encouraged to ultimately improve the state of the art in deformable mirror technology. Process improvements are needed to improve repeatability, yield, and performance precision of current devices.
- Multiplexers with ultralow power dissipation for electrical connection to deformable mirrors.
- Low-order wavefront sensors for measuring wavefront instabilities to enable real-time control and postprocessing of aberrations.
- Thermally and mechanically insensitive optical benches and systems.

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.

In addition this subtopic solicits proposals to develop components that improve the footprint, robustness, power consumption, reliability, and wavefront quality of high-contrast, low-temporal bandwidth, adaptive optics systems. These include application-specific integrated circuit (ASIC) drivers that easily integrate with the deformable mirrors, improved connectivity technologies, as well as high-actuator-count deformable mirrors with high-quality, ultrastable wavefronts.

It also seeks coronagraph masks that can be tested in ground-based high-contrast testbeds in place at a number of institutions, as well as devices to measure the masks to inform optical models. The masks include transmissive scalar, polarization-dependent, and spatial apodizing masks, including those with extremely low reflectivity regions that allow them to be used in reflection.

The subtopic seeks samples of optical coatings that reduce polarization and can be applied to large optics as well as methods and instruments to characterize them over large optical surfaces.

Finally, for starshades, the subtopic seeks low-reflectivity and potentially diffraction-controlling edges that minimize scattered sunlight while also remaining robust to handling and cleaning. Low-reflectivity optical coatings that can be applied to the surfaces for the large (hundreds of square meters) optical shield are also desired.

**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:**

Under this Subtopic a concept study provided as a final report in Phase I is acceptable and a prototype for Phase II is acceptable.

**State of the Art and Critical Gaps:**

Coronagraphs have been demonstrated to achieve high contrast in moderate bandwidth in laboratory environments. Starshades will enable even deeper contrast over broader bands but to date have demonstrated deep contrast in narrow band light. The extent to which the telescope optics will limit coronagraph performance is a function of the quality of the optical coating and the ability to control polarization over the full wavefront. Neither of these technologies is well characterized at levels required for $10^{10}$ contrast. Wavefront control using deformable mirrors is critical. Controllability and stability to picometer levels is required. To
date, deformable mirrors have been up to the task of providing contrast approaching $10^{10}$, but they require thousands of wires, and overall wavefront quality and stroke remain concerns.

Relevance / Science Traceability:

These technologies are directly applicable to the Nancy Grace Roman Space Telescope (NGRST) coronagraph instrument (CGI), and the HabEx and LUVOIR concept studies.

References:

See SPIE conference papers and articles published in the Journal of Astronomical Telescopes and Instrumentation on high-contrast coronagraphy, segmented coronagraph design and analysis, and starshades.

Websites:

- Exoplanet Exploration - Planets Beyond Our Solar System: [https://exoplanets.jpl.nasa.gov](https://exoplanets.jpl.nasa.gov) [69]
- Exoplanet Exploration Program: [https://exoplanets.nasa.gov/exep/](https://exoplanets.nasa.gov/exep/) [70]
- Goddard Space Flight Center: [https://www.nasa.gov/goddard](https://www.nasa.gov/goddard) [71]

S2.02 Precision Deployable Optical Structures and Metrology

Lead Center: GSFC

Participating Center(s): GSFC

Scope Title:

Assembled Deployable Optical Metering Structures and Instruments

Scope Description:

Future space astronomy missions from ultraviolet to millimeter wavelengths will push the state of the art in current optomechanical technologies. Size, dimensional stability, temperature, risk, manufacturability, and cost are important factors, separately and in combination. The Large Ultraviolet Optical Infrared Surveyor (LUVOIR) calls for deployed apertures as large as 15 m in diameter; the Origins Space Telescope (OST), for operational temperatures as low as 4 K; and LUVOIR and the Habitable Exoplanet Observatory (HabEx), for exquisite optical quality. Methods to construct large telescopes in space are also under development. Additionally, sunshields for thermal control and starshades for exoplanet imaging require deployment schemes to achieve 30- to 70-m-class space structures.

This subtopic addresses the need to mature technologies that can be used to fabricate 10- 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. 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, 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 precisions (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 diameter for ground test characterization. Proposals should show an understanding of one or more relevant science needs, and present a feasible plan to fully develop the relevant subsystem technologies and to transition into future NASA program(s).

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

Desired Deliverables Description:

For Phase I, a successful deliverable would include a demonstration of the functionality and/or performance of a system/subsystem with model predictions to explain observed behavior as well as make predictions on future designs.

For Phase II this should be demonstrated on units that can be scaled to future flight sizes.

State of the Art and Critical Gaps:

The James Webb Space Telescope, currently set to launch in 2021, represents the state of the art in large deployable telescopes. The Wide Field Infrared Survey Telescope’s (WFIRST) coronagraph instrument (CGI) will drive telescope/instrument stability requirements to new levels. The mission concepts in the upcoming Astro2020 decadal survey will push technological requirements even further in the areas of deployment, size, stability, lightweighting, and operational temperature. Each of these mission studies have identified technology gaps related to their respective mission requirements.
Relevance / Science Traceability:

These technologies are directly applicable to the WFIRST CGI and the HabEx, LUVOIR, and OST mission concepts.

References:

- Habitable Exoplanet Observatory (HabEx): https://www.jpl.nasa.gov/habex/ [27]
- What is an Exoplanet? https://exoplanets.nasa.gov/what-is-an-exoplanet/technology/ [72]
- NASA in-Space Assembled Telescope (iSAT) Study: https://exoplanets.nasa.gov/exep/technology/in-space-assembly/iSAT_study/ [73]

S2.03 Advanced Optical Systems and Fabrication/Testing/Control Technologies for Extended-Ultraviolet/Optical and Infrared Telescope

Lead Center: GSFC

Participating Center(s): GRC, GSFC, JPL, LaRC

Scope Title:

Optical Components and Systems for Large Telescope Missions

Scope Description:

Accomplishing NASA’s high-priority science at all levels (flagship, probe, Medium-Class Explorers (MIDEX), Small Explorers (SMEX), rocket, and balloon) requires low-cost, ultrastable, normal-incidence mirror systems with low mass-to-collecting area ratios. Here, a mirror system is defined as the mirror substrate, supporting structure, and associated actuation and thermal management systems. After performance, the most important metric for an advanced optical system is affordability or areal cost (cost per square meter of collecting aperture).

Current normal-incidence space mirrors cost $4 million to $6 million per square meter of optical surface area. This research effort seeks to improve the performance of advanced precision optical components while reducing their cost by 5× to 50×, to between $100K/m² and $1M/m².

Specific metrics are defined for each wavelength application region:
1. Aperture diameter for all wavelengths, except far-infrared (IR):

- Monolithic: 1 to 8 m
- Segmented: 3 to 20 m

2. For ultraviolet (UV)/optical:

- Areal cost: <$500K/m²
- Wavefront figure: <5 nm rms (via passive design or active deformation control)
- Wavefront stability: <10 pm/10 min
- First mode frequency: 60 to 500 Hz
- Actuator resolution: <1 nm rms
- Optical pathlength stability: <1 pm/10,000 sec for precision metrology
- Areal density: <15 kg/m² (<35 kg/m² with backplane)
- Operating temperature range: 250 to 300 K

3. For far-IR:

- Aperture diameter: 1 to 4 m (monolithic) or 5 to 10 m (segmented)
- Telescope: diffraction-limited at <30 µm at operating temperature 4 K
- Cryodeformation: <100 nm rms
- Areal cost: <$500K/m²
- Production rate: >2 m² per month
- Areal density: <15 kg/m² (<40 kg/m² with backplane)
- Thermal conductivity: at 4 K, >2 W/m·K
- Survivability at temperatures ranging from 315 to 4 K

4. For extreme ultraviolet (EUV):

- Surface slope: <0.1 µrad

Also needed is the ability to fully characterize surface errors and predict optical performance.

Proposals must show an understanding of one or more relevant science needs and present a feasible plan to develop the proposed technology for infusion into a NASA program: suborbital rocket or balloon; competed SMEX or MIDEX; or Decadal-class mission. Successful proposals will demonstrate an ability to manufacture, test, and control ultra-low-cost optical systems that can meet science performance requirements and mission requirements (including processing and infrastructure issues). Material behavior, process control, active and/or passive optical performance, and mounting/deploying issues should be resolved and demonstrated.
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
- Prototype
- Hardware

Desired Deliverables Description:

- An ideal Phase I deliverable would be a precision optical system of at least 0.25 m; a relevant subcomponent of a system; a prototype demonstration of a fabrication, test, or control technology leading to a successful Phase II delivery; or a reviewed preliminary design and manufacturing plan that demonstrates feasibility. While detailed analysis will be conducted in Phase II, the 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.
- An ideal Phase II project would further advance the technology to produce a flight-qualifiable optical system greater than 0.5 meters or relevant subcomponent (with a TRL in the 4 to 5 range) or a working fabrication, test, or control system. Phase I and Phase II mirror system or component deliverables would be accompanied by all necessary documentation, including the optical performance assessment and all data on processing and properties of its substrate materials. A successful mission-oriented Phase 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 normal incidence space mirrors cost $4 million to $6 million per square meter of optical surface area. This research effort seeks a cost reduction for precision optical components by $100K/m² to $1M/m².

Relevance / Science Traceability:

S2.03 primary supports potential Astrophysics Division missions. S2.03 has made optical systems in the past for potential balloon experiments. Future potential Decadal missions include Laser Interferometer Space Antenna (LISA), Habitable Exoplanet Observatory (HabEx), Large UV/Optical/Near-IR Surveyor (LUVOIR) and the Origins Space Telescope (OST).

References:
The HabEx and LUVOIR space telescope studies are developing concepts for UVOIR space telescopes for exo-Earth discovery and characterization, exoplanet science, general astrophysics and solar system astronomy.

- The HabEx Interim Report is available at: https://www.jpl.nasa.gov/habex/pdf/interim_report.pdf [74]
- The LUVOIR Interim Report is available at: https://asd.gsfc.nasa.gov/luvoir/ [26].
- The OST mission is described on the website: https://origins.ipac.caltech.edu [76]
- The Space Infrared Interferometric Telescope (SPIRIT) and its optical system requirements description: https://asd.gsfc.nasa.gov/cosmology/spirit/ [77]
- LISA mission description: https://lisa.nasa.gov/ [78]

**Scope Title:**

Balloon Planetary Telescope

**Scope Description:**

Astronomy from a stratospheric balloon platform offers numerous advantages. At typical balloon cruise altitudes (100,000 to 130,000 ft.), 99%+ of the atmosphere is below the balloon, and the attenuation due to the remaining atmosphere is small, especially in the near-ultraviolet (NUV) band and in the infrared (IR) bands near 2.7 and 4.25 µm. The lack of atmosphere nearly eliminates scintillation and allows the resolution potential of relatively large optics to be realized, and the small amount of atmosphere reduces scattered light and allows observations of brighter objects even during daylight hours.

Potential balloon science missions are either in the UV/optical (UVO) or in the infrared/far-infrared (IR/FIR).

- UVO science missions require a 1-m-class telescope diffraction limited at 500 nm or a primary mirror system that can maintain <10 nm rms surface figure error for elevation angles ranging from 0° to 60° over a temperature range of 220 to 280 K.
- IR science missions require 1.5-m-class telescopes diffraction limited at 5 µm.
- FIR missions require 2-m-class (or larger) telescopes diffraction limited at 50 µm.

In all cases, the telescopes need to achieve:

- Mass: <300 kg
- Shock: 10G without damage
- Elevation: 0° to 60°
- Temperature: 220 to 280 K
For packaging reasons, the primary mirror assembly must have a radius of curvature 3 m (nominal) and a mass <150 kg.

**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

**Desired Deliverables Description:**

- Phase I will produce a preliminary design and report including initial design requirements such as wavefront error budget, mass allocation budget, structural stiffness requirements, etc. as well as trade studies performed and analysis that compares the design to the expected performance over the specified operating range. Development challenges shall be identified during Phase I, including trade studies and challenges to be addressed during Phase II with subsystem proof-of-concept demonstration hardware.

- If Phase II can only produce a subscale component, then it should also produce a detailed final design, including final requirements (wavefront error budget, mass allocation, etc.) and a performance assessment over the specified operating range.

**State of the Art and Critical Gaps:**

Current SOA (state-of-the-art) mirrors made from Zerodur\(^{(C)}\) or ULE\(^{(C)}\), for example, require lightweighting to meet balloon mass limitations and cannot meet diffraction limited performance over the wide temperature range due to the coefficient of thermal expansion limitations.

**Relevance / Science Traceability:**

“Vision and Voyages for Planetary Science in the Decade 2013-2022”

- Page 22, last paragraph of NASA Telescope Facilities within the Summary Section:

  Balloon- and rocket-borne telescopes offer a cost-effective means of studying planetary bodies at wavelengths inaccessible from the ground. Because of their modest costs and development times, they also provide training opportunities for would-be developers of future spacecraft instruments. Although NASA’s Science Mission Directorate regularly flies balloon missions into the stratosphere, there are few funding opportunities to take advantage of this resource for planetary science because typical planetary grants are too small to support these missions.
A funding line to promote further use of these suborbital observing platforms for planetary observations would complement and reduce the load on the already oversubscribed planetary astronomy program.

- Page 203, 5th paragraph of section titled Earth and Space-Based Telescopes: Significant planetary work can be done from balloon-based missions flying higher than 45,000 ft. This altitude provides access to electromagnetic radiation that would otherwise be absorbed by Earth’s atmosphere and permits high-spatial-resolution imaging unaffected by atmospheric turbulence. These facilities offer a combination of cost, flexibility, risk tolerance, and support for innovative solutions that is ideal for the pursuit of certain scientific opportunities, the development of new instrumentation, and infrastructure support. Given the rarity of giant-planet missions, these types of observing platforms (high-altitude telescopes on balloons and sounding rockets) can be used to fill an important data gap.

Potential advocates include planetary scientists at Goddard Space Flight Center (GSFC), Johns Hopkins Applied Physics Laboratory (APL), and Southwest Research Institute, etc.

References:

- For additional discussion of the advantages of observations from stratosphere platforms, refer to:
- Additional information about scientific balloons can be found at: [https://www.csbf.nasa.gov/docs.html][80]

Scope Title:

Large Ultraviolet/Optical/near-IR (LUVOIR) Surveyor and Habitable Exoplanet (HabEx) Missions

Scope Description:

Potential ultraviolet/optical (UVO) missions require 4- to 16-m monolithic or segmented primary mirrors with <5 nm rms surface figures. Active or passive alignment and control is required to achieve system-level diffraction-limited performance at wavelengths less than 500 nm (<40-nm rms wavefront error, WFE). Additionally, a potential exoplanet mission, using an internal coronagraph, requires total telescope wavefront stability on the order of 10 pm rms per 10 min. This stability specification places severe constraints on the dynamic mechanical and thermal performance of 4-m and larger telescope. Potential enabling technologies include: active thermal control systems, ultrastable mirror support structures, athermal telescope structures, ultrastable mirror struts, ultrastable joints with low coefficient of thermal expansion (CTE) and high stability, and vibration compensation.

Mirror areal density depends upon available launch vehicle capacities to Sun-Earth L2 (i.e., 15 kg/m² for a 5-m-fairing Evolved Expendable Launch Vehicle (EELV) versus 150 kg/m² for a 10-m-fairing Space Launch (SLS)). Regarding areal cost, a good goal is to keep the total cost of the primary mirror at or below $100M. Thus, an 8-m-class mirror (with 50 m² of collecting area) should have an areal cost of less than $2M/m². And, a 16-m-class mirror (with 200 m² of collecting area) should have an areal cost of less than $0.5M/m².
Key technologies to enable such a mirror include new and improved:

- Mirror substrate materials and/or architectural designs.
- Processes to rapidly fabricate and test UVO quality mirrors.
- Mirror support structures, joints, and mechanisms that are athermal or have zero CTE at the desired scale.
- Mirror support structures, joints, and mechanisms that are ultrastable at the desired scale.
- Mirror support structures with low mass that can survive launch at the desired scale.
- Mechanisms and sensors to align segmented mirrors to <1 nm rms precisions.
- Thermal control (<1 mK) to reduce wavefront stability to <10 pm rms per 10 min.
- Dynamic isolation (>140 dB) to reduce wavefront stability to <10 pm rms per 10 min.

Also needed is the ability to fully characterize surface errors and predict optical performance via integrated optomechanical modeling.

Potential solutions for substrate material/architecture include, but are not limited to: ultra-uniform low-CTE glasses, silicon carbide, nanolaminates, or carbon-fiber-reinforced polymer. Potential solutions for mirror support structure material/architecture include, but are not limited to: additive manufacturing, nature-inspired architectures, nanoparticle composites, carbon fiber, graphite composite, ceramic or SiC materials, etc. Potential solutions for new fabrication processes include, but are not limited to: additive manufacture, direct precision machining, rapid optical fabrication, roller embossing at optical tolerances, slumping, or replication technologies to manufacture 1- to 2-m- (or larger) precision quality components. Potential solutions for achieving the 10-pm wavefront stability include, but are not limited to: metrology, passive, and active control for optical alignment and mirror phasing; active vibration isolation; metrology; and passive and active thermal control.

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 08.2 Observatories

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Hardware
- Software

Desired Deliverables Description:

- An ideal Phase I deliverable would be a precision optical system of at least 0.25 m; a relevant subcomponent of a system; a prototype demonstration of a fabrication, test, or control technology leading to a successful Phase II delivery; or a reviewed
preliminary design and manufacturing plan that demonstrates feasibility. While detailed analysis will be conducted in Phase II, the 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.

- An ideal Phase II project would further advance the technology to produce a flight-qualifiable optical system greater than 0.5 m or relevant subcomponent (with a TRL in the 4 to 5 range) or a working fabrication, test, or control system. Phase I and Phase II mirror system or component deliverables would be accompanied by all necessary documentation, including the optical performance assessment and all data on processing and properties of its substrate materials. A successful mission-oriented Phase 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:**

The precision fabrication of large mirrors is a daunting task. The fabrication process needs to be scaled from the state-of-the-art (SOA) Hubble mirror at 2.4 m both in precision and dimensions of the mirrors.

**Relevance / Science Traceability:**

S2.03 primary supports potential Astrophysics Division missions. S2.03 has made optical systems in the past for potential balloon experiments. Future potential Decadal missions include Laser Interferometer Space Antenna (LISA), Habitable Exoplanet Observatory (HabEx), Large UV/Optical/Near-IR Surveyor (LUVOIR) and the Origins Space Telescope (OST).

**References:**

The HabEx and LUVOIR space telescope studies are developing concepts for UVOIR space telescopes for exo-Earth discovery and characterization, exoplanet science, general astrophysics, and solar system astronomy.

- The HabEx Interim Report is available at: [https://www.jpl.nasa.gov/habex/](https://www.jpl.nasa.gov/habex/) [27]
- The LUVOIR Interim Report is available at: [https://asd.gsfc.nasa.gov/luvoir/](https://asd.gsfc.nasa.gov/luvoir/) [26]

The OST is a single-aperture far-infrared telescope concept.

- The OST mission is described at: [https://asd.gsfc.nasa.gov/firs/](https://asd.gsfc.nasa.gov/firs/) [52]
- The Space Infrared Interferometric Telescope (SPIRIT) and its optical system requirements are described at: [https://asd.gsfc.nasa.gov/cosmology/spirit/](https://asd.gsfc.nasa.gov/cosmology/spirit/) [77]
Near-Infrared Lidar Beam Expander Telescope

Scope Description:

Potential airborne coherent lidar missions need compact 15-cm diameter 20× magnification beam expander telescopes. Potential space-based coherent lidar missions need at least 50-cm 65× magnification beam expander telescopes. Candidate coherent lidar systems (operating with a pulsed 2-µm laser) have a narrow, almost diffraction-limited field-of-view, close to 0.8 lambda/D half angle. Aberrations, especially spherical aberration, in the optical telescope can decrease the signal.

Additionally, the telescope beam expander should maintain the laser beam’s circular polarization. The incumbent telescope technology is a Dall-Kirkham beam expander. Technology advance is needed to make the beam expander more compact with less mass while retaining optical performance, and to demonstrate the larger diameter. Additionally, technology for nonmoving scanning of the beam expander output is needed.

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 08.2 Observatories

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

- An ideal Phase I deliverable would be a precision optical system of at least 0.15 m or a relevant subcomponent of a system. While detailed analysis will be conducted in Phase II, the preliminary design should address how optical, mechanical (static and dynamic), and thermal designs and performance analysis will be done to show compliance with all requirements. Past experience or technology demonstrations that support the design and manufacturing plans will be given appropriate weight in the evaluation.

- An ideal Phase II project would further advance the technology to produce a flight-qualifiable optical system greater than 0.5 m or relevant subcomponent (with a TRL in the 4 to 5 range). Phase I and Phase II system or component deliverables would be accompanied by all necessary documentation, including the optical performance assessment and all data on processing and properties of its substrate materials. A successful mission-oriented Phase 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:

The current state of the art (SOA) is a commercial off-the-shelf (COTS) beam expander with a 15-cm-diameter primary mirror, a heavy aluminum structure, an Invar rod providing thermally insensitive primary-to-secondary mirror separation, and a manually adjustable and lockable variable-focus setting by changing the mirror separation. Critical gaps include (1) a 50-to 70-cm-diameter primary mirror beam expander that features near-diffraction-limited performance; low mass design; minimal aberrations with an emphasis on spherical; characterization of the polarization changes versus beam cross section, assuming input circular polarization; a lockable electronic focus adjustment; both built-in and removable fiducial aids for aligning the input laser beam to the optical axis; and a path to space qualification and (2) a 15-cm-diameter primary mirror beam expander with the same features for airborne coherent lidar systems.

Relevance / Science Traceability:

Science Mission Directorate (SMD) desires both an airborne coherent-detection wind-profiling lidar systems and space-based wind measurement. The space mission has been recommended to SMD by both the 2007 and 2017 Earth Science Decadal Surveys. SMD has incorporated the wind lidar mission in its planning and has named it “3-D Winds”. SMD recently held the Earth Venture Suborbital competition for 5 years of airborne science campaigns. The existing coherent wind lidar at Langley, Doppler Aerosol Wind (DAWN), was included in three proposals that are under review. Furthermore, SMD is baselining DAWN for a second Convective Processes Experiment (CPEX-) type airborne science campaign and for providing calibration/validation assistance to the European Space Agency (ESA) Aeolus space mission. DAWN flies on the DC-8, and it is highly desired to fit DAWN on other NASA and National Oceanic and Atmospheric Administration (NOAA) aircraft. DAWN needs to lower its mass for several of the aircraft, and a low-mass telescope retaining the required performance is needed. Additionally, an electronic remote control of telescope focus is needed to adapt to aircraft cruise altitude and weather conditions during science flights.

References:

- NRC Decadal Surveys
at: http://sites.nationalacademies.org/DEPS/ESAS2017/index.htm [81]
  - See also supplemental material
    at: http://dx.doi.org/10.1175/MWR-D-16-0386.s1 [84]
Scope Title:
Fabrication, Test, and Control of Advanced Optical Systems

Scope Description:

Future ultraviolet (UV)/optical/near-infrared (NIR) telescopes require mirror systems that are very precise and ultrastable.

Regarding precision, this subtopic encourages proposals to develop technology that makes a significant advance in the ability to fabricate and test an optical system.

One area of current emphasis is the ability to nondestructively characterize coefficient of thermal expansion (CTE) homogeneity in 4-m-class Zerodur and 2-m-class ULE mirror substrates to an uncertainty of 1 ppb/K and a spatial sampling of 100×100. This characterization capability is needed to select mirror substrates before they undergo the expense of turning them into a lightweight space mirror.

Regarding stability, to achieve high-contrast imaging for exoplanet science using a coronagraph instrument, systems must maintain wavefront stability to <10 pm rms over intervals of ~10 min during critical observations. The ~10-min time period of this stability is driven by current wavefront sensing and control techniques that rely on stellar photons from the target object to generate estimates of the system wavefront. This subtopic aims to develop new technologies and techniques for wavefront sensing, metrology, and verification and validation of optical system wavefront stability.

Current methods of wavefront sensing include image-based techniques such as phase retrieval, focal-plane contrast techniques such as electric field conjugation and speckle nulling, and low-order and out-of-band wavefront sensing that use nonscience light rejected by the coronagraph to estimate drifts in the system wavefront during observations. These techniques are limited by the low stellar photon rates of the dim objects being observed (~5 to 11 Vmag), leading to 10s of minutes between wavefront control updates.

New methods may include: new techniques of using out-of-band light to improve sensing speed and spatial frequency content, new control laws incorporating feedback and feedforward for more optimal control, new algorithms for estimating absolute and relative wavefront changes, and the use of artificial guide stars for improved sensing signal-to-noise ratio and speed.

Current methods of metrology include edge sensors (capacitive, inductive, or optical) for maintaining segment cophasing, and laser distance interferometers for absolute measurement of system rigid body alignment. Development of these techniques to improve sensitivity, speed, and component reliability is desired. Low-power, high-reliability electronics are also needed.
Finally, metrology techniques for system verification and validation at the picometer level during integration and test (I&T) are needed. High speed spatial and speckle interferometers are currently capable of measuring single-digit picometer displacements and deformations on small components in controlled environments. Extension of these techniques to large-scale optics and structures in typical I&T environments is needed.

**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 08.2 Observatories

**Desired Deliverables of Phase I and Phase II:**

- Research
- Analysis
- Hardware
- Software

**Desired Deliverables Description:**

- An ideal Phase I deliverable would be a prototype demonstration of a fabrication, test or control technology leading to a successful Phase II delivery, or a reviewed preliminary design and manufacturing plan that demonstrates feasibility.
- While detailed analysis will be conducted in Phase II, the 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.

**State of the Art and Critical Gaps:**

Wavefront (WF) sensing using star images, including dispersed-fringe and phase-retrieval methods, is at TRL 6, qualified for space by the James Webb Space Telescope (JWST). WF sensing and control for coronagraphs, including electric field conjugation and low-order WF sensing (LOWFS), is at TRL4 and is being developed and demonstrated by Wide Field Infrared Survey Telescope Coronagraph Instrument (WFIRST/CGI).

Laser-distance interferometers for point-to-point measurements with accuracies from nanometers to picometers have been demonstrated on the ground by the Space Interferometry Mission and other projects, and on orbit by the LISA Pathfinder and Grace Follow-On mission. Application to telescope alignment metrology has been demonstrated on testbeds, to TRL4 for nanometer accuracy. Picometer accuracy for telescopes awaits demonstration.

Edge sensors are in use on segmented ground telescopes but are not yet on space telescopes. New designs are needed to provide picometer sensitivity and millimeter range in a space-qualified package.

Higher order WF sensing for coronagraphs using out-of-band light is beginning development, with data limited to
computer simulations.

Relevance / Science Traceability:

These technologies are enabling for coronagraph-equipped space telescopes, segmented space telescopes, and others that utilize actively controlled optics. The Large UV/Optical/IR Surveyor (LUVOIR) and Habitable Exoplanet Observatory (HabEx) mission concepts currently under study provide good examples.

References:

- The HabEx interim report is available at: https://www.jpl.nasa.gov/habex/ [27]
- The LUVOIR interim report is available at: https://asd.gsfc.nasa.gov/luvoir/reports/ [87]

Scope Title:

Optical Components and Systems for Potential Infrared/Far-Infrared Missions

Scope Description:

Far-infrared surveyor mission described in NASA’s Astrophysics Roadmap, "Enduring Quests, Daring Visions":

In the context of subtopic S2.03, the challenge is to take advantage of relaxed tolerances stemming from a requirement for long-wavelength (30 µm) diffraction-limited performance in the fully integrated optical telescope assembly to minimize the total mission cost through innovative design and material choices and novel approaches to fabrication, integration, and performance verification.

A far-infrared surveyor is a cryogenic far-infrared (IR) mission, which could be either a large single-aperture telescope or an interferometer. There are many common and a few divergent optical system requirements between the two architectures.

Common requirements:

- Telescope operating temperature of ~4 K.
- Telescope diffraction-limited at 30 µm at the operating temperature.
- Mirror survivability at temperatures ranging from 315 to 4 K.
- Mirror substrate thermal conductivity at 4 K of >2 W/m·K.
- Zero or low CTE mismatch between mirror substrate and backplane.

Divergent requirements:

- Large single-aperture telescope:
  - Segmented primary mirror, circular or hexagonal.
  - Primary mirror diameter 5 to 10 m.
  - Possible 3 degree-of-freedom (tip, tilt, and piston) control of mirror segments on orbit.
- Interferometer:
- Monolithic primary mirrors.
- Afocal, off-axis telescope design.
- Primary mirror diameter 1 to 4 m.

Success metrics:

- Areal cost <$500K/m$^2$.
- Areal density <15 kg/m$^2$ (<40 kg/m$^2$ with backplane).
- Production rate >2 m$^2$ per month.
- Short time span for optical system integration and test.

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
- Prototype
- Hardware

Desired Deliverables Description:

- An ideal Phase I deliverable would be a cryogenic optical system of at least 0.25 m and suitable for a far-infrared mission or a relevant subcomponent of a system. While detailed analysis will be conducted in Phase II, the 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.
- An ideal Phase II project would further advance the technology to produce a flight-qualifiable optical system greater than 0.5 m; a relevant subcomponent (with a TRL in the 4 to 5 range); or a working fabrication, test, or control system. Phase I and Phase II mirror system or component deliverables would be accompanied by all necessary documentation, including the optical performance assessment and all data on processing and properties of its substrate materials. A successful mission-oriented Phase 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) is represented by the Herschel Space Observatory (3.5-m monolith; SiC) and James
Webb Space Telescope (6.5-m segmented primary mirror; beryllium). Technologies are needed to advance the fabrication precision and the size of the mirrors, both monolithic and segmented, beyond the current SOA.

Relevance / Science Traceability:

The technology is relevant to the Far-Infrared Surveyor mission described in NASA’s Astrophysics Roadmap and prioritized in NASA’s Program Annual Technology Reports for Cosmic Origins and Physics of the Cosmos. A future NASA far-IR astrophysics mission will answer compelling questions, such as:

- How common are life-bearing planets?
- How do the conditions for habitability develop during the process of planet formation?
- How did the universe evolve in response to its changing ingredients (buildup of heavy elements and dust over time)?

To answer these questions, NASA will need telescopes and interferometers that reach fundamental sensitivity limits imposed by astrophysical background photon noise. Only telescopes cooled to a cryogenic temperature can provide such sensitivity.

Novel approaches to fabrication and test developed for a far-IR astrophysics mission may be applicable to far-IR optical systems employed in other divisions of the NASA Science Mission Directorate (SMD), or to optical systems designed to operate at wavelengths shorter than the far-IR.

References:

- The Origins Space Telescope (OST) final report is at: [https://asd.gsfc.nasa.gov/firs/](https://asd.gsfc.nasa.gov/firs/) [52]
- Program Annual Technology Reports (PATR) can be downloaded from the NASA Physics of the Cosmos and Cosmic Origins (PCOS/COR) Technology Development website at: [https://apd440.gsfc.nasa.gov/technology/](https://apd440.gsfc.nasa.gov/technology/) [89]

Scope Title:

Low-Cost Compact Reflective Telescope for CubeSAT Missions

Scope Description:

The need exists for a low-cost, compact (e.g., CubeSAT-class), scalable, diffraction-limited, athermalized, off-axis reflective telescopes. Typically, specialty optical aperture systems are designed and built as “one-offs,” which are inherently high in cost and often out of scope for smaller projects. A Phase I would investigate current compact off-axis reflective designs and develop a trade space to identify the most effective path forward. The work would include a strategy for aperture diameter scalability, athermalization, and low-cost fabrication. Detailed optical designs would be developed along with detailed structural, thermal, optical performances (STOP) analyses confirming diffraction limited operation across a wide range of operational disturbances, both structural dynamic and thermal. Phase II may follow up with development of prototypes, built at multiple aperture diameters and fidelities.
This Scope topic solicits solutions for two applications: near-infrared- and short-wave-infrared- (NIR/SWIR-) band communication and the Lightning Imaging Sensor.

NIR/SWIR optical-communication-support hardware should be assumed towards an integrated approach, including fiber optics, fast-steering mirrors, and applicable detectors.

The Lightning Imaging Sensor application requires a telescope that will fit inside a 6U or smaller CubeSAT with an 80° field-of-view, is diffraction limited at 500 nm (nominal), and has high spectral transmission at both 337 and 777 nm.

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 08.2 Observatories

Desired Deliverables of Phase I and Phase II:
   - Prototype
   - Hardware
   - Analysis

Desired Deliverables Description:

   - An ideal Phase I deliverable would be a prototype unobscured telescope with the required performance and size, or a reviewed preliminary design and manufacturing plan that demonstrates feasibility. While detailed analysis will be conducted in Phase II, the 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.
   - An ideal Phase II project would further advance the technology to produce a flight-qualifiable optical system with the required performance for a CubeSAT mission. Phase I and Phase II mirror system or component deliverables would be accompanied by all necessary documentation, including the optical performance assessment and all data on processing and properties of its substrate materials. A successful mission-oriented Phase 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:

Currently, the state of the art for reflective optical system for communications applications are:

1. On-axis or axisymmetric designs are typically used for (space) optical communications and imaging, which inherently are problematic due to the central obscuration.
2. Off-axis designs provide superior optical performance due to the clear aperture, however, are rarely considered due to complex design, manufacturing, and metrology procedures needed.
3. Currently flying Lightning Imaging Sensor is a large refractive lens optimized for single-wavelength operation. A reflective system is required for dual-wavelength operation. Also, a compact design is required to fit inside a CubeSat.

Relevance / Science Traceability:

Optical communications enable high-data-rate downlink of science data. The initial motivation for this scalable off-axis optical design approach is for bringing high-performance reflective optics within reach of laser communication projects with limited resources. However, this exact optical hardware is applicable for any diffraction-limited, athermalized, science imaging application. Any science mission could potentially be able to select from a “catalog” of optical aperture systems that would already have (flight) heritage and reduced risks.

References:

- An example of an on-axis design has been utilized in the Lunar Laser Communications Demonstration (LLCD): https://www.spiedigitallibrary.org/conference-proceedings-of-spie/10563/105630X/NASAs-current-activities-in-free-space-optical-communications/10.1117/12.2304175.full?SSO=1 [90]
- An example of an off-axis design is being developed by the Jet Propulsion Laboratory (JPL) for Deep Space Optical Communications (DSOC): https://www.spiedigitallibrary.org/conference-proceedings-of-spie/10096/100960V/Discovery-deep-space-optical-communications-DSOC-transceiver/10.1117/12.2256001.full [93]
- Information about NASA’s current (large-scale) Lightning Imaging Sensor can be found at: https://gpm.nasa.gov/missions/TRMM/satellite/LIS [94]

S2.04 X-Ray Mirror Systems Technology, Coating Technology for X-Ray-UV-OIR, and Free-Form Optics

Lead Center: GSFC

Participating Center(s): JPL, MSFC

Scope Title:
X-Ray Mirror Systems Technology, Coating Technology for X-Ray-UV-OIR, and Free-Form Optics

Scope Description:

The National Academy Astro2010 Decadal Report identifies studies of optical components and ability to manufacture, coat, and perform metrology needed to enable future x-ray observatory missions.

The Astrophysics Decadal specifically calls for optical coating technology investment for future ultraviolet (UV), optical, exoplanet, and infrared (IR) missions, and the Heliophysics 2009 Roadmap identifies the coating technology for space missions to enhance rejection of undesirable spectral lines and improve space/solar-flux durability of extreme UV (EUV) optical coatings, as well as coating deposition to increase the maximum spatial resolution.

Future optical systems for NASA's low-cost missions, CubeSat, and other small-scale payloads, are moving away from traditional spherical optics to nonrotationally symmetric surfaces with anticipated benefits of free-form optics such as fast wide-field and distortion-free cameras.

This subtopic solicits proposals in the following three focus areas:

- X-ray manufacturing, coating, testing, and assembling complete mirror systems in addition to maturing the current technology.
- Coating technology including carbon nanotubes (CNTs) for a wide range of wavelengths from x-ray to IR (x-ray, EUV, Lyman UV (LUV), vacuum UV (VUV), visible, and IR).
- Free-form optics design, fabrication, and metrology for CubeSat, SmallSat, and various coronagraphic 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 08.2 Observatories

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Typical deliverables based on sub-elements of this subtopic:

Phase I:

- X-ray optical mirror system: Analysis, reports, prototype.
- Coating: Analysis, reports, software, demonstration of the concept and prototype.
- Free-form optics: Analysis, design, software and hardware prototype of optical components.

Phase II:

- X-ray optical mirror system: Analysis and prototype.
- Coating: Analysis, reports, software, demonstration of the concept and prototype.
- Free-form optics: Analysis, design, software and hardware prototype of optical components

State of the Art and Critical Gaps:
This subtopic focuses on three areas of technology development:

- This work is a very costly and time consuming. Most of SOA (state of the art) requiring improvement is ~10 arcsec angular resolution. SOA straylight suppression is bulky and ineffective for wide-field of view telescopes. We seek significant reduction in both expense and time. Reduce the areal cost of telescope by 2x such that the larger collecting area can be produced for the same cost or half the cost.
- Coating technology for wide range of wavelengths from x-ray to IR (x-ray, EUV, LUV, VUV, visible, and IR). The current x-ray coating is defined by NuSTAR. Current EV is defined by Heliophysics (80% reflectivity from 60 to 200 nm). Current UVOIR is defined by Hubble. MgF2 over coated aluminum on 2.4-m mirror. This coating has birefringence concerns and marginally acceptable reflectivity between 100 to 200 nm.
- Free-form optics design, fabrication, and metrology for package constrained imaging systems. This field is in early stages of development. Improving the optical surfaces with large field of view and fast F/#s is highly desirable.

Relevance / Science Traceability:

S2.04 supports variety of Astrophysics Division missions. The technologies in this subtopic encompasses fields of x-ray, coating technologies ranging from UV to IR, and free-form optics in preparation for Decadal missions such as HabEx, LUVOIR, and OST.

Optical components, systems, and stray light suppression for x-ray missions: The 2010 National Academy Decadal Report specifically identifies optical components and the ability to manufacture and perform precise metrology on them needed to enable several different future missions (Next Generation x-ray Optics, NGXO). The National Research Council (NRC) NASA Technology Roadmap Assessment ranked advanced mirror technology for new x-ray telescopes as the #1 Object C technology requiring NASA investment.

Free-form optics: NASA missions with alternative low-cost science and small-size payload are increasing. However, the traditional interferometric testing as a means of metrology are unsuited to free-form optical surfaces because of changing curvature and lack of symmetry. Metrology techniques for large fields of view and fast F/#s in small-size instruments is highly desirable, specifically if they could enable cost-effective manufacturing of these surfaces (CubeSat, SmallSat, NanoSat, various coronagraphic instruments).

Coating for x-ray, EUV, LUV, UV, visible, and IR telescopes: Astrophysics Decadal specifically calls for optical coating technology investment for: Future UV/Optical and Exoplanet missions (Habitable Exoplanet Observatory (HabEx) or Large Ultraviolet Optical Infrared Surveyor (LUVOIR)). Heliophysics 2009 Roadmap identifies optical coating technology investments for: Origins of Near-Earth Plasma (ONEP); Ion-Neutral Coupling in the Atmosphere (INCA); Dynamic Geospace Coupling (DGC); Fine-scale Advanced Coronal Transition-Region Spectrograph (FACTS); Reconnection and Micro-scale (RAM); and Solar-C Nulling polarimetry/coronagraph for exoplanet imaging and characterization, dust and debris disks, extra-galactic studies, and relativistic and nonrelativistic jet studies.

References:

The Habitable Exoplanet Observatory (HabEx) is a concept for a mission to directly image planetary systems around Sun-like stars. HabEx will be sensitive to all types of planets; however, its main goal is, for the first time, to directly image Earth-like exoplanets, and characterize their atmospheric content. By measuring the spectra of these planets, HabEx will search for signatures of habitability such as water, and be sensitive to gases in the atmosphere possibility indicative of biological activity, such as oxygen or ozone.

The study pages are available at:

- Habitable Exoplanet Observatory (HabEx): https://www.jpl.nasa.gov/habex/ [27]
- LUVOIR: https://asd.gsfc.nasa.gov/luvoir/ [26]
- The LYNX Mission Concept: https://wwwastro.msfc.nasa.gov/lynx/ [28]
- The Large UV/Optical/IR Surveyor (LUVOIR) is a concept for a highly capable, multiwavelength space observatory with ambitious science goals. This mission would enable great leaps forward in a broad range
of science, from the epoch of re-ionization, through galaxy formation and evolution, star and planet formation, to solar system remote sensing. LUVOIR also has the major goal of characterizing a wide range of exoplanets, including those that might be habitable—or even inhabited. The LUVOIR Interim Report is available at:
https://asd.gsfc.nasa.gov/luvoir/

- The Origins Space Telescope (OST) is the mission concept for the Far-IR Surveyor study. NASA's Astrophysics Roadmap, Enduring Quests, Daring Visions, recognized the need for an Origins Space Telescope mission with enhanced measurement capabilities relative to those of the Herschel Space Observatory, such as a 3-order-of-magnitude gain in sensitivity, angular resolution sufficient to overcome spatial confusion in deep cosmic surveys or to resolve protoplanetary disks, and new spectroscopic capability. The community report is available at:
  https://science.nasa.gov/science-committee/subcommittees/nac-astrophysics-subcommittee/astrophysics-roadmap

Scope Title:
X-Ray Mirror Systems Technology

Scope Description:

NASA large x-ray observatory requires low-cost, ultrastable, lightweight mirrors with high-reflectance optical coatings and effective stray-light suppression. The current state of the art of mirror fabrication technology for x-ray missions is very expensive and time consuming. Additionally, a number of improvements such as 10 arcsec angular resolutions and 1 to 5 m² collecting area are needed for this technology. Likewise, the stray-light suppression system is bulky and ineffective for wide-field-of-view telescopes.

In this area, we are looking to address the multiple technologies including: improvements to manufacturing (machining, rapid optical fabrication, slumping, or replication technologies), improved metrology, performance prediction and testing techniques, active control of mirror shapes, new structures for holding and actively aligning of mirrors in a telescope assembly to enable x-ray observatories while lowering the cost per square meter of collecting aperture and effective design of stray-light suppression in preparation for the Decadal Survey of 2020. Additionally, we need epoxies to bond mirrors that are made of silicon. The epoxies should absorb infrared (IR) radiation (with wavelengths between 1.5 and 6 µm that traverses silicon with little or no absorption) and therefore can be cured quickly with a beam of IR radiation. Currently, x-ray space mirrors cost $4 million to $6 million per square meter of optical surface area. This research effort seeks a cost reduction for precision optical components by 5 to 50 times, to less than $1M to $100K per square meter.

Additionally, proposals are solicited to develop new advanced-technology computer-numerical-control (CNC) machines to polish inside and/or outside surfaces of full-shell (between 100 and 1,000 mm in height, 100 to 2,800 mm in diameter, varying radial prescription along azimuth, and ~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, and out-of-round <2 µm). Current state-of-the-art technology in CNC polishing of full-shell, grazing-incidence optics yields 2.5 arcsec HPD on the outside of a mandrel used for replicating shells. Technology advances beyond current state of the art include application of CNC and deterministic polishing techniques that (1) allow for direct force closed-loop control, (2) reduce alignment precision requirements, and (3) optimize the machine for polishing cylindrical optics through simplifying the axis arrangement and the layout of the cavity of the CNC polishing machine.

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 deliverable based on sub-elements of this subtopic:
X-ray optical mirror system—Demonstration, analysis, reports, software, and hardware prototype:

- Phase I deliverables: Reports, analysis, demonstration, and prototype
- Phase II deliverables: Analysis, demonstration, and prototype

State of the Art and Critical Gaps:

X-ray optics manufacturing, metrology, coating, testing, and assembling complete mirror systems in addition to maturing the current technology. This work is very costly and time-consuming. Most of the SOA (state of the art) requiring improvement is ~10 arcsec angular resolution. SOA stray-light suppression is bulky and ineffective for wide-field of view telescopes. We seek a significant reduction in both expense and time. Reduce the areal cost of a telescope by 2× such that the larger collecting area can be produced for the same cost or half the cost.

The gaps to be covered in this track are:

- Lightweight, low-cost, ultrastable mirrors for large x-ray observatory.
- Stray-light suppression systems (baffles) for large advanced x-ray observatories.
- Ultrastable, inexpensive lightweight x-ray telescope using grazing-incidence optics for high-altitude balloon-borne and rocket-borne mission.

Relevance / Science Traceability:

The 2010 National Academy Decadal Report specifically identifies optical components and the ability to manufacture and perform precise metrology on them needed to enable several different future missions (Lynx and Advanced X-ray Imaging Satellite (AXIS)).

The National Research Council NASA Technology Roadmap Assessment ranked advanced mirror technology for new x-ray telescopes as the #1 Object C technology requiring NASA investment.

References:

NASA High Energy Astrophysics (HEA) mission concepts including x-ray missions and studies are available at:

- [https://heasarc.gsfc.nasa.gov/docs/heasarc/missions/concepts.html](https://heasarc.gsfc.nasa.gov/docs/heasarc/missions/concepts.html) [96]

Scope Title:

Coating Technology for X-Ray-UV-OIR

Scope Description:

The optical coating technology is a mission-enabling feature that enhances the optical performance and science return of a mission. Lowering the areal cost of coating determines if a proposed mission could be funded in the current cost environment. The most common forms of coating used on precision optics are antireflective (AR) coating and high-reflective (HR) coating.

The current coating technology of optical components needed to support the 2020 Astrophysics Decadal process. Historically, it takes 10 years to mature mirror technology from TRL 3 to 6.

To achieve these objectives requires sustained systematic investment.
The telescope optical coating needs to meet low-temperature operation requirement. It’s desirable to achieve 35 K in future.

A number of future NASA missions require suppression of scattered light. For instance, the precision optical cube utilized in a beam-splitter application forms a knife-edge that is positioned within the optical system to split a single beam into two halves. The scattered light from the knife-edge could be suppressed by carbon nanotube (CNT) coating. Similarly, the scattered light for gravitational-wave application and lasercom system where the simultaneous transmit/receive operation is required, could be achieved by a highly absorbing coating such as CNT. Ideally, the application of CNT coating needs to:

- Achieve broadband (visible plus near infrared (IR)) reflectivity of 0.1% or less.
- Resist bleaching of significant albedo changes over a mission life of at least 10 years.
- Withstand launch conditions such 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/cm² density, and 1-kW/nsec pulses.
- Adhere to the multilayer dielectric or protected metal coating, including ion beam sputtering (IBS) coating.

NASA’s Laser Interferometer Space Antenna (LISA) mission on-axis design telescope operates both in transmission and reception simultaneously where the secondary mirror sends the transmitted beam directly back at the receiver. The apodized petal-shaped mask inherently suppress the diffraction once patterned at the center of the secondary mirror. The emerging cryogenic etching of black-silicon has demonstrated bidirectional reflectance distribution function (BRDF) ultralow specular reflectance of $1 \times 10^{-7}$ in the range of 500 to 1,064 nm. The advancement of this technology is desired to obtain ultralow reflectivity.

- Improve the specular reflectance to $1 \times 10^{-10}$ and hemispherical reflectance better than 0.1%.
- Improve the cryogenic etching process to provide a variation of the reflectance (apodization effect) by increasing or decreasing the height of the grass.
- Explore etching process and duration.

**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:**

Coating—Analysis, reports, software, demonstration of the concept, and prototype:

- Phase I deliverables: Report, analysis, demonstration, and prototype.
- Phase II deliverables: Analysis, demonstration and prototype.

**State of the Art and Critical Gaps:**

Coating Technology (for wide range of wavelengths from x-ray to IR: x-ray, extended UV (EUV), Lyman UV (LUV), vacuum UV (VUV), visible, and IR):

- The current x-ray coating is defined by Nuclear Spectroscopic Telescope Array (NuSTAR).
• Current EUV is defined by Heliophysics (80% reflectivity from 60 to 200 nm).
• Current UVOIR is defined by Hubble. MgF2 overcoated aluminum on 2.4-m mirror. This coating has birefringence concerns and marginally acceptable reflectivity between 100 and 200 nm.

Metrics for X-Ray:

• Multilayer high-reflectance coatings for hard x-ray mirrors.
• Multilayer depth gradient coatings for 5 to 80 keV with high broadband reflectivity.
• Zero-net-stress coating of iridium or other high-reflectance elements on thin substrates (<0.5 mm).

Metrics for EUV:

• Reflectivity >90% from 6 to 90 nm onto a <2 m mirror substrate.

Metrics for Large UV/Optical/IR Surveyor (LUVOIR):

• Broadband reflectivity >70% from 90 to 120 nm (LUV) and >90% from 120 nm to 2.5 µm (VUV/visible/IR).
• Reflectivity non-uniformity <1% 90 nm to 2.5 µm.
• Induced polarization aberration <1% 400 nm to 2.5 µm spectral range from mirror coating applicable to a 1- to 8-m substrate.

Metrics for LISA:

• HR: Reflectivity >99% at 1,064 +/- 2 nm with very low scattered light and polarization-independent performance over apertures of ~0.5 m.
• AR: Reflectivity <0.005% at 1,064 +/- 2 nm.
  ◦ Low-absorption, low-scatter, laser-line optical coatings at 1,064 nm.
  ◦ High reflectivity, R > 0.9995.
  ◦ Performance in a space environment without significant degradation over time, due for example to radiation exposure or outgassing.
  ◦ High polarization purity, low optical birefringence over a range of incident angles from ~5° 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. Cleaning should not degrade the 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, adhere to the multilayer dielectric or protected metal coating.

Black-Silicon Cryogenic Etching (new):

• Broadband UV+visible+NIR+IR, reflectivity of 0.01% or less, adhere to the multilayer dielectric (silicon) or protected metal.

Software tools to simulate and assist the anisotropic etching by employing variety of modeling techniques such as
rigorous coupled wave analysis (RCWA), method of moments (MOM), finite-difference time domain (FDTD), finite element method (FEM), transfer matrix method (TMM), and effective medium theory (ETM).

Relevance / Science Traceability:

- Coating for x-ray, EUV, LUV, UV, visible, and IR telescopes: Astrophysics Decadal specifically calls for optical coating technology investment for: Future UV/optical and exoplanet missions.
- Heliophysics 2009 Roadmap identifies optical coating technology investments for: Origins of Near-Earth Plasma (ONEP), Ion-Neutral Coupling in the Atmosphere (INCA), Dynamic Geospace Coupling (DGC), Fine-scale Advanced Coronal Transition-Region Spectrograph (FACTS), Reconnection and Microscale (RAM), and Solar-C.
- LISA requires low-scatter HR coatings and low reflectivity coatings for scatter suppression near 1064 nm. Polarization-independent performance is important.
- Nulling polarimetry/coronagraphy for exoplanets imaging and characterization, dust and debris disks, extragalactic studies, and relativistic and nonrelativistic jet studies.

References:

Laser Interferometer Space Antenna (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.

- More information can be found at: https://lisa.nasa.gov [78]

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 as they provide nonrotationally symmetric optics, which allow for better packaging while maintaining desired image quality. Currently, the 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 operational temperature range of un-obscured 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.

Specific metrics are:

- Design: Innovative design methods/tools for free-form systems, including applications to 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 Angstroms. 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 are also desired for flagship missions for ultraviolet (UV) and coronagraphy applications, with 10-cm- to 1-m-diameter surfaces having figure error <5 nm rms and roughness <1 Angstroms 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:

Optical components—Demonstration, analysis, design, metrology, software, and hardware prototype:

- Phase I deliverables: Report, analysis, demonstration, and prototype.
- Phase II deliverables: Analysis, demonstration, and prototype.

State of the Art and Critical Gaps:

Free-form optics design, fabrication, and metrology for package constrained imaging systems. This field is in early stages of development. Improving the optical surfaces with large field-of-view and fast F/#s is highly desirable.

Relevance / Science Traceability:

NASA missions with alternative low-cost science and small-size payload are increasing. However, the traditional interferometric testing as a means of metrology is unsuited to freeform optical surfaces due to changing curvature and lack of symmetry. Metrology techniques for large fields-of-view and fast F/#s in small size instruments are highly desirable specifically if they could enable cost-effective manufacturing of these surfaces. (CubeSat, SmallSat, and NanoSat). Additionally, design studies for large observatories such as Origins Space Telescope (OST) and Large UV/Optical/IR Surveyor (LUVOIR, currently being proposed for the 2020 Astrophysics Decadal Survey) 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:

A presentation on application of Freeform Optics at NASA is available at:

- Applications for Freeforms Optics at NASA, [https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170010419.pdf](https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170010419.pdf) [97]
- Alignment and Testing for a Freeform Telescope, [https://ntrs.nasa.gov/citations/20180007557](https://ntrs.nasa.gov/citations/20180007557) [98]
- Freeform Surface Characterization and Instrument Alignment for Freeform Space Applications, [https://ntrs.nasa.gov/citations/20190025929](https://ntrs.nasa.gov/citations/20190025929) [99]

S2.05 Technology for the Precision Radial Velocity Measurement Technique

Lead Center: GSFC

Participating Center(s): GSFC

Scope Title:
Components, Assemblies, and Subsystems for Extreme Precision Radial Velocity Measurements and Detection of Extrasolar Planets

Scope Description:

Astronomical spectrographs have proven to be powerful tools for exoplanet searches. When a star experiences periodic motion due to the gravitational pull of an orbiting planet, its spectrum is Doppler modulated in time. This is the basis for the precision radial velocity (PRV) method, one of the first and most efficient techniques for detecting and characterizing exoplanets. Because spectrographs have their own drifts, which must be separated from the periodic Doppler shift, a stable reference is always needed for calibration. Optical frequency combs (OFCs) and line-referenced etalons are capable of providing the spectral rulers needed for PRV detection of exoplanets. Although “stellar jitter” (a star’s photospheric velocity contribution to the RV signal) is unavoidable, the contribution to the error budget from Earth’s atmosphere would be eliminated in future space missions. Thus, there is a need to develop robust spectral references, especially at visible wavelengths to detect and characterize Earth-like planets in the habitable zone of their Sun-like host stars, with size, weight, and power (SWaP) suitable for space-qualified operation to calibrate the next generation of high-resolution spectrographs with precision corresponding to <~1 cm/s over multiple years of observations.

This subtopic solicits proposals to develop cost-effective component and subsystem technology for low-SWaP, long-lived, robust implementation of RV measurement instruments both on the ground and in space. Research areas of interest include but are not limited to:

- Integrated photonic spectrographs.
- Spectrograph gratings.
- PRV spectrograph calibration sources.
- High efficiency photonic lanterns.
- Advanced optical fiber delivery systems and subsystems with high levels of image scrambling and modal noise reduction.
- Software for advanced statistical techniques to mitigate effects of telluric absorption and stellar jitter on RV precision and accuracy.

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:

- Hardware
- Software

Desired Deliverables Description:

- Phase I will emphasize research aspects for technical feasibility, infusion potential into ground or space operations, clear and achievable benefits (e.g., reduction in SWaP and/or cost, improved RV precision), and show a path towards a Phase II proposal. Phase I deliverables include feasibility and concept-of-operations of the research topic, simulations and measurements, validation of the proposed approach to develop a given product (TRL 3 to 4), and a plan for further development of the specific capabilities or products to be performed in Phase II.
Early development and delivery of prototype hardware/software is encouraged.

- Phase II will emphasize hardware/software development with delivery of specific hardware or software products for NASA targeting demonstration operations at a ground-based telescope in coordination with the lead NASA center. Phase II deliverables include a working prototype or engineering model of the proposed product/platform or software along with documentation of development, capabilities, and measurements (showing specific improvement metrics); and tools as necessary. Proposed prototypes shall demonstrate a path towards a flight-capable platform. Opportunities and plans should also be identified and summarized for potential commercialization or NASA infusion.

**State of the Art and Critical Gaps:**

High-resolving-power spectrographs (R ~ 150,000) with simultaneous UV, visible, and NIR coverage and exquisite long-term stability are required for PRV studies. Classical bulk optic spectrographs traditionally used for PRV science impose architectural constraints due to their large mass and limited optical flexibility. Integrated photonic spectrographs are wafer-thin devices that could reduce instrument volume by up to 3 orders of magnitude. Spectrometers that are fiber fed, with high illumination stability, excellent wavelength calibration, and precise temperature and pressure control represent the immediate future of precision RV measurements.

Traditional RV spectrographs would benefit from improvements in grating technology. Diffraction-limited PRV spectrographs require echelle gratings with low wavefront error and high efficiency, both of which are very challenging to achieve. Echelle spectrographs are designed to operate at high angle-of-incidence and very high diffraction order. Hence, the grating must have very accurate groove placement (for low wavefront error) and very flat groove facets (for high efficiency). For decades, echelle gratings have been fabricated by diamond ruling, but it is difficult to achieve all aspects of the performance required for PRV instruments. Newer grating fabrication techniques using lithographic methods to form the grooves may be a promising approach. As spectrograph stability imposes limits on how precisely RV can be measured, spectral references play a critical role in characterizing and ensuring this precision. Only laser frequency combs (LFCs) and line-referenced Fabry-Pérot etalons are capable of providing the broad spectral coverage and long-term stability needed for extreme PRV detection of exoplanets. Although both frequency combs and etalons can deliver high-precision spectrograph calibration, the former requires relatively complex hardware in the visible portion of the spectrum.

Commercial fiber laser astrocombs covering 450 to 1400 nm at 25 GHz line spacing and <3-dB intensity variations over the entire bandwidth are available for ground-based astronomical spectrographs. However, the cost for these systems is often so prohibitive that recent RV spectrograph projects either do not use a LFC or include it only as a future upgrade. Alternatively, astrocombs produced by electro-optic modulation (EOM) of a laser source have been demonstrated in the NIR. EOM combs produce modes spaced at a radiofrequency (RF) modulation frequency, typically 10 to 30 GHz. Significantly, EOM combs avoid the line filtering step required by commercial mode-locked fiber laser combs. Comb frequency stabilization can be accomplished by referencing the laser pump source to a molecular absorption feature or another frequency comb. Where octave spanning EOM combs are available, f-2f self-referencing provides the greatest stability. EOM combs must be spectrally broadened to provide the bandwidth necessary for PRV applications. This is accomplished through pulse amplification followed by injection into highly nonlinear fiber or nonlinear optical waveguides.

Power consumption of the frequency comb calibration system will be a significant driver of mission cost for space-based PRV systems and motivates the development of a comb system that operates with less than 20 W of spacecraft power. Thus, for flight applications, it is highly desirable to develop frequency comb technology with low power consumption; ~10 to 30 GHz mode spacing; compact size; broad (octave spanning) spectral grasp across both the visible and NIR; low phase noise; stability traceable to the International System of Units definition of the second; and importantly, long life.
The intrinsic illumination stability of the spectrometer also sets a fundamental measurement floor. As the image of the star varies at the entrance to the spectrometer because of atmospheric effects and telescope guiding errors, so too does the recorded stellar spectrum, leading to a spurious RV offset. Current seeing-limited PRV instruments use multimode optical fibers, which provide some degree of azimuthal image scrambling, to efficiently deliver stellar light from the telescope focal plane to the spectrometer input. Novel-core-geometry fibers, in concert with dedicated optical double-scramblers, are often used to further homogenize and stabilize the telescope illumination pattern in both the image and pupil planes. However, these systems still demonstrate measurable sensitivity to incident illumination variations from the telescope and atmosphere. Furthermore, as spectral resolution requirements increase, the commensurate increase in instrument size becomes impractical. Thus, the community has turned to implementing image and pupil slicers to reformat the near or far fields of light entering the spectrometer by preferentially redistributing starlight exiting the fiber to maintain high spectral resolution, efficiency, and compact spectrometer size.

Relevance / Science Traceability:

The NASA Strategic Plan (2018) and Space Mission Directorate Science Plan (2014) both call for discovery and characterization of habitable Earth analogs and the search for biosignatures on those worlds. These goals were endorsed and amplified upon in the recent National Academy of Science (NAS) Exoplanet Report, which emphasized that a knowledge of the orbits and masses is essential to the complete and correct characterization of potentially habitable worlds. PRV measurements are needed to follow up on the transiting worlds discovered by Kepler, K2, and Transiting Exoplanet Survey Satellite (TESS). The interpretation of the transit spectra that the James Webb Space Telescope (JWST) will obtain will depend on knowledge of a planet’s surface gravity, which comes from its radius (from the transit data) and its mass (from PRV measurements or, in some cases, transit timing variations). Without knowledge of a planet's mass, the interpretation of its spectrum is subject to many ambiguities.

These ambiguities will only be exacerbated for the direct-imaging missions such as the proposed Habitable Exoplanet Observatory (HabEx) and Large Ultraviolet Optical Infrared Surveyor (LUVOIR) flagships, which will obtain spectra of Earth analogs around a few tens to hundreds of stars. Even if a radius can be inferred from the planet's brightness and an estimate of its albedo, the lack of a dynamical mass precludes any knowledge of the planet's density, bulk composition, and surface gravity, which are needed to determine, for example, absolute gas column densities. Moreover, a fully characterized orbit is challenging to determine from just a few direct images and may even be confused in the presence of multiple planets. Is a planet in a highly eccentric orbit habitable or not? Only dynamical (PRV) measurements can provide such information. Thus, highly precise and highly stable PRV measurements are absolutely critical to the complete characterization of habitable worlds.

The NAS report also noted that measurements from space might be a final option if the problem of telluric contamination cannot be solved. The Earth’s atmosphere will limit
precise radial velocity measurements to ~10 cm/s at wavelengths longer than ~700 nm and greater than 30 cm/s at wavelengths >900 nm, making it challenging to mitigate the effects of stellar activity without a measurement of the color dependence due to stellar activity in the PRV time series. A space-based PRV mission, such as has been suggested in the NASA EarthFinder mission concept study, may be necessary. If so, the low SWaP technologies developed under this SBIR program could help enable space-based implementations of the PRV method.

References:

Precision Radial Velocity:


Photonic Lanterns:


Astrocombs:


Nonlinear Waveguides:


Spectral Flattening:


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**S3.01 Power Generation and Conversion**

Lead Center: GRC

Participating Center(s): JPL

Scope Title:

Photovoltaic Energy Conversion

**Scope Description:**

This subtopic is seeking photovoltaic cell and blanket technologies that lead to significant improvements in overall solar array performance for missions in areas of scientific interest including high-intensity, high-temperature (HIHT); low-intensity, low-temperature (LILT); and high-radiation environments. Additionally sought are solar power systems that can provide high power in compactly stowed volumes for small spacecraft.

These improvements may be achieved by optimizing the cell technology to operate in HIHT/LILT, increasing end of life (EOL) performance, increasing photovoltaic cell efficiency above 35% at 1 AU, and decreasing solar cell module/blanket stowed volume. Missions at distances of greater than 1 AU may include an inner planetary flyby, as such technologies that optimize solar cell string length to account for the changes in power generation are also of interest.

Photovoltaic energy conversion: advances in, but not limited to, the following: (1) Photovoltaic cell and blanket technologies capable of LILT operation applicable to outer planetary (low solar intensity) missions; (2) Photovoltaic cell and blanket technologies capable of HIHT operation applicable to inner planetary missions; (3) Photovoltaic cell and blanket technologies that enhance and extend performance in lunar applications including orbital, surface, and transfer; and (4) Solar cell and blanket technologies to support missions in high-radiation, LILT environments near Jupiter and its moons.
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
- 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 system deployable systems. There are very limited demonstrated technology for HIHT and LILT missions. 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 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 arrays, and a wide range of environmental operating conditions.

Relevance / Science Traceability:

These technologies are relevant to any space science, Earth science, planetary surface, or other science mission that requires affordable high-efficiency photovoltaic power production for orbiters, flyby craft, landers, and rovers.

Specific requirements can be found in the References, but include many future Science Mission Directorate (SMD) missions. Specific requirements for orbiters and flybys to Outer planets include: LILT capability (>38% at 10 AU and <140 °C), radiation tolerance (6×10^{15} 1 MeV e/cm²), high power (>50 kW at 1 AU), low mass (3× lower than the standard operating procedure (SOP)), low volume (3× lower than SOP), long life (>15 years), and high reliability.

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

NASA outlines New Lunar Science, Human Exploration Missions: [108]

NASA Science Missions: [109]

References:

- Solar Power Technologies for Future Planetary Science Missions: [110]
- NASA outlines New Lunar Science, Human Exploration Missions: [108]
S3.02 Dynamic Power Conversion

Lead Center: GRC

Scope Title:

Dynamic Power Conversion

Scope Description:

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

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

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

Desired Deliverables Description:

Phase I deliverables: results of a feasibility study and analysis, as described in a final report.

Phase II deliverables: 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.

State of the Art and Critical Gaps:

Radioisotope power systems are critical for long-duration NASA missions in dark, dusty, or harsh environments. Thermoelectric systems have been used on the very successful RPSs flown in the past, but are limited in efficiency. Dynamic thermal energy conversion provides significantly higher efficiency, and through proper engineering of the noncontact moving components, can eliminate wear mechanisms and provide long life. Although high-efficiency performance of dynamic power convertors has been proven, reliable and robust systems tolerant of off-nominal operation are needed. In addition to convertors appropriate for GPHS RPSs, advances in much smaller and lower power dynamic power conversion systems are sought that can utilize RHUs for applications such as distributed sensor systems, small spacecraft, and other systems that take advantage of lower power electronics for the exploration of surface phenomenon on icy moons and other bodies of interest. Although the power convertor advances are essential, to develop reliable and robust systems for future flight advances in convertor components as well as RPS integration components are also needed. These would include efficient alternators able to survive 200 °C, robust high-temperature-tolerant regenerators, robust high-efficiency recuperators, heat pipes, radiators, and controllers applicable to Stirling flexure-bearing, Stirling gas-bearing, or Brayton convertors.

Relevance / Science Traceability:

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

References:


Scope Title:
**Additive Manufacturing Microfabrication of Stirling Heat Engine Regenerators**

**Scope Description:**

In space applications where solar power is not practical, dynamic power conversion is an effective alternative. Of the several technologies used for dynamic power conversion, free-piston Stirling heat engines, coupled with alternators, offer high thermal-to-electric conversion efficiency, low mass, and long life. One component of Stirling heat engines that contributes to their excellent efficiency is the regenerator, which acts as a heat exchanger/storage for the working fluid as it passes from the heat acceptor to the rejector and again as it returns to the acceptor to repeat the cycle. The current state of the art in the construction of regenerators results in a cylindrical annulus made up of heat- and corrosion-resistant, short metallic fibers in diameters of 20 to 40 µm, packed to form an annulus with a porosity of 80% to 90% (solid fraction 10% to 20%), and sintered to achieve structural stability.

In some instances, these random fiber regenerators have released small particle debris due to less-than-complete sintering of the fiber matrix, presenting a risk of interference in the very small running clearance gaps of the displacer and power pistons, and potentially negatively affecting the performance and robustness of the heat engine. NASA has engaged in initial studies to determine the feasibility of producing continuous regenerator matrices through additive manufacturing (AM), and while these studies show promise, it has been determined that limitations of selective laser melting in the minimum achievable feature size and spacing between features prevents realization of performance goals. Sought are advances in AM microfabrication that demonstrate:

1. Applicability to high-temperature, corrosion-resistant metal alloys (Inconel, FeCrAlY, etc.).
2. Capability of creating ligaments in diameters as small as 20 µm, with spacing between ligaments as small as 100 µm.
3. Capability of producing cylindrical annuli on the order of 5.5 cm O.D. and 4.0 cm I.D. in axial lengths of up to 5 cm. Axial length may be achieved by stacking multiple components of shorter lengths.
4. Reasonable build time to support on-demand production.
5. Ability to create regenerator matrices that are stable and robust in the anticipated vibro-acoustic environments associated with space missions (launch, pyroshock, entry/descent/landing, etc.).

**Expected TRL or TRL Range at completion of the Project:** 1 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: results of a feasibility study and analysis, as described in a final report.

Phase II deliverables: prototype hardware that has demonstrated basic functionality in a laboratory environment, the appropriate research and analysis used to develop the hardware, and maturation options.
State of the Art and Critical Gaps:

Radioisotope power systems (RPS) are critical for long duration NASA missions to destinations sufficiently far from the Sun that solar power is impractical, and for missions to permanently shadowed areas of planetary bodies and their moons. Thermoelectric power systems (RTG) have enjoyed much success in past missions, but their efficiency is limited. Dynamic RPS offer significantly higher efficiency, resulting in lower system mass and reduced radioisotope inventory for a given power output. Advances in microfabrication of regenerators are needed for reduction of risk associated with stability of the regenerator matrix and improvements in reliability and robustness to support long mission durations.

Relevance / Science Traceability:

The technology described here aligns with the Science Mission Directorate Planetary Science Division (SMD/PSD) requirements for space power and energy storage and provides a low-TRL pathway for technologies that may contribute to a reduction of risk and improvements in reliability and robustness of Stirling heat engines in space-power applications.

References:


S3.03 Energy Storage for Extreme Environments

Lead Center: GRC

Participating Center(s): JPL

Scope Title:

Energy Storage for Extreme Environments

Scope Description:

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

Future science missions will require advanced primary and secondary battery systems capable of operating at temperature extremes from -200 °C for outer planet missions to 400 to 500 °C for Venus missions, and a span of -230 to +120 °C for missions to the lunar surface. Operational durations of 30 to 60 days for Venus; 30 to 60 days for deep-space environments such as Europa, Enceladus, and Titan; and 14-day eclipses for lunar night survival and operations on the Moon are of interest. Advancements to battery energy storage capabilities that address operation for one of the listed missions (Venus, deep space, or lunar) combined with high specific energy and energy density (>250 Wh/kg and >500 Wh/L for rechargeable or >800 Wh/kg and >1000 Wh/L for nonrechargeable at the cell level) are of interest in this solicitation. Novel battery-pack-level designs and technologies that enhance
battery reliability and safety and support improved thermal management are also of interest. Combinations of cell-level improvements and/or battery-system-level improvement for enhanced temperature capability will be considered.

Furthermore, missions that incorporate nonrechargeable (primary) batteries will benefit from instrumentation or modeling that can effectively determine state of charge to a high degree of accuracy and/or state of health, particularly those missions that use cell chemistries with discharge voltage profiles that are a weak function of state of charge or state of health such as lithium carbon monofluoride (Li-CFx) cells. Technologies of interest include: radiation-hardened (to 1 Mrad total ionizing dose) coulomb integration application-specific integrated circuits (ASIC) or hybrid circuits, with >1% accuracy over 1 to 20 A, operating over 24 to 36 V; computational models that can predict state of charge/state of health for primary cells; nondestructive instrumentation that can detect state of charge/state of health for primary and secondary cells.

**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

**Desired Deliverables Description:**

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

**State of the Art and Critical Gaps:**

State-of-the-art primary and rechargeable cells are limited in both capacity and temperature range. Typical primary Li-SO₂ and Li-SOCl₂ operate within a maximum temperature range of -40 to 80 °C but suffer from capacity loss, especially at low temperatures. At -40 °C, the cells will provide roughly half the capacity available at room temperature. Similarly, rechargeable Li-ion cells operate within a narrow temperature range of -20 to 40 °C and also suffer from capacity loss at lower temperatures. The lower limit of temperature range of rechargeable cells can be extended through the use of low-temperature electrolytes, but with limited rate capability and concerns over lithium plating on charge. There is currently a gap that exists for high-temperature batteries, primary and rechargeable, that can operate at Venus atmospheric temperatures. In addition, there is a gap in the ability to accurately predict or measure the amount of usable capacity of primary battery cells, particularly after a long mission cruise with exposure to varying temperatures and ionizing radiation dose. This solicitation is aimed at the development of cells that can maintain performance at extreme temperatures to minimize or eliminate the need for strict thermal management of the batteries (which adds complexity and mass to the spacecraft) as well as instrumentation or modeling to predict state of charge/state of health of primary batteries for deep-space missions.

**Relevance / Science Traceability:**

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

References:

NASA Science: https://science.nasa.gov/ [112]

Solar Electric Propulsion: https://www1.grc.nasa.gov/space/sep/ [113]

S3.04 Guidance, Navigation, and Control
Lead Center: GSFC
Participating Center(s): JPL, MSFC

Scope Title:

Guidance, Navigation, and Control

Scope Description:

NASA seeks innovative, groundbreaking, and high-impact developments in spacecraft guidance, navigation, and control technologies in support of future science and exploration mission requirements. This subtopic covers mission-enabling technologies that have significant size, weight and power, cost, and performance (SWaP-CP) improvements over the state-of-the-art commercial off-the-shelf (COTS) capabilities in the areas of S, Absolute and Relative Navigation Systems, and Pointing Control Systems, and Radiation-Hardened Guidance, Navigation, and Control (GNC) Hardware.

Component technology developments are sought for the range of flight sensors, actuators, and associated algorithms and software required to provide these improved capabilities. Technologies that apply to most spacecraft platform sizes will be considered.

Advances in the following areas are sought:

- Spacecraft Attitude Determination and Control Systems: Sensors and actuators that enable <0.1 arcsecond-level pointing knowledge and arcsecond-level control capabilities for large space telescopes, with improvements in size, weight, and power requirements.
- Absolute and Relative Navigation Systems: Autonomous onboard flight navigation sensors and algorithms incorporating both spaceborne and ground-based absolute and relative measurements. For relative navigation, machine vision technologies apply. Special considerations will be given to relative navigation sensors enabling precision formation flying, astrometric alignment of a formation of vehicles, robotic servicing and sample return capabilities, and other GNC techniques for enabling the collection of distributed science measurements. In addition, flight sensors and algorithms that support onboard terrain relative navigation are of interest.
- Pointing Control Systems: Mechanisms that enable milliarcsecond-class pointing performance on any spaceborne pointing platforms. Active and passive vibration isolation systems, innovative actuation feedback, or any such technology that can be used to enable other areas within this subtopic applies.

- Radiation-Hardened Hardware: GNC sensors that could operate in a high radiation environment, such as the Jovian environment.

- Increasing the fundamental precision of gyroscopes and accelerometers that utilize optical cavities could benefit autonomous navigation and open up new science possibilities. Two strategies may be pursued to increase the precision. First, can the scale factor be increased without a concomitant increase in the quantum noise? Possible approaches include but are not limited to: (a) the use of fiber optics to increase cavity length without increasing SWaP and (b) exploitation of the degeneracies known as exceptional points (EPs) that occur in non-Hermitian systems. Prominent examples of such systems include parity-time symmetric systems and cavities containing a fast-light medium. It remains to be seen, however, whether the boost in scale factor near an EP can result in increased precision or is entirely counteracted by additional quantum noise. Proposals are sought that seek to answer this question through theoretical or experimental means in passive and active systems, including continuous-wave and pulsed lasers. Second, can the quantum noise be reduced without a concomitant reduction in scale factor? The frequency measurement in a laser gyro or accelerometer only involves the uncertainty in phase. Therefore, the relevant quantum noise might be reduced by squeezing. Proposals are sought that investigate and utilize squeezing, for example via the propagation of quantum solitons, for the improvement of inertial sensors.

Proposals should show an understanding of one or more relevant science or exploration needs and present a feasible plan to fully develop a technology and infuse it into a NASA program.

This subtopic is for all mission-enabling GNC technology in support of Science Mission Directorate (SMD) missions and future mission concepts. Proposals for the development of hardware, software, and/or algorithms are all welcome. The specific applications could range from CubeSats/SmallSats, to ISS payloads, to flagship missions.

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

Desired Deliverables Description:
Prototype hardware/software, documented evidence of delivered TRL (test report, data,
etc.), summary analysis, supporting documentation.

- 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 as described in a final report.
- Phase II technology development efforts shall deliver a component/prototype at the TRL 5 to 6 level consistent with NASA SBIR/STTR Technology Readiness Level (TRL) Descriptions. Delivery of final documentation, test plans, and test results are required. Delivery of a hardware component/prototype under the Phase II contract is preferred.

State of the Art and Critical Gaps:

Capability area gaps:

- Spacecraft GNC Sensors—highly integrated, low-power, low-weight, radiation-hard component sensor technologies, and multifunctional components.
- Spacecraft GNC Estimation and Control Algorithms—sensor fusion, autonomous proximity operations algorithm, robust distributed vehicle formation sensing and control algorithms.

Relevance / Science Traceability:

Science areas: Heliophysics, Earth Science, Astrophysics, and Planetary missions’ capability requirement areas:

- Spacecraft GNC Sensors—optical, radio-frequency (RF), inertial, and advanced concepts for onboard sensing of spacecraft attitude and orbit states
- Spacecraft GNC Estimation and Control Algorithms—innovative concepts for onboard algorithms for attitude/orbit determination and control for single spacecraft, spacecraft rendezvous and docking, and spacecraft formations.

References:

- 2020 NASA Technology Taxonomy: https://go.nasa.gov/3hGhFJf [60]
- 2017 NASA Strategic Technology Investment Plan: https://go.usa.gov/xU7sE_ [61]

S3.05 Terrestrial Balloons and Planetary Aerial Vehicles

Lead Center: GSFC

Participating Center(s): AFRC, JPL
NASA is interested in scientific exploration of Venus using aerial vehicles to perform in situ investigations of its atmosphere, surface, and interior structure. The 2019 Venus Exploration Analysis Group (VEXAG) Strategic Plan identified several key science objectives that are ideally suited to aerial platforms. The areas of scientific interest include: Atmospheric Gas Composition, Cloud and Haze Particle Characterization, Atmospheric Structure, Surface Imaging, and Geophysical Investigations.

Venus features a challenging atmospheric environment that significantly impacts the design and operation of aerial vehicles. NASA is currently developing concepts for controlled-variable-altitude balloons with payloads of up to 200 kg operating at an altitude range between 52 and 62 km over a latitude range of 0° to +/-60°. Proposals for the following Venus aerial vehicle components are encouraged: (1) Entry, deployment, inflation technologies for a Venus balloon, (2) Instrument sondes, and (3) Helium transfer pump.

1. The most critical phase of a Venus balloon mission is the transition from atmospheric entry to a free-flying configuration. Concepts for any or all of the critical phases of the transition are desired: deployment of the balloon from the atmospheric entry vehicle, inflation of the balloon, and separation of the balloon from the inflation system and parachute system.

2. Deployment of instrument sondes from the payload could enhance and lengthen the balloon mission operating lifetime by reducing payload mass as lift capability is lost over time. Sondes with a mass up to 5 or 10 kg should be capable of operating for several hours, carry a small science instrument payload, and be able to communicate with the primary balloon mission. The sondes envisioned for this solicitation are categorized into ascending and descending investigations. Ascending science investigations carry small science payloads up to 70 km altitude, and descending science investigations carry a small science payload down to near the surface (i.e., <10 km altitude). Proposals offering both heavier-than-air and lighter-than-air (relative to the Venus atmosphere) solutions are solicited. Furthermore, the sonde concepts may have powered propulsion or unpowered flight. Suggested vehicle types include, but are not limited to:
   - Solar-heated balloons that would operate on the sunlit side. This kind of sonde would be deployed from the payload gondola, auto-inflate in a free fall through the atmosphere, and attain float as the solar balloon heats from the Sun. This could possibly operate either above or below the primary balloon mission altitude range.
   - Probes deployed from the payload gondola that perform stabilized vertical descents, gliding descents, powered ascents, or a combination of both
ascents and descents.

3. A controlled-variable-altitude balloon may use a pump to transfer helium from a zero-pressure balloon into a superpressure balloon. Pumping technologies capable of pumping helium with a pressure rise of 50 kPa at 100 liters per minute are desired. Multistage or parallel flow pump solutions are acceptable for consideration. Light weight and high efficiency are important factors in the pump since it must fly with the balloon payload.

It is expected that a Phase I effort will consist of a system-level design and a proof-of-concept experiment on one or more key components. Proposers should be familiar with the atmospheric pressure, temperature, solar, infrared (IR) heating, and corrosion aspects of the Venus atmosphere as described in this call. The atmospheric temperature ranges from -30°C at 62 km to 62°C at 52 km, the pressure ranges from about 18 kPa at 62 km to 80 kPa at 52 km (Venus International Reference Atmosphere, VIRA [see Kliore, 1985]), the solar flux can be as high as 2,300 W/m² at 62 km, and the IR heat flux coming up from the lower atmosphere can be as high as 830 W/m² at 52 km [Crisp, 1986]. The sulfuric acid vapor abundance is less than less than 1 ppmv at 52 km and above [Oschlisniok, 2012]. The sulfuric acid liquid aerosols have a concentration between 75% (pH -1.5) and 90% (pH -2.0) [Titov, 2018]. Although the cloud droplets are highly acidic, they are very small, typically in the range of 1 to 10 µm in diameter, and fairly diffuse, with cloud droplet abundance only on the order of 100 droplets/cm³ for the 1-µm-sized particles; and on the order of 10 droplets/cm³ for the larger (r > 3µm) particles. The maximum observed aqueous H₂SO₄ content in the balloon operating environment is on the order of only 30 mg/m³ [Knollenberg, 1980]. Additional information on the Venus atmospheric environment can be found in the References section.

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

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

Desired Deliverables Description:

It is expected that a Phase I effort will consist of a system-level design and a proof-of-concept experiment on one or more key components. Deliverable items for Phase I shall be a final report describing the results of the concept analysis and demonstration of any key component technology developed.

The Phase II effort will focus on the development of a concept prototype and feasibility testing. Phase II deliverable should include a final report on design concept documentation, test reports, and photos of any prototypes that were built and tested.

State of the Art and Critical Gaps:

Terrestrial-based aerial vehicles, including lighter-than-air and heavier-than-air vehicles, are mature technologies and continue advancing in capability, reliability, and autonomy. However, these need adaptation for operation in the Venus environment.
Several gaps exist in aerial vehicle technology for Venus atmospheric flight:

1. There is a strong need for aerial deployment systems for balloons and their payloads since most balloons are launched from the ground and from the upper atmosphere. Methods for deployment may leverage techniques for Mars entry vehicle systems that deploy from an aeroshell and eventually separate from a parachute. However, a balloon inflation inserted into the middle of this sequence is a complicating element and preventing damage to the balloon is paramount.

2. Small instrument sondes or vehicles for expanding the exploration range and mission duration have not been sufficiently developed for a Venus mission to be included as part of future mission proposals. Novel vehicles for conducting science that can be deployed from the balloon payload could play an important role in meeting these objectives. The guidance, stabilization, and control of sondes has been identified as a need for collecting images of the surface during a deep atmospheric descent.

3. Altitude variation of a balloon requires changing the density of the lifting gas. There are no commercially available pumps in the market today that have the pressure rise and flow rate capabilities needed for a Venus balloon. Most pumps or compressors are not built to be lightweight, which is of critical importance on a balloon mission.

Relevance / Science Traceability:

Relevance: The Mars Helicopter, Ingenuity, and the Titan Dragonfly mission show there is significant interest in planetary aerial vehicles for science investigations. It is in NASA’s interest through the SBIR program to continue fostering innovative ideas to extend our exploration capabilities by developing technologies for Venus aerial mission concepts.

JPL’s Solar System Mission Formulation Office and the NASA Science Mission Directorate’s Planetary Science Division advocate Venus aerial vehicle platform development. NASA recently completed the Venus Flagship Mission concept study, which included a balloon system for the Planetary Decadal Survey [Gilmore, 2020].

Science Traceability: The 2019 VEXAG Venus Strategic Plan identified several key science investigations that are ideally suited to aerial platforms. The areas of scientific interest include: Atmospheric Gas Composition, Cloud and Haze Particle Characterization, Atmospheric Structure, Surface Imaging and Geophysical Investigations. The variable-altitude aerial vehicle platform is ideal for investigating these science goals and objectives. Building the variable-altitude balloon requires the development of several key components as identified in this call.

References:


• The VEXAG Strategic Plan 2019 is found at: https://www.lpi.usra.edu/vexag/reports/Combined_VEXAG_Strategic_Documents_Current.pdf [114]


Scope Title:

Improved Downlink Satellite Communications for Balloons

Scope Description:

Improved downlink bit rates and innovative solutions using satellite relay communications from balloon payloads are needed. Long-duration balloon flights currently utilize satellite communications systems to relay science and operations data from the balloon to ground-based control centers. The current maximum downlink bit rate is 150 kbps, operating continuously during the balloon flight. Future requirements are for bit rates of 1 Mbps or more. Improvements in bit rate performance, reduction in size and mass of existing systems, or reductions in cost of high-bit-rate systems are needed. Tracking and Data Relay Satellite System (TDRSS) and Iridium satellite communications are currently used for balloon payload applications. A commercial S-band TDRSS transceiver and a mechanically steered 18 dBi gain antenna provide 150 kbps continuous downlink. TDRSS K-band transceivers are available but are currently cost prohibitive. Open port Iridium service is also in use, but the operational cost is high per byte transferred.

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 05.5 Revolutionary Communications Technologies

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
 Desired Deliverables Description:

Phase I: Desired deliverables include: (1) results of analysis or simulation or (2) test results of actual prototype hardware and/or software.

Phase II: Deliverables could include a prototype that could be test flown on a balloon mission.

State of the Art and Critical Gaps:

Current commercially available satellite relays systems that could be used for balloon flight are either too costly or do not provide the needed downlink data rates. Tracking and Data Relay Satellite System (TDRSS) and Iridium satellite communications are currently used for balloon payload applications. A commercial S-band TDRSS transceiver and a mechanically steered 18-dBi-gain antenna provide 150 kbps continuous downlink. TDRSS K-band transceivers are available but are currently cost prohibitive. Open port Iridium service is also in use, but the operational cost is high per byte transferred.

Relevance / Science Traceability:


Improvements to satellite communications for research balloons would enable greater and better data collection, possibly extended flight duration, and other such potential benefits.

References:

- NASA’s SuperTIGER Balloon Flies Again to Study Heavy Cosmic Particles: [https://sites.wff.nasa.gov/code820/](https://sites.wff.nasa.gov/code820/) [115]
- GUSTO (Galactic/Extragalactic ULDB Spectroscopic Terahertz Observatory) mission is a planned high-altitude balloon mission that will carry an infrared telescope to measure emissions from the interstellar medium. The mission is being developed by NASA's Explorers Program - GUSTO, University of Arizona (Prof. Chris Walker).
- Scientific balloon information: [https://sites.wff.nasa.gov/code820/technology_capabilities.html](https://sites.wff.nasa.gov/code820/technology_capabilities.html) [116]
- 2020 NASA Technology Taxonomy: [https://www.nasa.gov/offices/oct/taxonomy/index.html](https://www.nasa.gov/offices/oct/taxonomy/index.html) [117]

Scope Title:

Steerable Recovery/Parachute System
Scope Description:

NASA is looking for an innovative way to reduce the termination dispersions from a few miles to within 1/2 to 1/4 mile of the predicted termination point by the use of a steerable parachute recovery system (SPRS). The SPRS will need to be able to maneuver around infrastructure (e.g., oil wells, power lines, wind mills), protected areas (e.g., national parks, special habitats), natural resources (e.g., rivers, mountains, lakes), and other areas of interest (e.g., farm land). The SPRS will need to provide real-time maneuverability for a science gondola from a remote operations control room using the communications and telemetry systems provided by the Columbia Scientific Balloon Facility (CSBF). The system should be lightweight, no more than 75 lb including power.

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

- Research
- Analysis
- Prototype

Desired Deliverables Description:

The deliverables for Phase I include a trade study of the potential systems, a simulation of how each system should work, and a report on the recommendation of one to two systems to be further developed in Phase II. It is anticipated that these products are achievable given the SBIR time and funding constraints.

The deliverables for Phase II includes an engineering development unit and testing with a report of the results.

State of the Art and Critical Gaps:

A scientific balloon floats at an average altitude of 110,000 ft or more and carries science payloads up to 8,000 lb. At the end of a scientific balloon mission, the science payload on the gondola (from this point on “science gondola”) is separated from the balloon and falls to Earth on a parachute following the wind currents at the time of release and lands on cardboard crush pads. In most cases this allows recovery of the science gondola, though the payload and gondola may be in areas that are hard to reach using conventional recovery trucks. However, there are rare cases where the science gondola falls either in water or in areas that require special equipment or are difficult for recovery (e.g., inaccessible area).

Currently, trajectory predictions for termination are within a few miles and are dependent on models, map overlays (showing restricted air space, national/state parks), and observations from a plane on areas along the trajectory to determine the best area to terminate the balloon and bring the science gondola safely to the ground. Some items that are considered during the termination discussions are science mission minimums, trajectory predictions (e.g., national or state parks, lakes, mountains, rivers, infrastructure, crop lands), weather conditions, and risk to the public. Current state of the art does not include steerable systems in balloon parachutes. Success in this endeavor will entail primarily steerability, but this also results frequently in a safety analysis, which will allow more “green lights” for launch than would otherwise be the case.

Relevance / Science Traceability:

This subtopic will be relevant to any mission directorate, commercial entity, or other government agency that drops payloads from an altitude, including the Balloon Program. Other potentially interested projects include NASA sounding rockets, UAV, and aircraft programs.

References:

Scope Title:

Relative Wind Speed Sensor for Scientific Balloons

Scope Description:

A trajectory control system (TCS) for high-altitude scientific ballooning has been a long-term goal of NASA’s Balloon Program Office (BPO). One milestone in the critical path of TCS development is the ability to measure the speed of the winds seen by the gondola during a balloon mission. In addition, NASA has identified wind-speed measurements from a balloon explorer under the TX10.1.2 of the 2020 NASA Technology Taxonomy (see References below). Currently, the BPO has no method of measuring relative winds (wind speed relative to the gondola) in situ above ~15 km in altitude for terrestrial applications. Although several methods of wind speed measurement exist for a variety of applications, there is effort required to port those technologies for the conventional balloon float environment. The goal of this technology development is to develop a sensor to meet the following specifications:

1. Measure relative wind in three axes (u, v, and w).
2. Operate at 4.4 mbar (~36.5 km altitude) or lower pressure.
3. Operate in air temperature from -70 to +65 °C.
4. Accuracy of 10 cm/s or better.
5. Resolution of 5 cm/s or better.
6. Sample rate of 1 Hz or faster.
7. Power consumption of 30 W or less at steady state.
8. Mass of 20 kg or less.
9. Withstand shocks of 10g or greater.

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:

- Prototype
- Hardware
- Software

Desired Deliverables Description:

Phase I: Deliver a conceptual design package for a prototype unit that meets the design goals and accuracy.

Phase II: Deliver a prototype and an accompanying acceptance package that describes the prototype unit in detail and provides experimental validation of the unit having met the design goals and accuracy as well as all accompanying software/firmware required for operation of the sensor.
**State of the Art and Critical Gaps:**

Wind speed measurements at balloon float altitudes have several benefits: First, a relative wind sensor will enable the TCS development by providing a means to measure the speed imparted to the balloon by a future TCS concept. Second, science gondolas with fine pointing requirements must point against the relative wind. Currently, a data set of example relative wind does not exist, which requires science groups to design robust control systems for their telescopes or instruments. Third, relative wind is responsible for any convective cooling seen on large structures, such as baffles on telescopes, which is currently poorly understood. In general, relative wind speed measurements will aide in prolonging flights (both with a TCS and by refining flight prediction capabilities) and enable more informed design of gondola structures and heating systems.

Commercially available wind speed sensors (anemometers) have been shown to not be capable of accurately measuring the wind speed above ~15 km in altitude. In addition, this technology (if realized) would enable the development of a trajectory control system for balloon missions, which is critical for achieving the goal of 100-day missions at 36 km in the Southern Hemisphere.

**Relevance / Science Traceability:**

A relative wind sensor for balloon missions would benefit the Science Mission Directorate (SMD)/Astrophysics mission by furthering the state of the art in sensor technology. In addition, the development of a relative wind sensor is a key milestone in the path towards a trajectory control system for high-altitude balloons. Specifically, NASA’s Super Pressure Balloon (SPB) would benefit from trajectory control while pursuing 100-day flights in the Southern Hemisphere.

**References:**

Scientific balloon information: [https://sites.wff.nasa.gov/code820/technology_capabilities.html](https://sites.wff.nasa.gov/code820/technology_capabilities.html) [116]

2020 NASA Technology Taxonomy: [https://www.nasa.gov/offices/oct/taxonomy/index.html](https://www.nasa.gov/offices/oct/taxonomy/index.html) [117]

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**S3.06 Thermal Control Systems**

Lead Center: GSFC

Participating Center(s): JPL, JSC, LaRC, MSFC

**Scope Title:**

Coatings for Lunar Regolith Dust Mitigation for Thermal Radiators and Extreme Environments

**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 provides a passive means for instrument temperature control. The utilization of variable emittance devices further enables active control of the instrument temperature when the heat output from the instrument or the thermal environment of the radiator changes. With NASA's new initiative to return to the Moon, a new coating technology that will keep surfaces clean and sanitary is needed. New coating formulations utilizing durable, anticontamination and self-cleaning properties that will disallow the accumulation of dust, dirt, and foreign materials are highly desirable. These coatings can have low absorbance and high infrared (IR) emittance properties or be transparent for use on existing thermal coating systems. The goal of this technology is to preserve optimal long-term performance of spacecraft and habitation components and systems. Furthermore, coatings that can survive and operate in extreme environments (cryogenic or high temperature) are desirable.

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 Deliverables

- Successfully develop the formulations of the coating that leads to the desired dust mitigation.
- Deliverable of coupon.
- Samples of the hardware for further testing at NASA facilities.
- Final report.

Phase II Deliverables

- Results of performance characterization tests.
- Results of stability test of the coating formulations and its mechanical durability test under the influence of simulated space and lunar environmental conditions.
- Deliverable of test coupon
- Final report.

State of the Art and Critical Gaps:

There are limited options for durable, stable thermal control coatings that are dust shedding in charging environments. Current state-of-the-art, sprayable radiation-stable coatings are able to coat complex, irregular surfaces, but they are porous and will become imbedded with dust and particulates. Other surface films tend to be less optically stable and may charge in the plasma environment, thereby attracting lunar regolith to their surfaces. Mirrors have the limitations of requiring flat surfaces and are not conformal in nature. Currently, no single thermal control surface appears to provide stability, durability, and meet optical property requirements for sustained durations in space and lunar environments.

Relevance / Science Traceability:

Many Science Mission Directorate (SMD) missions will greatly benefit from this dust mitigation thermal coating technology: any lunar-relating project and projects involved with robotic science rovers and landers.

References:
The following website provides links to some references for dust mitigation coatings such as lotus thermal coatings: https://ntrs.nasa.gov/search.jsp?R=20150020486 [120]

The following website provides links to some references for extreme environment coatings: https://vfm.jpl.nasa.gov/files/EE-Report_FINAL.pdf [121]

References in Subtopic Z13.01, Active and Passive Dust Mitigation Surfaces.

Scope Title:

Heat Pumps for High-Temperature Sink Environments

Scope Description:

Operations in extreme environments where the environment sink temperature exceeds spacecraft hardware limits will require active cooling if long-duration survivability is expected. Robotic science rovers operating on the Lunar surface over diurnal cycles face extreme temperature environments. Landers with clear views of the sky can often achieve sufficient heat rejection with a zenith or, if sufficiently far from the equator, an anti-Sun-facing radiator. However, science rovers must accommodate random orientations with respect to the surface and Sun. Terrain features can then result in hot environment sink temperatures beyond operating limits, even with shielded and articulated radiator assemblies. Lunar dust degradation on radiator thermo-optical properties can also significantly affect effective sink temperatures. During the Lunar night, heat rejection paths must be turned off to preclude excessive battery mass or properly routed to reclaim nuclear-based waste heat.

Science needs may drive rovers to extreme terrains where steady heat rejection is not otherwise possible. The paradigm of swarms or multiple smaller rovers enabled by commercial lander opportunities will need to leverage standard rover bus designs to permit flexibility. A heat pump provides the common extensibility for thermal control over the lunar diurnal. Active cooling systems or heat pumps are commonly used on spacecraft. Devices used include mechanical cryocoolers and thermoelectric coolers. For higher loads, vapor compression systems have been flown and, more recently, reverse turbo-Brayton-cycle coolers are being developed under NASA's Game Changing program for high load, high-temperature-lift cryocoolers. However, technology gaps exist for midrange heat pumps that are suitable for small science rovers where internal heat dissipation may range from 20 to 100 W.

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

Desired Deliverables Description:

- Conceptual design.
- Physics-based analysis or model.
- Proof-of-concept hardware (Phase I).
- Proof-of-concept hardware tested against simulated loads in proposed environments (Phase II).
- Final report.

State of the Art and Critical Gaps:

Specifically, heat pump systems are needed for the following:

- Temperature lift from a cold side at <50 °C to an environmental sink temperature as high as 75 °C (temperature lift of 50 °C or heat rejection rate of 230 W/m²), with a system coefficient of performance >2.5.
System should be tolerant of being powered down during the lunar night and restarted during the day reliably over multiple diurnals.

Exported vibrations, if any, should be minimal for compatibility with science instruments.

Novel heat pump systems are desired. Enabling improvements over state-of-the-art systems are also welcome.

Relevance / Science Traceability:

NASA's lunar initiative and Planetary Science Division form the primary customer base for this technology. Missions that directly address the National Research Council Planetary Science Decadal Survey may be users of this technology.

References:

- Apollo Lunar Roving Vehicle Documentation: [https://www.hq.nasa.gov/alsj/alsj-LRVdocs.html](https://www.hq.nasa.gov/alsj/alsj-LRVdocs.html) [122]
- Apollo Experience Report - Thermal Design of Apollo Lunar Surface Experiments Package: [https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19720013192.pdf](https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19720013192.pdf) [123]

Scope Title:

Advanced Manufacturing of Loop Heat Pipe Evaporator

Scope Description:

A loop heat pipe (LHP) is a very versatile heat transport device that has been used on many spacecraft. At the heart of the LHP is the evaporator and reservoir assembly. During the manufacturing, tedious processes are required to machine the porous primary wick and insert it into the evaporator, and both ends of the wick need to be sealed for liquid and vapor separation. One commonly used method for vapor seal is to use a bimetallic knife-edge joint, which is more prone to failure over long-term exposure to thermal cycles and shock and vibration. These tedious manufacturing processes add to the cost of the traditional LHP. A new manufacturing technique that will allow the primary wick to be welded directly to the reservoir without the use of a knife-edge seal is needed in order to reduce the cost and enhance the reliability.

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:

- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

- Successfully develop advanced techniques to manufacture the LHP evaporator and reservoir assembly.
- Demonstrate the performance of the evaporator/reservoir performance in an LHP setup (Phase I).
- Demonstrate the performance of the evaporator/reservoir performance in an LHP setup optimized to operate in simulated realistic environments with appropriate cycling (Phase II).
- Final report.

State of the Art and Critical Gaps:

The LHP evaporator contains a porous wick, which provides the capillary pumping capability to sustain the fluid
flow in the loop. The smaller the pore size of the wick, the higher its capillary pumping capability. However, a smaller pore size results in a higher flow resistance that must be overcome by the capillary force. Traditional sintered metal wicks have a pore size on the order of 1 µm and porosity around 0.4 to 0.6. In order to replace the traditional porous wick, the new wick produced by the advanced manufacturing technology must have comparable pore size and porosity. The smallest pore size currently produced by direct metal laser sintering is on the order of 10 µm.

**Relevance / Science Traceability:**

Traditional LHPs are used on many NASA missions including ICESat (Ice, Cloud, and Land Elevation Satellite), ICESat-2, Swift, Aura, Geostationary Operational Environmental Satellite (GOES), Geostationary Operational Environmental Satellite-R Series (GOES-R), and Surface Water and Ocean Topography (SWOT). Similar future SMD (Science Mission Directorate) missions, especially those using small satellites, can greatly benefit from this technology.

**References:**


**Scope Title:**

Approaches and Techniques for Lunar Surface Payload Survival

**Scope Description:**

The lunar environment poses significant challenges to small, low-power (~100 W or less) payloads, rovers, and landers required for lunar science. The lunar day/night cycle is approximately one Earth month. During that time, surface temperatures on the lunar surface can reach 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. Higher heat dissipation capacity should be addressed in Z2.01.

This call seeks to solicit innovative proposals to enable lunar science in the difficult lunar environment. Example technologies may include, but are not limited to, active loops that may be turned off and are freeze tolerant, zero- or low-power nonconsumable/regenerative heat generation sources, high-thermal-capacitance thermal storage, advanced insulation, and passive switching with high turndown ratios (e.g., >400:1). Furthermore, small form factors are also desired. 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, etc.

**Expected TRL or TRL Range at completion of the Project:** 3 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

**Desired Deliverables Description:**

Thermal management approaches, techniques, and hardware components to enable the accommodation of
temperature extremes encountered in the lunar environment. Concept model deliverable for Phase I and prototype demonstration in relevant environment in Phase II.

**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.

While interest in lunar science and the development of abilities to deliver payloads to the lunar surface are resurgent, the capability to operate through the entire lunar environment is critical. In the absence of perpetual power supplies like radioisotope thermoelectric generators (RTGs), thermal management approaches to accommodate the lunar extremes, extended day/night cycles, and shadowed regions are seen as enabling.

**Relevance / Science Traceability:**

Science Mission Directorate (SMD) lunar surface science investigations will employ small, low-power payloads that will require advanced thermal control approaches and techniques to survive and operate for extended duration through extreme thermal environments on the lunar surface.

NASA has plans to purchase services for delivery of payloads to the Moon through the Commercial Lunar Payload Services (CLPS) contract. Under this subtopic, proposals may include efforts to develop payloads for flight demonstration of relevant technologies in the lunar environment. The CLPS payload accommodations will vary depending on the particular service provider and mission characteristics. Additional information on the CLPS program and providers can be found at this link: [https://www.nasa.gov/content/commercial-lunar-payload-services](https://www.nasa.gov/content/commercial-lunar-payload-services) [125]. CLPS missions will typically carry multiple payloads for multiple customers. Smaller, simpler, and more self-sufficient payloads are more easily accommodated and would be more likely to be considered for a NASA-sponsored flight opportunity. Commercial payload delivery services may begin as early as 2020, and flight opportunities are expected to continue well into the future. In future years it is expected that larger and more complex payloads will be accommodated. Selection for award under this solicitation will not guarantee selection for a lunar flight opportunity.

**References:**

- The Surveyor Program: [https://history.nasa.gov/TM-3487/ch2-1.htm](https://history.nasa.gov/TM-3487/ch2-1.htm) [127]
- The Surveyor Program: [https://www.lpi.usra.edu/lunar/missions/surveyor/(link is external)](https://www.lpi.usra.edu/lunar/missions/surveyor/(link is external)) [128]
- Missions - Lunokhod 01: [https://solarsystem.nasa.gov/missions/lunokhod-01/in-depth/](https://solarsystem.nasa.gov/missions/lunokhod-01/in-depth/) [129]
- Missions - Lunokhod 02: [https://solarsystem.nasa.gov/missions/lunokhod-02/in-depth/](https://solarsystem.nasa.gov/missions/lunokhod-02/in-depth/) [130]

**S3.08 Command, Data Handling, and Electronics**

Lead Center: GSFC

Participating Center(s): JPL, LaRC, MSFC

Scope Title:
Command, Data Handling, and Electronics

Scope Description:

NASA's space-based observatories, flyby spacecraft, orbiters, landers, and robotic and sample-return missions require robust command and control capabilities. Advances in technologies relevant to command and data handling and instrument electronics are sought to support NASA’s goals and several missions and projects under development.

The 2021 subtopic goals are to develop platforms for the implementation of miniaturized highly integrated avionics and instrument electronics that:

- Are consistent with the performance requirements for NASA missions.
- Minimize required mass/volume/power as well as development cost/schedule resources.
- Can operate reliably in the expected thermal and radiation environments.

Successful proposal concepts should significantly advance the state of the art. Furthermore, proposals developing hardware should indicate an understanding of the intended operating environment, including temperature and radiation. Note that environmental requirements vary significantly from mission to mission. For example, some low-Earth-orbit missions have a total ionizing dose (TID) radiation requirement of less than 10 krad(Si), whereas planetary missions can have requirements well in excess of 1 Mrad(Si).

Specific technologies sought by this subtopic include:

- Radiation-hardened mixed-signal structured application-specific integrated circuit (ASIC) platforms to enable miniaturized and low-power science sensor readout and control, with sufficient capability to implement 12-bit digital-to-analog converters (DACs) monotonic and 12- to 16-bit digital-to-analog converters (ADCs) (<100 kHz 16-bit and 1 to 2 MHz 12-bit) and also charge-sensitive amplifiers for solid-state detectors and readout integrated circuit (ROIC) for silicon photomultipliers.
- Radiation-hardened ASIC devices to enable direct capture of analog waveforms.
- Multiple-output point-of-load power regulator: This module, preferably implemented utilizing one or more controller ASICs, will source a minimum of three settable output voltages when provided with an input voltage between +5 and +12 V. Output voltages shall be independently settable to any voltage between 3.3 and 0.9 V with efficiency of at least 95%. Regulation, noise filtering, and other operational specifications should be commensurate with industry standards for space-based systems. Output current in the 10 A range to handle field-programmable gate array (FPGA) core requirements. The module should provide standard spacecraft power supply features, including overvoltage protection, fault tolerance, load monitoring, sequencing, synchronization, and soft start and should allow control and status monitoring by a remote power system controller. Using fewer external components is also highly desirable. There is also interest in a
capability to provide data over power line communication to the converter for control and monitoring functions. The offeror should determine radiation-tolerance levels achievable utilizing commercially available processes and indicate, in the proposal, the radiation-tolerance goals.

- High-density high-reliability interconnections: A high-reliability connector or interconnect mechanism that can operate in space environments (vacuum, vibration) and deliver hundreds of signal/power connections while using as little physical board area as possible is desired. The connector wiring and cabling in addition to the connector shape and size should be considered in providing a complete system that further reduces the size and weight of the harnessing. The design should handle everything from carrying power to high-speed (10+ Gbps) impedance-controlled connections. The design should be scalable in different sizes to accommodate fewer connections and save board space. Low insertion force is desirable. Right angle and stacking design options should be considered.

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
- Software

Desired Deliverables Description:

Desired Phase I deliverables include designs, simulations, and analyses to demonstrate viability of proposed components.

Desired Phase II deliverables:

- For mixed-signal structured ASIC platforms—include a prototype mixed-signal ASIC implemented with a proof-of-concept end-user design. The proof-of-concept design should demonstrate the stated performance capabilities of the ASIC.
- For the direct analog waveform capture ASIC—should include a prototype ASIC device implemented on a test board and demonstration of the waveform capture capabilities of the device.
- For the multiple output point of load switcher—a prototype multi-output point of load regulator. The regulator should be integrated onto a test board and be performance tested under varying resistive, capacitive, and transient load conditions.
- For the high density high-reliability interconnect—prototypes of the connection system (different size, orientations, wiring, etc.). The connector should be integrated onto a test board where its performance (speed, cross talk, etc.) can be verified.
State of the Art and Critical Gaps:

There is a need for a broader range of mixed-signal structured ASIC architectures. This includes the need for viable options for mixed ASICs with high-resolution, low-noise analog elements, especially 12-bit DACs and 12- to 16-bit ADCs. The current selection of mixed-signal structured ASICs is limited to 10-bit designs, which do not provide the accuracy or resolution to perform the science required of many of the instruments currently being flown. Mixed-signal structured ASICs can integrate many functions and therefore can save considerable size, weight, and power over discrete solutions—significantly benefiting NASA missions. The lack of parts with high-precision analog is greatly limiting their current application.

There are multiple output point-of-load converters available from commercial companies. The existing commercial parts require many external components, eliminating their space savings. Commercial parts are not built on radiation-tolerant processes.

Current connectors and interconnect harnessing are too large, especially for small satellites and CubeSats. As the size of the printed circuit boards has shrunk, the percent of board space being used by the input/output (I/O) connectors has become unacceptable. The connectors are taking away from circuitry and sensors that could be providing additional functionality and science products. High-density commercial connectors tend to be lacking in their general ruggedness, outgassing, and ability to prevent intermittent connections in high-vibration environments like orbital launches.

Relevance / Science Traceability:

Mixed-signal structured ASIC architectures are relevant to increasing science return and lowering costs for missions across all Science Mission Directorate (SMD) divisions. However, the benefits are most significant for miniaturized instruments and subsystems that must operate in harsh environments. These missions include interplanetary CubeSats and SmallSats, outer planets instruments, and heliophysics missions to harsh radiation environments. For all missions, the higher accuracy would provide better science or allow additional science through the higher density integration.

Multi-output point-of-load converters and high-density high-reliability interconnects are relevant to miniaturizing electronics. Miniaturized flight electronics allows one to fit more functionality into less volume, allowing smaller spacecraft to perform science that was previously done by larger satellites. These missions include interplanetary CubeSats and SmallSats, outer planets instruments, and heliophysics missions.

References:

The following resources may be helpful for descriptions of radiation effects in electronics:

- NASA Technical Reports Server: [https://ntrs.nasa.gov/][131]
- NASA Electronic Parts and Packaging Program: [https://nepp.nasa.gov/][132]
- NASA/GSFC Radiation Effects and Analysis Home
S4.02 Robotic Mobility, Manipulation and Sampling

Lead Center: JPL

Participating Center(s): ARC, GRC, GSFC

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 from planets and other planetary bodies including the moon, Mars, Venus, Ceres, Europa, Titan, Enceladus, comets, and asteroids.

Mobility technologies are needed to enable access to steep and rough terrain for planetary bodies where gravity dominates, such as Earth’s Moon and Mars. Wheeled, legged, and aerial solutions are of interest. Wheel concepts with good tractive performance in loose sand while being robust to harsh rocky terrain are of interest. Technologies to enable mobility on small bodies and access to liquid below the surface (e.g., in conduits or deep oceans) are desired, as well as the associated sampling technologies.

Manipulation technologies are needed to deploy sampling tools to the surface, transfer samples to in situ instruments and sample storage containers, and hermetically seal sample chambers. Sample acquisition tools are needed to acquire samples on planetary and small bodies through soft and hard materials, including ice. Minimization of mass and ability to work reliably in the harsh mission environment are important characteristics for the tools. Finally, design for planetary protection and contamination control is important for sample acquisition and handling systems.

Component technologies for low-mass and low-power systems tolerant to the in situ environment (e.g., temperature, radiation, and dust) are of particular interest. Technical feasibility and value should be demonstrated during Phase I via analysis or prototype demonstration, and a full capability unit of at least TRL 4 should be delivered in Phase II. Proposals should show an understanding of relevant science needs and engineering constraints and present a feasible plan (to include a discussion of challenges and appropriate testing) to fully develop a technology and infuse it into a NASA program. Specific areas of interest include the following (order does not reflect priority):

- Surface mobility and sampling systems for planets, small bodies, and moons.
- Near-subsurface sampling tools such as icy-surface drills to 30 cm depth deployed from a manipulator.
- Subsurface ocean access such as via a deep drill system.
- Sample handling technologies that minimize cross contamination and preserve mechanical integrity of samples.
- Pneumatic sample transfer systems and particle flow measurement sensors.
- Low-mass/power vision systems and processing capabilities that enable fast surface traverse.
- Active lighting stereo systems for landers and rovers.
- Force-torque sensors that can operate in cryogenic and high-radiation environments such as Europa.
- Electromechanical connectors enabling tool change-out in dirty environments.
- Tethers and tether play-out and retrieval system.
- Miniaturized flight motor controllers.
- Cryogenic operation actuators.
- Robotic arms for low-gravity environments.

**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:**

Hardware, software, and designs for component robotic systems.

- Phase I: proof of concept to include research and analysis along with design in a final report.
- Phase II: prototype for further testing.

**State of the Art and Critical Gaps:**

Scoops, powder drills, and rock core drills and their corresponding handling systems have been developed for sample acquisition on Mars and asteroids. Non-flight systems have been developed for sampling on comets, Venus, and Earth's Moon. Some of these environments still present risk and have gaps that need to be addressed (i.e. Venus).

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.

**Relevance / Science Traceability:**

The subtopic supports multiple programs within Science Mission Directorate (SMD). The Mars program has had infusion of technologies such as a force-torque sensor in the Mars 2020 mission. Recent awards would support the Ocean Worlds program with surface and deep drills for Europa, and future awards could include technologies to support missions to Enceladus, Titan, and other planetary bodies with subsurface oceans. Sample-return missions could 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 return to Earth's Moon, the mobility and sampling technologies could support future robotic missions to the Moon.

**References:**

- Mars Exploration/Program & Missions, [https://mars.nasa.gov/programmissions/](https://mars.nasa.gov/programmissions/) [134]
- Solar System Exploration, [https://solarsystem.nasa.gov/](https://solarsystem.nasa.gov/) [135]
- Ocean Worlds website: [https://www.nasa.gov/specials/ocean-worlds/](https://www.nasa.gov/specials/ocean-worlds/) [63]
- Ocean Worlds article: [https://science.nasa.gov/news-articles/ocean-worlds](https://science.nasa.gov/news-articles/ocean-worlds) [136]
S4.03 Spacecraft Technology for Sample Return Missions

Lead Center: GSFC

Participating Center(s): GRC, GSFC

Scope Title:

Critical Technologies for Sample-Return Missions

Scope Description:

This Subtopic focuses on robotic sample-return (SR) missions that require landing on large bodies (e.g., Luna, Mars Sample Return (MSR)), as opposed to particulate-class SR missions (e.g., Genesis, Hayabusa) or touch-and-go (TAG) missions to relatively small asteroids or comets (e.g., OSIRIS-Rex, Hayabusa2). The mission destinations envisioned are dwarf planets (e.g., Vesta, Ceres) and planet or planet moons (e.g., Phobos, Europa). These are the most challenging missions in NASA's portfolio but also the most scientifically promising, given the vast array of instruments available on Earth to study the retrieved samples. The challenges associated with these SR missions may be grouped into four categories: (1) Mass-efficient spacecraft architectures (e.g., efficient propulsion or materials that significantly reduce the mass of the launch payload required), (2) Sample handling (e.g., subsurface acquisition mechanisms), (3) Sample integrity (e.g., surviving reentry), and (4) Planetary protection/contamination control (PP/CC) (e.g., preventing leakage into the orbital sample (OS) canister). This Subtopic seeks potential solutions to areas (1), (3), and (4), considering it best that technologies associated with (2), sample handling, be directed to Subtopic S4.02. The intent is to have this Subtopic S4.03 manage only those technologies in areas (1), (3), and (4) that are specifically related to SR missions; technology solutions related to other classes of missions should instead be directed to Subtopics S4.04 (Extreme Environments) and S4.05 (Contamination Control and Planetary Protection).

The heightened need for mass-efficient solutions in these SR missions stems from their extreme payload mass “gear ratio.” For example, the entire MSR campaign will require three heavy launch vehicle launches with rough spacecraft mass of 5,000 kg each in order to bring back multiple samples with an estimated total mass of 0.5 kg. Clearly, any mass savings in the ascent vehicle’s gross liftoff mass (GLOM) or in the lander mass, for example, would yield many times more savings in the launch payload mass, enhancing the feasibility of these missions.

Once acquired, samples must be structurally and thermally preserved through safe landing and transport to Johnson Space Center (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. Potential solutions include near isotropic and crushable high-strength energy-absorbent materials that can withstand the ballistic impact landing. Materials that offer thermal isolation in addition to energy absorption are highly desirable given the reentry environment. In the case of cryogenically preserved samples, the technical challenge includes development of thermal control systems to ensure volatiles are conserved.

Finally, acquired samples must be chemically and biologically preserved in their original condition. Examples of PP/CC technology solutions sought include:

- **Materials selection**: selection of metallic materials (non-organic) for the interior of the OS capsule as well as materials that allow preferable surface treatments and bake-out sterilization approaches.
• Surface science topics: Adsorber coatings/materials for contaminant adsorption (getter-type materials, such as aluminum oxide, porous polymer resin) and/or low-surface-energy materials to minimize contaminant deposition.

• Characterization of contamination sources on lander, rover, capsule, ascent vehicle, and orbiter, for design of adequate mitigation measures.

**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

**Desired Deliverables Description:**

A Phase I deliverable would be a final report that describes the requisite research and detailed design accomplished under the project.

A Phase II deliverable would be successful demonstration of an appropriate-TRL performance test, such as at representative scale and environment, along with all the supporting analyses, design, and hardware specifications.

**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. This most challenging kind of SR mission has only been successfully done in the Soviet Luna program that returned 326 g of Moon samples in three missions—out of eleven attempts—in the early 1970s. Hayabusa2 and OSIRIS-Rex are TAG SR missions that are expected to return samples in December 2020 from asteroid Ryugu and in September 2023 from asteroid Bennu, respectively. The first segment of NASA’s MSR mission is the sample collection rover Perseverance, launch of which took place in July 2020. The MSR sample retrieval segment (lander, fetch rover, Mars Ascent Vehicle) is scheduled to begin Phase A development in October 2020 for a 2026 launch. The third MSR segment will be ESA’s Earth return vehicle (ERV).

The content and breadth of this Solicitation is informed by lessons learned in MSR over the Pre-Phase A years. Future SR missions are in need of technology improvements in each of the critical areas targeted: mass efficiency, sample acquisition, sample integrity, and planetary protection.

This solicitation seeks proposals that have the potential to increase the Technology Readiness Level from 3 or 4 to 6 within 5 years, and within the cost constraints of the Phases I, II, and III of this SBIR Program. Such progress would allow full flight qualification of the resulting hardware within 5 to 10 years.

**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. Table S.1 of *Vision and Voyages for Planetary Science in the Decade 2013-2022* (2011) correlates ten "Priority Questions" drawn from three Crosscutting Science Themes, with "Missions in the Recommended Plan that Address Them". SR missions are shown to address eight out of the ten questions and cover every crosscutting theme, including Building New Worlds, Planetary Habitats, and Workings of Solar Systems.

**References:**

Vision and Voyages for Planetary Science in the Decade 2013-2022, [http://nap.edu/13117](http://nap.edu/13117) [137]


Comet Nucleus Sample Return (CNSR), [https://ntrs.nasa.gov/search.jsp?R=20180002990](https://ntrs.nasa.gov/search.jsp?R=20180002990) [140]

### S4.04 Extreme Environments Technology

**Lead Center:** GSFC

**Participating Center(s):** GRC, GSFC, LaRC

**Scope Title:**

**Scope Description:**

This subtopic addresses NASA's need to develop technologies for producing space systems that can operate without environmental protection housing in the extreme environments of NASA missions. Key performance parameters of interest are survivability and operation under the following conditions:

1. Very low temperature environments (e.g., temperatures at the surface of Titan and of other Ocean Worlds as low as -180 °C; and in permanently shadowed craters on the Moon).
2. Combination of low-temperature and radiation environments (e.g., surface conditions at Europa of -180 °C with very high radiation).
3. Very high temperature, high pressure, and chemically corrosive environments (e.g., Venus surface conditions, having very high pressure and temperature of 486 °C).

NASA is interested in expanding its ability to explore the deep atmospheres and surfaces of planets, asteroids, and comets through the use of long-lived (days or weeks) balloons and landers. survivability in extreme high temperatures and high pressures is also required for deep atmospheric probes to the giant planets. Proposals are sought for technologies that are suitable for remote-sensing applications at cryogenic temperatures and in situ atmospheric and surface explorations in the high-temperature, high-pressure environment at the Venustus surface (485 °C, 93 atm) or in low-temperature environments such as those of Titan (-180 °C), Europa (-220 °C), Ganymede (-200 °C), Mars, the Moon, asteroids, comets, and other small bodies.

Also, Europa-Jupiter missions may have a mission life of 10 years, and the radiation environment is estimated at 2.9 Mrad total ionizing dose (TID) behind 0.1-in-thick aluminum. Proposals are sought for technologies that enable
NASA's long-duration missions to extreme wide-temperature and cosmic radiation environments. High reliability, ease of maintenance, low volume, low mass, and low outgassing characteristics are highly desirable. Special interest lies in development of the following technologies that are suitable for the environments discussed above:

- Wide-temperature-range precision mechanisms: for example, beam-steering, scanner, linear, and tilting multi-axis mechanisms.
- Radiation-tolerant/radiation-hardened low-power, low-noise, mixed-signal mechanism control electronics for precision actuators and sensors.
- Wide-temperature-range feedback sensors with sub-arcsecond/nanometer precision.
- Long-life, long-stroke, low-power, and high-torque force actuators with sub-arc-second/nanometer precision.
- Long-life bearings/tribological surfaces/lubricants.
- High-temperature analog and digital electronics, electronic components, and in-circuit energy storage (capacitors, inductors, etc.) elements.
- High-temperature actuators and gear boxes for robotic arms and other mechanisms.
- Low-power and wide-operating-temperature radiation-tolerant/radiation-hardened radio-frequency (RF) electronics.
- Radiation-tolerant/radiation-hardened low-power/ultra-low-power, wide-operating-temperature, low-noise mixed-signal electronics for space-borne systems such as guidance and navigation avionics and instruments.
- Radiation-tolerant/radiation-hardened wide-operating-temperature power electronics.
- Radiation-tolerant/radiation-hardened electronic packaging (including shielding, passives, connectors, wiring harness, and materials used in advanced electronics assembly).

Research should be conducted to demonstrate technical feasibility during Phase I and show a path toward a Phase II hardware demonstration, and when possible, deliver a demonstration unit for functional and environmental testing at the completion of the Phase II contract.

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

**Primary Technology Taxonomy:**
Level 1: TX 04 Robotics Systems  
Level 2: TX 04.2 Mobility  
Desired Deliverables of Phase I and Phase II:

- Prototype  
- Hardware  
- Research  
- Analysis

**Desired Deliverables Description:**

Provide research and analysis for Phase I as a final report.

Deliverables for Phase II include proof-of-concept working prototypes that demonstrate the innovations defined in the proposal and enable direct operation in extreme environments.

**State of the Art and Critical Gaps:**

Future NASA missions to high-priority targets in our solar system will require systems that have to operate at extreme environmental conditions. NASA missions to the surfaces of Europa and other Ocean Worlds bodies will be exposed to temperatures as low as -180 ºC and radiation levels that are at megarad levels. Operation in permanently shadowed craters on the Moon is also a region of particular interest. In addition, NASA missions to the Venus surface and deep atmospheric probes to Jupiter or Saturn will be exposed to high temperatures, high pressures, and chemically corrosive environments.
Current state-of-practice for development of space systems for the above missions is to place hardware developed with conventional technologies into bulky and power-inefficient environmentally protected housings. The use of environmental protection housing will severely increase the mass of the space system and limit the life of the mission and the corresponding science return. This solicitation seeks to change the state of the practice by support technologies that will enable development of lightweight, highly efficient systems that can readily survive and operate in these extreme environments without the need for the environmental protection systems.

Relevance / Science Traceability:

Relevance to SMD (Science Mission Directorate) is high.

Low-temperature survivability is required for surface missions to Titan (-180 °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 baseline concept with a mission life of 10 years, the radiation environment is estimated at 2.9 Mrad TID behind 0.1-in-thick aluminum. Lunar equatorial region temperatures swing from -180 °C to +130 °C during the lunar day/night cycle, and shadowed lunar pole temperatures can drop to -230 °C.

Advanced technologies for high-temperature systems (electronics, electromechanical, and mechanical) and pressure vessels are needed to ensure NASA can meet its long-duration (days instead of hours) life target for its science missions that operate in high-temperature and high-pressure environments.

References:


Proceedings of the meetings of the Venus Exploration Analysis Group (VEXAG), https://www.lpi.usra.edu/vexag/[142]

Proceedings of the meetings of the Outer Planet Assessment Group (OPAG), https://www.lpi.usra.edu/opag/[143]

S4.05 Contamination Control and Planetary Protection

Lead Center: GSFC

Scope Title:

CC and PP Implementation and Verification

Scope Description:

The planetary protection (PP) and contamination control (CC) subtopic focuses on mission-enabling and capability-driven technologies to improve NASA's ability to prevent forward and backward contamination. Forward contamination is the transfer of viable organisms from Earth to another body. Backward contamination is the transfer of material posing a biological threat back to Earth's biosphere. NASA is seeking innovative technologies or applications of technologies to facilitate meeting portions of forward and backward contamination requirements to include:
Improvements to spacecraft cleaning and sterilization that remain compatible with spacecraft materials and assemblies.

Prevention of recontamination and cross contamination throughout the spacecraft lifecycle.

Improvements to detection and verification of organic compounds and biologicals on spacecraft, to include microbial detection and assessments for viable organism and deoxyribonucleic-acid- (DNA-) based verification technologies to encompass sampling devices, sample processing, and sample analysis pipelines.

Active in situ recontamination/decontamination approaches (e.g., in situ heating of sample containers to drive off volatiles prior to sample collection) and in situ/in-flight sterilization approaches (e.g., UV or plasma) for surfaces.

Enabling end-to-end sample return functions to assure containment and pristine preservation of materials gathered on NASA missions.

For CC efforts, understanding contaminants and preventing contamination supports the preservation of sample science integrity and ensures spacecraft function nominally. NASA is seeking analytical and physics-based modeling technologies and techniques to quantify and validate submicron particulate contamination, low-energy surface material coatings to prevent contamination, and modeling and analysis of particles to ensure hardware and instrumentation meet organic contamination requirements.

Examples of outcomes:

- End-to-end microbial reduction/sterilization technology for larger spacecraft subsystems.
- Microbial reduction/sterilization technology for spacecraft components.
- Ground-based biological contamination/recontamination mitigation system that can withstand spacecraft assembly and testing operations.
- In-flight spacecraft component-to-component cross-contamination mitigation system.
- Viable organism and/or DNA sample collection devices, sample processing (e.g., low biomass extraction), and sample analysis (e.g., bioinformatic pipelines for low biomass).
- Real-time, rapid device for detection and monitoring of viable organism contamination on low-biomass surfaces or in cleanroom air.
- Bioburden spacecraft cleanliness monitors for assessing surface cleanliness throughout flight and surface operations during missions.
- DNA-based system to elucidate abundance, diversity, and planetary protection relevant functionality of microbes present on spacecraft surfaces.
- An applied molecular identification technology to tag/label biological contamination on outbound spacecraft.
- Low surface area energy coatings.
- Molecular adsorbers (“getters”).
- Experimental technologies for measurement of outgassing rates lower than $1.0 \times 10^{-15} \text{ g/cm}^2/\text{s}$ with mass spectrometry, under flight conditions (low and high operating temperatures) and with combined exposure to natural environment (e.g., high-energy radiation, ultraviolet radiation, atomic oxygen exposure).
- Physics-based technologies for particulate transport modeling and analysis for continuum, rarefied, and molecular flow environments, with electrostatic, vibro-acoustic, particle detachment and attachment capabilities.
- Modeling and analysis technologies for view-factor computation technologies for complex geometries with articulation (e.g., rotating solar arrays, articulating robotic arms).

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:
Desired Deliverables Description:

Phase I deliverable: proof-of-concept study for the approach to include data validation and modeling.

Phase II: detailed analysis and prototype for testing.

Areas to consider for deliverables are, 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.

State of the Art and Critical Gaps:

PP state of the art leverages the technologies resulting from the 1960s to 1970s Viking spacecraft assembly and test era. The predominant means to control biological contamination on spacecraft surfaces is using some combination of heat microbial reduction processing and solvent cleaning (e.g., isopropyl alcohol cleaning). Notably, vapor hydrogen peroxide is a NASA-approved process, but the variability of the hydrogen peroxide concentration, delivery mechanism, and material compatibility concerns still tends to be a hurdle to infuse it on a flight mission with complex hardware and multiple materials for a given component. Upon microbial reduction, the hardware then is protected in a cleanroom environment (ISO 8 or better) using protective coverings when hardware is not being assembled or tested. Biological cleanliness is then verified through the NASA standard assay, which is a culture-based method. Rapid cleanliness assessments can be performed, but are not currently accepted as a verification methodology, to inform engineering staff about biological cleanliness during critical hardware assembly or tests that include the total adenosine triphosphate (tATP) and limulus amoebocyte lysate (LAL) assays. Terminal sterilization has been conducted with recontamination prevention for in-flight biobarriers employed for the entire spacecraft (Viking) or a spacecraft subsystem (Phoenix spacecraft arm). In addition to the hardware developed approaches for compliance, environmental assessments are implemented to understand recontamination potential for cleanroom surfaces and air. Although the NASA standard assay is performed on the cleanroom surfaces, DNA-based methodologies have been adopted to include 16S and 18S ribosomal-ribonucleic-acid- (rRNA-) targeted sequencing, while metagenomic approaches are currently undergoing development. Thus, the critical PP gaps include the assessment of DNA from low-biomass surfaces (<0.1 ng/µL DNA, using current technologies, from 1 to 5 m² of surface), sampling devices that are suitable for low biomass and compounds (e.g., viable organisms, DNA) but also compliant with cleanroom and electrostatic discharge limits, quantification of the widest spectrum of viable organisms, enhanced microbial reduction/sterilization modalities that are compatible with flight materials, and a ground- and flight-based recontamination systems.

CC requirements and practices are also evolving rapidly as mission science objectives targeting detection of organics and life are driving stricter requirements and improved characterization of flight-system- and science-instrument-induced contamination. State-of-the-art CC includes:

- Testing and measurement of outgassing rates down to $3.0 \times 10^{15} \text{ g/cm}^2/\text{s}$ with mass spectrometry, under flight conditions (low and high operating temperatures) and with combined exposure to natural environment (high-energy radiation, ultraviolet radiation, atomic oxygen exposure).
- Particulate transport modeling and analysis for continuum, rarefied, and molecular flow environments with electrostatic, vibro-acoustic, particle detachment and attachment capabilities.
• Modeling and analysis of molecular return flux using direct simulation Monte Carlo (DSMC) and the Bhatnagar–Gross–Krook (BGK) formulations.

Relevance / Science Traceability:

Protection requirements has emerged in recent years with increased interest in investigating bodies with the potential for life detection such as Europa, Enceladus, Mars, etc. and the potential for sample return from such bodies. The development of such technologies would enable missions to be able to be responsive to PP requirements as they would be able to assess viable organisms and establish microbial reduction technologies to achieve acceptable microbial bioburden levels for sensitive life detection instruments to prevent inadvertent “false positives,” to ensure compliance sample return planetary protection and science requirements, and to provide a means to comply with probabilistic-based planetary protection requirements for biologically sensitive missions (e.g., outer planets and sample return).

References:

Planetary Protection, https://planetaryprotection.nasa.gov/ [144]


S5.01 Technologies for Large-Scale Numerical Simulation

Lead Center: ARC

Participating Center(s): GSFC

Scope Title:

Exascale Computing

Scope Description:

NASA scientists and engineers are increasingly turning to large-scale numerical simulation on supercomputers to advance understanding of complex Earth and astrophysical systems and to conduct high-fidelity aerospace engineering analyses. The goal of this subtopic is to increase the mission impact of NASA's investments in supercomputing systems and associated operations and services. Specific objectives are to:

• Decrease the barriers to entry for prospective supercomputing users.
• Minimize the supercomputer user's total time-to-solution (e.g., time to discover, understand, predict, or design).
• Increase the achievable scale and complexity of computational analysis, data ingest, and data communications.
• Reduce the cost of providing a given level of supercomputing performance for NASA applications.
• Enhance the efficiency and effectiveness of NASA's supercomputing operations and services.

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. The approach of this subtopic is to seek novel software and hardware technologies that provide notable benefits to NASA's supercomputing users and facilities and to infuse these technologies into NASA supercomputing operations. Successful technology
development efforts under this subtopic would be considered for follow-on funding by, and infusion into, NASA's high-end computing (HEC) projects: the High End Computing Capability project at Ames and the Scientific Computing project at Goddard. To assure maximum relevance to NASA, funded SBIR contracts under this subtopic are engaged to interact with one or both HEC projects and with key HEC users where appropriate. During the project the lead PI is encouraged to interact with the technical monitor on NASA HEC needs. Projects that require access to NASA HEC resources must provide adequate justification, and proposers should realize that it takes significant amount of time to gain access to on-site resources due to security requirements, which could jeopardize Phase I deliverable timelines. In addition, these resources are heavily used and would be limited for use for SBIR projects.

The technology areas of this subtopic are aligned with two objectives of the NSCI, the National Strategic Computing Initiative, announced by the White House in July 2015. These technologies that are amenable to quick, small efforts for advancement: (1) Technologies to accelerate delivery of a capable exascale computing system delivering approximately 100× the performance of current systems across a range of applications (NSCI Objective 1) and (2) Technologies to increase coherence between the technology base used for modeling and simulation and that used for data analytic computing (NSCI Objective 2).

**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

**Desired Deliverables Description:**

Novel software and hardware technologies that provide notable benefits to NASA's supercomputing users and facilities, and to infuse these technologies into NASA supercomputing operations. Successful technology development efforts under this subtopic would be considered for follow-on funding by, and infusion into, NASA's HEC projects: the High End Computing Capability project at Ames and the Scientific Computing project at Goddard.

The expected deliverable for Phase I is research that demonstrates technical feasibility as described in a final report, and the deliverable for Phase II is a prototype demonstration.

Offerors should demonstrate awareness of the state of the art of their proposed technology, and should leverage existing commercial capabilities and research efforts where appropriate. Open-source software and open standards are strongly preferred. Note that the NASA supercomputing environment is characterized by:

- HEC systems operating behind a firewall to meet strict 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.

**State of the Art and Critical Gaps:**

The state of the art and the critical gaps of the main technologies areas are:
1. NASA science requires at least 100× more powerful supercomputers and 1000× higher application parallelism in 10 years, at the same power.
2. Current technologies for high-fidelity computational simulations and data analytics are distinct, and interfacing them is inefficient.

**Relevance / Science Traceability:**

Virtually all high-end computing systems and applications can benefit from the deliverables of this subtopic. As the demand for high-end computing continue to grow, there is an increasing need for the solicited technologies in both the government and industry.

**References:**

NASA High-End Computing Capability Project: [https://www.nas.nasa.gov/hecc/about/hecc_project.htm](https://www.nas.nasa.gov/hecc/about/hecc_project.htm) [146]

The National Strategic Computing Initiative: [https://www.nitrd.gov/nsci/index.aspx](https://www.nitrd.gov/nsci/index.aspx) [147]

**S5.03 Accelerating NASA Science and Engineering through the Application of Artificial Intelligence**

*Lead Center: ARC*

*Participating Center(s): ARC, JPL, LaRC*

**Scope Title:**

**Accelerating NASA Science and Engineering Through the Application of Artificial Intelligence**

**Scope Description:**

NASA researchers are increasingly using artificial intelligence (AI) and machine learning (ML) technologies across science and engineering to address questions that previously could not be studied, in order to open up new insights. From both the Government and commercial sectors the volume and variety of datasets is increasing at an exponential rate, making it more of a challenge to NASA science and engineering. This subtopic is looking for innovative proposals using AI/ML to address the following unique problems across NASA. Proposals MUST specify and be in alignment with existing and/or future NASA programs to address or extend a specific need.

This subtopic has the following three critical areas: (1) AI/ML at the Extreme Edge, (2) Rapid Detection of Land Coverage Change, and (3) Rapid Identification of Events in High-Resolution Earth System Model Data. This goal is accomplished by more completely specifying smaller, better defined areas that rest squarely within Focus Area 13 (Information Technologies for Science Data). Proposals for fault management should be addressed in S5.05 Fault Management Technologies (Focus Area 3 Autonomous Systems for Space Exploration). Further, proposals for small spacecraft trajectory control should be addressed in Z3.02 Artificial Intelligence (AI)/Machine Learning (ML) for Small Spacecraft Swarm Trajectory Control (Focus Area 11 Spacecraft and Platform Subsystems), and proposals for autonomous systems should be addressed in the STTR Topic T4 Autonomous Systems for Space Exploration (subtopic - Integrated Data Uncertainty Management & Representation for Trusted Autonomy in Space).

Proposals should address one of the following focus areas:
AI/ML at the Extreme Edge

- With the increase in data rates for instruments, there is an increasing need to compute at the edge, often in constrained computing environments.
- NASA is interested in the application of AI/ML on spacecraft, rovers, within a constellation of SmallSats, or other remote sensing platforms where the latency and bandwidth between the remote platform and the ground station are not sufficient to adequately download all data. An example of this is the Magnetospheric Multiscale (MMS) mission where a fraction (approximately 2%) of the data taken will be transferred back to Earth.
- How can training of models be done efficiently at the edge to detect anomalies, perform classifications, segmentation, or run other types of AI/ML models?

Rapid Detection of Land Cover Change

- Remote-sensing data of the Earth (both from NASA and commercial sources) is also continuing to increase at dramatic rates, and NASA is interested in using AI/ML to enable the rapid detection of changes in the land use and anomalies across multiple data sets.
- This will require the potential fusion of multiple satellite datasets, intersensor calibration, geolocation, and more.

Rapid Identification of Events in High-Resolution Earth System Model Data

- The Global Modeling and Assimilation Office (GMAO) uses a general circulation model (GCM) called the Goddard Earth Observing System (GEOS) high-performance application to produce model output for instrument design. These nature runs are free-running atmospheric models that are driven by sea surface temperatures with resulting datasets being very large (on the order of petabytes).
- Instrument teams then use the GEOS output to study the potential impact of additional observations on specific weather phenomena such as hurricanes, weather fronts, mesoscale convective cells, and more.
- NASA is interested in models that can be trained to rapidly identify these various weather phenomena in the GEOS nature run data. This will be used to create a searchable catalogue of these events for use in observing system simulation experiments (OSSEs).

Research proposed to this subtopic should demonstrate technical feasibility during Phase I, and in partnership with scientists and/or engineers, show a path toward a Phase II prototype demonstration, with significant communication with missions and programs to later plan a potential Phase III infusion. It is highly desirable that the proposed projects lead to solutions that will be infused into NASA programs and projects.

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

**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:**

- Prototype
- Software
- Research

**Desired Deliverables Description:**

Data products developed under this subtopic may be developed for broad public dissemination or used within a narrow scientific community. It is expected that the training sets, models, and resulting data products will be publicly accessible.

In general, the desired outcomes for this subtopic include: (1) new or accelerated science and engineering products, (2) training data sets and trained models specifically for a given problem but that can also be used as a basis for furthering other science and engineering research and development, and (3) resulting data products that can be used and infused in NASA science projects and potentially used to develop new missions.
More specifically,

- Phase I should be used to establish a proof of concept with deliverables including a final report, any software developed, training sets, etc.
- Phase II will expand on this proof of concept to a full prototype with a very similar set of deliverables, including a final report, software, training sets, etc.

**State of the Art and Critical Gaps:**

NASA science and engineering is making large strides in the use of AI technologies (which includes both machine learning and deep learning). However, the datasets and requirements are growing so rapidly that additional support is needed to fill in gaps. In addition, emerging computational platforms now provide significant improvements in computing capabilities to enable AI to be applied to a wide variety of applications in science and engineering. These emerging computational capabilities have the potential to dramatically speed up AI calculations, and these systems are even being used as the reference architecture for exascale high-performance computing systems.

**Relevance / Science Traceability:**

Broad applicability across throughout the decadal surveys and satellite development requirements. Specific missions include the Europa Lander, Mars 2020, and more:

- Spacecraft, rovers, constellation of SmallSats, or other remote sensing platforms.
- Global Modeling and Assimilation Office (GMAO) assimilation: Augment Earth system modeling or data assimilation.
- Carbon Cycle Ecosystems Office (CCOE): Wide variety of applications given the diversity of data sets from sparse in-situ to global satellite measurements.
- Earth Observing System Data and Information System (EOSDIS)/Distributed Active Archive Centers (DAACs): Harnessing the potential for new discoveries across the wide array of observation data.
- Computational and Information Sciences and Technology Office (CISTO - Code 606): Technologies used for new data science.
- NASA Center for Climate Simulation (NCCS - Code 606.2): Building applications toward exascale computing.

**References:**

- NASA Goddard Institute for Space Studies: [https://www.giss.nasa.gov/](https://www.giss.nasa.gov/) [152]
- NASA Earth Science Data: [https://earthdata.nasa.gov/](https://earthdata.nasa.gov/) [153]
- NASA Center for Climate Simulation: [https://www.nccs.nasa.gov/](https://www.nccs.nasa.gov/) [154]
- NASA High-End Computing (HEC) Program: [https://www.hec.nasa.gov/](https://www.hec.nasa.gov/) [155]

In addition, proposers are encourage to search the NASA Technical Report Server (NTRS) for additional information to help guide potential solutions:

- [https://ntrs.nasa.gov/](https://ntrs.nasa.gov/) [79]
S5.04 Integrated Science Mission Modeling

Lead Center: ARC

Participating Center(s): GSFC

Scope Title:

Innovative System Modeling Methods and Tools

Scope Description:

NASA seeks innovative systems modeling methods and tools addressing the following needs:

1. Define, design, develop, and execute future science missions by developing and utilizing advanced methods and tools that empower more comprehensive, broader, and deeper system and subsystem modeling while enabling these models to be developed earlier in the lifecycle. Ideally, the proposed solutions should leverage MBSE (Model-Based Systems Engineering)/SysML (System Markup Language) approaches being piloted across NASA, allow for easier integration of disparate model types, and be compatible with current agile design processes.

2. Enable disciplined system analysis for the design of future missions, including modeling of decision support for those missions and integrated models of technical and programmatic aspects of future missions.

3. Evaluate technology alternatives and impacts, science valuation methods, and programmatic and/or architectural trades.

4. 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:

- Conceptual phase models and tools that allow design teams to easily develop, populate, and visualize very broad, multidimensional trade spaces; methods for characterizing and selecting optimum candidates from those trade spaces, particularly at the architectural level. There is specific interest in models and tools that facilitate comprehensive comparison of architectural variants of systems.

- 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 as well as in growing usage of autocoding.
  - To operate within highly distributed, collaborative design environments, where models and/or infrastructure that support/encourage designers are geographically separated (including Open Innovation environments). This includes considerations associated with near-real-time (concurrent) collaboration processes and associated model integration and configuration management practices.
  - To be capable of execution at variable levels of fidelity/uncertainty. Ideally, models should have the ability to quickly adjust fidelity to match the requirements of the simulation (e.g., from broad-and-shallow to in-depth and back again).

- Target models (e.g., phenomenological or geophysical models) that represent planetary surfaces, interiors, atmospheres, etc., and associated tools and methods that allow for integration into system design/process models for simulation of instrument responses. These models may be algorithmic or numeric, but should be useful to designers wishing to optimize remote sensing systems for those planets.

Note that this topic area addresses a broad potential range of science mission-oriented modeling tools and methods. This includes the integration of these tools into broader model-based engineering frameworks, and also includes proposals with MBSE/SysML as the primary focus.
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.X Other Software, Modeling, Simulation, and Information Processing

Desired Deliverables of Phase I and Phase II:

- Prototype
- Software
- Research

Desired Deliverables Description:

Phase I should provide a final report that describes the methodology and proof of concept of adaptability of the model for NASA use.

At the completion of Phase II, NASA desires a working prototype suitable for demonstrations with "real" data to make a compelling case for NASA usage. Use and development of the model—including any and all work performed to verify and validate it—should be documented.

State of the Art and Critical Gaps:

There currently are a variety of models, methods, and tools in use across the Agency and with our industry partners. These are often custom, phase-dependent, and poorly interfaced to other tools. The disparity between the creativity in the early phases and the detail-oriented focus in later phases has created phase transition boundaries, where missions not only change teams but tools and methods as well. We aim to improve this.

As NASA continues its move into greater use of models for formulation and development of NASA projects and programs, there are recurring challenges to address. This 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 demonstrations of capability and methodologies for achieving the above.

The explosion of MBX (model-based everything) has led to a proliferation of models, modeling processes, and the integration/aggregation thereof. The model results are often combined with no clear understanding of the fidelity/credibility. While some NASA personnel are looking for greater accuracy and "single source of truth," others are looking for the generation and exploration of massive trade spaces. Both greater precision and greater robustness will require addressing the cross-cutting challenges cited above.

Relevance / Science Traceability:

Several concept/feasibility studies for potential large (flagship) Astrophysics missions are in progress: Large UV/Optical/IR Surveyor (LUVOIR), Origins Space Telescope (OST), Habitable Exoplanet Observatory (HabEx), and Lynx. Following the 2020 Astrophysics decadal rankings, one of these will likely proceed to early Phase A, where the infusion of new and advanced systems modeling tools and methods would be a potential game-changer in terms of rapidly navigating architecture trades, requirements development and flow-down, and design optimization.

A variety of planetary missions requires significant modeling and simulation across a variety of possible trade
spaces. The portions of this topic area focused on breadth and variable fidelity will support them.

References:

- Habitable Exoplanet Observatory (HabEx): [https://www.jpl.nasa.gov/habex/](https://www.jpl.nasa.gov/habex/) [27]
- Lynx: [https://wwwastro.msfc.nasa.gov/lynx/](https://wwwastro.msfc.nasa.gov/lynx/) [28]
- Wide Field Infrared Survey Telescope (WFIRST): [https://www.nasa.gov/content/goddard/wfirst-wide-field-infrared-survey](https://www.nasa.gov/content/goddard/wfirst-wide-field-infrared-survey) [157]
- Mars Exploration/Program & Missions: [https://mars.nasa.gov/programmissions/](https://mars.nasa.gov/programmissions/) [134]
- JPL Missions: [https://www.jpl.nasa.gov/missions/](https://www.jpl.nasa.gov/missions/) [159]

S5.05 Fault Management Technologies

Lead Center: JPL

Participating Center(s): ARC, MSFC

Scope Title:

Development, Design, and Implementation of Fault Management Technologies

Scope Description:

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

Fault Management (FM) is a key component of system autonomy, serving to detect, interpret, and mitigate failures that threaten mission success. Robust FM must address the full range of hardware failures, 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. Despite lessons learned from past missions, spacecraft failures are still not uncommon and reuse of FM approaches is limited, illustrating deficiencies in our approach to handling faults in all phases of the flight project lifecycle.

While this subtopic addresses particular interest in onboard FM capabilities (viz. onboard sensing approaches, computing, algorithms, and models to assess and maintain spacecraft health), the 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 on-board fault management.

Needed innovations in FM can be grouped into the following two categories:

1. Fault Management Operations Approaches: This category encompasses FM "in-the-loop," including algorithms, computing, state estimation/classification, machine learning, and model-based reasoning. Further research into fault detection and diagnosis, prognosis, fault recovery, and mitigation of unrecoverable faults is needed to realize greater system autonomy.
2. Fault Management 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 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, 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 and only this subtopic if their design or application is specific to detection, classification, or
mitigation of system faults and off-nominal system behavior. While 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 techniques can be easily adapted to spacecraft.

Related technologies, but without a primary focus on resolution of system faults, such as machine-learning
approaches to spacecraft characterization or science data preprocessing, autonomy architectures, or generalized
system modeling and design tools, should be directed to other subtopics such as S5.03, Accelerating NASA
Science and Engineering through the Application of Artificial Intelligence, or S5.04, Integrated Science Mission
Modeling.

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:

- Increased spacecraft resilience against faults and failures.
- Increased 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 extent of testing required, completeness of verification planned, and residual risk resulting from
  incomplete coverage.
- Increase data integrity between multidiscipline tools.
- 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.

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:

The aim of the Phase I project should be to demonstrate the technical feasibility of the proposed innovation and
thereby bring the innovation closer to commercialization. Note, however, the research and development (R&D)
undertaken in Phase I is intended to have high technical risk, and so it is expected that not all projects will achieve
the desired technical outcomes.
The required deliverable at the end of an SBIR Phase I contract is a report that summarizes the project’s technical accomplishments. As noted above, it is intended that proposed efforts conduct an initial proof of concept, after which successful efforts would be considered for follow-on funding by Science Mission Directorate (SMD) missions as risk-reduction and infusion activities. Research should be conducted to demonstrate technical feasibility and NASA relevance during Phase I and show a path toward a Phase II prototype demonstration.

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

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

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

Phase II proposals require at minimum a report describing the technical accomplishments of the Phase I award and how these results support the underlying commercial opportunity. Describing the commercial potential is best done through experiment: Ideally the Phase II report should describe 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 such as the following:

- Delivery of the technology in software form, as a reference application, or through provision of trial or evaluation materials to future customers.
- Technical manuals, such as functional descriptions, specifications, and users guides.
- Conference papers or other publications.
- Establishment of a preliminary performance model describing technology metrics and requirements.

Each of these measures represents a step taken to mature the technology and further reduce the difficulty in reducing it to practice. Although it is established that further development and customization will continue beyond Phase II, ideally 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.

The SBIR program is an appropriate venue because of the following factors:

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

Relevance / Science Traceability:

FM technologies are applicable to all SMD missions, albeit with different emphases. Medium-to-large missions have very low tolerance for risk of mission failure, leading to a need for sophisticated and comprehensive 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 (currently in assembly, test, and launch operations (ATLO), 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, V&V of FM capabilities, and 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): 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).
- Search for Extrasolar Planets (observation): Provide sufficient system reliability through onboard detection, reasoning, and response to enable long-period, stable observations. Provide onboard or onground 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).

References:
• NASA's approach to FM and the various needs are summarized in the NASA FM Handbook: [160]
• Additional information is included in the talks presented at the 2012 FM Workshop:
  o [161] https://www.nasa.gov/centers/oce/documents/2012_fm_workshop.html
    particularly https://www.nasa.gov/pdf/637595main_day_1-brian_muirhead.pdf
• Another resource is the NASA Technical Memorandum "Introduction to System Health Engineering and Management for Aerospace (ISHEM),"
  https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20060003929.pdf [163]
    This is greatly expanded on in the following publication: Johnson, S. (ed): System Health
  us/System+Health+Management%3A+with+Aerospace+Applications-p-9781119998730 [164]
• FM technologies are strongly associated with autonomous systems as a key component of situational
  awareness and system resilience. A useful overview was presented at the 2018 SMD Autonomy
  Workshop, archiving a number of talks on mission challenges and design concepts:

S5.06 Space Weather Research-to-Operations/Operations-to-Research (R2O/O2R) Technology Development

Lead Center: ARC

Participating Center(s): ARC, JPL, JSC, LaRC, MSFC

Scope Title:

Space Weather Research-to-Operations/Operations-to-Research (R2O/O2R) Technology Development

Scope Description:

Space weather has the potential to disrupt telecommunications; aircraft and satellite systems; electric power
subsystmes; and position, navigation, and timing services. Given the importance of these systems to our national
well-being, NASA's Heliophysics Division invests in activities to improve the understanding of these phenomena
and to enable new monitoring, prediction, and mitigation strategies.

The national direction for this work is organized by the Space Weather Operations, Research, and Mitigation
(SWORM) Working Group, which is a Federal interagency coordinating body organized under the Space Weather,
Security, and Hazards (SWSH) Subcommittee. The SWSH is a part of the National Science and Technology
Council (NSTC) Committee on Homeland and National Security, organized under the Office of Science and
Technology Policy (OSTP). The SWORM coordinates Federal Government departments and agencies to meet the

NASA's role under the National Space Weather Strategy and Action Plan is to provide increased understanding of
the fundamental physics of the Sun-Earth system through space-based observations and modeling, the
development of new space-based space weather technologies and missions, and monitoring of space weather for
NASA's space missions. This includes research that advances operational space weather needs.

This subtopic solicits new, enabling space weather technologies as part of NASA's response to these national
objectives. While this subtopic will consider all concepts demonstrably related to NASA's R2O/O2R responsibilities
outlined in the Strategy and Action Plan, four areas have been identified for priority development:
1. Space Weather Forecasting Technologies and Techniques: Innovative technologies and techniques are solicited that explore and enable the transition of tools, models, data, and knowledge from research to operational environments. This includes the preparation and validation of existing science models that may be suitable for transition to operational use. Consultation with existing NASA capabilities that prepare space weather forecasting products for later use—such as the Space Radiation Analysis Group (SRAG) at Johnson Space Center (JSC), the Community Coordinated Modeling Center (CCMC) at Goddard Space Flight Center (GSFC), and the Short-term Prediction Research and Transition (SPoRT) Center at Marshall Space Flight Center (MSFC)—may be appropriate. Areas of special interest include, but are not limited to:

- Lunar space environment characterization tools that can be employed by NASA to enhance protection of crewed and uncrewed missions to cis-lunar and lunar surface missions.
- Specifications and/or forecasts of the energetic particle and plasma conditions encountered by spacecraft within Earth’s magnetosphere, as well as products that directly aid in spacecraft anomaly resolution; and end-users such as spacecraft operators.
- Approaches that potentially lead to a 2- to 3-day forecasting of atmospheric drag effects on satellites and improvement in the quantification of orbital uncertainties in low-Earth-orbit (LEO) altitude ranges (up to ~2000 km).
- Techniques that enable the characterization and prediction of ionospheric variability that induces scintillations, which impact communication and global navigation and positioning systems.
- Longer range (2 to 3 days) forecasting of SPEs (solar particle events) and an improved all-clear SPE-forecasting capability.

2. Space Weather Advanced Data-Driven Discovery Techniques: A particular challenge is to combine the sparse, vastly distributed data sources available with realistic models of the near-Earth space environment. Data assimilation and other cutting-edge data-driven discovery innovations are solicited that enable tools and protocols for the operational space weather community. Priority will be given to proposals that:

- Develop data assimilation space weather applications or technologies desired by established space weather operational organizations.
- Integrate data from assets that typically do not share similar time series, utilize different measurement techniques (e.g., imaging vs. in situ particles and fields), or are distributed throughout the heliosphere.
- Provide new data-driven operational forecasting tools that can be straightforwardly validated by the CCMC or another equally robust validation methodology.
- Integrate underutilized resources (e.g., space-based radio occultation for ionospheric specification or U.S. Geological Survey (USGS) ground conductivity measurements related to geomagnetically induced currents).

3. Space Weather Mitigation Technologies: The 2019 National Space Weather Strategy and Action Plan specifically calls out the need to test, evaluate, and deploy technologies and devices to mitigate the effects of space weather on communication systems, geomagnetic disturbances on the electrical power grid, or radiation events on satellites. Additionally, it identifies a need for robust situational awareness capabilities, driven by improved understanding and characterization of the effects space weather phenomena have on Earth and in the space environment, to inform decision making and enable the execution of missions susceptible to disruptions from space weather. It also includes the development of processes to improve the transition of research approaches to operations.

4. Space Weather Instrumentation: Heliophysics science relies on a wide variety of instrumentation for its research and often makes its data available in near real time for space weather forecasting purposes. Concepts are solicited for instrumentation concepts, flight architectures, and reporting systems that enable enhanced, more informative, robust, and effective measurements for space weather monitoring and forecasting systems. Opportunities for improving measurements include increased spatial and temporal resolution, fidelity, promptness, and measurement system reliability. This includes the miniaturization of existing systems and/or technologies deployable as an array of CubeSats, as a hosted payload on satellite or other platform, or as a small complete mission making use of a rideshare opportunity. In order to be considered for investment, SBIR technologies should demonstrate comparable, or better, precision and accuracy when compared to the current state of the art. Further, SBIR instrument designs should avoid duplicating current NASA research spacecraft arrays or detector systems, including those currently in
formulation or development (e.g., Interstellar Mapping and Acceleration Probe (IMAP), Geospace Dynamics Constellation (GDC), Medici, Explorer concepts, etc.).

Proposals must demonstrate an understanding of the current state of the art, describe how the proposed innovation is superior, and provide a feasible plan to develop the technology and infuse it into a specific activity listed within the National Space Weather Strategy and Action Plan.

**Expected TRL or TRL Range at completion of the Project:** 3 to 8

**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:**

- Prototype
- Hardware
- Software

**Desired Deliverables Description:**

Space weather is a broad umbrella encompassing science, engineering, applications, and operations. The ultimate goal of this SBIR subtopic is to generate products or services (“deliverables”) that enable end-user action. The deliverables can be applied, for example, to space weather hazard assessments, to real-time situational awareness, or to plan protective mitigation actions. Deliverables can be in the form of new data, new techniques, new instrumentation, and/or predictive models that are prepared/validated for transition into operations.

- Phase I deliverables are proof-of-concept data and/or detailed technique, instrument, or model development plans with sufficient fidelity to assess technical, management, cost, and schedule risk. Phase I 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 deliverables are functioning prototype versions of the proposed technologies that have been tested in a realistic environment or within a standard space weather community development and validation framework. 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:**

We do not yet know how to predict what needs to be predicted, we do not yet know how quantitatively good/bad our operational capabilities are (metrics), mechanisms do not yet exist to enable a broad range of the community to participate in the improvement of operational models, and the research environment advances understanding rather than the improvement of operational products.

Space weather poses a constant threat to the Nation’s critical infrastructure, our satellites in orbit, and our crewed and uncrewed space activities. Extreme space weather events can cause substantial harm to our Nation’s security and economic vitality.

Preparing for space weather events is an important aspect of American resilience that bolsters national and homeland security and facilitates continued U.S. leadership in space. A robust space weather program and its associated forecasting capabilities are essential for NASA’s future exploration success.

**Relevance / Science Traceability:**

This SBIR subtopic enables NASA to demonstrate progress against NASA Goal 1.4: Understand the Sun and its interactions with Earth and the solar system, including space weather.
These applied research projects directly address NASA’s role within the SWORM Working Group, which is a Federal interagency coordinating body organized under the SWSH Subcommittee. The SWSH is a part of the NSTC Committee on Homeland and National Security, organized under the OSTP. The SWORM coordinates Federal Government departments and agencies to meet the goals and objectives specified in the National Space Weather Strategy and Action Plan released in March 2019.

The Heliophysics Space Weather Science and Applications (SWxSA) Program establishes an expanded role for NASA in space weather science under a single element. It is consistent with the recommendation of the National Research Council (NRC) Decadal Survey and the OSTP/SWORM 2019 National Space Weather Strategy and Action Plan. It competes ideas and products, leverages existing agency capabilities, collaborates with other agencies, and fosters partnership with user communities. The SWxSA program is distinguishable from other heliophysics research elements in that it is specifically focused on investigations that significantly advance understanding of space weather and then apply this progress to enable more accurate characterization and predictions with longer lead time. The Heliophysics Living with a Star (LWS) Program has established a path forward to meet NASA’s obligations to the research relevant to space weather and is a significant source of input to SWxSA.

Further involvement by the emerging Heliophysics space weather commercial community has the potential to significantly advance the space weather application obligations portion of the mandate.

Astronauts are not protected by the Earth’s atmosphere and are exposed to space radiation such as galactic cosmic rays and solar energetic particles. A robust space weather program and associated forecasting capabilities is essential for NASA’s future exploration success.

References:

- The SWORM Working Group is a Federal interagency coordinating body organized under the SWSH Subcommittee. THE SWSH is a part of the NSTC Committee on Homeland and National Security, organized under the OSTP. The SWORM coordinates Federal Government departments and agencies to meet the goals and objectives specified in the National Space Weather Strategy and Action Plan released in March 2019. See: https://www.sworm.gov/ [168]
- An Executive Order (EO) on Coordinating National Resilience to Electromagnetic Pulses (EMP) was released by the White House on March 26, 2019. The EO identifies the disruptive impacts an EMP has on technology and critical infrastructure systems, whether the EMP is human made or naturally occurring. The EO outlines how the Federal Government will prepare for and mitigate the effects of EMPs by an efficient and cost-effective approach.