



NASA SBIR 2016 Phase I Solicitation

Science

Sensors, Detectors and Instruments Topic S1

NASA's Science Mission Directorate (SMD) (<http://nasascience.nasa.gov/> [1]) encompasses research in the areas of Astrophysics, Earth Science, Heliophysics and Planetary Science. The National Academy of Science has provided NASA with recently updated Decadal surveys that are useful to identify technologies that are of interest to the above science divisions. Those documents are available at the following locations:

- Astrophysics – (http://sites.nationalacademies.org/bpa/BPA_049810 [2]).
- Planetary – (<http://solarsystem.nasa.gov/2013decadal/index.cfm> [3]).
- Earth Science – (<http://science.nasa.gov/earth-science/decadal-surveys/> [4]).
- Heliophysics the 2009 technology roadmap can be downloaded here (<http://science.nasa.gov/heliophysics/> [5]).

A major objective of SMD instrument development programs is to implement science measurement capabilities with smaller or more affordable spacecraft so development programs can meet multiple mission needs and therefore make the best use of limited resources. The rapid development of small, low-cost remote sensing and in-situ instruments is essential to achieving this objective. For Earth Science needs, in particular, the subtopics reflect a focus on instrument development for airborne and Unmanned Aerial Vehicle (UAV) platforms. Astrophysics has a critical need for sensitive detector arrays with imaging, spectroscopy, and polarimetric capabilities, which can be demonstrated on ground, airborne, balloon, or suborbital rocket instruments. Heliophysics, which focuses on measurements of the sun and its interaction with the Earth and the other planets in the solar system, needs a significant reduction in the size, mass, power, and cost for instruments to fly on smaller spacecraft. Planetary Science has a critical need for miniaturized instruments with in-situ sensors that can be deployed on surface landers, rovers, and airborne platforms. The following subtopics are concomitant with these objectives and are organized by technology.

Sub Topics:

S1.01 Lidar Remote Sensing Technologies

Lead Center: LaRC

Participating Center(s): GSFC, JPL

NASA recognizes the potential of lidar technology in meeting many of its science objectives by providing new capabilities or offering enhancements over current measurements of atmospheric and topographic parameters from ground, airborne, and space-based platforms. To meet NASA's requirements for remote sensing from space, advances are needed in state-of-the-art lidar technology with an emphasis on compactness, efficiency, reliability, lifetime, and high performance. Innovative lidar subsystem and component technologies that directly address the measurement of atmospheric constituents and surface topography of the Earth, Mars, the Moon, and other planetary bodies will be considered under this subtopic. Compact, high-efficiency lidar instruments for deployment on unconventional platforms, such as balloon, small sat, and CubeSat are also considered and encouraged.

Proposals must show relevance to the development of lidar instruments that can be used for NASA science-focused measurements or to support current technology programs. Meeting science needs leads to four primary instrument types:

- *Backscatter* - Measures beam reflection from aerosols to retrieve the opacity of a gas.

- *Ranging* - Measures the return beam's time-of-flight to retrieve distance.
- *Doppler* - Measures wavelength changes in the return beam to retrieve relative velocity.
- *Differential absorption* - Measures attenuation of two different return beams (one centered on a spectral line of interest) to retrieve concentration of a trace gas.

Phase I research should demonstrate technical feasibility and show a path toward a Phase II prototype unit. Phase II prototypes should be capable of laboratory demonstration and preferably suitable for operation in the field from a ground-based station, an aircraft platform, or any science platform amply defended by the proposer. For the 2016 SBIR Program, NASA is soliciting the component and subsystem technologies described below.

- Compact and rugged single-frequency continuous-wave and pulsed lasers operating between 0.28- μm and 2.05- μm wavelengths suitable for lidar. Specific wavelengths are of interest to match absorption lines or atmospheric transmission: 0.28 to 0.32- μm (ozone absorption), 0.45 to 0.49- μm (transmission through ocean water), 0.532- μm , 0.817 to 0.830- μm (water lines), 1.0- μm , 1.57- μm (CO_2 line), 1.65- μm (methane line), and 2.05- μm (CO_2 line). For wavelengths associated with an absorption line, tunability on the order tens of nanometers is desired. Architectures involving new developments in diode laser, quantum cascade laser, and fiber laser technology are especially encouraged. For pulsed lasers two different regimes of repetition rate and pulse energies are desired: from 8-kHz to 10-kHz with pulse energy greater than 1-mJ and from 20-Hz to 100-Hz with pulse energy greater than 100-mJ.
- Optical amplifiers for increasing the energy of pulsed lasers in the wavelength range of 0.28- μm to 2.05- μm . Specific wavelengths of interest are listed above in the bullet above. Also, amplifier and modulator combinations for converting continuous-wave lasers to a pulsed format are encouraged. Amplifier designs must preserve the wavelength stability and spectral purity of the input laser.
- Ultra-low noise photoreceiver modules, operating at 1.6- μm wavelength, consisting of the detection device, complete Dewar/cooling systems, and associated amplifiers. General requirements are: large single-element active detection diameter (>200 micron), high quantum efficiency (>85%), noise equivalent power of the order of 10-14 W/sqrt(Hz), and bandwidth greater than 10 MHz.
- Novel, highly efficient approaches for High Spectral Resolution Lidar (HSRL) receivers. New approaches for high-efficiency measurement of HSRL aerosol properties at 1064, 532 and/or 355-nm. New or improved approaches are sought that substantially increase detection efficiency over current state of the art. Ideally, complete receiver subsystems will be proposed that can be evaluated and/or implemented in instrument concept designs.
- New space lidar technologies that use small and high-efficiency diode or fiber lasers to measure range and surface reflectance of asteroids and comets from >100 km altitude during mapping to <1 m during landing and sample return at a fraction of the power, mass, and cost of the Mercury Laser Altimeter (i.e., less than 7.4kg, 17W, and 28x28x26cm). The technologies can significantly extend the receiver dynamic range of the current space lidar without movable attenuators, providing sufficient link margin for the longest range but not saturating during landing. The output power of the laser transmitters should be continuously adjusted according to the spacecraft altitude. The receiver should have single photon sensitivity to achieve a near-quantum limited performance for long distance measurement. The receiver integration time can be continuously adjusted to allow trade-off between the maximum range and measurement rate. The lidar should have multiple beams so that it can measure not only the range but also surface slope and orientation.
- Narrow linewidth and frequency stable laser transmitter at 780-nm wavelength for development of low-cost, compact, and eye-safe high spectral resolution lidar (HSRL) for ground-based profile measurements of aerosol and cloud intensive and extensive properties. Desired specifications include pulse energy of 5 to 20-mJ, pulse repetition rate of 1 to 10-kHz, wavelength near 780-nm coincident with rubidium vapor line, linewidth < 10-MHz, spectral purity > 99.9%, and wavelength tunability of at least 0.5-nm around central wavelength.

S1.02 Microwave Technologies for Remote Sensing

Lead Center: JPL

Participating Center(s): GSFC

NASA employs active (radar) and passive (radiometer) microwave sensors for a wide range of remote sensing applications (for example, see (<http://www.nap.edu/catalog/11820.html> [6])). These sensors include low frequency

(less than 10 MHz) sounders to G-band (160 GHz) radars for measuring precipitation and clouds, for planetary landing, upper atmospheric monitoring, and global snow coverage, topography measurement and other Earth and planetary science applications. We are seeking proposals for the development of innovative technologies to support these future radar and radiometer missions and applications. The areas of interest for this call are listed below.

Single Pole Double Throw Switch with the following specifications:

- Frequency: 183 GHz, 325 GHz, or 380 GHz.
- Bandwidth: > 15 GHz.
- Insertion Loss: < 2 dB.
- Isolation: > 15 dB.

Calibration of sub-mm wave radiometers is limited in large part to external sources due to the lack of suitable switches for internal calibration. This increases the mass and cost of these instruments. A SPDT switch at 180 or 340 GHz will significantly reduce the cost and complexity of radiometers at these frequencies.

NEW: GaN Schottky diode technology for ultra-high power local oscillator power sources

This includes the development of GaN epi-structures on Si or SiC substrates suitable for millimeter-wave operations (SOA electron mobility >1000 cm²/V·s for 5E16 to 1E17 cm⁻³ epi doping levels, and discrete GaN Schottky diodes (power handling capabilities > 200 mW/diode).

Technology for compact Dual Frequency (Ka and W-band) quasi-optical radar front end

W-band (94 GHz +/- 50 MHz):

- Single Polarization Tx, Dual Polarization Rx using a quasioptical duplexer such as a faraday rotator.

Ka-band (35.5 GHz +/- 100 MHz):

- Dual Polarization Tx and Rx.
- Shared beam waist with W-band.
- Waveguide duplexer and OMT okay.

The Decadal Survey ACE mission calls for a dual-frequency (Ka/W-band) radar for observation of clouds and light precipitation from space. Recently a similar but more compact and low cost radar is considered for operation on the International Space Station (ISS). Compared to traditional ferrite material based radar Tx/Rx front-end, quasi-optical front-end offers significantly low loss and high power handling capability, which have direct impact on radar performance. A compact dual-frequency and dual-polarization quasi-optical radar front-end has not been developed and is in critical need for ISS, ACE and suborbital airborne radars.

Interconnection technologies to enable highly integrated, low loss distribution networks that integrate power splitters, couplers, filters, and/or isolators in a compact package

Technologies are sought that integrate X, Ku, and Ka-bands transmit/receive modules with antenna arrays and/or LO distribution networks for F- and/or G-band receiver arrays.

Dual-frequency (Ka/W-band), dual polarization compact quasi-optical front-end for cloud radars.

- Freq: 35.5 GHz ± 100MHz.
- 94 GHz ± 100MHz.
- Loss: < 0.5 dB.
- Polarization Isolation: > 30 dB.

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- Polarization: V and H.

640 GHz Heterodyne Polarimeter with I, Q, U Channels

Current 640 GHz polarimetric radiometers are either unsuitably large for space in terms of Mass/Volume/Power, or are direct-detection instruments that lack the ability to reject ozone emission contamination by selectively filtering the signal in the IF stages. This technology would help enable polarimetric measurements to provide microphysical parameterization of ice clouds applicable to ACE.

Low power RFI mitigating receiver back ends for broad band microwave radiometers

NASA requires a low power, low mass, low volume, and low data rate RFI mitigating receiver back end that can be incorporated into existing and future radiometer designs. The system should be able to channelize up to 1 GHz with 16 sub bands and be able to identify RFI contamination using tools such as kurtosis.

Compact 10+ Watt W-band transceiver including:

- SSPA, LNA, Circulator, and receiver protection switches.
- Mixer and 2 GHz Band-Pass Filter.
- 10-Watt SSPA, <1 dB transmit loss, 7 dB Rx Noise Figure.
- Approximately 3.5" x 3.5" x 4" dimensions.

NEW: Compact, highly integrated technologies enabling Altimetry/Velocimetry for space qualified radars

- Frequency: C-band to K-band.
- 0.2% range and 1% velocity accuracies.
- Operating range 6000m to 0 m.
- Compact antenna development.
- Integrated digital backend.
- Highly integrated MMIC for radar systems/subsystems.
- < 3kg and 1U (10 x 10 x 3 cm³) for electronics.

Deployable 1-D Parabolic Antenna

- At least 2 m x 2 m in dimensions.
- Operable up to Ka-band (35.5 GHz).

Deployable 1-D parabolic antenna technology at Ka-band will allow higher gain and better spatial resolution for future flight precipitation measurement missions.

Technology for low-power, rad-tolerant broad band spectrometer back ends for microwave radiometers

Includes - digitizers with 20 Gsps, 20 GHz bandwidth, 4 or more bit and simple interface to FPGA; ASIC implementations of polyphase spectrometer digital signal processing with ~1 watt/GHz. 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.

A compact, broadband (6-12 GHz or 10-30 GHz), low insertion loss isolator

- < 0.3 insertion loss.
- 20 dB input and output return loss.

The isolator should be compatible with either microstrip or CPW for ease of transition with the rest of the system.

Ka-band Power Amplifier for CubeSats

- F = 35.7 GHz +/- 200MHz.
- Volume: <1U (10 x10 x10 cm³).
- Psat >32W.
- Gain > 35 dB.
- PAE > 20%.
- Pulsed, 12% duty cycle.
- Current state of the art amplifiers are limited to 7W at < 15% efficiencies.

Development of on-wafer high frequency probes above 300 GHz for cryogenic temperatures

Passive or active cooled space missions will benefit from early performance characterization and selection at operating temperatures. The conventional test on individual packaged components is expensive and time consuming.

Advanced Deployable Antennas for CubeSats

- F = 35.7 GHz +/- 200MHz capable of 1D scanning.
- F = 94.05 GHz ± 50MHz.
- Aperture size = 2 m.
- Gain > 48dB @36GHz.
- Sidelobe ratio > 20dB.
- Stowed volume: <2.5U (25 x 10 x 10 cm³).
- Polarization: Linear.

Components for addressing gain instability in LNA based radiometers from 100 and 600 GHz

NASA requires low insertion loss solutions to the challenges of developing stable radiometers and spectrometers operating above 100 GHz that employ LNA based receiver front ends. This includes noise diodes with ENR>10dBm and with better than ? 0.01 dB/°C thermal stability when integrated with a proper electrical circuit, Dicke switches with better than 30 dB isolation, phase modulators, and low loss isolators along with fully integrated state-of-art receiver systems operating at room and cryogenic temperatures.

NEW: Wideband Antenna Technologies for GPRs

- Conformal / planar.
- 0.1 - 3 GHz bandwidth.
- Separate tx/rx with high isolation (> 30 dB).

S1.03 Sensor and Detector Technology for Visible, IR, Far IR and Submillimeter

Lead Center: JPL

Participating Center(s): ARC, GSFC, LaRC

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 - (<http://www.nap.edu/catalog/11820.html> [6]).
- Planetary science - (<http://www.nap.edu/catalog/10432.html> [7]).
- Astronomy and astrophysics - (<http://www.nap.edu/books/0309070317/html/> [8]).

Development of un-cooled or cooled infrared detectors (hybridized or designed to be hybridized to an appropriate

read-out integrated circuit) with $NEP < 20 \text{ mK}$, $QE > 30\%$ and dark currents $< 1.5 \times 10^{-6} \text{ A/cm}^2$ in the 5-14 μm infrared wavelength region. Array formats may be variable, 640 x 512 typical, with a goal to meet or exceed 2k X 2k pixel arrays. Evolve new technologies such as InAs/GaSb type-II strained layer super-lattices to meet these specifications.

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, nanowire or heterodyne detector technologies made using high temperature superconducting films (YBCO, MgB₂) or engineered semiconductor materials, especially 2-Dimensional Electron Gas (2-DEG) and Quantum Wells (QW) that operate at temperatures achieved by standard 1 or 2 stage flight qualified cryocoolers and do not require cooling to liquid helium temperatures. Candidate missions are thermal imaging, LANDSAT Thermal InfraRed Sensor (TIRS), Climate Absolute Radiance and Refractivity Observatory (CLARREO), BOREal Ecosystem Atmosphere Study (BOREAS), Methane Trace Gas Sounder or other infrared earth observing missions.

1k x 1k or larger format MCT detector arrays with cutoff wavelength extended to 12 microns for use in missions to NEOs, comets and the outer planets.

Compact, low power, readout electronics for Kinetic Inductance Detector arrays with $> 8 \text{ bit}$ ADC at $> 500 \text{ MHz}$ sampling rate that channelizes into 1000 readout tones each with $> 5 \text{ kHz}$ of bandwidth. This type of readout would be used for photometers and spectrometers for astrophysics focal planes, and earth or planetary remote sensing instruments.

Development of new or improved large-format focal plane array Readout Integrated Circuit (ROIC) architectures to provide advanced detection features for overcoming existing limitations for low background astronomical applications. The main limitations of existing source-follower unit cells include potential image persistence and interpixel capacitance induced crosstalk. These limitations have complicated the use of these ROICs in a number of past missions, and will likely be even more constraining as detector performance improves. An improvement of a factor of 2 or more over current state-of-the-art would be of interest. Ideally, this would be done without compromising any good characteristics, but even in the case of a modest degradation in some parameters (like noise), the new features may prove to be superior for some applications.

Development of a robust wafer-level 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 arrays. Initially the technology can be demonstrated at the '1-inch' die level but should be do-able at the 4-inch wafer level.

New or improved, lightweight spectrometer operating over the spectral range 350 – 2300 nm with 4 nm spectral sampling and that is capable of making irradiance measurements of both the sun and the moon.

S1.04 Detector Technologies for UV, X-Ray, Gamma-Ray and Cosmic-Ray Instruments

Lead Center: GSFC

Participating Center(s): JPL, MSFC

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, 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, Vision Missions, and Earth Science Decadal Survey missions. Details of these can be found at the following URLs:

- General Information on Future NASA Missions - (<http://www.nasa.gov/missions> [9]).
- Specific mission pages:

- Future planetary programs - (http://nasascience.nasa.gov/planetary-science/mission_list [10]).
- Earth Science Decadal missions - (<http://www.nap.edu/catalog/11820.html> [6]).
- Helio Probes - (http://nasascience.nasa.gov/heliophysics/mission_list [11]).
- X-ray Astrophysics - (http://sites.nationalacademies.org/bpa/BPA_049810 [2]).

Specific technology areas are:

- Significant improvement in wide band gap semiconductor materials, such as AlGa_N, ZnMgO and SiC, individual detectors, and detector arrays for operation at room temperature or higher for missions such as Geo-CAPE, NWO, ATALAST and planetary science composition measurements.
- Highly integrated, low noise (< 300 electrons rms with interconnects), low power (< 100 uW/channel) mixed signal ASIC readout electronics as well as charge amplifier ASIC readouts with tunable capacitive inputs to match detector pixel capacitance. See needs of National Research Council's Earth Science Decadal Survey (NRC, 2007): Future Missions include GEOCAPE, HyspIRI, GACM, future GOES and SOHO programs and planetary science composition measurements.
- Visible-blind SiC Avalanche Photodiodes (APDs) for EUV photon counting are required. The APDs must show a linear mode gain >10E6 at a breakdown reverse voltage between 80 and 100V. The APD's must demonstrate detection capability of better than 6 photons/pixel/s down to 135nm wavelength. See needs of National Research Council's Earth Science Decadal Survey (NRC, 2007): Tropospheric ozone.
- Large area (3 m²) photon counting near-UV detectors with 3 mm pixels and able to count at 10 MHz. Array with high active area fraction (>85%), 0.5 megapixels and readout less than 1 mW/channel. Future instruments are focal planes for JEM-EUSO and OWL ultra-high energy cosmic ray instruments and ground Cherenkov telescope arrays such as CTA, and ring-imaging Cherenkov detectors for cosmic ray instruments such as BESS-ISO. As an example (JEM-EUSO and OWL), imaging from low-Earth orbit of air fluorescence, UV light generated by giant air showers by ultra-high energy (E >10E19 eV) cosmic rays require the development of high sensitivity and efficiency detection of 300-400 nm UV photons to measure signals at the few photon (single photo-electron) level. A secondary goal minimizes the sensitivity to photons with a wavelength greater than 400 nm. High electronic gain (10E4 to 10E6), low noise, fast time response (<10 ns), minimal dead time (<5% dead time at 10 ns response time), high segmentation with low dead area (<20% nominal, <5% goal), and the ability to tailor pixel size to match that dictated by the imaging optics. Optical designs under consideration dictate a pixel size ranging from approximately 2 x 2 mm² to 10 x 10 mm². Focal plane mass must be minimized (2g/cm² goal). Individual pixel readout is required. The entire focal plane detector can be formed from smaller, individual sub-arrays.

S1.05 Particles and Field Sensors and Instrument Enabling Technologies

Lead Center: GSFC

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

Advanced sensors for the detection of elementary particles (atoms, molecules and their ions) and electric and magnetic fields in space and associated instrument technologies are often critical for enabling transformational science from the study of the sun's outer corona, to the solar wind, to the trapped radiation in Earth's and other planetary magnetic fields, and to the atmospheric composition of the planets and their moons. Improvements in particles and fields sensors and associated instrument technologies enable further scientific advancement for upcoming NASA missions such as CubeSats, Explorers, STP, and planetary exploration missions. Technology developments that result in a reduction in size, mass, power, and cost will enable these missions to proceed. Of interest are advanced magnetometers, electric field booms, ion/atom/molecule detectors, and associated support electronics and materials. Specific areas of interest include:

- High efficiency conversion surfaces for the conversion of Energetic Neutral Atoms (ENAs) to ions for increasing the sensitivity of low energy ENA instruments.
 - Science Traceability: Decadal survey missions: IMAP, MEDICI, DRIVE Initiative, EXPLORERS DISCOVERY, CubeSats / Smallsats, Sounding Rockets.
 - Need Horizon: 1 to 3 years, 3 to 5 years.
 - State of the Art: The efficiency of present SOA conversion surfaces is 1-2%. This is quite low and results to low sensitivities. An efficiency increase to 10% will lead to increased sensitivity by a factor

- of x 5 to 10 and /or smaller instruments sizes / resources.
- Importance: Very High – Critical need for next generation low energy ENA instruments.
- Very low energy threshold < 5eV particle detectors for direct neutral particle detection.
 - Science Traceability: Explorer missions, Decadal survey missions IMAP, MEDICI, DYNAMICS, DRIVE Initiative, DISCOVERY and CubeSat/Smallsat missions.
 - Need Horizon: 1 to 3 years.
 - State of the Art: SOA solid state detectors have an energy threshold for particle detection of ~1keV. Although this problem can be overcome in charged particle detection with pre acceleration, it poses a severe limitation in direct neutral particle. New detectors with low energy threshold will enable a whole new class of instruments and improve existing instruments.
 - Importance: Very High – Critical need for next generation direct neutral instruments.
- UV filters that greatly attenuate UV Ly radiation but let particles freely pass through. Enabling technology for direct particle detection.
 - Science Traceability: Decadal survey missions: IMAP, MEDICI, DRIVE Initiative, EXPLORERS DISCOVERY, CubeSats / Smallsats, Sounding Rockets.
 - Need Horizon: 1 to 3 years, 3 to 5 years.
 - State of the Art: Particle detectors are very sensitive to UV light. The commonly used technology for direct particle detection is very thin foil that attenuate UV light but at the same time pose an energy threshold / scatter particles. A possible micro porous type of detector that greatly attenuates UV but let particles pass through will greatly improve current instruments.
 - Importance: Very High – Critical need for next generation particle instruments.
- Strong, compactly stowed magnetically clean magnetic field booms possibly using composite materials that deploy mag sensors (including internal harness) to distances up to 10 meters, for Cubesats;
 - Science Traceability: Explorer missions, DRIVE Initiative, CubeSat/Smallsat missions.
 - Need Horizon: 1 to 3 years.
 - State of the Art: Such a boom up to 10 meters long will high quality electric field measurements from small platforms.
 - Importance: Very High for future Cubesat and SmallSat stand alone and constellation missions.
- Strong, lightweight, thin, rigid, compactly stowed electric field booms possibly using composite materials that deploy sensors (including internal harness) to distances of 10 m or more
 - Explorer missions, DRIVE Initiative, CubeSat/Smallsat missions.
 - Need Horizon: 1 to 3 years, 3 to 5 years.
 - Particle detectors are very sensitive to UV light. The commonly used technology for direct particle detection is very thin foil that attenuate UV light but at the same time pose an energy threshold / scatter particles. A possible micro porous type of detector that greatly attenuates UV but let particles pass through will greatly improve current instruments.
 - Importance: Very High for future Cubesat and SmallSat stand alone and constellation missions.

S1.06 In Situ Sensors and Sensor Systems for Lunar and Planetary Science

Lead Center: JPL

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

This subtopic solicits development of advanced instrument technologies and components suitable for deployment on 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. In addition, technologies that can increase instrument resolution and sensitivity or achieve new & innovative scientific measurements are solicited. For example missions, see (<http://science.hq.nasa.gov/missions> [12]). For details of the specific requirements see the National Research Councils, Vision and Voyages for Planetary Science in the Decade 2013-2022 (<http://solarsystem.nasa.gov/2013decadal/> [13]). Technologies that support NASA's New Frontiers and Discovery missions to various planetary bodies are of top priority.

In-situ technologies are being sought to achieve much higher resolution and sensitivity with significant improvements over existing technologies. Orbital sensors and technologies that can provide significant improvements over previous orbital missions are also sought. Specifically, this subtopic solicits instrument development that provides significant advances in the following areas, broken out by planetary body:

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- *Mars* - Sub-systems relevant to current in-situ instrument needs (e.g., lasers and other light sources from UV to microwave, X-ray and ion sources, detectors, mixers, mass analyzers, etc.) or electronics technologies (e.g., FPGA and ASIC implementations, advanced array readouts, miniature high voltage power supplies). Technologies that support high precision in-situ measurements of elemental, mineralogical, and organic composition of planetary materials are sought. Conceptually simple, low risk technologies for in-situ sample extraction and/or manipulation including fluid and gas storage, pumping, and chemical labeling to support analytical instrumentation. Seismometers, mass analyzers, technologies for heat flow probes, and atmospheric trace gas detectors. Improved robustness and g-force survivability for instrument components, especially for geophysical network sensors, seismometers, and advanced detectors (iCCDs, PMT arrays, etc.). Instruments geared towards rock/sample interrogation prior to sample return are desired.
 - *Europa & Io* - 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) for candidate instruments on proposed missions such as Europa Clipper and Io Volcano.
 - *Titan* - Low mass and power sensors, mechanisms and concepts for converting terrestrial instruments such as turbidimeters and echo sounders for lake measurements, weather stations, surface (lake and solid) properties packages, etc. to cryogenic environments (95K). Mechanical and electrical components and subsystems that work in cryogenic (95K) environments; sample extraction from liquid methane/ethane, sampling from organic 'dunes' at 95K 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, air sampling mechanisms for mass analyzers, and aerosol detectors are also solicited.
 - *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 are particularly desired.
 - *Small Bodies* - Technologies that can enable sampling from asteroids and from depth in a comet nucleus, improved in-situ analysis of comets. Also, imagers and spectrometers that provide high performance in low light environments dust environment measurements & 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.). Specifically, advancements geared towards instruments that enable elemental or mineralogy analysis (such as high-sensitivity X-ray and UV-fluorescence spectrometers, UV/fluorescence flash lamp/camera systems, scanning electron microscopy with chemical analysis capability, time-of-flight mass spectrometry, gas chromatography and tunable diode laser sensors, calorimetry, laser-Raman spectroscopy, imaging spectroscopy, and LIBS) are sought. These developments should be geared towards sample interrogation, prior to possible sample return.
 - *Saturn, Uranus and Neptune* - Technologies are sought for components, sample acquisition and instrument systems that can enhance mission science return and withstand the low-temperatures/high-pressures of the atmospheric probes during entry.
 - *The Moon* - This solicitation seeks advancements in the areas of compact, light-weight, low power instruments geared towards in-situ lunar surface measurements, geophysical measurements, lunar atmosphere and dust environment measurements & regolith particle analysis, lunar resource identification, and/or quantification of potential lunar resources (e.g., oxygen, nitrogen, and other volatiles, fuels, metals, etc.). Specifically, advancements geared towards instruments that enable elemental or mineralogy analysis (such as high-sensitivity X-ray and UV-fluorescence spectrometers, UV/fluorescence flash lamp/camera systems, scanning electron microscopy with chemical analysis capability, time-of-flight mass spectrometry, gas chromatography and tunable diode laser sensors, calorimetry, laser-Raman spectroscopy, imaging spectroscopy, and LIBS) are sought. These developments should be geared towards sample interrogation, prior to possible sample return. Systems and subsystems for seismometers and heat flow sensors capable of long-term continuous operation over multiple lunar day/night cycles with improved sensitivity at lower mass and reduced power consumption are sought. Also of interest are portable surface ground penetrating radars to characterize the thickness of the lunar regolith, as well as, low mass, thermally stable hollow cubes and retro-reflector array assemblies for lunar surface laser ranging. Of secondary importance are instruments that measure the micrometeoroid and lunar secondary ejecta environment, plasma environment, surface electric field, secondary radiation at the lunar surface, and dust concentrations and its diurnal dynamics are sought. Further, lunar regolith particle analysis techniques are desired (e.g., optical

interrogation or software development that would automate integration of suites of multiple back scatter electron images acquired at different operating conditions, as well as permit integration of other data such as cathodoluminescence and energy-dispersive x-ray analysis.)

Proposers are strongly encouraged to relate their proposed development to:

- NASA's future planetary exploration goals.
- 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.

S1.07 Airborne Measurement Systems

Lead Center: GSFC

Participating Center(s): ARC, GRC, JPL, KSC, LaRC, MSFC, SSC

Measurement system miniaturization and/or increased performance is needed to support for NASA's airborne science missions, particularly those utilizing the Global Hawk, SIERRA-class, Dragon Eye or other unmanned aircraft. The subject airborne instruments are intended as calibration/validation systems for space-based measurements, or to provide local measurements not available from space-based instruments. Linkages to other subtopics such as S3.04 Unmanned Aircraft and Sounding Rocket Technologies are encouraged. Complete instrument systems are desired, including features such as remote/unattended operation and data acquisition, low power consumption, and minimum size and weight. Desired sensors include:

- High accuracy and precision atmospheric measurements of Nitrous Oxide, Ammonia, Sulfur Dioxide, Dimethyl Sulfide, Carbonyl Sulfide and Formaldehyde, with significant improvements over the current state-of-the-art, such as measurement speed, resolution, or system weight/volume.
- Preconcentration instruments for the measurement of the isotopic composition of atmospherically relevant trace gases (CO₂, CH₄, O₃, Ozone depleting substances and isotopomer, etc.) in are using optical, mass-spectrometric, and other types of detection. Proposals are invited for the development of versatile preconcentration instrumentation that initially can be used with a range of measurement instrumentation as well as for field and laboratory applications.
- Spectrally resolved absorption and extinction of atmospheric aerosols (0.1 to 10 micron).
- Multiphase Precipitation (0.1 mm to 20 mm with 5 % accuracy in three dimensions).
- Size distribution, phase, and asymmetry of atmospheric aerosols and cloud particles (0.1 micron to 200 micron with 10% accuracy).
- Three-dimensional wind measurement (1 mps accuracy/resolution at 10 Hz sampling).

S1.08 Surface & Sub-surface Measurement Systems

Lead Center: ARC

Participating Center(s): GSFC, JPL, LaRC, MSFC, SSC

Surface & Sub-surface Measurement Systems are sought with relevance to future space missions such as Active Sensing of CO₂ Emissions over Nights, Days, and Seasons (ASCENDS), Orbiting Carbon Observatory – 2 (OCO-2), Global Precipitation Measurement (GPM), Geostationary Coastal and Air Pollution Events (GEO-CAPE), Hyperspectral InfraRed Imager (HyspIRI), Aerosol, Cloud, and Ecosystems (ACE, including Pre-ACE/PACE). Early adoption for alternative uses by NASA, other agencies, or industry is desirable and recognized as a viable path towards full maturity. Sensor system innovations with significant near-term commercial potential that may be suitable for NASA's research after full development are of interest:

- Precipitation (e.g., motion stabilized disdrometer for shipboard deployments).
- Aquatic suspended particle concentrations and spectra of mineral and biogenic (phytoplankton and detritus) components.
- Miniaturized, stable, pH sensors for ocean applications to support validation of OCO-2 that can be used in the ARGO network.
- Miniaturized gas sensors or small instruments for carbon dioxide, methane, etc., only where the sensing technology solution will clearly exceed current state of the art for its targeted application.
- Miniaturized air-dropped sensors, for ocean surface and subsurface measurements such as conductivity, temperature, and depth.
- Multi-wavelength, LIDAR-based, atmospheric ozone and aerosol profilers for continuous, simultaneous observations from multiple locations. Examples include three-band ozone measurement systems operating in the UV spectrum (e.g., 280-316 nm, possibly tunable), or visible/infrared systems with depolarization sensitivity for aerosols and clouds.
- Portable, robust, ground based LIDAR system for 3D scanning of winds, temperature, density, and humidity with ability to scan horizontally and vertically with a range of up to 10 km
- Miniaturized, novel instrumentation for measuring inherent and apparent optical properties (specifically to support vicarious calibration and validation of ocean color satellites, i.e., reflectance, absorption, scattering), in-situ biogeochemical measurements of marine and aquatic components and rates including but not limited to nutrients, phytoplankton and their functional groups, and floating and submerged aquatic plants.
- Novel geophysical and diagnostic instruments suitable for ecosystem monitoring. Fielding for NASA's Applications and Earth Science Research activities is a primary goal.

S1.09 Cryogenic Systems for Sensors and Detectors

Lead Center: GSFC

Participating Center(s): ARC, JPL, MSFC

Cryogenic cooling systems often serve as enabling technologies for detectors and sensors flown on scientific instruments as well as advanced telescopes and observatories. As such, technological improvements to cryogenic systems further advance the mission goals of NASA through enabling performance (and ultimately science gathering) capabilities of flight detectors and sensors. There are four potential investment areas that NASA is seeking to expand state of the art capabilities for possible use on future programs such as WFirst (<http://wfirst.gsfc.nasa.gov/> [14]), the Europa Jupiter System Science missions (<http://www.nasa.gov/multimedia/podcasting/jpl-europa20090218.html> [15]) and PIXIE (Primordial Inflation Explorer). The topic areas are as follows:

Cryocooler Systems and Components

- *Miniaturized/Efficient Cryocooler Systems* - Cryocooler systems viable for application on SmallSat space platforms are sought. Present state of the art capabilities demonstrate approximately 0.4W of cooling capacity at 77K provided an input power of 5W. Contemporary system mass is on the order of 400 grams. Desired performance specifications for cryocoolers sought include a cooling capability on the order of 0.2W at temperatures spanning 30K - 80K. Desired masses and input powers will be < 400 grams and < 5W respectively. Component level improvements are also desirable.
- *Low Temperature/Input Power Cooling Systems* - Low temperature/Input Power Cooling systems are sought for application on future Planetary missions that require performance in space environments that have limited access to power. Contemporary cooling systems are incapable of providing cooling loads as high as 0.2W at 30K while rejecting heat to an ambient environment of approximately 150K. Cooling systems providing cooling capacities of approximately 0.3W at 35K with heat rejection capability to temperature sinks at 150 K or lower are of interest. Component level improvements are also desirable.
- *High Capacity/Efficiency Cryocooler Systems* - High Capacity/Efficiency cryocoolers are of interest for use on future science missions. State of the art high capacity cryocooler systems have demonstrated cooling capabilities spanning 0.3W - 1W with a load temperature of 20K and < 0.3 W at 10K. High Capacity cryocoolers are available at low to mid TRL levels for both Pulse Tube (e.g., 5W cooling capacity at 20K)

and Turbo Brayton (e.g., cooling capacity of 20W at 20K) configurations. Desired cryocooler systems will provide cold tip operational temperatures spanning 10K to 20K with a cooling capacity of > 4W at 20K or more than 0.3 W at 10 K. Very low vibration systems with these capabilities are desirable. Component level improvements that increase overall efficiency are also desirable.

Sub-Kelvin Cooling Systems

- *Magnetic Cooling Systems* - State of the art sub-Kelvin temperature control architectures that use magnetic cooling consist of ADR (Adiabatic Demagnetization Refrigeration) systems. The Astro-H FM (Flight Model) ADR represents the state of the art in ADR system and component level technologies for space application. Future missions requiring cooling to sub-Kelvin levels will look to use new and improved ADR systems. AMRR (Active Magnetic Regenerative Refrigeration) systems are a related magnetic cooling technology that requires system and component level development in order to attain sub-Kelvin cooling levels. Improvements at the component level may lead to better overall system performance and increased hold times at target temperatures. Both of these are highly advantageous and desirable to future science missions. Specific components sought include:
 - Low current superconducting magnets (3-4 Tesla at temperatures > 15K).
 - Heat Switches (including optimization of current designs, such as low thermal conductivity heat switch shells)
 - High cooling power density magnetocaloric materials, especially single crystals with volume > 20 cm³.
 - Active/Passive magnetic shielding (for use with 3-4 Tesla magnets).
 - Superconducting leads (10K - 90K) capable of 10 A operation with 1 mW conduction.
 - 10 mK- 300 mK high resolution thermometry.

Proposals considered viable for Phase I award will seek to validate hypotheses through proof of concept testing at relevant temperatures.

Advanced Telescope Systems Topic S2

The NASA Science Missions Directorate seeks technology for cost-effective high-performance advanced space telescopes for astrophysics and Earth science. Astrophysics applications require large aperture light-weight highly reflecting mirrors, deployable large structures and innovative metrology, control of unwanted radiation for high-contrast optics, precision formation flying for synthetic aperture telescopes, and cryogenic optics to enable far infrared telescopes. A few of the new astrophysics telescopes and their subsystems will require operation at cryogenic temperatures as cold as 4-degrees Kelvin. This topic will consider technologies necessary to enable future telescopes and observatories collecting electromagnetic bands, ranging from UV to millimeter waves, and also include gravity waves. The subtopics will consider all technologies associated with the collection and combination of observable signals. Earth science requires modest apertures in the 2 to 4 meter size category that are cost effective. New technologies in innovative mirror materials, such as silicon, silicon carbide and nanolaminates, innovative structures, including nanotechnology, and wavefront sensing and control are needed to build telescopes for Earth science.

Sub Topics:

S2.01 Proximity Glare Suppression for Astronomical Coronagraphy

Lead Center: JPL

Participating Center(s): ARC, GSFC

This subtopic addresses the unique problem of imaging and spectroscopic characterization of faint astrophysical objects that are located within the obscuring glare of much brighter stellar sources. Examples include planetary systems beyond our own, the detailed inner structure of galaxies with very bright nuclei, binary star formation, and stellar evolution. Contrast ratios of one million to ten billion over an angular spatial scale of 0.05-1.5 arcsec are typical of these objects. Achieving a very low background requires control of both scattered and diffracted light. The failure to control either amplitude or phase fluctuations in the optical train severely reduces the effectiveness of starlight cancellation schemes.

This innovative research focuses on advances in coronagraphic instruments, starlight cancellation instruments, and potential occulting technologies that operate at visible and near infrared wavelengths. The ultimate application of these instruments is to operate in space as part of a future observatory mission. 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

- Image plane hybrid metal/dielectric, and polarization apodization masks in linear and circular patterns.
- Transmissive holographic masks for diffraction control and PSF apodization.
- Sharp-edged, low-scatter pupil plane masks.
- Low-scatter, low-reflectivity, sharp, flexible edges for control of scatter in starshades.
- Systems to measure spatial optical density, phase inhomogeneity, scattering, spectral dispersion, thermal variations, and to otherwise estimate the accuracy of high-dynamic range apodizing masks.
- Pupil remapping technologies to achieve beam apodization.
- Techniques to characterize highly aspheric optics.
- Methods to distinguish the coherent and incoherent scatter in a broad band speckle field.
- Coherent fiber bundles consisting of up to 10,000 fibers with lenslets on both input and output side, such that both spatial and temporal coherence is maintained across the fiber bundle for possible wavefront/amplitude control through the fiber bundle.

Wavefront Measurement and Control Technologies

- Small stroke, high precision, deformable mirrors and associated driving electronics scalable to 10,000 or more actuators (both to further the state-of-the-art towards flight-like hardware and to explore novel concepts). Multiple deformable mirror technologies in various phases of development and processes are encouraged to ultimately improve the state-of-the-art in deformable mirror technology. Process improvements are needed to improve repeatability, yield, and performance precision of current devices.
- Instruments to perform broad-band sensing of wavefronts and distinguish amplitude and phase in the wavefront.
- Integrated mirror/actuator programmable deformable mirror.
- Multiplexers with ultra-low power dissipation for electrical connection to deformable mirrors.
- Low-order wavefront sensors for measuring wavefront instabilities to enable real-time control and post-processing of aberrations.
- Thermally and mechanically insensitive optical benches and systems.
- Optical Coating and Measurement Technologies:
- Instruments capable of measuring polarization cross-talk and birefringence to parts per million.
- Highly reflecting, uniform, broadband coatings for large (> 1 m diameter) optics.
- Polarization-insensitive coatings for large optics.
- Methods to measure the spectral reflectivity and polarization uniformity across large optics.
- Methods to apply carbon nanotube coatings on the surfaces of the coronagraphs for broadband suppression from visible to NIR.

Other

- Methods to fabricate diffractive patterns on large optics to generate astrometric reference frames.
- Artificial star and planet point sources, with $1e10$ dynamic range and uniform illumination of an $f/25$ optical system, working in the visible and near infrared.
- Deformable, calibrated, collimating source to simulate the telescope front end of a coronagraphic system undergoing thermal deformations.
- Technologies for high contrast integral field spectroscopy, in particular for microlens arrays with or without

accompanying mask arrays, working in the visible and NIR (0.4 - 1.8 microns), with lenslet separations in the 0.1 - 0.4 mm range, in formats of ~140x140 lenslets.

S2.02 Precision Deployable Optical Structures and Metrology

Lead Center: JPL

Participating Center(s): GSFC, LaRC

Planned future NASA Missions in astrophysics, such as the Wide-Field Infrared Survey Telescope (WFIRST) and the New Worlds Technology Development Program (coronagraph, external occulter and interferometer technologies) will push the state of the art in current optomechanical technologies. Mission concepts for New Worlds science would require 10 - 30 m class, cost-effective telescope observatories that are diffraction limited at wavelengths from the visible to the far IR, and operate at temperatures from 4 - 300 K. In addition, ground based telescopes such as the Cerro Chajnantor Atacama Telescope (CCAT) requires similar technology development.

The desired areal density is 1 - 10 kg/m² with a packaging efficiency of 3-10 deployed/stowed diameter. Static and dynamic wavefront error tolerances to thermal and dynamic perturbations may be achieved through passive means (e.g., via a high stiffness system, passive thermal control, jitter isolation or damping) or through active opto-mechanical control. Large deployable multi-layer structures in support of sunshades for passive thermal control and 20m to 50m class planet finding external occulters are also relevant technologies. Potential architecture implementations must package into an existing launch volume, deploy and be self-aligning to the micron level. The target space environment is expected to be the Earth-Sun L2.

This subtopic solicits proposals to develop enabling, cost effective component and subsystem technology for deploying large aperture telescopes with low cost. Research areas of interest include:

- Precision deployable structures and metrology for optical telescopes (e.g., innovative active or passive deployable primary or secondary support structures).
- Architectures, packaging and deployment designs for large sunshields and external occulters.
- In particular, important subsystem considerations may include:
- Innovative concepts for packaging fully integrated subsystems (e.g., power distribution, sensing, and control components).
- Mechanical, inflatable, or other precision deployable technologies.
- Thermally-stable materials (CTE < 1ppm) for deployable structures.
- Innovative systems, which minimize complexity, mass, power and cost.
- Innovative testing and verification methodologies.

The goal for this effort is to mature technologies that can be used to fabricate 16 m class or greater, lightweight, ambient or cryogenic flight-qualified observatory systems. 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. Proposals with system solutions for large sunshields and external occulters will also be accepted. A successful proposal shows a path toward a Phase II delivery of demonstration hardware scalable to 5 meter diameter for ground test characterization.

Before embarking on the design and fabrication of complex space-based deployable telescopes, additional risk reduction in operating an actively controlled telescope in orbit is desired. To be cost effective, deployable apertures that conform to a cubesat (up to 3-U) or ESPA format are desired. Consequently, deployment hinge and latching concepts, buildable for these missions and scaleable to larger systems are desired. Such a system should allow <25 micron deployment repeatability and sub-micron stability for both thermal and mechanical on-orbit disturbances. A successful proposal would deliver a full-scale cubesat or ESPA ring compatible deployable aperture with mock optical elements.

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).

S2.03 Advanced Optical Systems and Fabrication/Testing/Control Technologies for EUV/Optical and IR Telescope

Lead Center: MSFC

Participating Center(s): GSFC, JPL

This subtopic solicits solutions in the following areas:

- Components and Systems for potential EUV, UV/O or Far-IR mission telescopes.
- Technology to fabricate, test and control potential UUV, UV/O or Far-IR telescopes.

Please note: an emphasis regarding mirror systems is the mirror substrate support structure. The Technical Challenges contains information on specific technologies which need developing for each area.

Proposals must show an understanding of one or more relevant science needs, and present a feasible plan to develop the proposed technology for infusion into a NASA program: sub-orbital rocket or balloon; competed SMEX or MIDEX; or, Decadal class mission.

This subtopic matures technologies needed to affordably manufacture, test or operate complete mirror systems or telescope assemblies. Traditionally, this subtopic matured technology from TRL3 to TRL4. Now, there is an additional opportunity to propose in Phase II for an effort larger than a traditional Phase II for the purpose of maturing demonstrated component level technologies (TRL4) to demonstrated system level technologies (TRL6) by using them to manufacture complete telescope systems. A requirement of this option is that there must be an identified NASA program that will fly the developed new technology system.

An ideal Phase I deliverable would be a precision optical system of at least 0.25 meters; or a relevant sub-component of a system; or a prototype demonstration of a fabrication, test or control technology leading to a successful Phase II delivery; or a reviewed preliminary design and manufacturing plan which 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 analysis will be done to show compliance with all requirements. Past experience or technology demonstrations which support the design and manufacturing plans will be given appropriate weight in the evaluation.

An ideal Phase II project would further advance the technology to produce a flight-qualifiable optical system greater than 0.5 meters or relevant sub-component (with a TRL in the 4 to 5 range); or a working fabrication, test or control system. Phase 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 which can be integrated into the potential mission; and, demonstrate an understanding of how the engineering specifications of their system meets the performance requirements and operational constraints of the mission (including mechanical and thermal stability analysis).

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.

Introduction

The 2010 National Academy Astro2010 Decadal Report specifically identified large light-weight mirrors as a key technology needed to enable potential Extreme Ultraviolet (EUV), Ultraviolet/Optical (UV/O) and Infrared (IR) to Far-IR missions.

The 2012 National Academy report "NASA Space Technology Roadmaps and Priorities" states that one of the top technical challenges in which NASA should invest over the next five years is developing a new generation of larger effective aperture, lower-cost astronomical telescopes that enable the discovery of habitable planets, facilitate advances in solar physics, and enable the study of faint structures around bright objects.

Finally, NASA is developing a heavy lift space launch system (SLS) with an 8 to 10 meter fairing and 40 to 50 mt capacity to SE-L2. SLS will enable extremely large space telescopes, such as 12 to 30 meter class segmented primary mirrors for UV/optical or infrared wavelengths.

Technical Challenges

To accomplish NASA's high-priority science requires low-cost, ultra-stable, large-aperture, normal incidence mirrors with low mass-to-collecting area ratios. Specifically needed for a potential UVO mission are normal incidence 4-meter (or larger) diameter mirrors with 5 nm RMS surface figure error; and, active or passive alignment and control of normal-incidence imaging systems to achieve diffraction limited performance at wavelengths less than 500 nm (< 40 nm RMS wavefront error, WFE). Additionally, potential Exoplanet mission, using an internal coronagraph, requires total telescope wavefront stability on order of 10 pico-meters RMS per 10 minutes. This stability specification places severe constraints on the dynamic mechanical and thermal performance of 4 meter and larger telescope. To meet this performance requirement requires ultra-stable mirror support structures. Finally, specifically needed for potential IR/Far-IR missions are normal incidence 8-meter (or larger) diameter mirrors with cryo-deformations < 100 nm rms.

In all cases, the most important metric for an advanced optical system (after performance) 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 a cost reduction for precision optical components by 5 to 50 times, to between \$100K/m² to \$1M/m².

Development is required to fabricate components and systems to achieve the following Metrics:

- Areal Cost $< \$500\text{K}/\text{m}^2$ (for UV/Optical).
- Areal Cost $< \$100\text{K}/\text{m}^2$ (for Infrared).
- Monolithic - 1 to 8 meters.
- Segmented > 4 meters (total aperture).
- Wavefront Figure < 5 nm RMS (for UV/Optical).
- Cryo-deformation < 100 nm RMS (for Infrared).
- Slope < 0.1 micro-radian (for EUV).
- Wavefront Stability < 10 pm/10 min (for Coronagraphy).
- Actuator Resolution < 1 nm rms (UV/Optical).

Finally, also needed is ability to fully characterize surface errors and predict optical performance.

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

This subtopic solicits proposals in the following areas:

- Components, Systems, and Technologies of potential X-Ray missions.
- Coating technologies for X-Ray, EUV, Visible, and IR telescopes.
- Free-form Optics surfaces design, fabrication, and metrology.

This subtopic focuses on three areas of technology development:

- X-Ray manufacturing, coating, testing, and assembling complete mirror systems in addition to maturing the current technology.
- Coating technology for wide range of wavelengths from X-Ray to IR (X-Ray, EUV, Visible, and IR).
- Free-form Optics design, fabrication, and metrology for CubeSat, SmallSat and Visible Nulling Coronagraph (VNC).

A typical Phase I proposal for X-Ray technology would address the relevant optical sub-component of a system with necessary coating and stray light suppression for X-Ray missions or prototype demonstration of a fabricated system and its testing. Similarly, a Coating technology proposal would address fabrication and testing of optical surfaces for a wide range of wavelengths from X-Ray to IR. The Free-form Optics proposals tackle the challenges involved in design, fabrication, and metrology of non-spherical surfaces for small-size missions such as CubeSat, NanoSat, and visible nulling coronagraph.

In a nutshell, a successful proposal demonstrates a low-cost ability to address NASA's science mission needs and technical challenges specified under each category of Technical Challenges.

Introduction

The National Academy Astro2010 Decadal Report identifies studies of optical components and ability to manufacture, coat, and perform metrology needed to enable future X-Ray observatory missions such as Next Generation of X-Ray Observatories (NGXO).

The Astrophysics Decadal specifically calls for optical coating technology investment for future UV, Optical, Exoplanet, and IR missions while Heliophysics 2009 Roadmap identifies the coating technology for space missions to enhance rejection of undesirable spectral lines, improve space/solar-flux durability of EUV optical coatings, and 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 non-spherical surfaces with anticipated benefits of freeform optics such as fast wide-field and distortion-free cameras.

Technical Challenges

X-Ray Optical Component, Systems, and Technologies

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

In this area, we are looking to address the multiple technologies including: improvements to manufacturing (machining, rapid optical fabrication, slumping or replication technologies), improved metrology, performance prediction and testing techniques, active control of mirror shapes, new structures for holding and actively aligning of mirrors in a telescope assembly to enable X-Ray observatories while lowering the cost per square meter of collecting aperture and effective design of stray-light suppression in preparation for the Decadal Survey of 2020. Currently, X-Ray space mirrors cost \$4 million to \$6 million per square meter of optical surface area. This research effort seeks a cost reduction for precision optical components by 5 to 50 times, to less than \$1M to \$100 K/m².

Coating Technologies for X-Ray, EUV, Visible, and IR Telescopes

The optical coating technology is a mission-enabling feature that determines 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 current coating technology of optical components needs to achieve TRL-6 by approximately 2018 to support the 2020 Astrophysics Decadal process. A number of optical coating metrics specific each wavelength are desired as:

The Optical Coating Metrics

- X-Ray Metrics:
 - Multilayer high-reflectance coatings for hard X-Ray mirrors similar to NuSTAR.
 - Multilayer depth gradient coatings for 5 to 80 KeV with high broadband reflectivity.
 - Zero-net-stress coating for iridium or other high-reflectance elements on thin substrates (< 0.5 mm).
- EUV Metrics:

- Reflectivity > 90% from 6 nm to 200 nm and depositable onto a < 2 meter mirror substrate.
- UVOIR Metrics:
- Broadband reflectivity > 60% and uniform polarization from 90 nm to 2500 nm and depositable onto 2, 4, and 6 meter mirror substrates.
- Non-Stationary Metric:
 - Non- uniform optical coating to be used in both reflection and transmission that vary with location and optical surface. Variation pertains to ratio of reflectivity to transmissivity, optical field amplitude, phase, and polarization change. The optical surface area ranges from 1/2 to 6 cm.

Scattered Light Suppression Using Carbon Nanotube (CNT) Coating

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

- Broadband (visible plus Near IR), reflectivity of 0.1% or less
- Resist bleaching of significant albedo changes over a mission life of ~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 CE and ~ 0.1 GW/cm² density, and 1 kW/nanosecond pulses
- Adhere to the multi-layer dielectric or protected metal coating including Ion Beam Sputtering (IBS) coating

Freeform Optics Design, Fabrication, and Metrology

Future NASA missions with alternative low-cost science and small-size payload are constrained by the traditional spherical form of optics. These missions could benefit greatly by the freeform optics as they provide non-spherical optics with better aerodynamic characteristics for spacecraft with lightweight components to meet the mission requirements. Currently, the design and utilization of conformal and freeform shapes are costly due to fabrication and metrology of these parts. 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. For the coronagraphic applications, freeform optical components allow coronagraphic nulling without shearing and increase the useful science field of view. In this category, freeform optical prescription for surfaces of 0.5 cm to 6 cm diameters with tolerances of 1 to 2 nm rms are needed. In this respect, the freeform refers to either 2nd order conic prescription with higher order surface polished onto it or without underlying conic prescription with no steps in the surface. The optics with underlying conic prescription would need to be in F/# range of F/2 to F/20. In addition to the freeform fabrication, the metrology of freeform optical components is difficult and challenging due to the large departure from planar or spherical shapes accommodated by conventional interferometric testing. New methods such as multibeam low-coherence optical probe and slope sensitive optical probe are highly desirable.

Ultra-Stable X-Ray grazing-incident Telescopes for Sub-Orbital Balloons and Rocket-borne Missions

Technology maturation to build complete low-cost, lightweight X-ray telescopes with grazing-incident optics that can be flown on potential long duration high-altitude balloon-borne or rocket-borne missions. The focus here is to 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.

Spacecraft and Platform Subsystems Topic S3

The Science Mission Directorate will carry out the scientific exploration of our Earth, the planets, moons, comets, and asteroids of our solar system and the universe beyond. SMD's future direction will be moving away from exploratory missions (orbiters and flybys) into more detailed/specific exploration missions that are at or near the surface (landers, rovers, and sample returns) or at more optimal observation points in space. These future destinations will require new vantage points, or would need to integrate or distribute capabilities across multiple assets. Future destinations will also be more challenging to get to, have more extreme environmental conditions

and challenges once the spacecraft gets there, and may be a challenge to get a spacecraft or data back from.

A major objective of the NASA science spacecraft and platform subsystems development efforts are to enable science measurement capabilities using smaller and lower cost spacecraft to meet multiple mission requirements thus making the best use of our limited resources. To accomplish this objective, NASA is seeking innovations to significantly improve spacecraft and platform subsystem capabilities while reducing the mass and cost that would in turn enable increased scientific return for future NASA missions.

A spacecraft bus is made up of many subsystems like: propulsion; thermal control; power and power distribution; attitude control; telemetry command and control; transmitters/antenna; computers/on-board processing/software; and structural elements. Science platforms of interest could include unmanned aerial vehicles, sounding rockets, or balloons that carry scientific instruments/payloads, to planetary ascent vehicles or Earth return vehicles that bring samples back to Earth for analysis. This topic area addresses the future needs in many of these sub-system areas, as well as their application to specific spacecraft and platform needs.

Innovations for 2016 are sought in the areas of:

- Command and Data Handling, and Instrument Electronics
- Power Generation and Conversion
- Propulsion Systems for Robotic Science Missions
- Power Electronics and Management, and Energy Storage
- Unmanned Aircraft and Sounding Rocket Technologies
- Thermal Control Systems
- Guidance, Navigation and Control
- Terrestrial and Planetary Balloons

For planetary missions, planetary protection requirements vary by planetary destination, and additional backward contamination requirements apply to hardware with the potential to return to Earth (e.g., as part of a sample return mission). Technologies intended for use at/around Mars, Europa (Jupiter), and Enceladus (Saturn) must be developed so as to ensure compliance with relevant planetary protection requirements. Constraints could include surface cleaning with alcohol or water, and/or sterilization treatments such as dry heat (approved specification in NPR 8020.12; exposure of hours at 115° C or higher, non-functioning); penetrating radiation (requirements not yet established); or vapor-phase hydrogen peroxide (specification pending). The following references discuss some of NASA's science mission and technology needs:

- The Astrophysics Roadmap - (<http://nasascience.nasa.gov/about-us/science-strategy> [16]).
- Astrophysics Decadal Survey - "New Worlds, New Horizons: in Astronomy and Astrophysics" (http://www.nap.edu/catalog.php?record_id=12951 [17]).
- The Earth Science Decadal Survey - (http://books.nap.edu/catalog.php?record_id=11820 [18]).
- The Heliophysics roadmap - "The Solar and Space Physics of a New Era: Recommended Roadmap for Science and Technology 2009 - 2030" (http://sec.gsfc.nasa.gov/2009_Roadmap.pdf [19]).
- The 2011 Planetary Science Decadal Survey was released March 2011. This decadal survey is considering technology needs - (<http://www.nap.edu/catalog/13117/vision-and-voyages-for-planetary-science-in-the-decade-2013-2022> [20]).

Sub Topics:

S3.01 Power Generation and Conversion

Lead Center: GRC

Participating Center(s): ARC, JPL, JSC

Future NASA science missions will employ Earth orbiting spacecraft, planetary spacecraft, balloons, aircraft, surface assets, and marine craft as observation platforms. Proposals are solicited to develop advanced power-generation and conversion technologies to enable or enhance the capabilities of future science missions. Requirements for these missions are varied and include long life, high reliability, significantly lower mass and volume, higher mass specific power, and improved efficiency over the state of practice for components and

systems. Other desired capabilities are high radiation tolerance and the ability to operate in extreme environments (high and low temperatures and over wide temperature ranges).

While power-generation technology affects a wide range of NASA missions and operational environments, technologies that provide substantial benefits for key mission applications/capabilities are being sought in the following areas:

Photovoltaic Energy Conversion

Photovoltaic cell, blanket, and array technologies that lead to significant improvements in overall solar array performance (i.e., conversion efficiency >33%, array mass specific power >300watts/kilogram, decreased stowed volume, reduced initial and recurring cost, long-term operation in high radiation environments, high power arrays, and a wide range of space environmental operating conditions) are solicited. Photovoltaic technologies that provide enhancing and/or enabling capabilities for a wide range of aerospace mission applications will be considered. Technologies that address specific NASA Science mission needs include:

- Photovoltaic cell and blanket technologies capable of low intensity, low-temperature operation applicable to outer planetary (low solar intensity) missions.
- Photovoltaic cell, blanket and array technologies capable of enhancing solar array operation in a high intensity, high-temperature environment (i.e., inner planetary and solar probe-type missions).
- Solar arrays to support Extreme Environments Solar Power type missions, including long-lived, radiation tolerant, cell and blanket technologies capable of operating in environments characterized by varying degrees of light intensity and temperature.
- Lightweight solar array technologies applicable to science missions using solar electric propulsion. Current science missions being studied require solar arrays that provide 1 to 20 kilowatts of power at 1 AU, greater than 300 watts/kilogram specific power, operation in the range of 0.7 to 3 AU, low stowed volume, and the ability to provide operational array voltages up to 300 volts.

Stirling Power Conversion: advances in, but not limited to, the following

- Novel Stirling convertor configurations that provide high efficiency (>25%), low mass, long life (>10 yrs), and high reliability for use in 100-500 We Stirling radioisotope generators.
- Advanced Stirling convertor components including hot-end heat exchangers, cold-end heat exchangers, regenerators, linear alternators, engine controllers, and radiators.
- Innovative Stirling generator features that improve the fault tolerance (e.g., heat source backup cooling devices, mechanical balancers) or expand the mission applications (e.g., duplex power and cooling systems).

Direct Energy Conversion; advances in, but not limited to, the following

Recent advancements in alpha/beta-voltaic energy conversion devices have the potential to increase the power level, improve reliability, and increase the lifetime of this power technology. The increased use of cubesat/smallsat technology and autonomous remote sensors in support of NASA Science Mission goals has demonstrated the need for low-power, non-solar energy sources. The area of Direct Energy Conversion seeks technology advancements that address, but are not limited to:

- Experimental demonstration of long life (multiyear) alpha-voltaic and beta-voltaic devices with device-level conversion efficiencies in excess of 10%, high reliability, minimal operational performance degradation, and the ability to scale up to 1-10 W of electrical power output with system-level specific power of 5 W/kg or higher.

S3.02 Propulsion Systems for Robotic Science Missions

Lead Center: GRC

Participating Center(s): JPL, MSFC

The Science Mission Directorate (SMD) needs spacecraft with more demanding propulsive performance and flexibility for more ambitious missions requiring high duty cycles, more challenging environmental conditions, and extended operation. Planetary spacecraft need the ability to rendezvous with, orbit, and conduct in-situ exploration of planets, moons, and other small bodies in the solar system

(http://solarsystem.nasa.gov/multimedia/download-detail.cfm?DL_ID=742 [21]). Future spacecraft and constellations of spacecraft will have high-precision propulsion requirements, usually in volume- and power-limited envelopes.

This subtopic seeks innovations to meet SMD propulsion in chemical and electric propulsion systems related to sample return missions to Mars, small bodies (like asteroids, comets, and Near-Earth Objects), outer planet moons, and Venus. Additional electric propulsion technology innovations are also sought to enable low cost systems for Discovery class missions, and low-power, nuclear electric propulsion (NEP) missions. Roadmaps for propulsion technologies can be found from the National Research Council

(http://www.nap.edu/openbook.php?record_id=13354&page=168 [22]) and NASA's Office of the Chief Technologist (http://www.nasa.gov/pdf/501329main_TA02-InSpaceProp-DRAFT-Nov2010-A.pdf [23]).

Proposals should show an understanding of the state of the art, how their technology is superior, and of one or more relevant science needs. The proposals should provide a feasible plan to fully develop a technology and infuse it into a NASA program.

Advanced Electric Propulsion Components

This subtopic also seeks proposals that explore uses of technologies that will provide superior performance in for high specific impulse/low mass electric propulsion systems at low cost. These technologies include:

- High thrust-to-power ion thruster component or system technologies. Key characteristics include:
 - Power < 14 kW.
 - T/P > SOA Hall Effect Thrusters at comparable specific impulse ranging from 1500-3000 seconds.
 - Lifetimes > 10,000 hours.
 - Thruster components including, but not limited to, advanced cathodes, rf devices, advanced grids, lower-cost components.
 - Any long-life, electric propulsion technology between 1 to 10 kW/thruster that would enable a low-power nuclear electric propulsion system based on a kilowatt nuclear reactor.
 - Instrumentation and support equipment that will enable or improve ground testing of electric propulsion power processor units.

Secondary Payload Propulsion

The secondary payload market shows significant promise to enable low cost science missions. Launch vehicle providers, like SLS, are considering a large number of secondary payload opportunities. The majority of small satellite missions flown are often selected for concept or component demonstration activities as the primary objectives. Opportunities are anticipated to select future small satellite missions based on application goals (i.e., science return). However, several technology limitations prevent high value science from low-cost small spacecraft, such as post deployment propulsion capabilities. Additionally, propulsion systems often place constraints on handling, storage, operations, etc. that may limit secondary payload consideration. It is desired to have a wide range of Delta-V capability to provide 100-1000s of m/s.

Specifically, proposals are sought for:

- Chemical and/or electric propulsion systems with green/non-toxic propellants,
- RF devices,
- Improved operational life over SOA propulsion systems, and
- 1U sized solar electric ionized gas propulsion unit with delta V of 1-8 km/s for 6U CubeSat, and a clear plan for demonstrated constellation station keeping capability for 6 months in LEO.

In addressing technology requirements, proposers should identify potential mission applications and quantify the expected advancement over state-of-the-art alternatives.

Note to Proposer - Topics under the Human Exploration and Operations Directorate also addresses advanced propulsion. Proposals more aligned with exploration mission requirements should be proposed in H2.

S3.03 Power Electronics and Management, and Energy Storage

Lead Center: GRC

Participating Center(s): ARC, GSFC, JPL, JSC

NASA's science

vision (http://science.nasa.gov/media/medialibrary/2014/05/02/2014_Science_Plan-0501_tagged.pdf [24]) is to use the vantage point of space to achieve with the science community and our partners a deep scientific understanding of the Sun and its effects on the solar system, our home planet, other planets and solar system bodies, the interplanetary environment, and the universe beyond. Scientific priorities for future planetary science missions are guided by the recommendations of the decadal surveys published by the National Academies. The goal of the decadal surveys is to articulate the priorities of the scientific community, and the surveys are therefore the starting point for NASA's strategic planning process in science (http://science.nasa.gov/media/medialibrary/2014/04/18/FY2014_NASA_StrategicPlan_508c.pdf [25]). The most recent planetary science decadal survey, Vision and Voyages for Planetary Science in the Decade 2013 - 2022, was released in 2011. This report recommended a balanced suite of missions to enable a steady stream of new discoveries and capabilities to address challenges such as sample return missions and outer planet exploration. Under this subtopic, proposals are solicited to develop energy storage and power electronics to enable or enhance the capabilities of future NASA science missions. The unique requirements for the power systems for these missions can vary greatly, with advancements in components needed above the current State of the Art (SOA) for high energy density, high power density, long life, high reliability, low mass/volume, radiation tolerance, and wide temperature operation. Other subtopics which could potentially benefit from these technology developments include S4.04 Extreme Environments Technology, and S4.01 Planetary Entry, Descent and Landing Technology. This subtopic is also directly tied to S3.02 Propulsion Systems for Robotic Science Missions for the development of advanced Power Processing Units and associated components.

Power Electronics and Management

NASA's Planetary Science Division is working to implement a balanced portfolio within the available budget and based on the decadal survey that will continue to make exciting scientific discoveries about our solar system. This balanced suite of missions show the need for low mass/volume power electronics and management systems and components that can operate in extreme environment for future NASA Science Missions. In addition, studying the Sun, the heliosphere, and other planetary environments as an interconnected system is critical for understanding the implications for Earth and humanity as we venture forth through the solar system. To that end, the NASA heliophysics program seeks to perform innovative space research missions to understand:

- The Sun and its variable activity.
- How solar activity impacts Earth and the solar system.
- Fundamental physical processes that are important at Earth and throughout the universe by using space as a laboratory.

Heliophysics also seeks to enable research based on these missions and other sources to understand the connections among the Sun, Earth, and the solar system for science and to assure human safety and security both on Earth and as we explore beyond it. Advances in electrical power technologies are required for the electrical components and systems of these future spacecrafts/platforms to address program size, mass, efficiency, capacity, durability, and reliability requirements. Radioisotope power systems (RPS), Advanced Modular Power Systems (AMPS) and In-Space Electric Propulsion (ISP) are several programs of interest which would directly benefit from advancements in this technology area. These types of programs, including Mars Sample Return using Hall thrusters and power processing units (PPUs), require advancements in radiation hardened power electronics, especially tolerant of single event upsets, and systems beyond the state-of-the-art. Of importance are expected improvements in energy density, speed, efficiency, or wide-temperature operation (-125° C to over 450° C) with a

number of thermal cycles. Novel approaches to minimizing the weight of advanced PPU's are also of interest. Advancements are sought for power electronic devices, components, packaging and cabling for programs with power ranges of a few watts for minimum missions to up to 20 kilowatts for large missions. In addition to electrical component development, RPS has a need for intelligent, fault-tolerant Power Management and Distribution (PMAD) technologies to efficiently manage the system power for these deep space missions.

Also, in order to maximize functional capability for Earth Observations, operate higher performance instruments and deliver significantly better data and imagery from a small spacecraft, more capable power systems are needed. NASA is interested in a power system (stretch goal of 100w) that can be integrated into a cubesat or nanosat for this purpose. The power system package must be restricted to 6U or 3U volume, and the design should minimize orientation restrictions. The system should be capable of operating for a minimum of 6 months in LEO.

SMD's In-space Propulsion Technology, Radioisotope Power Systems and Cubesat/Nanosat programs are direct customers of this subtopic.

Overall technologies of interest include:

- High power density/high efficiency power electronics and associated drivers for switching elements.
- Non-traditional approaches to switching devices, such as addition of graphene and carbon nano-tubes to material
- Radiation hardened (single event effects), 1200 V (or greater) MOSFETs and high speed diodes for high voltage space missions (300 V average, 600 V peak).
- Lightweight, highly conductive power cables and/or cables integrated with vehicle structures.
- Intelligent power management and fault-tolerant electrical components and PMAD systems.
- Advanced electronic packaging for thermal control and electromagnetic shielding
- Integrated packaging technology for modularity.
- Cubesat/nanosat power systems up to 100 watts

Patent 6,461,944, Methods for growth of relatively large step-free SiC crystal surfaces Neudeck, et al., October 8, 2002.

A method for growing arrays of large-area device-size films of step-free (i.e., atomically flat) SiC surfaces for semiconductor electronic device applications is disclosed. This method utilizes a lateral growth process that better overcomes the effect of extended defects in the seed crystal substrate that limited the obtainable step-free area achievable by prior art processes. The step-free SiC surface is particularly suited for the heteroepitaxial growth of 3C (cubic) SiC, AlN, and GaN films used for the fabrication of both surface-sensitive devices (i.e., surface channel field effect transistors such as HEMT's and MOSFET's) as well as high-electric field devices (pn diodes and other solid-state power switching devices) that are sensitive to extended crystal defects.

Energy Storage

Future science missions will require advanced primary and secondary battery systems capable of operating at temperature extremes from -100° C for Titan missions to 400 to 500° C for Venus missions, and a span of -230° C to +120° C for Lunar Quest. The Outer Planet Assessment Group and the 2011 PSD Relevant Technologies Document have specifically called out high energy density storage systems as a need for the Titan/Enceladus Flagship and planetary exploration missions. In addition, high energy-density rechargeable electrochemical battery systems that offer greater than 50,000 charge/discharge cycles (10 year operating life) for low-earth-orbiting spacecraft, 20 year life for geosynchronous (GEO) spacecraft, are desired. Advancements to battery energy storage capabilities that address one or more of the above requirements for the stated missions combined with very high specific energy and energy density (>200 Wh/kg for secondary battery systems), along with radiation tolerance are of interest.

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

Research should be conducted to demonstrate technical feasibility during Phase I and show a path toward a Phase

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

S3.04 Unmanned Aircraft and Sounding Rocket Technologies

Lead Center: GSFC

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

Unmanned Aircraft Systems Technologies

Breakthrough technologies are sought that will enhance performance and utility of NASA's Airborne Science fleet with unmanned aircraft systems (UAS). Novel instrumented platforms or innovative subsystems suitable for addressing specific Earth science research goals are desired. Relevant NASA and FAA requirements must be addressed. Potential concepts include:

- Long endurance (~1 month) small UAS for miniature (~2 lb) instrument packages scalable to larger platforms.
- Fuel cell propulsion and high efficiency airframes for high altitude/long endurance (HALE, target ~50 kft, 2 days endurance with 50 lb payload).
- Harsh environment flight (e.g., for volcanic eruptions, fires) including high density altitude (20 kft asl), high turbulence, high temperature (300 to 500° C), significant icing, or corrosive environments.
- Novel flight management approaches such as dynamic soaring, autonomous mission planning, terrain following, or autonomously linking aircraft.
- Small UAS for in-situ cloud measurements.
- Guided dropsondes.
- Airspace monitoring system for small UAS operations.
- Over-the-horizon communications systems with increased bandwidth.

Sounding Rocket Technologies

The NASA Sounding Rockets Program provides low-cost, sub-orbital access to space in support of space and Earth sciences research. NASA utilizes a variety of vehicle systems comprised of surplus and commercially available rocket motors, capable of lofting scientific payloads of up to 1300lbs, to altitudes from 100km to 1500km. NASA launches sounding rocket vehicles worldwide, from both land-based and water-based ranges, based on the science needs to study phenomenon in specific locations. Of particular interest are systems that will enable water recovery of payloads from high altitude flights from locations such as launch ranges at Wallops Island VA or Andoya, Norway. New telemetry approaches are also encouraged. Specific elements may include:

- High speed decelerators.
- Steerable high altitude parachute systems.
- Water recovery aids such as floatation devices, location systems, and robotic capabilities.
- Ruggedized over-the-horizon telemetry systems with increased bandwidth.
- Constellation communication for sub-to-main payload data telemetry
- 10 to 50 MB/s for primary data, 1 to 2 MB/s for sub payloads, ~30 cubic inches (without antenna), with C or S band desired

S3.05 Guidance, Navigation and Control

Lead Center: GSFC

Participating Center(s): ARC, JPL

NASA seeks innovative, ground breaking, and high impact developments in spacecraft guidance, navigation, and control technologies in support of future science and exploration mission requirements. This subtopic covers the technologies enabling significant performance improvements over the state of the art in the areas of spacecraft attitude determination and control, spacecraft absolute and relative orbit and attitude navigation, pointing control, and SmallSat/CubeSat technologies.

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 all spacecraft platform sizes will be considered. Special considerations will be given to emerging technologies applicable to SmallSat/CubeSat class spacecraft if they are technology leaps and mission enabling.

Advances in the following areas are sought:

- *Spacecraft Attitude Determination and Control Systems* - Sensors and actuators that enable milli-arcsecond class pointing 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 GN&C techniques for enabling the collection of distributed science measurements.
- *Pointing Control Systems* - Mechanisms that enable milli-arcsecond class pointing performance on any spaceborne pointing platforms. Active and passive vibration isolation systems, innovative actuation feedback, or any such technologies that can be used to enable other areas within this subtopic apply.
- *SmallSat/CubeSat Technologies* - Lightweight, low power, compact sensors and actuators that push the state-of-the-art for SmallSat/CubeSat attitude and orbit controls capabilities. Arcsecond-level pointing performance, non-propulsive orbit control, and radiation hardening technologies apply. NASA would like to utilize SmallSat/CubeSat technologies on missions beyond LEO therefore special considerations would be given to proposals addressing those needs.

Phase I research should be conducted to demonstrate technical feasibility as well as show a plan towards Phase II integration and component/prototype testing in a relevant environment. Phase II technology development efforts shall deliver component/prototype at the TRL 5-6 level consistent with NASA SBIR/STTR Technology Readiness Level (TRL) Descriptions. Delivery of final documentation, test plans, and test results are required. Delivery of a hardware component/prototype under the Phase II contract is preferred.

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

S3.06 Terrestrial and Planetary Balloons

Lead Center: GSFC

Participating Center(s): JPL

Terrestrial Balloons

NASA's Scientific Balloons provide practical and cost effective platforms for conducting discovery science, development and testing for future space instruments, as well as training opportunities for future scientists and engineers. Balloons can reach altitudes above 36 kilometers, with suspended masses up to 3600 kilograms, and can stay afloat for several weeks. Currently, the Balloon Program is on the verge of introducing an advanced balloon system that will enable 100 day missions at mid-latitudes and thus resemble the performance of a small spacecraft at a fraction of the cost. In support of this development, NASA is seeking innovative technologies in three key areas:

Power Storage

Improved and innovative devices to store electrical energy onboard balloon payloads are needed. Long duration balloon flights can experience 12 hours or more of darkness, and excess electrical power generated during the day from solar panels needs to be stored and used. Improvements are needed over the current state of the art in power density, energy density, overall size, overall mass and/or cost. Typical parameters for balloon are 28 VDC and 100 to 1000 watts power consumption. Rechargeable batteries are presently used for balloon payload applications. Lithium Ion rechargeable batteries with energy densities of 60 watt-hours per kilogram are the current state of the art. Higher power storage energy densities, and power generation capabilities of up to 2000 watts are needed for future support.

Satellite Communications

Improved and innovative downlink bitrates using satellite relay communications from balloon payloads are needed. Long duration balloon flights currently utilize satellite communication systems to relay science and operations data from the balloon to ground based control centers. The current maximum downlink bit rate is 150 kilobits per second operating continuously during the balloon flight. Future requirements are for bit rates of 1 megabit per second or more. Improvements in bit rate performance, reduction in size and mass of existing systems, or reductions in cost of high bit rate systems are needed. TDRSS and Iridium satellite communications are currently used for balloon payload applications. A commercial S-band TDRSS transceiver and 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 under development, but the operational cost is prohibitive.

UV Protection Technologies

Innovative, economic, and applicable processes or materials to protect the balloon flight train subsystems and the balloon components are needed. Long duration balloon missions on the order of 100 days will expose the balloon flight train subsystems such as the parachute, and the balloon components such as the high strength tendons, to the harmful effects of UV exposure. The impact may lead to shorter duration missions and/or severe damage to the science payloads. Innovative concepts are needed for the protection of these subsystems or components to eliminate or minimize these adverse UV effects. The proposed innovative concepts shall be economic and practical. It shall be easy to implement with no major impact on balloon design, fabrication, packaging, or launch operations.

Planetary Balloons

Innovations in materials, structures, and systems concepts have enabled the lifetime of Titan and Venus buoyant vehicles to play an expanding role in NASA's future Solar System Exploration Program. Balloons are expected to carry scientific payloads at Titan and Venus that will perform in-situ investigations of their atmospheres and near surface environments. Both Titan and Venus feature extreme environments that significantly impact the design of balloons for those two worlds and efficient use of energy is critical.

Proposals are sought in the following areas:

Floating Platforms for Venus (New)

NASA is interested in conducting long term monitoring of the Venus atmosphere and the signatures of seismic and volcanic events from the planetary surface using floating vehicles at altitudes of between 30 and 45 km for periods in excess of five years. Concepts that use ammonia or water as a source of buoyancy as well as conventional light gases hydrogen and helium should be considered. A primary focus should be on the design of the flotation device and the materials for achieving long duration operation. The temperature at 45 km is roughly 110° C; at 30 km it is about 225° C. 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.

Altitude and Positional Control for Titan Aerial Vehicles (NEW)

NASA is interested in Titan aerial vehicles that can both change altitude and also execute controlled movements in

latitude and longitude in order to target surface locations of interest. Innovative concepts are sought that can minimize the use of scarce power resources and can achieve controlled motions in latitude under all anticipated atmosphere conditions and in longitude for parts of the Titan year. The targeted capabilities for the system are as follows: altitude range between the surface and 15 km, system mass of payload, power and communications systems of 100 kg; average power usage for horizontal and vertical mobility of less than 50 watts. It is expected that a Phase I effort will consist of a complete system-level design and a proof-of-concept experiment on one or more key components.

S3.07 Thermal Control Systems

Lead Center: GSFC

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

Future Spacecraft and instruments for NASA's Science Mission Directorate will require increasingly sophisticated thermal control technology. Innovative proposals for the cross-cutting thermal control discipline are sought in the following areas:

- Components of advanced small spacecraft such as CubeSat/SmallSat will have very small masses (i.e., small thermal capacitance), and their temperatures are highly sensitive to variations in the component power output and spacecraft environmental temperature. Advanced thermal devices capable of maintaining components within their specified temperature ranges are needed. Some examples are:
 - Phase change systems with high thermal capacity and minimal structural mass.
 - High performance, low cost insulation systems for diverse environments.
 - High flux heat acquisition and transport devices; d) thermal coatings with low absorptance, high emittance, and good electrical conductivity; and e) a miniature pumped fluid loop system that is lightweight, provides radiator turndown, and consumes minimal power (< 2W).
- Current capillary heat transfer devices require tedious processes to insert the porous wick into the evaporator and to seal the wick ends for liquid and vapor separation. Advanced technology such as additive manufacturing is needed to simplify the processes and ensure good sealing at both ends of the wick, especially for miniature thermal systems for CubeSat/SmallSat applications. Additive manufacturing technology can also be used to produce integrated heat exchangers for pumped fluid loops in order to increase heat transfer performance while significantly reducing mass, labor and cost.
- Science missions are more dependent on optically sensitive instruments and systems, and effects of thermal distortion on the performance of the system are critical. Current Structural-Thermal-Optical (STOP) analysis has several codes that do some form of integrated analysis, but none that have the capability to analyze any optical system and do a full end-to-end analysis. An improvement of existing code is needed in order to yield software that can integrate with all commonly used programs at NASA for mechanical, structural, thermal and optical analysis. The software should be user-friendly, and allow full STOP analysis for performance predictions based on mechanical design, and structural/thermal material properties.
- Missions with high sink temperatures require temperature lifting devices in order to dissipate the heat. Some advanced devices having long life, high efficiency are sought for, including absorption/adsorption systems, advanced TECs, etc. The use of heat lift devices can also reduce the radiator area, hence realizing mass and volume savings.
- Current analysis for ablation analysis of re-entry vehicles utilizes various computer codes for predicting the following individual phenomena: aeroheating, ablation, thermal response behind the bond line, thermal radiation, and structural response to thermal and pressure environments. The interfaces between each code lead to potential errors, inaccuracy, and huge computer run time. What is needed is a single code that evaluates the trajectory or input conditions, predicts aeroheating over the surface, does an integrated ablation-thermal analysis, and then uses that thermal and pressure gradient to do a full structural analysis. Even better would be a link back to the aeroheating prediction code to revise the aeroheating based on shape change from structural analysis and ablation.
- New techniques for measuring the internal pressure of arcjet test samples are sought. Modern ablation codes such as FEAR and CHAR solve the Darcy flow equations to track both the internal pyrolysis gas pressure and mass flow. However, there is currently no data available to validate the internal pressure calculations due to a lack of a reliable and accurate measurement system. The internal pressure calculation becomes even more important when analyzing flexible thermal protection system materials

which are highly porous.

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

S3.08 Slow and Fast Light

Lead Center: MSFC

Steep dispersions in engineered media of a wide variety have opened up a new direction of research in optics. A positive dispersion can be used to slow the propagation of optical pulses to extremely small velocities. Similarly, a negative dispersion can lead to conditions where pulses propagate superluminally. These effects have now moved beyond the stage of intellectual curiosity, and have ushered in studies of a set of exciting applications of interest to NASA, ranging from ultraprecise superluminal gyroscopes to spectral interferometers having enhanced resolving power.

This research subtopic seeks slow-light and/or fast-light enhanced sensors for space applications of interest to NASA including:

Superluminal gyroscopes and accelerometers (both passive and active)

- Enhanced strain and displacement sensors for non-destructive evaluation and integrated vehicle health management applications.
- Slow-light-enhanced spectrally-resolved interferometers for astrophysical and Earth science observations, as well as for exploration goals.
- Other applications of slow and fast light related to NASA's mission areas.

Superluminal gyroscopes

In conventional ring laser gyroscopes, sensitivity increases with cavity size. Fast light, however, can be used to increase gyro sensitivity without having to increase size, for spacecraft navigation systems which are constrained by weight and volume. The increased sensitivity also opens up new science possibilities such as detection of subsurface geological features, tests of Lorentz invariance, improving the bandwidth sensitivity product for gravity wave detection, and tests of general relativity. This research subtopic seeks:

- Prototype fast light gyroscopes, active or passive, that unambiguously demonstrate a scale factor enhancement of at least 10 with the potential for 1000. The minimum or quantum-noise limited angular random walk (ARW) should also decrease.
- Designs for fast light gyros that do not require frequency locking, are not limited to operation at specific frequencies such as atomic or material resonances, and permit operation at any wavelength.
- Fast light gyroscope designs that are rugged, compact, monolithic, rad-hard, and tolerant to variations in temperature and varying G-conditions.

Slow-light enhanced spectral interferometers

Slow light has the potential to increase the resolving power of spectral interferometers such as Fourier transform spectrometers (FTS) for astrophysical applications without increasing their size. Mariner, Voyager, and Cassini all used FTS instruments for applications such as mapping atmospheres and examining ring compositions. The niche for FTS is usually thought to be for large wavelength (IR and beyond), wide-field, moderate spectral resolution instruments. Slow light, however, could help boost FTS spectral resolution making FTS instruments more competitive with grating-based instruments, and opening up application areas not previously thought to be accessible to FTS instruments, such as exoplanet detection. A slow-light FTS could also be hyper-spectral,

providing imaging capability. FTS instruments have been employed for remote sensing on NASA Earth Science missions, such as the Atmospheric Trace Molecule Spectroscopy (ATMOS), Cross-track Infrared Sounder (CrIS), and Tropospheric Emission Spectrometer (TES) experiments, and have long been considered for geostationary imaging of atmospheric greenhouse gases. This research subtopic seeks research and development of slow-light-enhanced spectral interferometers that are not restricted by material resonances and can operate at any wavelength. An inherent advantage of FTS systems are their wide bandwidth. It will therefore of importance to develop slow light FTS systems that can maintain a large operating bandwidth.

S3.09 Command, Data Handling, and Electronics

Lead Center: GSFC

Participating Center(s): JPL, LaRC

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

The 2016 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 science 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. Proposals should clearly:
 - State what the product is.
 - Identify the needs it addresses.
 - Identify the improvements over the current state of the art.
 - Outline the feasibility of the technical and programmatic approach.
 - Present how it could be infused into a NASA program.

Furthermore, proposals developing hardware should indicate an understanding of the intended operating environment, including temperature and radiation. It should be noted that environmental requirements can vary significantly from mission to mission. For example, some low earth orbit missions have a total ionizing dose (TID) radiation requirement of less than 10 krad(Si), while some planetary missions can have requirements well in excess of 1 Mrad(Si). For descriptions of radiation effects in electronics, the proposer may visit (<http://radhome.gsfc.nasa.gov/radhome/overview.htm> [26]).

If a Phase II proposal is awarded, the combined Phase I and Phase II developments should produce a prototype that can be characterized by NASA.

The technology priorities sought are listed below:

- *Spaceflight Multicore Middleware* - Current and emerging spaceflight processors are leveraging multi-core architectures to satisfy the ever increasing onboard processing demands. These architectures can provide increased processing bandwidth, power efficiency, and fault tolerance for onboard processing applications. However, these advantages come at the cost of increased hardware and software complexity. As software development is a major cost driver for missions, this increased complexity has the potential to significantly increase cost for future NASA missions. To address this risk, this subtopic solicits Spaceflight Multicore Middleware technology providing machine management for multicore processing devices. This middleware software layer shall primarily reside between the application layer and the operating system, with extensions into and below the OS as necessary, to provide intelligent resource, fault, and power management. By providing these functions, application software can be largely agnostic to underlying hardware, thereby reducing cost and complexity. It is desired that the middleware software support multiple processor architectures. Examples include, but not limited to, ARM, Freescale, Tiler, and LEON, and those that support a number of cores ranging from 2-32.

- *Advanced Spaceflight Memory* - As spaceflight processor technology advances to provide increased bandwidth, power efficiency, and flexibility, advanced spaceflight memory devices are needed to fully leverage these improvements. This subtopic solicits technologies enabling power efficient, high performance volatile spaceflight memory incorporating high speed, fault tolerant, serial interfaces, internal EDAC, power and fault management, and 2.5/3D manufacturing processes enabling implementation of miniaturized, highly-reliable fault tolerant systems.
- *Point-of-Load Power Converters* - Emerging spaceflight processors require multiple supply voltages, and multiple switched services for many of these voltages. Using currently available point-of-load power converters, an unacceptably large portion of future spaceflight computer boards will need to be dedicated for these devices. To address this concern, this subtopic solicits technologies enabling miniaturized spaceflight point-of-load power conversion and switching.
- *Radiation Shielding* - Innovative additive manufacturing and/or deposition technologies starting at TRL 3 are sought to create integral one-piece surface claddings of graded atomic number (Z) materials for use as radiation shielding for electronics. Shielding thicknesses must be able to achieve up to 3 g/cm² for initial shielding applications. At the end of Phase I, delivery of layered slabs and/or half sphere samples is expected with areal densities from 1 -3 g/cm²; samples must be able to show a strong interface property to avoid delamination and consistent density and thickness (areal density) uniformity.

This subtopic also solicits technologies enabling the use of COTS micropower/ultra-low power computing devices in highly reliable spacecraft avionics systems.

Robotic Exploration Technologies Topic S4

NASA is pursuing technologies to enable robotic exploration of the Solar System including its planets, their moons, and small bodies. NASA has a development program that includes technologies for the atmospheric entry, descent, and landing, mobility systems, extreme environments technology, sample acquisition and preparation for in-situ experiments, and in-situ planetary science instruments. Robotic exploration missions that are planned include a Europa Jupiter System mission, Titan Saturn System mission, Venus In-Situ Explorer, sample return from Comet or Asteroid and lunar south polar basin and continued Mars exploration missions launching every 26 months including a network lander mission, an Astrobiology Field Laboratory, a Mars Sample Return mission and other rover missions. Numerous new technologies will be required to enable such ambitious missions. The solicitation for in-situ planetary instruments can be found in the in-situ instruments section of this solicitation. See URL: (<http://solarsystem.nasa.gov/missions/index.cfm> [27]) for mission information. See URL: (<http://mars.jpl.nasa.gov/programmissions/technology/> [28]) for additional information on Mars Exploration technologies.

Planetary protection requirements vary by planetary destination, and additional backward contamination requirements apply to hardware with the potential to return to Earth (e.g., as part of a sample return mission). Technologies intended for use at/around Mars, Europa (Jupiter), and Enceladus (Saturn) must be developed so as to ensure compliance with relevant planetary protection requirements. Constraints could include surface cleaning with alcohol or water, and/or sterilization treatments such as dry heat (approved specification in NPR 8020.12; exposure of hours at 115° C or higher, non-functioning); penetrating radiation (requirements not yet established); or vapor-phase hydrogen peroxide (specification pending).

Sub Topics:

S4.01 Planetary Entry, Descent and Landing and Small Body Proximity Operation Technology

Lead Center: JPL

Participating Center(s): ARC, JSC, LaRC

NASA seeks innovative sensor technologies to enhance success for entry, descent and landing (EDL) operations on missions to other planetary bodies, including Earth's Moon, Mars, Venus, Titan, Europa, and proximity operations (including sampling and landing) on small bodies such as asteroids and comets.

Sensing technologies are desired that determine any number of the following:

- Terrain relative translational state (altimetry/3-axis velocimetry).
- Spacecraft absolute state in planetary/small-body frame (either attitude, translation, or both).
- Terrain point cloud (for hazard detection, absolute state estimation, landing/sampling site selection, and/or

body shape characterization).

- Atmosphere-relative measurements (velocimetry, pressure, temperature, flow-relative orientation).

NASA also seeks to use measurements made during EDL to better characterize the atmosphere of planetary bodies, providing data for improving atmospheric modeling for future landers or ascent vehicles.

Successful candidate sensor technologies can address this call by:

- Extending the dynamic range over which such measurements are collected (e.g., providing a single surface topology sensor that works over a large altitude range such as 1m to >10km, and high altitude rates such as greater than 45° /sec).
- Improving the state-of-the-art in measurement accuracy/precision/resolution for the above sensor needs.
- Substantially reducing the amount of external processing needed by the host vehicle to calculate the measurements.
- Significantly reducing the impact of incorporating such sensors on the spacecraft in terms of Size, Weight, and Power (SWaP), spacecraft accommodation complexity, and/or cost.
- Providing sensors that are robust to environmental dust/sand/illumination effects.
- Mitigation technologies for dust/particle contamination of optical surfaces such as sensor optics, with possible extensibility to solar panels and thermal surfaces for Lunar, asteroid, and comet missions.

For all the aforementioned technologies, candidate solutions are sought that can be made compatible with the environmental conditions of deep spaceflight, the rigors of landing on planetary bodies both with and without atmospheres, and planetary protection requirements.

NASA is also looking for high-fidelity real-time simulation and stimulation of passive and active optical sensors for computer vision at update rates greater than 2 Hz to be used for signal injection in terrestrial spacecraft system test beds. These solutions are to be focused on improving system-level performance Verification and Validation during spacecraft assembly and test.

NASA also seeks low-mass (on the order of the density of the fabric itself), fabric-and/or-fiber-embedded sensors and time-synchronized, distributed data collection systems (preferably less than 30 grams total) to measure the time history of load/stress/strain distributed across large (30+ meters), trailing-body deployable decelerator technologies such as parachutes and ballutes. The distributed sensors and data collection systems must be self-powered and capable of being pressure-packed into a compressed mortar canister installation package and stored for up to 1 year or more. All sensors and data collection packages in the distributed system are to record time-stamped peak sensor values and time histories, with time-stamp accuracies not to exceed 4 milliseconds relative to a central vehicle data collection system using IRIG and GPS technology for time-stamping and synchronization. Packages must survive the parachute deployment and inflation events and if data is stored locally on the individual devices, survive recovery from the ocean after many hours of immersion in seawater.

Submitted proposals should show an understanding of the current state of the art of the proposed technology and present a feasible plan to improve and infuse it into a NASA flight mission.

S4.02 Robotic Mobility, Manipulation and Sampling

Lead Center: JPL

Participating Center(s): AFRC, ARC, GSFC, JSC

Technologies for robotic mobility, manipulation, and sampling are needed to enable access to sites of interest and acquisition and handling of samples for in-situ analysis or return to Earth from planetary and solar system small bodies including Mars, Venus, comets, asteroids, and planetary moons (both rocky and icy).

Mobility technologies are needed to enable access to steep and rough terrain for planetary bodies where gravity dominates, such as the Moon and Mars. 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 in micro-gravity environments and access to liquid bodies below the surface such as in conduits and deep oceans are desired, as well as associated sampling technologies. Manipulation technologies are needed to deploy sampling tools to the

surface and transfer samples to in-situ instruments and sample storage containers, as well as hermetic sealing of sample chambers. On-orbit manipulation of a Mars sample cache canister is needed from capture to transfer into an Earth Entry Vehicle. 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.

Contamination control and planetary protection are important considerations for sample acquisition and handling technologies. Contamination may include Earth-source contaminants produced by the sampling tool, handling system, or deposited on the sampling location from another source on the rover or spacecraft. Cleaning to Sterility technologies are needed that will be compatible with spacecraft materials and processes. Surface cleaning validation methods are needed that can be used routinely to quantify trace amounts ($\sim\text{ng}/\text{cm}^2$) of organic contamination and submicron particle ($\sim 100\text{nm}$ size) contamination. Priority will be given to cleaning and sterilization methods that have potential for in-situ applications.

Component technologies for low-mass and low-power systems tolerant to the in-situ environment are of particular interest. Technical feasibility should be demonstrated during Phase I and a full capability unit of at least TRL 4 should be delivered in Phase II. Proposals should show an understanding of relevant science needs and engineering constraints and present a feasible plan to fully develop a technology and infuse it into a NASA program. Specific areas of interest include the following:

- Surface and subsurface sampling systems for planets, small bodies, and moons.
- Small body anchoring systems.
- Low mass/power vision systems and processing capabilities that enable fast surface traverse.
- Electro-mechanical connectors enabling tool change-out in dirty environments.
- Tethers and tether play-out and retrieval systems.
- Miniaturized flight motor controllers.
- Cleaning to sterility technologies that will be compatible with spacecraft materials and processes.
- Surface cleaning validation technology to quantify trace amount ($\sim\text{ng}/\text{cm}^2$) of organic contamination and submicron particle ($\sim 100\text{nm}$ size) contamination.
- Sample handling technologies that minimize cross contamination and preserve mechanical integrity of samples.

S4.03 Spacecraft Technology for Sample Return Missions

Lead Center: JPL

Participating Center(s): GRC

NASA plans to perform sample return missions from a variety of scientifically important targets including Mars, small bodies such as asteroids and comets, and outer planet moons. These types of targets present a variety of spacecraft technology challenges.

Some targets, such as Mars and some moons, have relatively large gravity wells and will require ascent propulsion. Includes propellants that are transported along with the mission or propellants that can be generated using local resources.

Other targets are small bodies with very complex geography and very little gravity, which present difficult navigational and maneuvering challenges.

In addition, the spacecraft will be subject to extreme environmental conditions including low temperatures (-270°C), dust, and ice particles.

Technology innovations should either enhance vehicle capabilities (e.g., increase performance, decrease risk, and improve environmental operational margins) or ease sample return mission implementation (e.g., reduce size, mass, power, cost, increase reliability, or increase autonomy).

S4.04 Extreme Environments Technology

Lead Center: JPL

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

NASA is interested in expanding its ability to explore the deep atmosphere and surface of giant 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 planets. Proposals are sought for technologies that are suitable for remote sensing applications at cryogenic temperatures, and in-situ atmospheric and surface explorations in the high-temperature high-pressure environment at the Venusian surface (485 °C, 93 atmospheres), or in low-temperature environments such as Titan (-180 °C), Europa (-220 °C), Ganymede (-200 °C), Mars, the Moon, asteroids, comets and other small bodies. Also Europa-Jupiter missions may have a mission life of 10 years and the radiation environment is estimated at 2.9 Mega-rad total ionizing dose (TID) behind 0.1 inch thick aluminum. Proposals are sought for technologies that enable NASA's long duration missions to extreme wide-temperature and cosmic radiation environments. High reliability, ease of maintenance, low volume, low mass, and low out-gassing characteristics are highly desirable. Special interest lies in development of following technologies that are suitable for the environments discussed above:

- Wide temperature range precision mechanisms i.e., 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-arc-second/nanometer precision.
- Long life, long stroke, low power, and high torque/force actuators with sub-arc-second/nanometer precision.
- Long life Bearings/tribological surfaces/lubricants.
- High temperature energy storage systems.
- High-temperature actuators and gear boxes for robotic arms and other mechanisms.
- Low-power and wide-operating-temperature radiation-tolerant /radiation hardened RF electronics.
- Radiation-tolerant/radiation-hardened low-power/ultra-low-powerwide-operating-temperature low-noise mixed-signal electronics for space-borne system such as guidance and navigation avionics and instruments.
- Radiation-tolerant/radiation-hardened power electronics.
- Radiation-tolerant/ radiation-hardened electronic packaging (including, shielding, passives, connectors, wiring harness and materials used in advanced electronics assembly).

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

S4.05 Contamination Control and Planetary Protection

Lead Center: JPL

A need to develop technologies to implement Contamination Control and Planetary Protection requirements has emerged in recent years with increased interest in investigating bodies with the potential for life detection such as Europa, Enceladus, Mars, etc. and the potential for sample return from such bodies. Planetary Protection is concerned with both 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 Planetary Protection requirements as well as analytical technologies that can ensure hardware and instrumentation can meet organic contamination requirements in an effort to preserve sample science integrity.

For contamination control efforts, analytical technologies and techniques for quantifying submicron particle and organic contamination for validating surface cleaning methods are needed. In particular, capabilities for measuring Total Organic Carbon (TOC) at $\ll 40$ ppb or $\ll 20$ ng/cm² on a surface and detection of particles < 0.2 microns in size are being sought. In addition, techniques for detection of one or more of the following molecules and detection level are being needed:

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- DNA (1 fmole).
 - Dipicolinic acid (1 pg).
 - N-acetylglucosamine (1 pg).
 - Glycine and alanine (1 pg).
 - Palmitic acid (1 pg).
 - Squalene (1 pg).
 - Pristane (1pg).
 - Chlorobenzene (<1 pg).
 - Dichloromethane (<1 pg).
 - Naphthalene (1 pg).

For many missions, Planetary Protection requirements are often implemented in part by processing hardware or potentially entire spacecraft with one or more sterilization processes. These processes are often incompatible with particular materials or components on the spacecraft and extensive effort is made to try to mitigate these issues. Innovative new or improved sterilization/re-sterilization processes are being sought for application to spacecraft hardware to increase effectiveness of reducing bio-load on spacecraft or increase process compatibility with hardware (e.g., toxicity to hardware, temperature, duration, etc.). Accepted processes currently include heat processing, gamma/electron beam irradiation, cold plasma, and vapor hydrogen peroxide. Options to improve materials and parts (e.g., sensors, seals, in particular, batteries, valves, and optical coatings) to be compatible with currently accepted processes, in particular heat tolerance, are needed. NASA is seeking novel technologies for preventing recontamination of sterilized components or spacecraft as a whole (e.g., biobarriers). In addition, 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 sterilization approaches (e.g., UV or plasma) for surfaces are desired.

Missions planning sample return from bodies such as Mars, Europa, and Enceladus are faced with developing technologies for sample return functions to assure containment of material from these bodies. Thus far, concepts have been developed specifically for Mars sample return but no end-to-end concepts have been developed that do not have technical challenges remaining in one or more areas. Options for sample canisters with seal(s) (e.g., brazing, explosive welding, soft) with sealing performed either on surface or in orbit and capability to verify seal(s), potentially by leak detection are needed. In addition, capability is needed for opening seals while maintaining sample integrity upon Earth return. These technologies need to be compatible with processes the materials may encounter over the lifecycle of the mission (e.g., high temperature heating). Containment assurance also requires technologies to break-the-chain of contact with the sampled body. Any native contamination on the returned sample container and/or Earth return vehicle must be either be fully contained, sterilized, or removed prior to return to Earth, therefore, technologies or concepts to mitigate this contamination are desired. Lightweight shielding technologies are also needed for meteoroid protection for the Earth entry vehicle and sample canister with capability to detect damage or breach to meet a 10⁻⁶ probability of loss of containment.

Information Technologies Topic S5

NASA Missions and Programs create a wealth of science data and information that are essential to understanding our earth, our solar system and the universe. Advancements in information technology will allow many people within and beyond the Agency to more effectively analyze and apply these data and information to create knowledge. For example, modeling and simulation are being used more pervasively throughout NASA, for both engineering and science pursuits, than ever before. These tools allow high fidelity simulations of systems in environments that are difficult or impossible to create on Earth, allow removal of humans from experiments in dangerous situations, provide visualizations of datasets that are extremely large and complicated, and aid in the design of systems and missions. In many of these situations, assimilation of real data into a highly sophisticated physics model is needed. Information technology is also being used to allow better access to science data, more effective and robust tools for analyzing and manipulating data, and better methods for collaboration between scientists or other interested parties. The desired end result is to see that NASA data and science information are used to generate the maximum possible impact to the nation: to advance scientific knowledge and technological capabilities, to inspire and motivate the nation's students and teachers, and to engage and educate the public.

Sub Topics:

S5.01 Technologies for Large-Scale Numerical Simulation

Lead Center: ARC

Participating Center(s): GSFC

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 on 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 should engage in direct interactions with one or both HEC projects, and with key HEC users where appropriate. Research should be conducted to demonstrate technical feasibility and NASA relevance during Phase I and show a path toward a Phase II prototype demonstration.

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

- HEC systems operating behind a firewall to meet strict IT security requirements.
- Communication-intensive applications.
- Massive computations requiring high concurrency.
- Complex computational workflows and immense datasets.
- The need to support hundreds of complex application codes - many of which are frequently updated by the user/developer.

As a result, solutions that involve the following must clearly explain how they would work in the NASA environment:

- Technologies involving elements operating outside of the NASA supercomputing firewall.
- Embarrassingly parallel computations.
- Technologies that require significant application re-engineering.

Projects need not benefit all NASA HEC users or application codes, but demonstrating applicability to an important NASA discipline, or even a key NASA application code, could provide significant value.

Specific technology areas of interest:

- *Efficient Computing* - In spite of the rapidly increasing capability and efficiency of supercomputers, NASA's HEC facilities cannot purchase, power, and cool sufficient HEC resources to satisfy all user demands. This subtopic element seeks dramatically more efficient and effective supercomputing approaches in terms of their ability to supply increased HEC capability or capacity per dollar and/or per Watt for real NASA applications. Examples include: novel computational accelerators and architectures; cloud supercomputing with high performance interconnects (e.g., InfiniBand); enhanced visualization technologies; improved

algorithms for key codes; power-aware "Green" computing technologies and techniques; and approaches to effectively manage and utilize many-core processors including algorithmic changes, compiler techniques and runtime systems.

- *User Productivity Environments* - The user interface to a supercomputer is typically a command line in a text window. This subtopic element seeks more intuitive, intelligent, user-customizable, and integrated interfaces to supercomputing resources, enabling users to more completely leverage the power of HEC to increase their productivity. Such an interface could enhance many essential supercomputing tasks: accessing and managing resources, training, getting services, developing and porting codes (e.g., debugging and performance analysis), running computations, managing files and data, analyzing and visualizing results, transmitting data, collaborating, etc.
- *Ultra-Scale Computing* - Over the next decade, the HEC community faces great challenges in enabling its users to effectively exploit next-generation supercomputers featuring massive concurrency to the tune of millions of cores. To overcome these challenges, this subtopic element seeks ultra-scale computing technologies that enable resiliency/fault-tolerance in extreme-scale (unreliable) systems both at job startup and during execution. Also of interest are system and software co-design methodologies, to achieve performance and efficiency synergies. Finally, tools are sought that facilitate verification and validation of ultra-scale applications and systems.

S5.02 Earth Science Applied Research and Decision Support

Lead Center: SSC

Participating Center(s): ARC, GSFC, JPL

The NASA Applied Sciences Program (<http://nasascience.nasa.gov/earth-science/applied-sciences> [29]) seeks innovative and unique approaches to increase the utilization and extend the benefit of Earth Science research data to better meet societal needs. One area of interest is new decision support tools and systems for a variety of ecological applications such as managing coastal environments, natural resources or responding to natural disasters.

Currently, creating decision support tools (DST) that effectively utilize remote sensing data requires significant efforts by experts in multiple domains. This creates a barrier to the widespread use of Earth observations by state and local governments, businesses, and the public. This subtopic aims to democratize the creation of Earth science driven decision support tools and to unleash a creative explosion of DST development that significantly increases the return on investment for Earth science missions.

Specifically, this subtopic develops core capabilities that can be integrated to build multiple remote sensing driven DSTs customized to the requirements of different users in varied fields. Proven development and commercialization strategies will be used to meet these objectives. Similar to Eclipse, this subtopic will create an open-source DST development framework that enables components from multiple providers to be seamlessly integrated. This subtopic will also create software components that plug into the framework and open source tools that help users create new components. The components will provide functionality ranging from basic operations, such as retrieval of data meeting user-specified criteria from online repositories and visualization, to sophisticated data processing and analysis algorithms, such as atmospheric correction, data fusion, computational model interfaces, and machine learning based quality control.

To expedite DST development and deployment by knowledgeable users, this subtopic seeks an open source graphical workflow tool, similar to Labview or Simulink, which enables well informed users to quickly create a functional DST from a catalog of software components. Ultimately, a more sophisticated graphical workflow development tool, similar to MIT's Scratch would enforce functionally, but not necessarily logically, "correct by construction" rules that would enable a broad population of people to successfully create DSTs. Open source and commercial components, as well as services, will be available through an online "store" similar to iTunes or Google Play.

The framework, components and resulting DSTs should be able to run in a commercial cloud such as Amazon EC2 or Google Compute Engine. Cloud enabled components and DSTs, those that can intelligently take advantage of flexible computing resources for processing, analysis, visualization, optimization, etc. are highly desired.

Ideally, users should be able to create, configure deploy DSTs, and view outputs such as status, reports, alerts,

plots, maps, etc. via desktop computers (Windows 7 and OS X) as well as tablet and smart phones running recent versions of Android (4.0 and later) and iOS (5.0 and later). An HTML5 web application in a standards compliant browser, such as Chrome, can provide the required level of interoperability and capability. Due to serious security issues, Java and Flash based approaches will not be considered.

S5.03 Enabling NASA Science through Large-Scale Data Processing and Analysis

Lead Center: GSFC

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

The size of NASA's observational data sets is growing dramatically as new mission data become available. In addition, NASA scientists continue to generate new models that regularly produce data sets of hundreds of terabytes or more. It is growing increasingly difficult for NASA to effectively analyze such large data sets for use within their science projects.

The following lists show representative examples of both observational and model generated data sets that are relevant to NASA science projects. This list is not meant to be all-inclusive, but rather to provide examples of data sets and to show the extent of the "Big Data" problems encountered by NASA. Some remote observation examples are the following:

- The HypsIRI mission is expected to produce an average science data rate of 800 million bits per second (Mbps).
- JPSS-1 will be 300 Mbps and NPP is already producing 300 Mbps, compared to 150 Mbps for the EOS-Terra, Aqua and Aura missions.
- SDO with a rate of 150 Mbps and 16.4 Gigabits for a single image from the HiRise camera on the Mars Reconnaissance Orbiter (MRO).
- Landsat and MODIS data sets continue to grow at extremely high rates.
- National Geospatial Agency (NGA) high-resolution imagery data of the Earth.

From the NASA climate models, some examples include:

- The MERRA2 reanalysis data set is approximately 400 TB.
- Several high-resolution nudged and free running climate simulations have generated Petabytes of data (all publically releasable).

This subtopic area seeks innovative, unique, forward-looking, and replicable approaches for using "Big Data" for NASA science programs. The emphasis of this subtopic is on the creation of novel analytics, tools, and infrastructure to enable high performance analytics across large observational and model data sets. *Proposals should be in alignment with existing and/or future NASA science programs*, and the reuse of existing NASA assets is strongly encouraged.

Specifically, innovative proposals are being sought to assist NASA science in the following areas (note that this list is not inclusive and is included to provide guidance for the proposers):

- New services and methods for high performance analytics that scale to extremely large data sets – of specific interest are the following:
 - Techniques for data mining, searching, fusion, subsetting, discovery, and visualization
 - Automated derivation of analysis products in large data sets, that can then be utilized into Science models – the following are two representative examples
 - Extraction of features (e.g., volcanic thermal measurement, plume measurement, automated flood mapping, disturbance mapping, change detection, etc.).
 - Geospatial and temporal correlation of climate events (e.g., hurricanes, mesoscale convective systems, atmospheric rivers, etc.).
- Methods to enable in-situ, data proximal, parallel data analytics that will accelerate the access, analysis, and distribution of large Science datasets.

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- Potential use of open source data analytic tools (such as Hadoop, MapReduce, Spark, etc.) to accelerate analytics.
 - Application of these tools to structured, binary, scientific data sets.
 - Performing analytics across both physically collocated and geographically distributed data.
 - High performance file systems and abstractions, such as the use of object storage file systems.

Research proposed to this subtopic should demonstrate technical feasibility during Phase I, and in partnership with scientists, 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 software that is infused into NASA programs and projects.

Tools and products developed under this subtopic may be developed for broad public dissemination or used within a narrow scientific community. These tools can be plug-ins or enhancements to existing software, on-line data/computing services, or new stand-alone applications or web services, provided that they promote interoperability and use standard protocols, file formats, and Application Programming Interfaces (APIs).

S5.04 Integrated Science Mission Modeling

Lead Center: JPL

Participating Center(s): GSFC, JSC, KSC

NASA seeks innovative systems modeling methods and tools to:

- 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. The capabilities should also allow for easier integration of disparate model types and be compatible with current agile design processes.
- Enable disciplined system analysis for the design of future missions, including modeling of decision support for those missions and integrated models of technical and programmatic aspects of future missions. Such models might also be made useful to evaluate technology alternatives and impacts, science valuation methods, and programmatic and/or architectural trades.

Specific areas of interest are listed below. Proposers are encouraged to address more than one of these areas with an approach that emphasizes integration with others on the list:

- Conceptual phase modeling and tools that assist design teams to 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 that are able to easily compare architectural variants of systems.
- Capabilities to rapidly and collaboratively generate models of function or behavior of complex systems, at either the system or 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 design efforts at the conceptual and preliminary design phases, while being compatible with transition to later phases.
 - 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).
- Processes, tools, and infrastructure to support modeling-as-design paradigms enabled by emerging model-based engineering (MBE) capabilities. MBE approaches allow a paradigm shift whereby integrated modeling becomes the inherent and explicit act of design, rather than a post hoc effort to represent designs converged using traditional methods. Modeling-as-design processes will first instantiate changes and/or

refinements to models at all relevant levels, accompanied by frequent simulations that drive the integrated models to elicit performance of the system being designed.

- Target models (e.g., phenomenological or geophysical models) that represent planetary surfaces, interiors, atmospheres, etc. and associated tools and methods that allow them to be integrated into system design models and processes such that instrument responses can be simulated and used to influence design. These models may be algorithmic or numeric, but they should be useful to designers wishing to optimize systems' remote sensing of those planets.

S5.05 Fault Management Technologies

Lead Center: ARC

Participating Center(s): JPL, MSFC

As science missions are given increasingly complex goals and have more pressure to reduce operations costs, system autonomy increases. Fault Management (FM) is one of the key components of system autonomy. FM consists of the operational mitigations of spacecraft failures. It is implemented with spacecraft hardware, on-board autonomous software that controls hardware, software, information redundancy, and ground-based software and operations procedures.

Many recent Science Mission Directorate (SMD) missions have encountered major cost overruns and schedule slips during test and verification of FM functions. These overruns are due to a lack of understanding of FM functions early in the mission definition cycles and to FM architectures that do not provide attributes of transparency, verifiability, fault isolation capability, or fault coverage. The NASA FM Handbook is under development to improve the FM design, development, verification and validation and operations processes. FM approaches, architectures, and tools are needed to improve early understanding of needed FM capabilities by project managers and FM engineers and to improve the efficiency of implementing and testing FM.

Specific objectives are to:

- Improve the ability to predict FM system complexity and estimate development and operations costs.
- Enable cost-effective FM design architectures and operations.
- Determine completeness and appropriateness of FM designs and implementations.
- Decrease the labor and time required to develop and test FM models and algorithms.
- Improve visualization of the full FM design across hardware, software, and operations procedures.
- Determine extent of testing required, completeness of verification planned, and residual risk resulting from incomplete coverage.
- Increase data integrity between multi-discipline tools.
- Standardize metrics and calculations across FM, SE, S&MA and operations disciplines.
- Increase reliability of FM systems.

Expected outcomes are better estimation and control of FM complexity and development costs, improved FM designs, and accelerated advancement of FM tools and techniques.

The approach of this subtopic is to seek the right balance between sufficient reliability and cost appropriate to the mission type and risk posture. Successful technology development efforts under this subtopic would be considered for follow-on funding by, and infusion into, SMD missions. Research should be conducted to demonstrate technical feasibility and NASA relevance during Phase I and show a path toward a Phase II prototype demonstration.

Offerors should demonstrate awareness of the state-of-the-art of their proposed technology, and should leverage existing commercial capabilities and research efforts where appropriate.

Specific technology in the forms listed below is needed to increase delivery of high quality FM systems. These approaches, architectures and tools must be consistent with and enable the NASA FM Handbook concepts and processes:

- *FM Design Tools* - System modeling and analyses significantly contributes to the quality of FM design;

however, the time it takes to translate system design information into system models often decreases the value of the modeling and analysis results. Examples of enabling techniques and tools are modeling automation, spacecraft modeling libraries, expedited algorithm development, sensor placement analyses, and system model tool integration.

- *FM Visualization Tools* - FM systems incorporate hardware, software, and operations mechanisms. The ability to visualize the full FM system and the contribution of each mechanism to protecting mission functions and assets is critical to assessing the completeness and appropriateness of the FM design to the mission attributes (mission type, risk posture, operations concept, etc.). Fault trees and state transition diagrams are examples of visualization tools that could contribute to visualization of the full FM design.
- *FM Verification and Validation Tools* - As complexity of spacecraft and systems increases, the extensiveness of testing required to verify and validate FM implementations can be resource intensive. Automated test case development, false positive/false negative test tools, model verification and validation tools, and test coverage risk assessments are examples of contributing technologies.
- *FM Design Architectures* - FM capabilities may be implemented through numerous system, hardware, and software architecture solutions. The FM architecture trade space includes options such as embedded in the flight control software or independent onboard software; on board versus ground-based capabilities; centralized or distributed FM functions; sensor suite implications; integration of multiple FM techniques; innovative software FM architectures implemented on flight processors or on Field Programmable Gate Arrays (FPGAs); and execution in real-time or off-line analysis post-operations. Alternative architecture choices such as model-based approaches could help control FM system complexity and cost and could offer solutions to transparency, verifiability, and completeness challenges.
- *Multi-discipline FM Interoperation* - FM designers, Systems Engineering, Safety and Mission Assurance, and Operations perform analyses and assessments of reliabilities, failure modes and effects, sensor coverage, failure probabilities, anomaly detection and response, contingency operations, etc. The relationships between multi-discipline data and analyses are inconsistent and misinterpreted. Resources are expended either in effort to resolve disconnects in data and analyses or worse, reduced mission success due to failure modes that were overlooked. Solutions that address data integrity, identification of metrics, and standardization of data products, techniques and analyses will reduce cost and failures.

Lidar Remote Sensing Technologies Topic S1.01

NASA recognizes the potential of lidar technology in meeting many of its science objectives by providing new capabilities or offering enhancements over current measurements of atmospheric and topographic parameters from ground, airborne, and space-based platforms. To meet NASA's requirements for remote sensing from space, advances are needed in state-of-the-art lidar technology with an emphasis on compactness, efficiency, reliability, lifetime, and high performance. Innovative lidar subsystem and component technologies that directly address the measurement of atmospheric constituents and surface topography of the Earth, Mars, the Moon, and other planetary bodies will be considered under this subtopic. Compact, high-efficiency lidar instruments for deployment on unconventional platforms, such as balloon, small sat, and CubeSat are also considered and encouraged.

Proposals must show relevance to the development of lidar instruments that can be used for NASA science-focused measurements or to support current technology programs. Meeting science needs leads to four primary instrument types:

- *Backscatter* - Measures beam reflection from aerosols to retrieve the opacity of a gas.
- *Ranging* - Measures the return beam's time-of-flight to retrieve distance.
- *Doppler* - Measures wavelength changes in the return beam to retrieve relative velocity.
- *Differential absorption* - Measures attenuation of two different return beams (one centered on a spectral line of interest) to retrieve concentration of a trace gas.

Phase I research should demonstrate technical feasibility and show a path toward a Phase II prototype unit. Phase II prototypes should be capable of laboratory demonstration and preferably suitable for operation in the field from a ground-based station, an aircraft platform, or any science platform amply defended by the proposer. For the 2016 SBIR Program, NASA is soliciting the component and subsystem technologies described below.

- Compact and rugged single-frequency continuous-wave and pulsed lasers operating between 0.28- μm and

2.05- μ m wavelengths suitable for lidar. Specific wavelengths are of interest to match absorption lines or atmospheric transmission: 0.28 to 0.32- μ m (ozone absorption), 0.45 to 0.49- μ m (transmission through ocean water), 0.532- μ m, 0.817 to 0.830- μ m (water lines), 1.0- μ m, 1.57- μ m (CO₂ line), 1.65- μ m (methane line), and 2.05- μ m (CO₂ line). For wavelengths associated with an absorption line, tunability on the order tens of nanometers is desired. Architectures involving new developments in diode laser, quantum cascade laser, and fiber laser technology are especially encouraged. For pulsed lasers two different regimes of repetition rate and pulse energies are desired: from 8-kHz to 10-kHz with pulse energy greater than 1-mJ and from 20-Hz to 100-Hz with pulse energy greater than 100-mJ.

- Optical amplifiers for increasing the energy of pulsed lasers in the wavelength range of 0.28- μ m to 2.05- μ m. Specific wavelengths of interest are listed above in the bullet above. Also, amplifier and modulator combinations for converting continuous-wave lasers to a pulsed format are encouraged. Amplifier designs must preserve the wavelength stability and spectral purity of the input laser.
- Ultra-low noise photoreceiver modules, operating at 1.6- μ m wavelength, consisting of the detection device, complete Dewar/cooling systems, and associated amplifiers. General requirements are: large single-element active detection diameter (>200 micron), high quantum efficiency (>85%), noise equivalent power of the order of 10-14 W/sqrt(Hz), and bandwidth greater than 10 MHz.
- Novel, highly efficient approaches for High Spectral Resolution Lidar (HSRL) receivers. New approaches for high-efficiency measurement of HSRL aerosol properties at 1064, 532 and/or 355-nm. New or improved approaches are sought that substantially increase detection efficiency over current state of the art. Ideally, complete receiver subsystems will be proposed that can be evaluated and/or implemented in instrument concept designs.
- New space lidar technologies that use small and high-efficiency diode or fiber lasers to measure range and surface reflectance of asteroids and comets from >100 km altitude during mapping to <1 m during landing and sample return at a fraction of the power, mass, and cost of the Mercury Laser Altimeter (i.e., less than 7.4kg, 17W, and 28x28x26cm). The technologies can significantly extend the receiver dynamic range of the current space lidar without movable attenuators, providing sufficient link margin for the longest range but not saturating during landing. The output power of the laser transmitters should be continuously adjusted according to the spacecraft altitude. The receiver should have single photon sensitivity to achieve a near-quantum limited performance for long distance measurement. The receiver integration time can be continuously adjusted to allow trade-off between the maximum range and measurement rate. The lidar should have multiple beams so that it can measure not only the range but also surface slope and orientation.
- Narrow linewidth and frequency stable laser transmitter at 780-nm wavelength for development of low-cost, compact, and eye-safe high spectral resolution lidar (HSRL) for ground-based profile measurements of aerosol and cloud intensive and extensive properties. Desired specifications include pulse energy of 5 to 20-mJ, pulse repetition rate of 1 to 10-kHz, wavelength near 780-nm coincident with rubidium vapor line, linewidth < 10-MHz, spectral purity > 99.9%, and wavelength tunability of at least 0.5-nm around central wavelength.

Sub Topics:

Microwave Technologies for Remote Sensing Topic S1.02

NASA employs active (radar) and passive (radiometer) microwave sensors for a wide range of remote sensing applications (for example, see (<http://www.nas.nasa.gov/catalog/11820.html> [6])). These sensors include low frequency (less than 10 MHz) sounders to G-band (160 GHz) radars for measuring precipitation and clouds, for planetary landing, upper atmospheric monitoring, and global snow coverage, topography measurement and other Earth and planetary science applications. We are seeking proposals for the development of innovative technologies to support these future radar and radiometer missions and applications. The areas of interest for this call are listed below.

Single Pole Double Throw Switch with the following specifications:

- Frequency: 183 GHz, 325 GHz, or 380 GHz.
- Bandwidth: > 15 GHz.
- Insertion Loss: < 2 dB.
- Isolation: > 15 dB.

Calibration of sub-mm wave radiometers is limited in large part to external sources due to the lack of suitable switches for internal calibration. This increases the mass and cost of these instruments. A SPDT switch at 180 or

340 GHz will significantly reduce the cost and complexity of radiometers at these frequencies.

NEW: GaN Schottky diode technology for ultra-high power local oscillator power sources

This includes the development of GaN epi-structures on Si or SiC substrates suitable for millimeter-wave operations (SOA electron mobility $>1000 \text{ cm}^2/\text{V}\cdot\text{s}$ for $5\text{E}16$ to $1\text{E}17 \text{ cm}^{-3}$ epi doping levels, and discrete GaN Schottky diodes (power handling capabilities $> 200 \text{ mW/diode}$).

Technology for compact Dual Frequency (Ka and W-band) quasi-optical radar front end

W-band (94 GHz +/- 50 MHz):

- Single Polarization Tx, Dual Polarization Rx using a quasioptical duplexer such as a faraday rotator.

Ka-band (35.5 GHz +/- 100 MHz):

- Dual Polarization Tx and Rx.
- Shared beam waist with W-band.
- Waveguide duplexer and OMT okay.

The Decadal Survey ACE mission calls for a dual-frequency (Ka/W-band) radar for observation of clouds and light precipitation from space. Recently a similar but more compact and low cost radar is considered for operation on the International Space Station (ISS). Compared to traditional ferrite material based radar Tx/Rx front-end, quasi-optical front-end offers significantly low loss and high power handling capability, which have direct impact on radar performance. A compact dual-frequency and dual-polarization quasi-optical radar front-end has not been developed and is in critical need for ISS, ACE and suborbital airborne radars.

Interconnection technologies to enable highly integrated, low loss distribution networks that integrate power splitters, couplers, filters, and/or isolators in a compact package

Technologies are sought that integrate X, Ku, and Ka-bands transmit/receive modules with antenna arrays and/or LO distribution networks for F- and/or G-band receiver arrays.

Dual-frequency (Ka/W-band), dual polarization compact quasi-optical front-end for cloud radars.

- Freq: $35.5 \text{ GHz} \pm 100\text{MHz}$.
- $94 \text{ GHz} \pm 100\text{MHz}$.
- Loss: $< 0.5 \text{ dB}$.
- Polarization Isolation: $> 30 \text{ dB}$.
- Polarization: V and H.

640 GHz Heterodyne Polarimeter with I, Q, U Channels

Current 640 GHz polarimetric radiometers are either unsuitably large for space in terms of Mass/Volume/Power, or are direct-detection instruments that lack the ability to reject ozone emission contamination by selectively filtering the signal in the IF stages. This technology would help enable polarimetric measurements to provide microphysical parameterization of ice clouds applicable to ACE.

Low power RFI mitigating receiver back ends for broad band microwave radiometers

NASA requires a low power, low mass, low volume, and low data rate RFI mitigating receiver back end that can be incorporated into existing and future radiometer designs. The system should be able to channelize up to 1 GHz with 16 sub bands and be able to identify RFI contamination using tools such as kurtosis.

Compact 10+ Watt W-band transceiver including:

- SSPA, LNA, Circulator, and receiver protection switches.
- Mixer and 2 GHz Band-Pass Filter.
- 10-Watt SSPA, <1 dB transmit loss, 7 dB Rx Noise Figure.
- Approximately 3.5" x 3.5" x 4" dimensions.

NEW: Compact, highly integrated technologies enabling Altimetry/Velocimetry for space qualified radars

- Frequency: C-band to K-band.
- 0.2% range and 1% velocity accuracies.
- Operating range 6000m to 0 m.
- Compact antenna development.
- Integrated digital backend.
- Highly integrated MMIC for radar systems/subsystems.
- < 3kg and 1U (10 x 10 x 3 cm³) for electronics.

Deployable 1-D Parabolic Antenna

- At least 2 m x 2 m in dimensions.
- Operable up to Ka-band (35.5 GHz).

Deployable 1-D parabolic antenna technology at Ka-band will allow higher gain and better spatial resolution for future flight precipitation measurement missions.

Technology for low-power, rad-tolerant broad band spectrometer back ends for microwave radiometers

Includes - digitizers with 20 Gsps, 20 GHz bandwidth, 4 or more bit and simple interface to FPGA; ASIC implementations of polyphase spectrometer digital signal processing with ~1 watt/GHz. 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.

A compact, broadband (6-12 GHz or 10-30 GHz), low insertion loss isolator

- < 0.3 insertion loss.
- 20 dB input and output return loss.

The isolator should be compatible with either microstrip or CPW for ease of transition with the rest of the system.

Ka-band Power Amplifier for CubeSats

- F = 35.7 GHz +/- 200MHz.
- Volume: <1U (10 x10 x10 cm³).
- Psat >32W.
- Gain > 35 dB.
- PAE > 20%.
- Pulsed, 12% duty cycle.
- Current state of the art amplifiers are limited to 7W at < 15% efficiencies.

Development of on-wafer high frequency probes above 300 GHz for cryogenic temperatures

Passive or active cooled space missions will benefit from early performance characterization and selection at operating temperatures. The conventional test on individual packaged components is expensive and time

consuming.

Advanced Deployable Antennas for CubeSats

- F = 35.7 GHz +/- 200MHz capable of 1D scanning.
- F = 94.05 GHz ± 50MHz.
- Aperture size = 2 m.
- Gain > 48dB @36GHz.
- Sidelobe ratio > 20dB.
- Stowed volume: <2.5U (25 x 10 x 10 cm³).
- Polarization: Linear.

Components for addressing gain instability in LNA based radiometers from 100 and 600 GHz

NASA requires low insertion loss solutions to the challenges of developing stable radiometers and spectrometers operating above 100 GHz that employ LNA based receiver front ends. This includes noise diodes with ENR>10dBm and with better than ? 0.01 dB/°C thermal stability when integrated with a proper electrical circuit, Dicke switches with better than 30 dB isolation, phase modulators, and low loss isolators along with fully integrated state-of-art receiver systems operating at room and cryogenic temperatures.

NEW: Wideband Antenna Technologies for GPRs

- Conformal / planar.
- 0.1 - 3 GHz bandwidth.
- Separate tx/rx with high isolation (> 30 dB).

Sub Topics:

Sensor and Detector Technology for Visible, IR, Far IR and Submillimeter Topic S1.03

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 - (<http://www.nap.edu/catalog/11820.html> [6]).
- Planetary science - (<http://www.nap.edu/catalog/10432.html> [7]).
- Astronomy and astrophysics - (<http://www.nap.edu/books/0309070317/html/> [8]).

Development of un-cooled or cooled infrared detectors (hybridized or designed to be hybridized to an appropriate read-out integrated circuit) with NE²T<20mK, QE>30% and dark currents <1.5x10⁻⁶ A/cm² in the 5-14 μm infrared wavelength region. Array formats may be variable, 640 x 512 typical, with a goal to meet or exceed 2k X 2k pixel arrays. Evolve new technologies such as InAs/GaSb type-II strained layer super-lattices to meet these specifications.

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, nanowire or heterodyne detector technologies made using high temperature superconducting films (YBCO, MgB₂) or engineered semiconductor materials, especially 2-Dimensional Electron Gas (2-DEG) and Quantum Wells (QW) that operate at temperatures achieved by standard 1 or 2 stage flight qualified cryocoolers and do not require cooling to liquid helium temperatures. Candidate missions are thermal imaging, LANDSAT Thermal InfraRed Sensor (TIRS), Climate Absolute Radiance and Refractivity Observatory (CLARREO), BOREal Ecosystem Atmosphere Study (BOREAS), Methane Trace Gas Sounder or other infrared earth observing missions.

1k x 1k or larger format MCT detector arrays with cutoff wavelength extended to 12 microns for use in missions to NEOs, comets and the outer planets.

Compact, low power, readout electronics for Kinetic Inductance Detector arrays with >8bit ADC at >500MHz sampling rate that channelizes into 1000 readout tones each with >5kHz of bandwidth. This type of readout would

be used for photometers and spectrometers for astrophysics focal planes, and earth or planetary remote sensing instruments.

Development of new or improved large-format focal plane array Readout Integrated Circuit (ROIC) architectures to provide advanced detection features for overcoming existing limitations for low background astronomical applications. The main limitations of existing source-follower unit cells include potential image persistence and interpixel capacitance induced crosstalk. These limitations have complicated the use of these ROICs in a number of past missions, and will likely be even more constraining as detector performance improves. An improvement of a factor of 2 or more over current state-of-the-art would be of interest. Ideally, this would be done without compromising any good characteristics, but even in the case of a modest degradation in some parameters (like noise), the new features may prove to be superior for some applications.

Development of a robust wafer-level 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 arrays. Initially the technology can be demonstrated at the '1-inch' die level but should be do-able at the 4-inch wafer level.

New or improved, lightweight spectrometer operating over the spectral range 350 – 2300 nm with 4 nm spectral sampling and that is capable of making irradiance measurements of both the sun and the moon.

Sub Topics:

Detector Technologies for UV, X-Ray, Gamma-Ray and Cosmic-Ray Instruments Topic S1.04

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, 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, Vision Missions, and Earth Science Decadal Survey missions. Details of these can be found at the following URLs:

- General Information on Future NASA Missions - (<http://www.nasa.gov/missions> [9]).
- Specific mission pages:
 - Future planetary programs - (http://nasascience.nasa.gov/planetary-science/mission_list [10]).
 - Earth Science Decadal missions - (<http://www.nap.edu/catalog/11820.html> [6]).
 - Helio Probes - (http://nasascience.nasa.gov/heliophysics/mission_list [11]).
 - X-ray Astrophysics - (http://sites.nationalacademies.org/bpa/BPA_049810 [2]).

Specific technology areas are:

- Significant improvement in wide band gap semiconductor materials, such as AlGaIn, ZnMgO and SiC, individual detectors, and detector arrays for operation at room temperature or higher for missions such as Geo-CAPE, NWO, ATALAST and planetary science composition measurements.
- Highly integrated, low noise (< 300 electrons rms with interconnects), low power (< 100 uW/channel) mixed signal ASIC readout electronics as well as charge amplifier ASIC readouts with tunable capacitive inputs to match detector pixel capacitance. See needs of National Research Council's Earth Science Decadal Survey (NRC, 2007): Future Missions include GEOCAPE, HyspIRI, GACM, future GOES and SOHO programs and planetary science composition measurements.
- Visible-blind SiC Avalanche Photodiodes (APDs) for EUV photon counting are required. The APDs must show a linear mode gain >10E6 at a breakdown reverse voltage between 80 and 100V. The APD's must demonstrate detection capability of better than 6 photons/pixel/s down to 135nm wavelength. See needs of National Research Council's Earth Science Decadal Survey (NRC, 2007): Tropospheric ozone.
- Large area (3 m²) photon counting near-UV detectors with 3 mm pixels and able to count at 10 MHz. Array with high active area fraction (>85%), 0.5 megapixels and readout less than 1 mW/channel. Future instruments are focal planes for JEM-EUSO and OWL ultra-high energy cosmic ray instruments and ground Cherenkov telescope arrays such as CTA, and ring-imaging Cherenkov detectors for cosmic ray instruments such as BESS-ISO. As an example (JEM-EUSO and OWL), imaging from low-Earth orbit of air

fluorescence, UV light generated by giant air showers by ultra-high energy ($E > 10^{19}$ eV) cosmic rays require the development of high sensitivity and efficiency detection of 300-400 nm UV photons to measure signals at the few photon (single photo-electron) level. A secondary goal minimizes the sensitivity to photons with a wavelength greater than 400 nm. High electronic gain (10^4 to 10^6), low noise, fast time response (< 10 ns), minimal dead time ($< 5\%$ dead time at 10 ns response time), high segmentation with low dead area ($< 20\%$ nominal, $< 5\%$ goal), and the ability to tailor pixel size to match that dictated by the imaging optics. Optical designs under consideration dictate a pixel size ranging from approximately 2×2 mm² to 10×10 mm². Focal plane mass must be minimized (2 g/cm² goal). Individual pixel readout is required. The entire focal plane detector can be formed from smaller, individual sub-arrays.

Sub Topics:

Particles and Field Sensors and Instrument Enabling Technologies Topic S1.05

Advanced sensors for the detection of elementary particles (atoms, molecules and their ions) and electric and magnetic fields in space and associated instrument technologies are often critical for enabling transformational science from the study of the sun's outer corona, to the solar wind, to the trapped radiation in Earth's and other planetary magnetic fields, and to the atmospheric composition of the planets and their moons. Improvements in particles and fields sensors and associated instrument technologies enable further scientific advancement for upcoming NASA missions such as CubeSats, Explorers, STP, and planetary exploration missions. Technology developments that result in a reduction in size, mass, power, and cost will enable these missions to proceed. Of interest are advanced magnetometers, electric field booms, ion/atom/molecule detectors, and associated support electronics and materials. Specific areas of interest include:

- High efficiency conversion surfaces for the conversion of Energetic Neutral Atoms (ENAs) to ions for increasing the sensitivity of low energy ENA instruments.
 - Science Traceability: Decadal survey missions: IMAP, MEDICI, DRIVE Initiative, EXPLORERS DISCOVERY, CubeSats / Smallsats, Sounding Rockets.
 - Need Horizon: 1 to 3 years, 3 to 5 years.
 - State of the Art: The efficiency of present SOA conversion surfaces is 1-2%. This is quite low and results to low sensitivities. An efficiency increase to 10% will lead to increased sensitivity by a factor of x 5 to 10 and /or smaller instruments sizes / resources.
 - Importance: Very High – Critical need for next generation low energy ENA instruments.
- Very low energy threshold < 5 eV particle detectors for direct neutral particle detection.
 - Science Traceability: Explorer missions, Decadal survey missions IMAP, MEDICI, DYNAMICS, DRIVE Initiative, DISCOVERY and CubeSat/Smallsat missions.
 - Need Horizon: 1 to 3 years.
 - State of the Art: SOA solid state detectors have an energy threshold for particle detection of ~ 1 keV. Although this problem can be overcome in charged particle detection with pre acceleration, it poses a severe limitation in direct neutral particle. New detectors with low energy threshold will enable a whole new class of instruments and improve existing instruments.
 - Importance: Very High – Critical need for next generation direct neutral instruments.
- UV filters that greatly attenuate UV Ly radiation but let particles freely pass through. Enabling technology for direct particle detection.
 - Science Traceability: Decadal survey missions: IMAP, MEDICI, DRIVE Initiative, EXPLORERS DISCOVERY, CubeSats / Smallsats, Sounding Rockets.
 - Need Horizon: 1 to 3 years, 3 to 5 years.
 - State of the Art: Particle detectors are very sensitive to UV light. The commonly used technology for direct particle detection is very thin foil that attenuate UV light but at the same time pose an energy threshold / scatter particles. A possible micro porous type of detector that greatly attenuates UV but let particles pass through will greatly improve current instruments.
 - Importance: Very High – Critical need for next generation particle instruments.
- Strong, compactly stowed magnetically clean magnetic field booms possibly using composite materials that deploy mag sensors (including internal harness) to distances up to 10 meters, for Cubesats;
 - Science Traceability: Explorer missions, DRIVE Initiative, CubeSat/Smallsat missions.
 - Need Horizon: 1 to 3 years.
 - State of the Art: Such a boom up to 10 meters long will high quality electric field measurements from small platforms.
 - Importance: Very High for future Cubesat and SmallSat stand alone and constellation missions.
- Strong, lightweight, thin, rigid, compactly stowed electric field booms possibly using composite materials

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- that deploy sensors (including internal harness) to distances of 10 m or more
- Explorer missions, DRIVE Initiative, CubeSat/Smallsat missions.
 - Need Horizon: 1 to 3 years, 3 to 5 years.
 - Particle detectors are very sensitive to UV light. The commonly used technology for direct particle detection is very thin foil that attenuates UV light but at the same time poses an energy threshold / scatter particles. A possible micro porous type of detector that greatly attenuates UV but lets particles pass through will greatly improve current instruments.
 - Importance: Very High for future Cubesat and SmallSat stand alone and constellation missions.

Sub Topics:

In Situ Sensors and Sensor Systems for Lunar and Planetary Science Topic S1.06

This subtopic solicits development of advanced instrument technologies and components suitable for deployment on 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. In addition, technologies that can increase instrument resolution and sensitivity or achieve new & innovative scientific measurements are solicited. For example missions, see (<http://science.hq.nasa.gov/missions> [12]). For details of the specific requirements see the National Research Councils, Vision and Voyages for Planetary Science in the Decade 2013-2022 (<http://solarsystem.nasa.gov/2013decadal/> [13]). Technologies that support NASA's New Frontiers and Discovery missions to various planetary bodies are of top priority.

In-situ technologies are being sought to achieve much higher resolution and sensitivity with significant improvements over existing technologies. Orbital sensors and technologies that can provide significant improvements over previous orbital missions are also sought. Specifically, this subtopic solicits instrument development that provides significant advances in the following areas, broken out by planetary body:

- *Mars* - Sub-systems relevant to current in-situ instrument needs (e.g., lasers and other light sources from UV to microwave, X-ray and ion sources, detectors, mixers, mass analyzers, etc.) or electronics technologies (e.g., FPGA and ASIC implementations, advanced array readouts, miniature high voltage power supplies). Technologies that support high precision in-situ measurements of elemental, mineralogical, and organic composition of planetary materials are sought. Conceptually simple, low risk technologies for in-situ sample extraction and/or manipulation including fluid and gas storage, pumping, and chemical labeling to support analytical instrumentation. Seismometers, mass analyzers, technologies for heat flow probes, and atmospheric trace gas detectors. Improved robustness and g-force survivability for instrument components, especially for geophysical network sensors, seismometers, and advanced detectors (iCCDs, PMT arrays, etc.). Instruments geared towards rock/sample interrogation prior to sample return are desired.
- *Europa & Io* - 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) for candidate instruments on proposed missions such as Europa Clipper and Io Volcano.
- *Titan* - Low mass and power sensors, mechanisms and concepts for converting terrestrial instruments such as turbidimeters and echo sounders for lake measurements, weather stations, surface (lake and solid) properties packages, etc. to cryogenic environments (95K). Mechanical and electrical components and subsystems that work in cryogenic (95K) environments; sample extraction from liquid methane/ethane, sampling from organic 'dunes' at 95K 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, air sampling mechanisms for mass analyzers, and aerosol detectors are also solicited.
- *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 are particularly desired.
- *Small Bodies* - Technologies that can enable sampling from asteroids and from depth in a comet nucleus, improved in-situ analysis of comets. Also, imagers and spectrometers that provide high performance in low light environments dust environment measurements & 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.). Specifically, advancements geared towards instruments that enable elemental or mineralogy analysis (such as high-sensitivity X-ray and UV-fluorescence spectrometers, UV/fluorescence flash lamp/camera systems, scanning electron microscopy with chemical analysis capability, time-of-flight mass spectrometry, gas chromatography and tunable diode laser sensors, calorimetry, laser-Raman spectroscopy, imaging spectroscopy, and LIBS) are sought. These developments should be geared towards sample interrogation, prior to possible sample return.

- *Saturn, Uranus and Neptune* - Technologies are sought for components, sample acquisition and instrument systems that can enhance mission science return and withstand the low-temperatures/high-pressures of the atmospheric probes during entry.
- *The Moon* - This solicitation seeks advancements in the areas of compact, light-weight, low power instruments geared towards in-situ lunar surface measurements, geophysical measurements, lunar atmosphere and dust environment measurements & regolith particle analysis, lunar resource identification, and/or quantification of potential lunar resources (e.g., oxygen, nitrogen, and other volatiles, fuels, metals, etc.). Specifically, advancements geared towards instruments that enable elemental or mineralogy analysis (such as high-sensitivity X-ray and UV-fluorescence spectrometers, UV/fluorescence flash lamp/camera systems, scanning electron microscopy with chemical analysis capability, time-of-flight mass spectrometry, gas chromatography and tunable diode laser sensors, calorimetry, laser-Raman spectroscopy, imaging spectroscopy, and LIBS) are sought. These developments should be geared towards sample interrogation, prior to possible sample return. Systems and subsystems for seismometers and heat flow sensors capable of long-term continuous operation over multiple lunar day/night cycles with improved sensitivity at lower mass and reduced power consumption are sought. Also of interest are portable surface ground penetrating radars to characterize the thickness of the lunar regolith, as well as, low mass, thermally stable hollow cubes and retro-reflector array assemblies for lunar surface laser ranging. Of secondary importance are instruments that measure the micrometeoroid and lunar secondary ejecta environment, plasma environment, surface electric field, secondary radiation at the lunar surface, and dust concentrations and its diurnal dynamics are sought. Further, lunar regolith particle analysis techniques are desired (e.g., optical interrogation or software development that would automate integration of suites of multiple back scatter electron images acquired at different operating conditions, as well as permit integration of other data such as cathodoluminescence and energy-dispersive x-ray analysis.)

Proposers are strongly encouraged to relate their proposed development to:

- NASA's future planetary exploration goals.
- 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.

Sub Topics:

Airborne Measurement Systems Topic S1.07

Measurement system miniaturization and/or increased performance is needed to support for NASA's airborne science missions, particularly those utilizing the Global Hawk, SIERRA-class, Dragon Eye or other unmanned aircraft. The subject airborne instruments are intended as calibration/validation systems for space-based measurements, or to provide local measurements not available from space-based instruments. Linkages to other subtopics such as S3.04 Unmanned Aircraft and Sounding Rocket Technologies are encouraged. Complete instrument systems are desired, including features such as remote/unattended operation and data acquisition, low power consumption, and minimum size and weight. Desired sensors include:

- High accuracy and precision atmospheric measurements of Nitrous Oxide, Ammonia, Sulfur Dioxide, Dimethyl Sulfide, Carbonyl Sulfide and Formaldehyde, with significant improvements over the current state-of-the-art, such as measurement speed, resolution, or system weight/volume.
- Preconcentration instruments for the measurement of the isotopic composition of atmospherically relevant trace gases (CO₂, CH₄, O₃, Ozone depleting substances and isotopomer, etc.) in are using optical, mass-spectrometric, and other types of detection. Proposals are invited for the development of versatile

preconcentration instrumentation that initially can be used with a range of measurement instrumentation as well as for field and laboratory applications.

- Spectrally resolved absorption and extinction of atmospheric aerosols (0.1 to 10 micron).
- Multiphase Precipitation (0.1 mm to 20 mm with 5 % accuracy in three dimensions).
- Size distribution, phase, and asymmetry of atmospheric aerosols and cloud particles (0.1 micron to 200 micron with 10% accuracy).
- Three-dimensional wind measurement (1 mps accuracy/resolution at 10 Hz sampling).

Sub Topics:

Surface & Sub-surface Measurement Systems Topic S1.08

Surface & Sub-surface Measurement Systems are sought with relevance to future space missions such as Active Sensing of CO₂ Emissions over Nights, Days, and Seasons (ASCENDS), Orbiting Carbon Observatory – 2 (OCO-2), Global Precipitation Measurement (GPM), Geostationary Coastal and Air Pollution Events (GEO-CAPE), Hyperspectral InfraRed Imager (HyspIRI), Aerosol, Cloud, and Ecosystems (ACE, including Pre-ACE/PACE). Early adoption for alternative uses by NASA, other agencies, or industry is desirable and recognized as a viable path towards full maturity. Sensor system innovations with significant near-term commercial potential that may be suitable for NASA's research after full development are of interest:

- Precipitation (e.g., motion stabilized disdrometer for shipboard deployments).
- Aquatic suspended particle concentrations and spectra of mineral and biogenic (phytoplankton and detritus) components.
- Miniaturized, stable, pH sensors for ocean applications to support validation of OCO-2 that can be used in the ARGO network.
- Miniaturized gas sensors or small instruments for carbon dioxide, methane, etc., only where the sensing technology solution will clearly exceed current state of the art for its targeted application.
- Miniaturized air-dropped sensors, for ocean surface and subsurface measurements such as conductivity, temperature, and depth.
- Multi-wavelength, LIDAR-based, atmospheric ozone and aerosol profilers for continuous, simultaneous observations from multiple locations. Examples include three-band ozone measurement systems operating in the UV spectrum (e.g., 280-316 nm, possibly tunable), or visible/infrared systems with depolarization sensitivity for aerosols and clouds.
- Portable, robust, ground based LIDAR system for 3D scanning of winds, temperature, density, and humidity with ability to scan horizontally and vertically with a range of up to 10 km
- Miniaturized, novel instrumentation for measuring inherent and apparent optical properties (specifically to support vicarious calibration and validation of ocean color satellites, i.e., reflectance, absorption, scattering), in-situ biogeochemical measurements of marine and aquatic components and rates including but not limited to nutrients, phytoplankton and their functional groups, and floating and submerged aquatic plants.
- Novel geophysical and diagnostic instruments suitable for ecosystem monitoring. Fielding for NASA's Applications and Earth Science Research activities is a primary goal.

Sub Topics:

Cryogenic Systems for Sensors and Detectors Topic S1.09

Cryogenic cooling systems often serve as enabling technologies for detectors and sensors flown on scientific instruments as well as advanced telescopes and observatories. As such, technological improvements to cryogenic systems further advance the mission goals of NASA through enabling performance (and ultimately science gathering) capabilities of flight detectors and sensors. There are four potential investment areas that NASA is seeking to expand state of the art capabilities for possible use on future programs such as WFIRST (<http://wfirst.gsfc.nasa.gov/> [14]), the Europa Jupiter System Science missions (<http://www.nasa.gov/multimedia/podcasting/jpl-europa20090218.html> [15]) and PIXIE (Primordial Inflation Explorer). The topic areas are as follows:

Cryocooler Systems and Components

- *Miniaturized/Efficient Cryocooler Systems* - Cryocooler systems viable for application on SmallSat space platforms are sought. Present state of the art capabilities demonstrate approximately 0.4W of cooling capacity at 77K provided an input power of 5W. Contemporary system mass is on the order of 400 grams.

Desired performance specifications for cryocoolers sought include a cooling capability on the order of 0.2W at temperatures spanning 30K - 80K. Desired masses and input powers will be < 400 grams and < 5W respectively. Component level improvements are also desirable.

- *Low Temperature/Input Power Cooling Systems* - Low temperature/Input Power Cooling systems are sought for application on future Planetary missions that require performance in space environments that have limited access to power. Contemporary cooling systems are incapable of providing cooling loads as high as 0.2W at 30K while rejecting heat to an ambient environment of approximately 150K. Cooling systems providing cooling capacities of approximately 0.3W at 35K with heat rejection capability to temperature sinks at 150 K or lower are of interest. Component level improvements are also desirable.
- *High Capacity/Efficiency Cryocooler Systems* - High Capacity/Efficiency cryocoolers are of interest for use on future science missions. State of the art high capacity cryocooler systems have demonstrated cooling capabilities spanning 0.3W - 1W with a load temperature of 20K and < 0.3 W at 10K. High Capacity cryocoolers are available at low to mid TRL levels for both Pulse Tube (e.g., 5W cooling capacity at 20K) and Turbo Brayton (e.g., cooling capacity of 20W at 20K) configurations. Desired cryocooler systems will provide cold tip operational temperatures spanning 10K to 20K with a cooling capacity of > 4W at 20K or more than 0.3 W at 10 K. Very low vibration systems with these capabilities are desirable. Component level improvements that increase overall efficiency are also desirable.

Sub-Kelvin Cooling Systems

- *Magnetic Cooling Systems* - State of the art sub-Kelvin temperature control architectures that use magnetic cooling consist of ADR (Adiabatic Demagnetization Refrigeration) systems. The Astro-H FM (Flight Model) ADR represents the state of the art in ADR system and component level technologies for space application. Future missions requiring cooling to sub-Kelvin levels will look to use new and improved ADR systems. AMRR (Active Magnetic Regenerative Refrigeration) systems are a related magnetic cooling technology that requires system and component level development in order to attain sub-Kelvin cooling levels. Improvements at the component level may lead to better overall system performance and increased hold times at target temperatures. Both of these are highly advantageous and desirable to future science missions. Specific components sought include:
 - Low current superconducting magnets (3-4 Tesla at temperatures > 15K).
 - Heat Switches (including optimization of current designs, such as low thermal conductivity heat switch shells)
 - High cooling power density magnetocaloric materials, especially single crystals with volume > 20 cm³.
 - Active/Passive magnetic shielding (for use with 3-4 Tesla magnets).
 - Superconducting leads (10K - 90K) capable of 10 A operation with 1 mW conduction.
 - 10 mK- 300 mK high resolution thermometry.

Proposals considered viable for Phase I award will seek to validate hypotheses through proof of concept testing at relevant temperatures.

Sub Topics:

Proximity Glare Suppression for Astronomical Coronagraphy Topic S2.01

This subtopic addresses the unique problem of imaging and spectroscopic characterization of faint astrophysical objects that are located within the obscuring glare of much brighter stellar sources. Examples include planetary systems beyond our own, the detailed inner structure of galaxies with very bright nuclei, binary star formation, and stellar evolution. Contrast ratios of one million to ten billion over an angular spatial scale of 0.05-1.5 arcsec are typical of these objects. Achieving a very low background requires control of both scattered and diffracted light. The failure to control either amplitude or phase fluctuations in the optical train severely reduces the effectiveness of starlight cancellation schemes.

This innovative research focuses on advances in coronagraphic instruments, starlight cancellation instruments, and potential occulting technologies that operate at visible and near infrared wavelengths. The ultimate application of these instruments is to operate in space as part of a future observatory mission. 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

- Image plane hybrid metal/dielectric, and polarization apodization masks in linear and circular patterns.
- Transmissive holographic masks for diffraction control and PSF apodization.
- Sharp-edged, low-scatter pupil plane masks.
- Low-scatter, low-reflectivity, sharp, flexible edges for control of scatter in starshades.
- Systems to measure spatial optical density, phase inhomogeneity, scattering, spectral dispersion, thermal variations, and to otherwise estimate the accuracy of high-dynamic range apodizing masks.
- Pupil remapping technologies to achieve beam apodization.
- Techniques to characterize highly aspheric optics.
- Methods to distinguish the coherent and incoherent scatter in a broad band speckle field.
- Coherent fiber bundles consisting of up to 10,000 fibers with lenslets on both input and output side, such that both spatial and temporal coherence is maintained across the fiber bundle for possible wavefront/amplitude control through the fiber bundle.

Wavefront Measurement and Control Technologies

- Small stroke, high precision, deformable mirrors and associated driving electronics scalable to 10,000 or more actuators (both to further the state-of-the-art towards flight-like hardware and to explore novel concepts). Multiple deformable mirror technologies in various phases of development and processes are encouraged to ultimately improve the state-of-the-art in deformable mirror technology. Process improvements are needed to improve repeatability, yield, and performance precision of current devices.
- Instruments to perform broad-band sensing of wavefronts and distinguish amplitude and phase in the wavefront.
- Integrated mirror/actuator programmable deformable mirror.
- Multiplexers with ultra-low power dissipation for electrical connection to deformable mirrors.
- Low-order wavefront sensors for measuring wavefront instabilities to enable real-time control and post-processing of aberrations.
- Thermally and mechanically insensitive optical benches and systems.
- Optical Coating and Measurement Technologies:
 - Instruments capable of measuring polarization cross-talk and birefringence to parts per million.
 - Highly reflecting, uniform, broadband coatings for large (> 1 m diameter) optics.
 - Polarization-insensitive coatings for large optics.
 - Methods to measure the spectral reflectivity and polarization uniformity across large optics.
 - Methods to apply carbon nanotube coatings on the surfaces of the coronagraphs for broadband suppression from visible to NIR.

Other

- Methods to fabricate diffractive patterns on large optics to generate astrometric reference frames.
- Artificial star and planet point sources, with $1e10$ dynamic range and uniform illumination of an $f/25$ optical system, working in the visible and near infrared.
- Deformable, calibrated, collimating source to simulate the telescope front end of a coronagraphic system undergoing thermal deformations.
- Technologies for high contrast integral field spectroscopy, in particular for microlens arrays with or without accompanying mask arrays, working in the visible and NIR (0.4 - 1.8 microns), with lenslet separations in the 0.1 - 0.4 mm range, in formats of $\sim 140 \times 140$ lenslets.

Sub Topics:

Precision Deployable Optical Structures and Metrology Topic S2.02

Planned future NASA Missions in astrophysics, such as the Wide-Field Infrared Survey Telescope (WFIRST) and

the New Worlds Technology Development Program (coronagraph, external occulter and interferometer technologies) will push the state of the art in current optomechanical technologies. Mission concepts for New Worlds science would require 10 - 30 m class, cost-effective telescope observatories that are diffraction limited at wavelengths from the visible to the far IR, and operate at temperatures from 4 - 300 K. In addition, ground based telescopes such as the Cerro Chajnantor Atacama Telescope (CCAT) requires similar technology development.

The desired areal density is 1 - 10 kg/m² with a packaging efficiency of 3-10 deployed/stowed diameter. Static and dynamic wavefront error tolerances to thermal and dynamic perturbations may be achieved through passive means (e.g., via a high stiffness system, passive thermal control, jitter isolation or damping) or through active optomechanical control. Large deployable multi-layer structures in support of sunshades for passive thermal control and 20m to 50m class planet finding external occulters are also relevant technologies. Potential architecture implementations must package into an existing launch volume, deploy and be self-aligning to the micron level. The target space environment is expected to be the Earth-Sun L2.

This subtopic solicits proposals to develop enabling, cost effective component and subsystem technology for deploying large aperture telescopes with low cost. Research areas of interest include:

- Precision deployable structures and metrology for optical telescopes (e.g., innovative active or passive deployable primary or secondary support structures).
- Architectures, packaging and deployment designs for large sunshields and external occulters.
- In particular, important subsystem considerations may include:
- Innovative concepts for packaging fully integrated subsystems (e.g., power distribution, sensing, and control components).
- Mechanical, inflatable, or other precision deployable technologies.
- Thermally-stable materials (CTE < 1ppm) for deployable structures.
- Innovative systems, which minimize complexity, mass, power and cost.
- Innovative testing and verification methodologies.

The goal for this effort is to mature technologies that can be used to fabricate 16 m class or greater, lightweight, ambient or cryogenic flight-qualified observatory systems. 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. Proposals with system solutions for large sunshields and external occulters will also be accepted. A successful proposal shows a path toward a Phase II delivery of demonstration hardware scalable to 5 meter diameter for ground test characterization.

Before embarking on the design and fabrication of complex space-based deployable telescopes, additional risk reduction in operating an actively controlled telescope in orbit is desired. To be cost effective, deployable apertures that conform to a cubesat (up to 3-U) or ESPA format are desired. Consequently, deployment hinge and latching concepts, buildable for these missions and scaleable to larger systems are desired. Such a system should allow <25 micron deployment repeatability and sub-micron stability for both thermal and mechanical on-orbit disturbances. A successful proposal would deliver a full-scale cubesat or ESPA ring compatible deployable aperture with mock optical elements.

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).

Sub Topics:

Advanced Optical Systems and Fabrication/Testing/Control Technologies for EUV/Optical and IR Telescope Topic S2.03

This subtopic solicits solutions in the following areas:

- Components and Systems for potential EUV, UV/O or Far-IR mission telescopes.
- Technology to fabricate, test and control potential UUV, UV/O or Far-IR telescopes.

Please note: an emphasis regarding mirror systems is the mirror substrate support structure. The Technical Challenges contains information on specific technologies which need developing for each area.

Proposals must show an understanding of one or more relevant science needs, and present a feasible plan to develop the proposed technology for infusion into a NASA program: sub-orbital rocket or balloon; competed SMEX or MIDEX; or, Decadal class mission.

This subtopic matures technologies needed to affordably manufacture, test or operate complete mirror systems or telescope assemblies. Traditionally, this subtopic matured technology from TRL3 to TRL4. Now, there is an additional opportunity to propose in Phase II for an effort larger than a traditional Phase II for the purpose of maturing demonstrated component level technologies (TRL4) to demonstrated system level technologies (TRL6) by using them to manufacture complete telescope systems. A requirement of this option is that there must be an identified NASA program that will fly the developed new technology system.

An ideal Phase I deliverable would be a precision optical system of at least 0.25 meters; or a relevant sub-component of a system; or a prototype demonstration of a fabrication, test or control technology leading to a successful Phase II delivery; or a reviewed preliminary design and manufacturing plan which 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 analysis will be done to show compliance with all requirements. Past experience or technology demonstrations which support the design and manufacturing plans will be given appropriate weight in the evaluation.

An ideal Phase II project would further advance the technology to produce a flight-qualifiable optical system greater than 0.5 meters or relevant sub-component (with a TRL in the 4 to 5 range); or a working fabrication, test or control system. Phase 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 which can be integrated into the potential mission; and, demonstrate an understanding of how the engineering specifications of their system meets the performance requirements and operational constraints of the mission (including mechanical and thermal stability analysis).

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.

Introduction

The 2010 National Academy Astro2010 Decadal Report specifically identified large light-weight mirrors as a key technology needed to enable potential Extreme Ultraviolet (EUV), Ultraviolet/Optical (UV/O) and Infrared (IR) to Far-IR missions.

The 2012 National Academy report "NASA Space Technology Roadmaps and Priorities" states that one of the top technical challenges in which NASA should invest over the next five years is developing a new generation of larger effective aperture, lower-cost astronomical telescopes that enable the discovery of habitable planets, facilitate advances in solar physics, and enable the study of faint structures around bright objects.

Finally, NASA is developing a heavy lift space launch system (SLS) with an 8 to 10 meter fairing and 40 to 50 mt capacity to SE-L2. SLS will enable extremely large space telescopes, such as 12 to 30 meter class segmented primary mirrors for UV/optical or infrared wavelengths.

Technical Challenges

To accomplish NASA's high-priority science requires low-cost, ultra-stable, large-aperture, normal incidence mirrors with low mass-to-collecting area ratios. Specifically needed for a potential UVO mission are normal incidence 4-meter (or larger) diameter mirrors with 5 nm RMS surface figure error; and, active or passive alignment and control of normal-incidence imaging systems to achieve diffraction limited performance at wavelengths less than 500 nm (< 40 nm RMS wavefront error, WFE). Additionally, potential Exoplanet mission, using an internal coronagraph, requires total telescope wavefront stability on order of 10 pico-meters RMS per 10 minutes. This stability specification places severe constraints on the dynamic mechanical and thermal performance

of 4 meter and larger telescope. To meet this performance requirement requires ultra-stable mirror support structures. Finally, specifically needed for potential IR/Far-IR missions are normal incidence 8-meter (or larger) diameter mirrors with cryo-deformations < 100 nm rms.

In all cases, the most important metric for an advanced optical system (after performance) 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 a cost reduction for precision optical components by 5 to 50 times, to between \$100K/m² to \$1M/m².

Development is required to fabricate components and systems to achieve the following Metrics:

- Areal Cost < \$500K/m² (for UV/Optical).
- Areal Cost < \$100K/m² (for Infrared).
- Monolithic - 1 to 8 meters.
- Segmented > 4 meters (total aperture).
- Wavefront Figure < 5 nm RMS (for UV/Optical).
- Cryo-deformation < 100 nm RMS (for Infrared).
- Slope < 0.1 micro-radian (for EUV).
- Wavefront Stability < 10 pm/10 min (for Coronagraphy).
- Actuator Resolution < 1 nm rms (UV/Optical).

Finally, also needed is ability to fully characterize surface errors and predict optical performance.

Sub Topics:

X-Ray Mirror Systems Technology, Coating Technology for X-Ray-UV-OIR, and Free-Form Optics Topic S2.04
This subtopic solicits proposals in the following areas:

- Components, Systems, and Technologies of potential X-Ray missions.
- Coating technologies for X-Ray, EUV, Visible, and IR telescopes.
- Free-form Optics surfaces design, fabrication, and metrology.

This subtopic focuses on three areas of technology development:

- X-Ray manufacturing, coating, testing, and assembling complete mirror systems in addition to maturing the current technology.
- Coating technology for wide range of wavelengths from X-Ray to IR (X-Ray, EUV, Visible, and IR).
- Free-form Optics design, fabrication, and metrology for CubeSat, SmallSat and Visible Nulling Coronagraph (VNC).

A typical Phase I proposal for X-Ray technology would address the relevant optical sub-component of a system with necessary coating and stray light suppression for X-Ray missions or prototype demonstration of a fabricated system and its testing. Similarly, a Coating technology proposal would address fabrication and testing of optical surfaces for a wide range of wavelengths from X-Ray to IR. The Free-form Optics proposals tackle the challenges involved in design, fabrication, and metrology of non-spherical surfaces for small-size missions such as CubeSat, NanoSat, and visible nulling coronagraph.

In a nutshell, a successful proposal demonstrates a low-cost ability to address NASAs science mission needs and technical challenges specified under each category of Technical Challenges.

Introduction

The National Academy Astro2010 Decadal Report identifies studies of optical components and ability to manufacture, coat, and perform metrology needed to enable future X-Ray observatory missions such as Next Generation of X-Ray Observatories (NGXO).

The Astrophysics Decadal specifically calls for optical coating technology investment for future UV, Optical, Exoplanet, and IR missions while Heliophysics 2009 Roadmap identifies the coating technology for space missions

to enhance rejection of undesirable spectral lines, improve space/solar-flux durability of EUV optical coatings, and 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 non-spherical surfaces with anticipated benefits of freeform optics such as fast wide-field and distortion-free cameras.

Technical Challenges

X-Ray Optical Component, Systems, and Technologies

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

In this area, we are looking to address the multiple technologies including: improvements to manufacturing (machining, rapid optical fabrication, slumping or replication technologies), improved metrology, performance prediction and testing techniques, active control of mirror shapes, new structures for holding and actively aligning of mirrors in a telescope assembly to enable X-Ray observatories while lowering the cost per square meter of collecting aperture and effective design of stray-light suppression in preparation for the Decadal Survey of 2020. Currently, X-Ray space mirrors cost \$4 million to \$6 million per square meter of optical surface area. This research effort seeks a cost reduction for precision optical components by 5 to 50 times, to less than \$1M to \$100 K/m².

Coating Technologies for X-Ray, EUV, Visible, and IR Telescopes

The optical coating technology is a mission-enabling feature that determines 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 current coating technology of optical components needs to achieve TRL-6 by approximately 2018 to support the 2020 Astrophysics Decadal process. A number of optical coating metrics specific each wavelength are desired as:

The Optical Coating Metrics

- X-Ray Metrics:
 - Multilayer high-reflectance coatings for hard X-Ray mirrors similar to NuSTAR.
 - Multilayer depth gradient coatings for 5 to 80 KeV with high broadband reflectivity.
 - Zero-net-stress coating for iridium or other high-reflectance elements on thin substrates (< 0.5 mm).
- EUV Metrics:
 - Reflectivity > 90% from 6 nm to 200 nm and depositable onto a < 2 meter mirror substrate.
 - UVOIR Metrics:
 - Broadband reflectivity > 60% and uniform polarization from 90 nm to 2500 nm and depositable onto 2, 4, and 6 meter mirror substrates.
- Non-Stationary Metric:
 - Non-uniform optical coating to be used in both reflection and transmission that vary with location and optical surface. Variation pertains to ratio of reflectivity to transmissivity, optical field amplitude, phase, and polarization change. The optical surface area ranges from 1/2 to 6 cm.

Scattered Light Suppression Using Carbon Nanotube (CNT) Coating

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

-
- Broadband (visible plus Near IR), reflectivity of 0.1% or less
 - Resist bleaching of significant albedo changes over a mission life of ~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 CE and ~ 0.1 GW/cm² density, and 1 kW/nanosecond pulses
 - Adhere to the multi-layer dielectric or protected metal coating including Ion Beam Sputtering (IBS) coating

Freeform Optics Design, Fabrication, and Metrology

Future NASA missions with alternative low-cost science and small-size payload are constrained by the traditional spherical form of optics. These missions could benefit greatly by the freeform optics as they provide non-spherical optics with better aerodynamic characteristics for spacecraft with lightweight components to meet the mission requirements. Currently, the design and utilization of conformal and freeform shapes are costly due to fabrication and metrology of these parts. 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-observed systems. For the coronagraphic applications, freeform optical components allow coronagraphic nulling without shearing and increase the useful science field of view. In this category, freeform optical prescription for surfaces of 0.5 cm to 6 cm diameters with tolerances of 1 to 2 nm rms are needed. In this respect, the freeform refers to either 2nd order conic prescription with higher order surface polished onto it or without underlying conic prescription with no steps in the surface. The optics with underlying conic prescription would need to be in F/# range of F/2 to F/20. In addition to the freeform fabrication, the metrology of freeform optical components is difficult and challenging due to the large departure from planar or spherical shapes accommodated by conventional interferometric testing. New methods such as multibeam low-coherence optical probe and slope sensitive optical probe are highly desirable.

Ultra-Stable X-Ray grazing-incident Telescopes for Sub-Orbital Balloons and Rocket-borne Missions

Technology maturation to build complete low-cost, lightweight X-ray telescopes with grazing-incident optics that can be flown on potential long duration high-altitude balloon-borne or rocket-borne missions. The focus here is to 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.

Sub Topics:

Power Generation and Conversion Topic S3.01

Future NASA science missions will employ Earth orbiting spacecraft, planetary spacecraft, balloons, aircraft, surface assets, and marine craft as observation platforms. Proposals are solicited to develop advanced power-generation and conversion technologies to enable or enhance the capabilities of future science missions. Requirements for these missions are varied and include long life, high reliability, significantly lower mass and volume, higher mass specific power, and improved efficiency over the state of practice for components and systems. Other desired capabilities are high radiation tolerance and the ability to operate in extreme environments (high and low temperatures and over wide temperature ranges).

While power-generation technology affects a wide range of NASA missions and operational environments, technologies that provide substantial benefits for key mission applications/capabilities are being sought in the following areas:

Photovoltaic Energy Conversion

Photovoltaic cell, blanket, and array technologies that lead to significant improvements in overall solar array performance (i.e., conversion efficiency >33%, array mass specific power >300watts/kilogram, decreased stowed volume, reduced initial and recurring cost, long-term operation in high radiation environments, high power arrays, and a wide range of space environmental operating conditions) are solicited. Photovoltaic technologies that provide enhancing and/or enabling capabilities for a wide range of aerospace mission applications will be considered. Technologies that address specific NASA Science mission needs include:

- Photovoltaic cell and blanket technologies capable of low intensity, low-temperature operation applicable to outer planetary (low solar intensity) missions.
- Photovoltaic cell, blanket and array technologies capable of enhancing solar array operation in a high

-
- intensity, high-temperature environment (i.e., inner planetary and solar probe-type missions).
 - Solar arrays to support Extreme Environments Solar Power type missions, including long-lived, radiation tolerant, cell and blanket technologies capable of operating in environments characterized by varying degrees of light intensity and temperature.
 - Lightweight solar array technologies applicable to science missions using solar electric propulsion. Current science missions being studied require solar arrays that provide 1 to 20 kilowatts of power at 1 AU, greater than 300 watts/kilogram specific power, operation in the range of 0.7 to 3 AU, low stowed volume, and the ability to provide operational array voltages up to 300 volts.

Stirling Power Conversion: advances in, but not limited to, the following

- Novel Stirling convertor configurations that provide high efficiency (>25%), low mass, long life (>10 yrs), and high reliability for use in 100-500 We Stirling radioisotope generators.
- Advanced Stirling convertor components including hot-end heat exchangers, cold-end heat exchangers, regenerators, linear alternators, engine controllers, and radiators.
- Innovative Stirling generator features that improve the fault tolerance (e.g., heat source backup cooling devices, mechanical balancers) or expand the mission applications (e.g., duplex power and cooling systems).

Direct Energy Conversion; advances in, but not limited to, the following

Recent advancements in alpha/beta-voltaic energy conversion devices have the potential to increase the power level, improve reliability, and increase the lifetime of this power technology. The increased use of cubesat/smallsat technology and autonomous remote sensors in support of NASA Science Mission goals has demonstrated the need for low-power, non-solar energy sources. The area of Direct Energy Conversion seeks technology advancements that address, but are not limited to:

- Experimental demonstration of long life (multiyear) alpha-voltaic and beta-voltaic devices with device-level conversion efficiencies in excess of 10%, high reliability, minimal operational performance degradation, and the ability to scale up to 1-10 W of electrical power output with system-level specific power of 5 W/kg or higher.

Sub Topics:

Propulsion Systems for Robotic Science Missions Topic S3.02

The Science Mission Directorate (SMD) needs spacecraft with more demanding propulsive performance and flexibility for more ambitious missions requiring high duty cycles, more challenging environmental conditions, and extended operation. Planetary spacecraft need the ability to rendezvous with, orbit, and conduct in-situ exploration of planets, moons, and other small bodies in the solar system

(http://solarsystem.nasa.gov/multimedia/download-detail.cfm?DL_ID=742 [21]). Future spacecraft and constellations of spacecraft will have high-precision propulsion requirements, usually in volume- and power-limited envelopes.

This subtopic seeks innovations to meet SMD propulsion in chemical and electric propulsion systems related to sample return missions to Mars, small bodies (like asteroids, comets, and Near-Earth Objects), outer planet moons, and Venus. Additional electric propulsion technology innovations are also sought to enable low cost systems for Discovery class missions, and low-power, nuclear electric propulsion (NEP) missions. Roadmaps for propulsion technologies can be found from the National Research Council

(http://www.nap.edu/openbook.php?record_id=13354&page=168 [22]) and NASA's Office of the Chief Technologist (http://www.nasa.gov/pdf/501329main_TA02-InSpaceProp-DRAFT-Nov2010-A.pdf [23]).

Proposals should show an understanding of the state of the art, how their technology is superior, and of one or more relevant science needs. The proposals should provide a feasible plan to fully develop a technology and infuse it into a NASA program.

Advanced Electric Propulsion Components

This subtopic also seeks proposals that explore uses of technologies that will provide superior performance in for high specific impulse/low mass electric propulsion systems at low cost. These technologies include:

- High thrust-to-power ion thruster component or system technologies. Key characteristics include:
 - Power < 14 kW.
 - T/P > SOA Hall Effect Thrusters at comparable specific impulse ranging from 1500-3000 seconds.
 - Lifetimes > 10,000 hours.
 - Thruster components including, but not limited to, advanced cathodes, rf devices, advanced grids, lower-cost components.
 - Any long-life, electric propulsion technology between 1 to 10 kW/thruster that would enable a low-power nuclear electric propulsion system based on a kilowatt nuclear reactor.
 - Instrumentation and support equipment that will enable or improve ground testing of electric propulsion power processor units.

Secondary Payload Propulsion

The secondary payload market shows significant promise to enable low cost science missions. Launch vehicle providers, like SLS, are considering a large number of secondary payload opportunities. The majority of small satellite missions flown are often selected for concept or component demonstration activities as the primary objectives. Opportunities are anticipated to select future small satellite missions based on application goals (i.e., science return). However, several technology limitations prevent high value science from low-cost small spacecraft, such as post deployment propulsion capabilities. Additionally, propulsion systems often place constraints on handling, storage, operations, etc. that may limit secondary payload consideration. It is desired to have a wide range of Delta-V capability to provide 100-1000s of m/s.

Specifically, proposals are sought for:

- Chemical and/or electric propulsion systems with green/non-toxic propellants,
- RF devices,
- Improved operational life over SOA propulsion systems, and
- 1U sized solar electric ionized gas propulsion unit with delta V of 1-8 km/s for 6U CubeSat, and a clear plan for demonstrated constellation station keeping capability for 6 months in LEO.

In addressing technology requirements, proposers should identify potential mission applications and quantify the expected advancement over state-of-the-art alternatives.

Note to Proposer - Topics under the Human Exploration and Operations Directorate also addresses advanced propulsion. Proposals more aligned with exploration mission requirements should be proposed in H2.

Sub Topics:

Power Electronics and Management, and Energy Storage Topic S3.03

NASA's science

vision (http://science.nasa.gov/media/medialibrary/2014/05/02/2014_Science_Plan-0501_tagged.pdf [24]) is to use the vantage point of space to achieve with the science community and our partners a deep scientific understanding of the Sun and its effects on the solar system, our home planet, other planets and solar system bodies, the interplanetary environment, and the universe beyond. Scientific priorities for future planetary science missions are guided by the recommendations of the decadal surveys published by the National Academies. The goal of the decadal surveys is to articulate the priorities of the scientific community, and the surveys are therefore the starting point for NASA's strategic planning process in science (http://science.nasa.gov/media/medialibrary/2014/04/18/FY2014_NASA_StrategicPlan_508c.pdf [25]). The most recent planetary science decadal survey, Vision and Voyages for Planetary Science in the Decade 2013 - 2022, was released in 2011. This report recommended a balanced suite of missions to enable a steady stream of new discoveries and capabilities to address challenges such as sample return missions and outer planet exploration. Under this subtopic, proposals are solicited to develop energy storage and power electronics to enable or enhance the capabilities of future NASA science missions. The unique requirements for the power systems for these missions can vary greatly, with advancements in components needed above the current State of the Art (SOA) for high energy density, high power density, long life, high reliability, low mass/volume, radiation tolerance, and wide temperature operation. Other subtopics which could potentially benefit from these technology

developments include S4.04 Extreme Environments Technology, and S4.01 Planetary Entry, Descent and Landing Technology. This subtopic is also directly tied to S3.02 Propulsion Systems for Robotic Science Missions for the development of advanced Power Processing Units and associated components.

Power Electronics and Management

NASA's Planetary Science Division is working to implement a balanced portfolio within the available budget and based on the decadal survey that will continue to make exciting scientific discoveries about our solar system. This balanced suite of missions show the need for low mass/volume power electronics and management systems and components that can operate in extreme environment for future NASA Science Missions. In addition, studying the Sun, the heliosphere, and other planetary environments as an interconnected system is critical for understanding the implications for Earth and humanity as we venture forth through the solar system. To that end, the NASA heliophysics program seeks to perform innovative space research missions to understand:

- The Sun and its variable activity.
- How solar activity impacts Earth and the solar system.
- Fundamental physical processes that are important at Earth and throughout the universe by using space as a laboratory.

Heliophysics also seeks to enable research based on these missions and other sources to understand the connections among the Sun, Earth, and the solar system for science and to assure human safety and security both on Earth and as we explore beyond it. Advances in electrical power technologies are required for the electrical components and systems of these future spacecrafts/platforms to address program size, mass, efficiency, capacity, durability, and reliability requirements. Radioisotope power systems (RPS), Advanced Modular Power Systems (AMPS) and In-Space Electric Propulsion (ISP) are several programs of interest which would directly benefit from advancements in this technology area. These types of programs, including Mars Sample Return using Hall thrusters and power processing units (PPUs), require advancements in radiation hardened power electronics, especially tolerant of single event upsets, and systems beyond the state-of-the-art. Of importance are expected improvements in energy density, speed, efficiency, or wide-temperature operation (-125° C to over 450° C) with a number of thermal cycles. Novel approaches to minimizing the weight of advanced PPUs are also of interest. Advancements are sought for power electronic devices, components, packaging and cabling for programs with power ranges of a few watts for minimum missions to up to 20 kilowatts for large missions. In addition to electrical component development, RPS has a need for intelligent, fault-tolerant Power Management and Distribution (PMAD) technologies to efficiently manage the system power for these deep space missions.

Also, in order to maximize functional capability for Earth Observations, operate higher performance instruments and deliver significantly better data and imagery from a small spacecraft, more capable power systems are needed. NASA is interested in a power system (stretch goal of 100w) that can be integrated into a cubesat or nanosat for this purpose. The power system package must be restricted to 6U or 3U volume, and the design should minimize orientation restrictions. The system should be capable of operating for a minimum of 6 months in LEO.

SMD's In-space Propulsion Technology, Radioisotope Power Systems and Cubesat/Nanosat programs are direct customers of this subtopic.

Overall technologies of interest include:

- High power density/high efficiency power electronics and associated drivers for switching elements.
- Non-traditional approaches to switching devices, such as addition of graphene and carbon nano-tubes to material
- Radiation hardened (single event effects), 1200 V (or greater) MOSFETs and high speed diodes for high voltage space missions (300 V average, 600 V peak).
- Lightweight, highly conductive power cables and/or cables integrated with vehicle structures.
- Intelligent power management and fault-tolerant electrical components and PMAD systems.
- Advanced electronic packaging for thermal control and electromagnetic shielding
- Integrated packaging technology for modularity.
- Cubesat/nanosat power systems up to 100 watts

Patent 6,461,944, Methods for growth of relatively large step-free SiC crystal surfaces Neudeck, et al., October 8, 2002.

A method for growing arrays of large-area device-size films of step-free (i.e., atomically flat) SiC surfaces for semiconductor electronic device applications is disclosed. This method utilizes a lateral growth process that better overcomes the effect of extended defects in the seed crystal substrate that limited the obtainable step-free area achievable by prior art processes. The step-free SiC surface is particularly suited for the heteroepitaxial growth of 3C (cubic) SiC, AlN, and GaN films used for the fabrication of both surface-sensitive devices (i.e., surface channel field effect transistors such as HEMT's and MOSFET's) as well as high-electric field devices (pn diodes and other solid-state power switching devices) that are sensitive to extended crystal defects.

Energy Storage

Future science missions will require advanced primary and secondary battery systems capable of operating at temperature extremes from -100° C for Titan missions to 400 to 500° C for Venus missions, and a span of -230° C to +120° C for Lunar Quest. The Outer Planet Assessment Group and the 2011 PSD Relevant Technologies Document have specifically called out high energy density storage systems as a need for the Titan/Enceladus Flagship and planetary exploration missions. In addition, high energy-density rechargeable electrochemical battery systems that offer greater than 50,000 charge/discharge cycles (10 year operating life) for low-earth-orbiting spacecraft, 20 year life for geosynchronous (GEO) spacecraft, are desired. Advancements to battery energy storage capabilities that address one or more of the above requirements for the stated missions combined with very high specific energy and energy density (>200 Wh/kg for secondary battery systems), along with radiation tolerance are of interest.

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

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

Sub Topics:

Unmanned Aircraft and Sounding Rocket Technologies Topic S3.04

Unmanned Aircraft Systems Technologies

Breakthrough technologies are sought that will enhance performance and utility of NASA's Airborne Science fleet with unmanned aircraft systems (UAS). Novel instrumented platforms or innovative subsystems suitable for addressing specific Earth science research goals are desired. Relevant NASA and FAA requirements must be addressed. Potential concepts include:

- Long endurance (~1 month) small UAS for miniature (~2 lb) instrument packages scalable to larger platforms.
- Fuel cell propulsion and high efficiency airframes for high altitude/long endurance (HALE, target ~50 kft, 2 days endurance with 50 lb payload).
- Harsh environment flight (e.g., for volcanic eruptions, fires) including high density altitude (20 kft asl), high turbulence, high temperature (300 to 500° C), significant icing, or corrosive environments.
- Novel flight management approaches such as dynamic soaring, autonomous mission planning, terrain following, or autonomously linking aircraft.
- Small UAS for in-situ cloud measurements.
- Guided dropsondes.
- Airspace monitoring system for small UAS operations.
- Over-the-horizon communications systems with increased bandwidth.

Sounding Rocket Technologies

The NASA Sounding Rockets Program provides low-cost, sub-orbital access to space in support of space and Earth sciences research. NASA utilizes a variety of vehicle systems comprised of surplus and commercially available rocket motors, capable of lofting scientific payloads of up to 1300lbs, to altitudes from 100km to 1500km. NASA launches sounding rocket vehicles worldwide, from both land-based and water-based ranges, based on the science needs to study phenomenon in specific locations. Of particular interest are systems that will enable water recovery of payloads from high altitude flights from locations such as launch ranges at Wallops Island VA or Andoya, Norway. New telemetry approaches are also encouraged. Specific elements may include:

- High speed decelerators.
- Steerable high altitude parachute systems.
- Water recovery aids such as floatation devices, location systems, and robotic capabilities.
- Ruggedized over-the-horizon telemetry systems with increased bandwidth.
- Constellation communication for sub-to-main payload data telemetry
- 10 to 50 MB/s for primary data, 1 to 2 MB/s for sub payloads, ~30 cubic inches (without antenna), with C or S band desired

Sub Topics:

Guidance, Navigation and Control Topic S3.05

NASA seeks innovative, ground breaking, and high impact developments in spacecraft guidance, navigation, and control technologies in support of future science and exploration mission requirements. This subtopic covers the technologies enabling significant performance improvements over the state of the art in the areas of spacecraft attitude determination and control, spacecraft absolute and relative orbit and attitude navigation, pointing control, and SmallSat/CubeSat technologies.

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 all spacecraft platform sizes will be considered. Special considerations will be given to emerging technologies applicable to SmallSat/CubeSat class spacecraft if they are technology leaps and mission enabling.

Advances in the following areas are sought:

- *Spacecraft Attitude Determination and Control Systems* - Sensors and actuators that enable milli-arcsecond class pointing 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 GN&C techniques for enabling the collection of distributed science measurements.
- *Pointing Control Systems* - Mechanisms that enable milli-arcsecond class pointing performance on any spaceborne pointing platforms. Active and passive vibration isolation systems, innovative actuation feedback, or any such technologies that can be used to enable other areas within this subtopic apply.
- *SmallSat/CubeSat Technologies* - Lightweight, low power, compact sensors and actuators that push the state-of-the-art for SmallSat/CubeSat attitude and orbit controls capabilities. Arcsecond-level pointing performance, non-propulsive orbit control, and radiation hardening technologies apply. NASA would like to utilize SmallSat/CubeSat technologies on missions beyond LEO therefore special considerations would be given to proposals addressing those needs.

Phase I research should be conducted to demonstrate technical feasibility as well as show a plan towards Phase II integration and component/prototype testing in a relevant environment. Phase II technology development efforts shall deliver component/prototype at the TRL 5-6 level consistent with NASA SBIR/STTR Technology Readiness Level (TRL) Descriptions. Delivery of final documentation, test plans, and test results are required. Delivery of a hardware component/prototype under the Phase II contract is preferred.

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

Sub Topics:

Terrestrial and Planetary Balloons Topic S3.06

Terrestrial Balloons

NASA's Scientific Balloons provide practical and cost effective platforms for conducting discovery science, development and testing for future space instruments, as well as training opportunities for future scientists and engineers. Balloons can reach altitudes above 36 kilometers, with suspended masses up to 3600 kilograms, and can stay afloat for several weeks. Currently, the Balloon Program is on the verge of introducing an advanced balloon system that will enable 100 day missions at mid-latitudes and thus resemble the performance of a small spacecraft at a fraction of the cost. In support of this development, NASA is seeking innovative technologies in three key areas:

Power Storage

Improved and innovative devices to store electrical energy onboard balloon payloads are needed. Long duration balloon flights can experience 12 hours or more of darkness, and excess electrical power generated during the day from solar panels needs to be stored and used. Improvements are needed over the current state of the art in power density, energy density, overall size, overall mass and/or cost. Typical parameters for balloon are 28 VDC and 100 to 1000 watts power consumption. Rechargeable batteries are presently used for balloon payload applications. Lithium Ion rechargeable batteries with energy densities of 60 watt-hours per kilogram are the current state of the art. Higher power storage energy densities, and power generation capabilities of up to 2000 watts are needed for future support.

Satellite Communications

Improved and innovative downlink bitrates using satellite relay communications from balloon payloads are needed. Long duration balloon flights currently utilize satellite communication systems to relay science and operations data from the balloon to ground based control centers. The current maximum downlink bit rate is 150 kilobits per second operating continuously during the balloon flight. Future requirements are for bit rates of 1 megabit per second or more. Improvements in bit rate performance, reduction in size and mass of existing systems, or reductions in cost of high bit rate systems are needed. TDRSS and Iridium satellite communications are currently used for balloon payload applications. A commercial S-band TDRSS transceiver and 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 under development, but the operational cost is prohibitive.

UV Protection Technologies

Innovative, economic, and applicable processes or materials to protect the balloon flight train subsystems and the balloon components are needed. Long duration balloon missions on the order of 100 days will expose the balloon flight train subsystems such as the parachute, and the balloon components such as the high strength tendons, to the harmful effects of UV exposure. The impact may lead to shorter duration missions and/or severe damage to the science payloads. Innovative concepts are needed for the protection of these subsystems or components to eliminate or minimize these adverse UV effects. The proposed innovative concepts shall be economic and practical. It shall be easy to implement with no major impact on balloon design, fabrication, packaging, or launch operations.

Planetary Balloons

Innovations in materials, structures, and systems concepts have enabled the lifetime of Titan and Venus buoyant vehicles to play an expanding role in NASA's future Solar System Exploration Program. Balloons are expected to carry scientific payloads at Titan and Venus that will perform in-situ investigations of their atmospheres and near surface environments. Both Titan and Venus feature extreme environments that significantly impact the design of balloons for those two worlds and efficient use of energy is critical.

Proposals are sought in the following areas:

Floating Platforms for Venus (New)

NASA is interested in conducting long term monitoring of the Venus atmosphere and the signatures of seismic and volcanic events from the planetary surface using floating vehicles at altitudes of between 30 and 45 km for periods in excess of five years. Concepts that use ammonia or water as a source of buoyancy as well as conventional light gases hydrogen and helium should be considered. A primary focus should be on the design of the flotation device and the materials for achieving long duration operation. The temperature at 45 km is roughly 110° C; at 30 km it is about 225° C. 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.

Altitude and Positional Control for Titan Aerial Vehicles (NEW)

NASA is interested in Titan aerial vehicles that can both change altitude and also execute controlled movements in latitude and longitude in order to target surface locations of interest. Innovative concepts are sought that can minimize the use of scarce power resources and can achieve controlled motions in latitude under all anticipated atmosphere conditions and in longitude for parts of the Titan year. The targeted capabilities for the system are as follows: altitude range between the surface and 15 km, system mass of payload, power and communications systems of 100 kg; average power usage for horizontal and vertical mobility of less than 50 watts. It is expected that a Phase I effort will consist of a complete system-level design and a proof-of-concept experiment on one or more key components.

Sub Topics:

Thermal Control Systems Topic S3.07

Future Spacecraft and instruments for NASA's Science Mission Directorate will require increasingly sophisticated thermal control technology. Innovative proposals for the cross-cutting thermal control discipline are sought in the following areas:

- Components of advanced small spacecraft such as CubeSat/SmallSat will have very small masses (i.e., small thermal capacitance), and their temperatures are highly sensitive to variations in the component power output and spacecraft environmental temperature. Advanced thermal devices capable of maintaining components within their specified temperature ranges are needed. Some examples are:
 - Phase change systems with high thermal capacity and minimal structural mass.
 - High performance, low cost insulation systems for diverse environments.
 - High flux heat acquisition and transport devices; d) thermal coatings with low absorptance, high emittance, and good electrical conductivity; and e) a miniature pumped fluid loop system that is lightweight, provides radiator turndown, and consumes minimal power (< 2W).
- Current capillary heat transfer devices require tedious processes to insert the porous wick into the evaporator and to seal the wick ends for liquid and vapor separation. Advanced technology such as additive manufacturing is needed to simplify the processes and ensure good sealing at both ends of the wick, especially for miniature thermal systems for CubeSat/SmallSat applications. Additive manufacturing technology can also be used to produce integrated heat exchangers for pumped fluid loops in order to increase heat transfer performance while significantly reducing mass, labor and cost.
- Science missions are more dependent on optically sensitive instruments and systems, and effects of thermal distortion on the performance of the system are critical. Current Structural-Thermal-Optical (STOP) analysis has several codes that do some form of integrated analysis, but none that have the capability to analyze any optical system and do a full end-to-end analysis. An improvement of existing code is needed in order to yield software that can integrate with all commonly used programs at NASA for mechanical, structural, thermal and optical analysis. The software should be user-friendly, and allow full STOP analysis for performance predictions based on mechanical design, and structural/thermal material properties.
- Missions with high sink temperatures require temperature lifting devices in order to dissipate the heat. Some advanced devices having long life, high efficiency are sought for, including absorption/adsorption systems, advanced TECs, etc. The use of heat lift devices can also reduce the radiator area, hence realizing mass and volume savings.
- Current analysis for ablation analysis of re-entry vehicles utilizes various computer codes for predicting the following individual phenomena: aeroheating, ablation, thermal response behind the bond line, thermal

radiation, and structural response to thermal and pressure environments. The interfaces between each code lead to potential errors, inaccuracy, and huge computer run time. What is needed is a single code that evaluates the trajectory or input conditions, predicts aeroheating over the surface, does an integrated ablation-thermal analysis, and then uses that thermal and pressure gradient to do a full structural analysis. Even better would be a link back to the aeroheating prediction code to revise the aeroheating based on shape change from structural analysis and ablation.

- New techniques for measuring the internal pressure of arcjet test samples are sought. Modern ablation codes such as FEAR and CHAR solve the Darcy flow equations to track both the internal pyrolysis gas pressure and mass flow. However, there is currently no data available to validate the internal pressure calculations due to a lack of a reliable and accurate measurement system. The internal pressure calculation becomes even more important when analyzing flexible thermal protection system materials which are highly porous.

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

Sub Topics:

Slow and Fast Light Topic S3.08

Steep dispersions in engineered media of a wide variety have opened up a new direction of research in optics. A positive dispersion can be used to slow the propagation of optical pulses to extremely small velocities. Similarly, a negative dispersion can lead to conditions where pulses propagate superluminally. These effects have now moved beyond the stage of intellectual curiosity, and have ushered in studies of a set of exciting applications of interest to NASA, ranging from ultraprecise superluminal gyroscopes to spectral interferometers having enhanced resolving power.

This research subtopic seeks slow-light and/or fast-light enhanced sensors for space applications of interest to NASA including:

Superluminal gyroscopes and accelerometers (both passive and active)

- Enhanced strain and displacement sensors for non-destructive evaluation and integrated vehicle health management applications.
- Slow-light-enhanced spectrally-resolved interferometers for astrophysical and Earth science observations, as well as for exploration goals.
- Other applications of slow and fast light related to NASA's mission areas.

Superluminal gyroscopes

In conventional ring laser gyroscopes, sensitivity increases with cavity size. Fast light, however, can be used to increase gyro sensitivity without having to increase size, for spacecraft navigation systems which are constrained by weight and volume. The increased sensitivity also opens up new science possibilities such as detection of subsurface geological features, tests of Lorentz invariance, improving the bandwidth sensitivity product for gravity wave detection, and tests of general relativity. This research subtopic seeks:

- Prototype fast light gyroscopes, active or passive, that unambiguously demonstrate a scale factor enhancement of at least 10 with the potential for 1000. The minimum or quantum-noise limited angular random walk (ARW) should also decrease.
- Designs for fast light gyros that do not require frequency locking, are not limited to operation at specific frequencies such as atomic or material resonances, and permit operation at any wavelength.
- Fast light gyroscope designs that are rugged, compact, monolithic, rad-hard, and tolerant to variations in temperature and varying G-conditions.

Slow-light enhanced spectral interferometers

Slow light has the potential to increase the resolving power of spectral interferometers such as Fourier transform spectrometers (FTS) for astrophysical applications without increasing their size. Mariner, Voyager, and Cassini all used FTS instruments for applications such as mapping atmospheres and examining ring compositions. The niche for FTS is usually thought to be for large wavelength (IR and beyond), wide-field, moderate spectral resolution instruments. Slow light, however, could help boost FTS spectral resolution making FTS instruments more competitive with grating-based instruments, and opening up application areas not previously thought to be accessible to FTS instruments, such as exoplanet detection. A slow-light FTS could also be hyper-spectral, providing imaging capability. FTS instruments have been employed for remote sensing on NASA Earth Science missions, such as the Atmospheric Trace Molecule Spectroscopy (ATMOS), Cross-track Infrared Sounder (CrIS), and Tropospheric Emission Spectrometer (TES) experiments, and have long been considered for geostationary imaging of atmospheric greenhouse gases. This research subtopic seeks research and development of slow-light-enhanced spectral interferometers that are not restricted by material resonances and can operate at any wavelength. An inherent advantage of FTS systems are their wide bandwidth. It will therefore be of importance to develop slow light FTS systems that can maintain a large operating bandwidth.

Sub Topics:

Command, Data Handling, and Electronics Topic S3.09

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

The 2016 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 science 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. Proposals should clearly:
 - State what the product is.
 - Identify the needs it addresses.
 - Identify the improvements over the current state of the art.
 - Outline the feasibility of the technical and programmatic approach.
 - Present how it could be infused into a NASA program.

Furthermore, proposals developing hardware should indicate an understanding of the intended operating environment, including temperature and radiation. It should be noted that environmental requirements can vary significantly from mission to mission. For example, some low earth orbit missions have a total ionizing dose (TID) radiation requirement of less than 10 krad(Si), while some planetary missions can have requirements well in excess of 1 Mrad(Si). For descriptions of radiation effects in electronics, the proposer may visit (<http://radhome.gsfc.nasa.gov/radhome/overview.htm> [26]).

If a Phase II proposal is awarded, the combined Phase I and Phase II developments should produce a prototype that can be characterized by NASA.

The technology priorities sought are listed below:

- *Spaceflight Multicore Middleware* - Current and emerging spaceflight processors are leveraging multi-core architectures to satisfy the ever increasing onboard processing demands. These architectures can provide increased processing bandwidth, power efficiency, and fault tolerance for onboard processing applications. However, these advantages come at the cost of increased hardware and software complexity. As software development is a major cost driver for missions, this increased complexity has the potential to significantly increase cost for future NASA missions. To address this risk, this subtopic solicits Spaceflight Multicore Middleware technology providing machine management for multicore processing devices. This middleware software layer shall primarily reside between the application layer and the operating system, with extensions into and below the OS as necessary, to provide intelligent resource, fault, and power management. By providing these functions, application software can be largely agnostic to underlying hardware, thereby reducing cost and complexity. It is desired that the middleware software support multiple

processor architectures. Examples include, but not limited to, ARM, Freescale, Tiler, and LEON, and those that support a number of cores ranging from 2-32.

- *Advanced Spaceflight Memory* - As spaceflight processor technology advances to provide increased bandwidth, power efficiency, and flexibility, advanced spaceflight memory devices are needed to fully leverage these improvements. This subtopic solicits technologies enabling power efficient, high performance volatile spaceflight memory incorporating high speed, fault tolerant, serial interfaces, internal EDAC, power and fault management, and 2.5/3D manufacturing processes enabling implementation of miniaturized, highly-reliable fault tolerant systems.
- *Point-of-Load Power Converters* - Emerging spaceflight processors require multiple supply voltages, and multiple switched services for many of these voltages. Using currently available point-of-load power converters, an unacceptably large portion of future spaceflight computer boards will need to be dedicated for these devices. To address this concern, this subtopic solicits technologies enabling miniaturized spaceflight point-of-load power conversion and switching.
- *Radiation Shielding* - Innovative additive manufacturing and/or deposition technologies starting at TRL 3 are sought to create integral one-piece surface claddings of graded atomic number (Z) materials for use as radiation shielding for electronics. Shielding thicknesses must be able to achieve up to 3 g/cm² for initial shielding applications. At the end of Phase I, delivery of layered slabs and/or half sphere samples is expected with areal densities from 1 -3 g/cm²; samples must be able to show a strong interface property to avoid delamination and consistent density and thickness (areal density) uniformity.

This subtopic also solicits technologies enabling the use of COTS micropower/ultra-low power computing devices in highly reliable spacecraft avionics systems.

Sub Topics:

Planetary Entry, Descent and Landing and Small Body Proximity Operation Technology Topic S4.01
NASA seeks innovative sensor technologies to enhance success for entry, descent and landing (EDL) operations on missions to other planetary bodies, including Earth's Moon, Mars, Venus, Titan, Europa, and proximity operations (including sampling and landing) on small bodies such as asteroids and comets.

Sensing technologies are desired that determine any number of the following:

- Terrain relative translational state (altimetry/3-axis velocimetry).
- Spacecraft absolute state in planetary/small-body frame (either attitude, translation, or both).
- Terrain point cloud (for hazard detection, absolute state estimation, landing/sampling site selection, and/or body shape characterization).
- Atmosphere-relative measurements (velocimetry, pressure, temperature, flow-relative orientation).

NASA also seeks to use measurements made during EDL to better characterize the atmosphere of planetary bodies, providing data for improving atmospheric modeling for future landers or ascent vehicles.

Successful candidate sensor technologies can address this call by:

- Extending the dynamic range over which such measurements are collected (e.g., providing a single surface topology sensor that works over a large altitude range such as 1m to >10km, and high attitude rates such as greater than 45° /sec).
- Improving the state-of-the-art in measurement accuracy/precision/resolution for the above sensor needs.
- Substantially reducing the amount of external processing needed by the host vehicle to calculate the measurements.
- Significantly reducing the impact of incorporating such sensors on the spacecraft in terms of Size, Weight, and Power (SWaP), spacecraft accommodation complexity, and/or cost.
- Providing sensors that are robust to environmental dust/sand/illumination effects.
- Mitigation technologies for dust/particle contamination of optical surfaces such as sensor optics, with possible extensibility to solar panels and thermal surfaces for Lunar, asteroid, and comet missions.

For all the aforementioned technologies, candidate solutions are sought that can be made compatible with the environmental conditions of deep spaceflight, the rigors of landing on planetary bodies both with and without atmospheres, and planetary protection requirements.

NASA is also looking for high-fidelity real-time simulation and stimulation of passive and active optical sensors for computer vision at update rates greater than 2 Hz to be used for signal injection in terrestrial spacecraft system test beds. These solutions are to be focused on improving system-level performance Verification and Validation during spacecraft assembly and test.

NASA also seeks low-mass (on the order of the density of the fabric itself), fabric-and/or-fiber-embedded sensors and time-synchronized, distributed data collection systems (preferably less than 30 grams total) to measure the time history of load/stress/strain distributed across large (30+ meters), trailing-body deployable decelerator technologies such as parachutes and ballutes. The distributed sensors and data collection systems must be self-powered and capable of being pressure-packed into a compressed mortar canister installation package and stored for up to 1 year or more. All sensors and data collection packages in the distributed system are to record time-stamped peak sensor values and time histories, with time-stamp accuracies not to exceed 4 milliseconds relative to a central vehicle data collection system using IRIG and GPS technology for time-stamping and synchronization. Packages must survive the parachute deployment and inflation events and if data is stored locally on the individual devices, survive recovery from the ocean after many hours of immersion in seawater.

Submitted proposals should show an understanding of the current state of the art of the proposed technology and present a feasible plan to improve and infuse it into a NASA flight mission.

Sub Topics:

Robotic Mobility, Manipulation and Sampling Topic S4.02

Technologies for robotic mobility, manipulation, and sampling are needed to enable access to sites of interest and acquisition and handling of samples for in-situ analysis or return to Earth from planetary and solar system small bodies including Mars, Venus, comets, asteroids, and planetary moons (both rocky and icy).

Mobility technologies are needed to enable access to steep and rough terrain for planetary bodies where gravity dominates, such as the Moon and Mars. 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 in micro-gravity environments and access to liquid bodies below the surface such as in conduits and deep oceans are desired, as well as associated sampling technologies. Manipulation technologies are needed to deploy sampling tools to the surface and transfer samples to in-situ instruments and sample storage containers, as well as hermetic sealing of sample chambers. On-orbit manipulation of a Mars sample cache canister is needed from capture to transfer into an Earth Entry Vehicle. 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.

Contamination control and planetary protection are important considerations for sample acquisition and handling technologies. Contamination may include Earth-source contaminants produced by the sampling tool, handling system, or deposited on the sampling location from another source on the rover or spacecraft. Cleaning to Sterility technologies are needed that will be compatible with spacecraft materials and processes. Surface cleaning validation methods are needed that can be used routinely to quantify trace amounts ($\sim\text{ng}/\text{cm}^2$) of organic contamination and submicron particle ($\sim 100\text{nm}$ size) contamination. Priority will be given to cleaning and sterilization methods that have potential for in-situ applications.

Component technologies for low-mass and low-power systems tolerant to the in-situ environment are of particular interest. Technical feasibility should be demonstrated during Phase I and a full capability unit of at least TRL 4 should be delivered in Phase II. Proposals should show an understanding of relevant science needs and engineering constraints and present a feasible plan to fully develop a technology and infuse it into a NASA program. Specific areas of interest include the following:

- Surface and subsurface sampling systems for planets, small bodies, and moons.
- Small body anchoring systems.
- Low mass/power vision systems and processing capabilities that enable fast surface traverse.
- Electro-mechanical connectors enabling tool change-out in dirty environments.
- Tethers and tether play-out and retrieval systems.
- Miniaturized flight motor controllers.
- Cleaning to sterility technologies that will be compatible with spacecraft materials and processes.
- Surface cleaning validation technology to quantify trace amount ($\sim\text{ng}/\text{cm}^2$) of organic contamination and submicron particle ($\sim 100\text{nm}$ size) contamination.

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- Sample handling technologies that minimize cross contamination and preserve mechanical integrity of samples.

Sub Topics:

Spacecraft Technology for Sample Return Missions Topic S4.03

NASA plans to perform sample return missions from a variety of scientifically important targets including Mars, small bodies such as asteroids and comets, and outer planet moons. These types of targets present a variety of spacecraft technology challenges.

Some targets, such as Mars and some moons, have relatively large gravity wells and will require ascent propulsion. Includes propellants that are transported along with the mission or propellants that can be generated using local resources.

Other targets are small bodies with very complex geography and very little gravity, which present difficult navigational and maneuvering challenges.

In addition, the spacecraft will be subject to extreme environmental conditions including low temperatures (-270°C), dust, and ice particles.

Technology innovations should either enhance vehicle capabilities (e.g., increase performance, decrease risk, and improve environmental operational margins) or ease sample return mission implementation (e.g., reduce size, mass, power, cost, increase reliability, or increase autonomy).

Sub Topics:

Extreme Environments Technology Topic S4.04

NASA is interested in expanding its ability to explore the deep atmosphere and surface of giant 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 planets. Proposals are sought for technologies that are suitable for remote sensing applications at cryogenic temperatures, and in-situ atmospheric and surface explorations in the high-temperature high-pressure environment at the Venusian surface (485 °C, 93 atmospheres), or in low-temperature environments such as Titan (-180 °C), Europa (-220 °C), Ganymede (-200 °C), Mars, the Moon, asteroids, comets and other small bodies. Also Europa-Jupiter missions may have a mission life of 10 years and the radiation environment is estimated at 2.9 Mega-rad total ionizing dose (TID) behind 0.1 inch thick aluminum. Proposals are sought for technologies that enable NASA's long duration missions to extreme wide-temperature and cosmic radiation environments. High reliability, ease of maintenance, low volume, low mass, and low out-gassing characteristics are highly desirable. Special interest lies in development of following technologies that are suitable for the environments discussed above:

- Wide temperature range precision mechanisms i.e., 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-arc-second/nanometer precision.
- Long life, long stroke, low power, and high torque/force actuators with sub-arc-second/nanometer precision.
- Long life Bearings/tribological surfaces/lubricants.
- High temperature energy storage systems.
- High-temperature actuators and gear boxes for robotic arms and other mechanisms.
- Low-power and wide-operating-temperature radiation-tolerant /radiation hardened RF electronics.
- Radiation-tolerant/radiation-hardened low-power/ultra-low-powerwide-operating-temperature low-noise mixed-signal electronics for space-borne system such as guidance and navigation avionics and instruments.
- Radiation-tolerant/radiation-hardened power electronics.
- Radiation-tolerant/ radiation-hardened electronic packaging (including, shielding, passives, connectors, wiring harness and materials used in advanced electronics assembly).

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

Sub Topics:

Contamination Control and Planetary Protection Topic S4.05

A need to develop technologies to implement Contamination Control and Planetary Protection requirements has emerged in recent years with increased interest in investigating bodies with the potential for life detection such as Europa, Enceladus, Mars, etc. and the potential for sample return from such bodies. Planetary Protection is concerned with both 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 Planetary Protection requirements as well as analytical technologies that can ensure hardware and instrumentation can meet organic contamination requirements in an effort to preserve sample science integrity.

For contamination control efforts, analytical technologies and techniques for quantifying submicron particle and organic contamination for validating surface cleaning methods are needed. In particular, capabilities for measuring Total Organic Carbon (TOC) at $\ll 40$ ppb or $\ll 20$ ng/cm² on a surface and detection of particles < 0.2 microns in size are being sought. In addition, techniques for detection of one or more of the following molecules and detection level are being needed:

- DNA (1 fmole).
- Dipicolinic acid (1 pg).
- N-acetylglucosamine (1 pg).
- Glycine and alanine (1 pg).
- Palmitic acid (1 pg).
- Squalene (1 pg).
- Pristane (1pg).
- Chlorobenzene (< 1 pg).
- Dichloromethane (< 1 pg).
- Naphthalene (1 pg).

For many missions, Planetary Protection requirements are often implemented in part by processing hardware or potentially entire spacecraft with one or more sterilization processes. These processes are often incompatible with particular materials or components on the spacecraft and extensive effort is made to try to mitigate these issues. Innovative new or improved sterilization/re-sterilization processes are being sought for application to spacecraft hardware to increase effectiveness of reducing bio-load on spacecraft or increase process compatibility with hardware (e.g., toxicity to hardware, temperature, duration, etc.). Accepted processes currently include heat processing, gamma/electron beam irradiation, cold plasma, and vapor hydrogen peroxide. Options to improve materials and parts (e.g., sensors, seals, in particular, batteries, valves, and optical coatings) to be compatible with currently accepted processes, in particular heat tolerance, are needed. NASA is seeking novel technologies for preventing recontamination of sterilized components or spacecraft as a whole (e.g., biobarriers). In addition, 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 sterilization approaches (e.g., UV or plasma) for surfaces are desired.

Missions planning sample return from bodies such as Mars, Europa, and Enceladus are faced with developing technologies for sample return functions to assure containment of material from these bodies. Thus far, concepts have been developed specifically for Mars sample return but no end-to-end concepts have been developed that do not have technical challenges remaining in one or more areas. Options for sample canisters with seal(s) (e.g., brazing, explosive welding, soft) with sealing performed either on surface or in orbit and capability to verify seal(s), potentially by leak detection are needed. In addition, capability is needed for opening seals while maintaining sample integrity upon Earth return. These technologies need to be compatible with processes the materials may encounter over the lifecycle of the mission (e.g., high temperature heating). Containment assurance also requires technologies to break-the-chain of contact with the sampled body. Any native contamination on the returned sample container and/or Earth return vehicle must be either be fully contained, sterilized, or removed prior to return to Earth, therefore, technologies or concepts to mitigate this contamination are desired. Lightweight shielding technologies are also needed for meteoroid protection for the Earth entry vehicle and sample canister with capability to detect damage or breach to meet a 10^{-6} probability of loss of containment.

Sub Topics:

Technologies for Large-Scale Numerical Simulation Topic S5.01

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 on 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 should engage in direct interactions with one or both HEC projects, and with key HEC users where appropriate. Research should be conducted to demonstrate technical feasibility and NASA relevance during Phase I and show a path toward a Phase II prototype demonstration.

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

- HEC systems operating behind a firewall to meet strict IT security requirements.
- Communication-intensive applications.
- Massive computations requiring high concurrency.
- Complex computational workflows and immense datasets.
- The need to support hundreds of complex application codes - many of which are frequently updated by the user/developer.

As a result, solutions that involve the following must clearly explain how they would work in the NASA environment:

- Technologies involving elements operating outside of the NASA supercomputing firewall.
- Embarrassingly parallel computations.
- Technologies that require significant application re-engineering.

Projects need not benefit all NASA HEC users or application codes, but demonstrating applicability to an important NASA discipline, or even a key NASA application code, could provide significant value.

Specific technology areas of interest:

- *Efficient Computing* - In spite of the rapidly increasing capability and efficiency of supercomputers, NASA's HEC facilities cannot purchase, power, and cool sufficient HEC resources to satisfy all user demands. This subtopic element seeks dramatically more efficient and effective supercomputing approaches in terms of their ability to supply increased HEC capability or capacity per dollar and/or per Watt for real NASA applications. Examples include: novel computational accelerators and architectures; cloud supercomputing with high performance interconnects (e.g., InfiniBand); enhanced visualization technologies; improved algorithms for key codes; power-aware "Green" computing technologies and techniques; and approaches to effectively manage and utilize many-core processors including algorithmic changes, compiler techniques

and runtime systems.

- *User Productivity Environments* - The user interface to a supercomputer is typically a command line in a text window. This subtopic element seeks more intuitive, intelligent, user-customizable, and integrated interfaces to supercomputing resources, enabling users to more completely leverage the power of HEC to increase their productivity. Such an interface could enhance many essential supercomputing tasks: accessing and managing resources, training, getting services, developing and porting codes (e.g., debugging and performance analysis), running computations, managing files and data, analyzing and visualizing results, transmitting data, collaborating, etc.
- *Ultra-Scale Computing* - Over the next decade, the HEC community faces great challenges in enabling its users to effectively exploit next-generation supercomputers featuring massive concurrency to the tune of millions of cores. To overcome these challenges, this subtopic element seeks ultra-scale computing technologies that enable resiliency/fault-tolerance in extreme-scale (unreliable) systems both at job startup and during execution. Also of interest are system and software co-design methodologies, to achieve performance and efficiency synergies. Finally, tools are sought that facilitate verification and validation of ultra-scale applications and systems.

Sub Topics:

Earth Science Applied Research and Decision Support Topic S5.02

The NASA Applied Sciences Program (<http://nasascience.nasa.gov/earth-science/applied-sciences> [29]) seeks innovative and unique approaches to increase the utilization and extend the benefit of Earth Science research data to better meet societal needs. One area of interest is new decision support tools and systems for a variety of ecological applications such as managing coastal environments, natural resources or responding to natural disasters.

Currently, creating decision support tools (DST) that effectively utilize remote sensing data requires significant efforts by experts in multiple domains. This creates a barrier to the widespread use of Earth observations by state and local governments, businesses, and the public. This subtopic aims to democratize the creation of Earth science driven decision support tools and to unleash a creative explosion of DST development that significantly increases the return on investment for Earth science missions.

Specifically, this subtopic develops core capabilities that can be integrated to build multiple remote sensing driven DSTs customized to the requirements of different users in varied fields. Proven development and commercialization strategies will be used to meet these objectives. Similar to Eclipse, this subtopic will create an open-source DST development framework that enables components from multiple providers to be seamlessly integrated. This subtopic will also create software components that plug into the framework and open source tools that help users create new components. The components will provide functionality ranging from basic operations, such as retrieval of data meeting user-specified criteria from online repositories and visualization, to sophisticated data processing and analysis algorithms, such as atmospheric correction, data fusion, computational model interfaces, and machine learning based quality control.

To expedite DST development and deployment by knowledgeable users, this subtopic seeks an open source graphical workflow tool, similar to Labview or Simulink, which enables well informed users to quickly create a functional DST from a catalog of software components. Ultimately, a more sophisticated graphical workflow development tool, similar to MIT's Scratch would enforce functionally, but not necessarily logically, "correct by construction" rules that would enable a broad population of people to successfully create DSTs. Open source and commercial components, as well as services, will be available through an online "store" similar to iTunes or Google Play.

The framework, components and resulting DSTs should be able to run in a commercial cloud such as Amazon EC2 or Google Compute Engine. Cloud enabled components and DSTs, those that can intelligently take advantage of flexible computing resources for processing, analysis, visualization, optimization, etc. are highly desired.

Ideally, users should be able to create, configure deploy DSTs, and view outputs such as status, reports, alerts, plots, maps, etc. via desktop computers (Windows 7 and OS X) as well as tablet and smart phones running recent versions of Android (4.0 and later) and iOS (5.0 and later). An HTML5 web application in a standards compliant browser, such as Chrome, can provide the required level of interoperability and capability. Due to serious security issues, Java and Flash based approaches will not be considered.

Sub Topics:

Enabling NASA Science through Large-Scale Data Processing and Analysis Topic S5.03

The size of NASA's observational data sets is growing dramatically as new mission data become available. In addition, NASA scientists continue to generate new models that regularly produce data sets of hundreds of terabytes or more. It is growing increasingly difficult for NASA to effectively analyze such large data sets for use within their science projects.

The following lists show representative examples of both observational and model generated data sets that are relevant to NASA science projects. This list is not meant to be all-inclusive, but rather to provide examples of data sets and to show the extent of the “Big Data” problems encountered by NASA. Some remote observation examples are the following:

- The HypsIRI mission is expected to produce an average science data rate of 800 million bits per second (Mbps).
- JPSS-1 will be 300 Mbps and NPP is already producing 300 Mbps, compared to 150 Mbps for the EOS-Terra, Aqua and Aura missions.
- SDO with a rate of 150 Mbps and 16.4 Gigabits for a single image from the HiRise camera on the Mars Reconnaissance Orbiter (MRO).
- Landsat and MODIS data sets continue to grow at extremely high rates.
- National Geospatial Agency (NGA) high-resolution imagery data of the Earth.

From the NASA climate models, some examples include:

- The MERRA2 reanalysis data set is approximately 400 TB.
- Several high-resolution nudged and free running climate simulations have generated Petabytes of data (all publically releasable).

This subtopic area seeks innovative, unique, forward-looking, and replicable approaches for using “Big Data” for NASA science programs. The emphasis of this subtopic is on the creation of novel analytics, tools, and infrastructure to enable high performance analytics across large observational and model data sets. *Proposals should be in alignment with existing and/or future NASA science programs*, and the reuse of existing NASA assets is strongly encouraged.

Specifically, innovative proposals are being sought to assist NASA science in the following areas (note that this list is not inclusive and is included to provide guidance for the proposers):

- New services and methods for high performance analytics that scale to extremely large data sets – of specific interest are the following:
 - Techniques for data mining, searching, fusion, subsetting, discovery, and visualization
 - Automated derivation of analysis products in large data sets, that can then be utilized into Science models – the following are two representative examples
 - Extraction of features (e.g., volcanic thermal measurement, plume measurement, automated flood mapping, disturbance mapping, change detection, etc.).
 - Geospatial and temporal correlation of climate events (e.g., hurricanes, mesoscale convective systems, atmospheric rivers, etc.).
- Methods to enable in-situ, data proximal, parallel data analytics that will accelerate the access, analysis, and distribution of large Science datasets.
 - Potential use of open source data analytic tools (such as Hadoop, MapReduce, Spark, etc.) to accelerate analytics.
 - Application of these tools to structured, binary, scientific data sets.
 - Performing analytics across both physically collocated and geographically distributed data.
 - High performance file systems and abstractions, such as the use of object storage file systems.

Research proposed to this subtopic should demonstrate technical feasibility during Phase I, and in partnership with scientists, 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 software that is infused into NASA programs and projects.

Tools and products developed under this subtopic may be developed for broad public dissemination or used within a narrow scientific community. These tools can be plug-ins or enhancements to existing software, on-line data/computing services, or new stand-alone applications or web services, provided that they promote interoperability and use standard protocols, file formats, and Application Programming Interfaces (APIs).

Sub Topics:

Integrated Science Mission Modeling Topic S5.04

NASA seeks innovative systems modeling methods and tools to:

- 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. The capabilities should also allow for easier integration of disparate model types and be compatible with current agile design processes.
- Enable disciplined system analysis for the design of future missions, including modeling of decision support for those missions and integrated models of technical and programmatic aspects of future missions. Such models might also be made useful to evaluate technology alternatives and impacts, science valuation methods, and programmatic and/or architectural trades.

Specific areas of interest are listed below. Proposers are encouraged to address more than one of these areas with an approach that emphasizes integration with others on the list:

- Conceptual phase modeling and tools that assist design teams to 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 that are able to easily compare architectural variants of systems.
- Capabilities to rapidly and collaboratively generate models of function or behavior of complex systems, at either the system or 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 design efforts at the conceptual and preliminary design phases, while being compatible with transition to later phases.
 - 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).
- Processes, tools, and infrastructure to support modeling-as-design paradigms enabled by emerging model-based engineering (MBE) capabilities. MBE approaches allow a paradigm shift whereby integrated modeling becomes the inherent and explicit act of design, rather than a post hoc effort to represent designs converged using traditional methods. Modeling-as-design processes will first instantiate changes and/or refinements to models at all relevant levels, accompanied by frequent simulations that drive the integrated models to elicit performance of the system being designed.
- Target models (e.g., phenomenological or geophysical models) that represent planetary surfaces, interiors, atmospheres, etc. and associated tools and methods that allow them to be integrated into system design models and processes such that instrument responses can be simulated and used to influence design. These models may be algorithmic or numeric, but they should be useful to designers wishing to optimize systems' remote sensing of those planets.

Sub Topics:

Fault Management Technologies Topic S5.05

As science missions are given increasingly complex goals and have more pressure to reduce operations costs, system autonomy increases. Fault Management (FM) is one of the key components of system autonomy. FM consists of the operational mitigations of spacecraft failures. It is implemented with spacecraft hardware, on-board autonomous software that controls hardware, software, information redundancy, and ground-based software and operations procedures.

Many recent Science Mission Directorate (SMD) missions have encountered major cost overruns and schedule slips during test and verification of FM functions. These overruns are due to a lack of understanding of FM functions early in the mission definition cycles and to FM architectures that do not provide attributes of transparency, verifiability, fault isolation capability, or fault coverage. The NASA FM Handbook is under development to improve the FM design, development, verification and validation and operations processes. FM approaches, architectures, and tools are needed to improve early understanding of needed FM capabilities by project managers and FM engineers and to improve the efficiency of implementing and testing FM.

Specific objectives are to:

- Improve the ability to predict FM system complexity and estimate development and operations costs.
- Enable cost-effective FM design architectures and operations.
- Determine completeness and appropriateness of FM designs and implementations.
- Decrease the labor and time required to develop and test FM models and algorithms.
- Improve visualization of the full FM design across hardware, software, and operations procedures.
- Determine extent of testing required, completeness of verification planned, and residual risk resulting from incomplete coverage.
- Increase data integrity between multi-discipline tools.
- Standardize metrics and calculations across FM, SE, S&MA and operations disciplines.
- Increase reliability of FM systems.

Expected outcomes are better estimation and control of FM complexity and development costs, improved FM designs, and accelerated advancement of FM tools and techniques.

The approach of this subtopic is to seek the right balance between sufficient reliability and cost appropriate to the mission type and risk posture. Successful technology development efforts under this subtopic would be considered for follow-on funding by, and infusion into, SMD missions. Research should be conducted to demonstrate technical feasibility and NASA relevance during Phase I and show a path toward a Phase II prototype demonstration.

Offerors should demonstrate awareness of the state-of-the-art of their proposed technology, and should leverage existing commercial capabilities and research efforts where appropriate.

Specific technology in the forms listed below is needed to increase delivery of high quality FM systems. These approaches, architectures and tools must be consistent with and enable the NASA FM Handbook concepts and processes:

- *FM Design Tools* - System modeling and analyses significantly contributes to the quality of FM design; however, the time it takes to translate system design information into system models often decreases the value of the modeling and analysis results. Examples of enabling techniques and tools are modeling automation, spacecraft modeling libraries, expedited algorithm development, sensor placement analyses, and system model tool integration.
- *FM Visualization Tools* - FM systems incorporate hardware, software, and operations mechanisms. The ability to visualize the full FM system and the contribution of each mechanism to protecting mission functions and assets is critical to assessing the completeness and appropriateness of the FM design to the mission attributes (mission type, risk posture, operations concept, etc.). Fault trees and state transition diagrams are examples of visualization tools that could contribute to visualization of the full FM design.
- *FM Verification and Validation Tools* - As complexity of spacecraft and systems increases, the extensiveness of testing required to verify and validate FM implementations can be resource intensive. Automated test case development, false positive/false negative test tools, model verification and validation tools, and test coverage risk assessments are examples of contributing technologies.
- *FM Design Architectures* - FM capabilities may be implemented through numerous system, hardware, and software architecture solutions. The FM architecture trade space includes options such as embedded in the flight control software or independent onboard software; on board versus ground-based capabilities; centralized or distributed FM functions; sensor suite implications; integration of multiple FM techniques; innovative software FM architectures implemented on flight processors or on Field Programmable Gate Arrays (FPGAs); and execution in real-time or off-line analysis post-operations. Alternative architecture choices such as model-based approaches could help control FM system complexity and cost and could

offer solutions to transparency, verifiability, and completeness challenges.

- *Multi-discipline FM Interoperation* - FM designers, Systems Engineering, Safety and Mission Assurance, and Operations perform analyses and assessments of reliabilities, failure modes and effects, sensor coverage, failure probabilities, anomaly detection and response, contingency operations, etc. The relationships between multi-discipline data and analyses are inconsistent and misinterpreted. Resources are expended either in effort to resolve disconnects in data and analyses or worse, reduced mission success due to failure modes that were overlooked. Solutions that address data integrity, identification of metrics, and standardization of data products, techniques and analyses will reduce cost and failures.

Sub Topics:
