



NASA SBIR 2017 Phase I Solicitation

Science

S1.01 Lidar Remote Sensing Technologies

Lead Center: JPL

Participating Center(s): JPL, LaRC

Technology Area: TA15 Aeronautics

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 2017 SBIR Program, NASA is soliciting the component and subsystem technologies described below:

- Compact and rugged single-frequency continuous-wave and pulsed lasers operating between 290 nm and 2.05 micrometer wavelengths suitable for Lidar. Specific wavelengths of interest to match absorption lines or atmospheric transmission: 0.29 – 0.32 micrometer (ozone absorption), 0.45 – 0.049 micrometer (ocean sensing), 0.532 micrometer, 0.815 micrometer (water line), 1.0 micrometer, 1.57 micrometer (CO₂ line), 1.65 micrometer (methane line), and 2.05 micrometer (CO₂ line). Architectures involving new developments in diode laser, quantum cascade laser, and fiber laser technology are especially encouraged. For pulsed lasers two different regimes of repetition rate and pulse energies are desired: from 1 kHz to 10 kHz with pulse energy greater than 1 mJ and from 20 Hz to 100 Hz with pulse energy greater than 100 mJ.
- Optical amplifiers for increasing the energy of pulsed lasers in the wavelength range of 0.28 micrometer to 2.05 micrometer. Specific wavelengths of interest are listed in the above bullet. 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 micrometer wavelength, consisting of the detection device, complete Dewar/cooling systems, and associated amplifiers. General requirements are: large single-element active detection diameter (>200 micrometer), 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 with a size, weight, and power substantially less than 28x28x26 cm³, 7.4 kg, and 17 W respectively. Technologies that 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.
- Fast laser beam steering mechanism to increase the sampling density, coverage, and signal to noise ratio of pulsed space-based Lidar. The mechanism needs to steer a 1064 nm pulsed laser beam through a set of at least 8 discrete and repeatable angles spanning a range of 10 mrad or greater along one dimension. The scan repetition rate needs to be 8 kHz or higher. Desired specifications include a pointing accuracy of 0.1 mrad or better, a settling time of <15 microseconds to switch between two angles apart, and a usable aperture of 10 mm (can be achieved using a beam expander as long as the outgoing beam meets all requirements).

S1.02 Technologies for Active Microwave Remote Sensing

Lead Center: JPL

Participating Center(s): GSFC

Technology Area: TA15 Aeronautics

NASA employs active microwave sensors for a wide range of remote sensing applications (for example, see <http://www.nap.edu/catalog/11820.html> [1]). These sensors include low frequency (less than 10 MHz) radar sounders to G-band (160 GHz) radars for measuring precipitation and clouds, for planetary landing, upper atmospheric monitoring, surface water monitoring, soil moisture 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 future radar missions and applications. The areas of interest for this call are listed below.

Deployable High-Frequency Antenna Technologies for CubeSats, NanoSats or SmallSats

Novel technologies are sought that enable X, Ku, Ka, W-band deployable antennas for small spacecraft, exceeding an effective deployed area of 3U or 30 cm x 30 cm. Techniques, hardware, electronics, materials, etc. are sought to advance the state of art in deployable high-frequency antennas for CubeSats, NanoSats or SmallSats.

Deployable Low-Frequency Antenna Technologies for CubeSats, Nano Sats or SmallSats

Novel technologies are sought that enable HF, VHF, UHF deployable, electrically large antennas (half-wavelength or greater) for small spacecraft. Techniques, hardware, electronics, materials, etc. are sought to advance the state of art in deployable low frequency antennas for CubeSats, NanoSats or SmallSats.

Efficient X-band High Power Amplifiers

Amplifiers for high power X-band radar remote sensing instruments are sought that push the state of art in efficiency, size and RF power. Solid state technologies, such as GaN are expected, but new developments in tube-based amplifiers (TWT, Pentode, etc.) are welcome. Technologies requiring high voltage power supplies (>>50V), should include challenges in power supply development.

Efficiency: >40% PAE

Output Power: >400W peak

Pulsed: ~30% duty cycle

Bandwidth: >50MHz

Deployable Cylindrical Parabolic Antenna including feed support structure

A singly-curved, offset fed parabolic antenna with feed structure to support a linear array feed (along the non-curved dimension) will be used to demonstrate advanced scanning cloud and precipitation radar operating at Ka- and W-band.

Frequency Range: 35 GHz, 94 GHz. Minimum Aperture Size: 1m x 2m (larger desirable)

Stowed Volume: 20cm x 20cm x 100 cm

Compact and modular backend radar subsystems for Cube/Small-Sats

Up/down converters: Ka, Ku, X, L to baseband

Receiver/ADCs: multichannel, >2GS/s, 12-bits or greater

Digital Processors: FPGA or GPU technologies on with performance on order of Xilinx V5, with significantly lower DC power consumption.

Synthesizers/AWGs: Stable signal sources, arbitrary waveform generators, required to generate standard radar waveforms.

VHF/P-band Dual-band Dual-Polarization Antenna Elements for Small Satellites or CubeSats

VHF/P-band Dual-band dual-polarization antenna elements for small satellites or cubesats are needed for signals-of-opportunity remote sensing. Specifications: 137 MHz and 255 MHz with ~10% bandwidth, dual polarization, stowable in <1U, deployable in zero gravity (1-G also desired), gain > 0 dBi. Combine into 2-element end-fire array.

Deployable Cylindrical Antennas

Deployable cylindrical parabolic antenna with up to a four square meter aperture. Performance up to 36 GHz desired.

Deployable W-band (94 GHz) antenna suitable for CubeSats and SmallSats

Aperture up to 1 square meter desired.

Reconfigurable Radar Processors

Radar processor capable of simultaneous or rapidly reconfigurable precipitation reflectivity and SAR measurements for multi-mode, multi-beam radars. Processor should be capable of high-altitude airborne operation with a path for spaceflight.

S1.03 Technologies for Passive Microwave Remote Sensing

Lead Center: JPL

Participating Center(s): JPL

Technology Area: TA15 Aeronautics

NASA employs passive microwave and millimeter-wave instruments for a wide range of remote sensing applications from measurements of the Earth's surface and atmosphere to cosmic background emission. Proposals are sought for the development of innovative technology to support future science and exploration missions MHz to THz sensors. Technology innovations should either enhance measurement capabilities (e.g., improve spatial, temporal, or spectral resolution, or improve calibration accuracy) or ease implementation in spaceborne missions (e.g., reduce size, weight, or power, improve reliability, or lower cost). While other concepts will be entertained, specific technology innovations of interest are listed below.

A radiometer-on-a-chip of either a switching or pseudo-correlation architecture with internal calibration sources is needed. Designs with operating frequencies at the conventional passive microwave bands (X, K, Ka) with dual-polarization inputs. Interfaces include waveguide input, power, control, and digital data output. Design features allowing subsystems of multiple (tens of) integrated units to be effectively realized.

A low-power, radiation tolerant, spectrometer back end capable of sampling a 4 GHz bandwidth with up to 16k channels desired.

Microwave integrated photonic components to demonstrate feasibility and utility for future microwave instruments. Components used in spectrometers, beam forming arrays, correlation arrays and other active or passive microwave instruments are sought.

Microwave to mm wave blackbody calibration target with a 65 dB return loss, an aperture of 8 cm, and performance from 50 GHz to 1 THz.

A focal plane array antenna design to enable large aperture microwave radiometers conical scanning reflector antennas fed by focal plane arrays are needed. Designs are desired for 4-to-12-meter apertures operating at K and Ka band are needed.

Development of microwave-on-wafer probe station for cryogenic circuit characterization. Proposed capability should support test and validation of normal metals and superconductors. Device under test temperature <2.2K desired, with control over the radiant environment and parasitic heat paths through probes. Demonstration from 0-50 GHz with a 2.4 mm compatible interface desired; however, proposed thermal design should define path forward or enable extension to application at millimeter wavelengths

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

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

Local Oscillator technologies for THz instruments. This can include: GaN based frequency multipliers that can work in the 200-400 with better than 30% efficiency GHz range (output frequency) with input powers up to 1 W. Graphene based devices that can work as frequency multipliers in the frequency range of 1-3 THz with efficiencies in the 10% range and higher.

Low DC power correlating radiometer front-ends and low 1/f-noise detectors for 100-700 GHz.

Laser-based THz local-oscillator (LO) ultra-broadband heterodyne mixers for remote sensing.

S1.04 Sensor and Detector Technology for Visible, IR, Far IR and Submillimeter

Lead Center: JPL

Participating Center(s): ARC, GSFC, LaRC

Technology Area: TA15 Aeronautics

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> [1]).
- Planetary science - (<http://www.nap.edu/catalog/10432.html> [2]).
- Astronomy and astrophysics - (<http://www.nap.edu/books/0309070317/html/> [3]).

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 >10bit ADC at >1GHz sampling rate with >2000 bands, ~5kHz bandwidth each with an operating power <300mW and operation at both room temperature and cryogenic temperatures.

New or improved technologies leading to measurement of 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 detectors or heterodyne detectors technologies made using high temperature superconducting films (YBCO, MgB₂) or engineered semiconductor materials, especially 2Dimensional Electron Gas (2DEG) and Quantum Wells (QW). 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.

Development of un-cooled or cooled Infrared detectors (hybridized or designed to be hybridized to an appropriate read-out integrated circuit) with NE Δ T<20mK, QE>30% and dark currents <1.5x10⁻⁶ A/cm² in the 5-14 μ m 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.

Development of a robust wafer-level integration technology that will allow high-frequency capable interconnects and allow two dis-similar 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 1-inch die level but should be do-able at 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.

Higher power THz local oscillators and backend electronics for high resolution spectroscopy for astrophysics. Local Oscillator capable of spectral coverage 2 – 5 THz; Output power upto >2 mW; Frequency agility with > 1GHz near chosen THz frequency; Continuous phase-locking ability over the THz laser tunable range with <100 kHz line width. Backend ASIC capable of binning >1GHz intermediate frequency bandwidth into 0.1-0.5 MHz channels with low power dissipation <0.5W.

S1.05 Detector Technologies for UV, X-Ray, Gamma-Ray and Cosmic-Ray Instruments

Lead Center: JPL

Participating Center(s): JPL, MSFC

Technology Area: TA15 Aeronautics

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, Solar-Terrestrial Probes, 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> [4]).
- Future planetary programs - (http://nasascience.nasa.gov/planetary-science/mission_list [5]).
- Earth Science Decadal missions - (<http://www.nap.edu/catalog/11820.html> [1]).
- Helio Probes - (http://nasascience.nasa.gov/heliophysics/mission_list [6]).
 - https://solar-orbiter.cnes.fr/en/SOLO/GP_spice.htm [7].
 - <http://foxsi.ssl.berkeley.edu/> [8].
- X-ray Astrophysics - (http://sites.nationalacademies.org/bpa/BPA_049810 [9]).
 - <http://wwwastro.msfc.nasa.gov/xrs/> [10].
 - <http://x-ifu.irap.omp.eu/> [11].

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, ATLAST 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 GEO-CAPE, 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.
- Visible-blind UV and EUV detectors with small (< 10 μ m) pixels, large format, photon-counting sensitivity and detectivity, low voltage and power requirements, and room-temperature operation suitable for mission concepts such as the EUV Spectrograph on the ESA-NASA Solar Orbiter.
- 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.
- Neutral density filter for hard x-rays (> 1 keV) to provide attenuation by a factor of 10 to 1000 or more. The filter must provide broad attenuation across a broad energy range (from 1 keV to ~100 keV or more) with a flat attenuation profile of better than 20%.
- Solar X-ray detectors with small independent pixels (< 250 μ m) and fast read-out (>10,000 count/s/pixel) over an energy range from < 5 keV to 300 keV.

- Proposals that address the development of supporting technologies that would help enable X-ray Surveyor mission that requires the development of X-ray microcalorimeter arrays with much larger field of view, $\sim 10^5$ - 10^6 pixels, of pitch ~ 25 - 100 μm , and ways to read out the signals. For example, modular superconducting magnetic shielding is sought that can be extended to enclose a full scale focal plane array. All joints between segments of the shielding enclosure must also be superconducting.
- For missions such as ATHENA X-IFU and X-ray Surveyor, improved long-wavelength blocking filters are needed for large-area, x-ray microcalorimeters. Filters with supporting grids are sought that, in addition to increasing filter strength, also enhance EMI shielding (1 - 10 GHz) and thermal uniformity for decontamination heating. X-ray transmission of greater than 80% at 600 eV per filter is sought, with infrared transmissions less than 0.01% and ultraviolet transmission of less than 5% per filter. Means of producing filter diameters as large as 10 cm should be considered.

S1.06 Particles and Field Sensors and Instrument Enabling Technologies

Lead Center: JPL

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

Technology Area: TA15 Aeronautics

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 reliable cold ionizers to ionize neutral gas as an alternative to thermionic emitters.
 - Science Traceability: Decadal survey missions: DRIVE Initiative, EXPLORERs DISCOVERY, CubeSats / Smallsats, Sounding Rockets.
 - Need Horizon: 1 to 3 years, 3 to 5 years.
 - Reliable and efficient cold ionizers are desired as an alternative to commonly used thermionic emitters. Possible use of nanotechnology. Efficiency $>1\%$.
 - Importance: Very High – Critical need for next generation low energy neutral particle spectrometers.
- 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.
- Control Element for High Voltage Power Supplies.
 - 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 art high voltage controller device with the following basic characteristic. Control from standard voltage of 3.3V to 5V, HV switch of up to 20KV, HV isolation up to 25KV, low leakage currents, slew rates of 100V/us on 10pf loads, mil spec temperature range, radiation tolerance up to 300 krad.

S1.07 In Situ Instruments/Technologies for Planetary Science

Lead Center: JPL

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

Technology Area: TA15 Aeronautics

This subtopic solicits development of advanced instrument technologies and components suitable for deployment on in-situ planetary and lunar missions. These technologies must be capable of withstanding operation in space and planetary environments, including the expected pressures, radiation levels, launch and impact stresses, and range of survival and operational temperatures. Technologies that reduce mass, power, volume, and data rates for instruments and instrument components without loss of scientific capability are of particular importance. 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 Council's, 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 capabilities. In-situ technologies amenable to Cubesats and Smallsats are also being solicited. Atmospheric probe sensors and technologies that can provide significant improvements over previous 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.
- *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. 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.). Advancements geared towards instruments that enable elemental or mineralogy analysis (such as high-sensitivity X-ray and UV-fluorescence spectrometers, UV/fluorescence systems, scanning electron microscopy with chemical analysis capability, mass spectrometry, gas chromatography and tunable diode laser sensors, calorimetry, imaging spectroscopy, and LIBS) are sought.
- *Saturn, Uranus and Neptune* - Components, sample acquisition, and instrument systems that can enhance mission science return and withstand the low-temperatures/high-pressures of the atmospheric probes during entry.
- *The Moon* - 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 Raman spectrometers, UV/fluorescence systems, scanning electron microscopy with chemical analysis capability, 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. 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.

S1.08 Surface & Sub-surface Measurement Systems

Lead Center: JPL

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

Technology Area: TA15 Aeronautics

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: JPL

Participating Center(s): ARC, JPL, MSFC

Technology Area: TA15 Aeronautics

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 flagship missions under consideration for the 2020 Astrophysics Decadal Survey (http://cor.gsfc.nasa.gov/docs/PCOS_facility_missions_report_final.pdf [16]). The topic areas are:

Cryocooler Systems and Components

- *Miniaturized/Efficient Cryocooler Systems* - Cryocooler systems are sought for application on SmallSat and small low power instrument space platforms. Present state-of-the-art capabilities provide 0.4 W of cooling at 77 K with approximately 5 W input power, while rejecting heat at 300 K, and having a system mass of 400 grams. Desired performance specifications for cryocoolers include a cooling capability on the order of 0.2 W at a temperature of approximately 30 K. For application on missions to outer planets, cryocoolers are needed with a cooling power of 0.3 W at approximately 35 K, with a heat rejection temperature as low as 150 K. Desired masses and input powers in both cases are < 400 grams and < 5W respectively. Component level improvements are also desirable.
- *Low Temperature/High Efficiency Cryocoolers* - High efficiency, multi-stage coolers with a low temperature stage capable of reaching 4 to 10 K will be needed for future astrophysics missions. Current state-of-the-art coolers include a device providing 0.04 W at 4.5 K and another providing 0.09 W at 6 K. Cryocoolers are sought that provide higher cooling power, for example >0.3 W at 10 K, with high efficiency. Devices that produce extremely low vibration, particularly at frequencies below a few hundred Hz are of special interest. Component level improvements are also desirable.
- *Cryogenic/Rad-Hard Accelerometers* - Accelerometers that can operate at 150 K, withstand a 0.01 Tesla magnetic field and are radiation hard to mega-rad level doses are needed for cryocooler control and monitoring in missions to outer planets.

Sub-Kelvin Cooling Systems

- *Magnetic Cooling Systems* - Sub-Kelvin cooling systems include Adiabatic Demagnetization Refrigerators (ADRs) and Active Magnetic Regenerative Refrigerators (AMRRs). The ADR in the Soft X-ray Spectrometer instrument on the Hitomi mission represents the state of the art in sub-Kelvin cooling systems for space application. Future missions requiring sub-Kelvin coolers will need devices that provide lower operating temperature (<50 mK), higher (preferably 100%) duty cycle, higher heat rejection temperature (preferably > 10K), higher overall system efficiency, and lower mass. Improvements at the component level are needed to achieve these goals. Specific components sought include:

- Compact, lightweight, low current superconducting magnets capable of producing a field of at least 4 Tesla while operating at a temperature of at least 10 K, and preferably above 15 K. Desirable properties include:
 - A high engineering current density, preferably $> 300 \text{ Amp/mm}^2$.
 - A field/current ratio of $>0.33 \text{ Tesla/Amp}$, and preferably $>0.66 \text{ Tesla/Amp}$.
 - Low hysteresis heating.
- Lightweight Active/Passive magnetic shielding (for use with 4 Tesla magnets) with low hysteresis and eddy current losses, and low remanence.
- Heat switches with on/off conductance ratio $> 3 \cdot 10^4$ and actuation time of $<10 \text{ s}$. Materials are also sought for gas gap heat switch shells: these are tubes with extremely low thermal conductance below 1 K; they must be impermeable to helium gas, have high strength, including stability against buckling, and have an inner diameter $> 20 \text{ mm}$.
- High cooling power density magnetocaloric materials, especially single crystals with volume $> 20 \text{ cm}^3$.
- 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.

S1.10 Atomic Interferometry

Lead Center: JPL

Participating Center(s): JPL

Technology Area: TA15 Aeronautics

Recent developments of laser control and manipulation of atoms have led to new types of precision inertial force and gravity sensors based on atom interferometry. Atom interferometers exploit the quantum mechanical wave nature of atomic particles and quantum gases for sensitive interferometric measurements. Ground-based laboratory experiments and instruments have already demonstrated beyond the state of the art performances of accelerometer, gyroscope, and gravity measurements. The microgravity environment in space provides opportunities for further drastic improvements in sensitivity and precision. Such inertial sensors will have great potential to provide new capabilities for NASA Earth and planetary gravity measurements, for spacecraft inertial navigation and guidance, and for gravitational wave detection and test of properties of gravity in space.

Currently the most mature development of atom interferometers as measurement instruments are those based on light pulsed atom interferometers with freefall cold atoms. There remain a number of technical challenges to infuse this technology in space applications. Some of the identified key challenges are (but not limited to):

- Compact high flux ultra-cold atom sources for free space atom interferometers (Example: $>1 \times 10^6$ total useful free-space atoms, $<1 \text{ nK}$, Rb, K, Cs, Yb, Sr, and Hg. Performance and species can be defined by offerors). Other related innovative methods and components for cold atom sources are of great interest, such as a highly compact and regulatable atomic vapor cell.
- Ultra-high vacuum technologies that allow completely sealed, non-magnetic enclosures with high quality optical access and the base pressure maintained $<1 \times 10^{-9} \text{ torr}$. Consideration should be given to the inclusion of cold atom sources of interest.
- Beyond the state-of-the-art photonic components at wavelengths for atomic species of interest, particularly at NIR and visible: efficient acousto-optic modulators (low RF power $\sim 200 \text{ mW}$, low thermal distortion, $\sim 80\%$ or greater diffraction efficiency); efficient electro-optic modulators (low bias drift, residual AM, and return loss, fiber-coupled preferred), miniature optical isolators ($\sim 30 \text{ dB}$ isolation or greater, $\sim -2 \text{ dB}$ loss or less), robust high-speed high-extinction shutters (switching time $< 1 \text{ ms}$, extinction $> 60 \text{ dB}$ are highly desired).
- Flight qualifiable lasers or laser systems of narrow linewidth, high tunability, and/or higher power for clock and cooling transitions of atomic species of interest. Cooling and trapping lasers: 10 kHz linewidth and ~ 1

W or greater total optical power. Compact clock lasers: 5×10^{-15} Hz/?1/2 near 1 s (wavelengths for Yb+, Yb, Sr clock transitions are of special interest).

- Analysis and simulation tool of a cold atom system in trapped and freefall states relevant to atom interferometer and clock measurements in space.

All proposed system performances can be defined by offerers with sufficient justification. Subsystem technology development proposals should clearly state the relevance, define requirements, relevant atomic species and working laser wavelengths, and indicate its path to a space-borne instrument.

S1.11 In Situ Instruments/Technologies for Ocean Worlds Life Detection

Lead Center: JPL

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

Technology Area: TA15 Aeronautics

This subtopic solicits development of in-situ instrument technologies and components to advance the maturity of science instruments focused on the detection of evidence of life, especially extant of life, in the Ocean Worlds (e.g., Europa, Enceladus, Titan, Ganymede, Callisto, Ceres, etc.). 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 synergistic NASA technology solicitation, see ROSES 2016/C.20 Concepts for Ocean worlds Life Detection Technology (COLDTECH) call:

<https://nspires.nasaprs.com/external/solicitations/summary.do?method=init&solId={5C43865B-0C93-6ECA-BCD2-A3783CB1AAC8}&path=init> [17]

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

- *Europa, Enceladus, Titan and other Ocean Worlds in general* - Technologies and components relevant to life detection instruments (e.g., microfluidic analyzer, MEMS chromatography/mass spectrometers, laser-ablation mass spectrometer, fluorescence microscopic imager, Raman spectrometer, tunable laser system, liquid chromatography/mass spectrometer, X-ray fluorescence, digital holographic microscope-fluorescence microscope, Antibody microarray biosensor, nanocantilever biodetector etc.) Technologies for high radiation environments, e.g., radiation mitigation strategies, radiation tolerant detectors, and readout electronic components, which enable orbiting instruments to be both radiation-hard and undergo the planetary protection requirements of sterilization (or equivalent).
- *Europa* - Life detection approaches optimized for evaluating and analyzing the composition of ice matrices with unknown pH and salt content. Instruments capable of detecting and identifying organic molecules (in particular biomolecules), salts and/or minerals important to understanding the present conditions of Europa's ocean are sought (such as high resolution gas chromatograph or laser desorption mass spectrometers, dust detectors, organic analysis instruments with chiral discrimination, etc.). These developments should be geared towards analyzing and handling very small sample sizes (mg to mg) and/or low column densities/abundances. Also of interest are imagers and spectrometers that provide high performance in low-light environments (visible and NIR imaging spectrometers, thermal imagers, etc.), as well as instruments capable of providing improving our understanding Europa's habitability by characterizing the ice, ocean, and deeper interior and monitoring ongoing geological activity such as plumes, ice fractures, and fluid motion (e.g., seismometers, magnetometers). Improvements to instruments capable of gravity (or other) measurements that might constrain properties such as ocean and ice shell thickness will also be considered.
- *Enceladus* - Life detection approaches optimized for analyzing plume particles, as well as for determining the chemical state of Enceladus' icy surface materials (particularly near plume sites). Instruments capable

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

- *Titan* - Life detection approaches optimized for searching for biosignatures and biologically relevant compounds in Titan's lakes, including the presence of diagnostic trace organic species, and also for analyzing Titan's complex aerosols and surface materials. Mechanical and electrical components and subsystems that work in cryogenic (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, solid, liquid, air sampling mechanisms for mass analyzers, and aerosol detectors are also solicited. Low mass and power sensors, mechanisms and concepts for converting terrestrial instruments such as turbidimeters and echo sounders for lake measurements, weather stations, surface (lake and solid) properties packages, etc. to cryogenic environments (95K).
- Other Ocean Worlds targets may include Ganymede, Callisto, Ceres, etc.

Proposers are strongly encouraged to relate their proposed development to:

- NASA's future Ocean Worlds exploration goals.
- 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.

S1.12 Sample Processing For Life Detection Investigations for Ocean Worlds

Lead Center: JPL

Participating Center(s): ARC, JPL

Technology Area: TA15 Aeronautics

This solicitation is for development of innovative sample processing technologies (methodologies and hardware) for the purposes of improving the resolution and sensitivity of life detection measurements and supporting habitability assessment of environmental samples from Ocean Worlds (e.g., Europa, Enceladus, Titan, etc.). Samples are expected to contain water, minerals, salts, etc. that may complicate measurements or interfere with interpretations. Thus, samples are expected to require separation of components as a preparatory step to analysis. Analytes of interest (e.g., organic molecules including biomolecules, cells, and inorganic solutes and particulates) in samples may also be too dilute and could escape detection unless concentration technologies are applied as a preparatory step. These technologies must be capable of operation under space and planetary conditions, including the extreme pressures, temperatures, radiation levels, stress from launch and impact. Technologies should be of low mass, power, volume; capable of radiation-hardening and sterilization; and require low data rates. Technologies that support minimal biological and analytical contamination of the full technological component and sample stream in order to meet planetary protection requirements and maintain sample integrity for mission-science investigations as well as those that support integration of contamination and/or analyte monitoring are solicited. For synergistic NASA technology solicitation, see ROSES 2016/C.20 Concepts for Ocean worlds Life Detection Technology

(COLDtech) call:

<https://nspires.nasaprs.com/external/solicitations/summary.do?method=init&solId={5C43865B-0C93-6ECA-BCD2-A3783CB1AAC8}&path=init> [17].

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

- *Europa, Enceladus, and other Ocean Worlds with liquid water and ice* - Technologies and components relevant to sample processing of water and ice samples from plumes, surface ice, subsurface ice, or sub-ice waters. Examples of such technologies include, but are not limited to: sonic processing; subcritical and critical solvent extraction; solid-phase extraction; cell isolation, concentration, and lysing; filtering, separation by osmosis and dialysis; chemical hydrolysis and derivatization; novel substrates or adaptives to enhance sensitivity or selectivity of target analytes; total organic carbon, pressure, temperature, pH, eH, dissolved ion monitoring and regulation components; miniaturized components such as microfluidic valves and pumps; and other fluid and solid handling systems following separation and concentration processing components).
- *Titan* – Sample-processing approaches optimized for particulate, inorganic chemicals, and organic molecules of possible biological origin in aerosols and surface materials. Mechanical and electrical components and subsystems that work in cryogenic (95K) and hydrocarbon-rich environments; sample extraction from liquid methane/ethane and/or hydrogen cyanide, sampling from organic 'dunes' at 95K and robust sample preparation and handling mechanisms that feed into spectral and mass analyzers, as well as X-ray detection devices are solicited.

Proposers are strongly encouraged to relate their proposed development to:

- NASA's future Ocean Worlds 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.

Development of these technologies may support environmental, laboratory, military and medical fields that require low mass, power and volume sample processing.

The Technologies for Detection of Extant Life subtopic seeks instruments and component technologies that will enable unambiguous determination of whether extant life is present in target environments on other solar system bodies. Because there is no single measurable signature of life, this will require advances in a variety of areas, from those involving sample processing to the detailed components of chemical and optical instruments. Searches for extant life can take place in a variety of environments, including ocean depths, ice sheets, dry deserts, seasonal flows, or even dense atmospheres; technologies are required for handling samples obtained from any or all of these environments. Preprocessing technologies required for those samples may include separation, concentration, dilution, drying, staining, mixing, and many other common processes for laboratory analysis, but which must be done in a remote, autonomous environment. Tests of whether a given sample contains or indicates the presence of extant life include the full range of microbiological and chemical techniques, but those that do not require the addition of potential biomarkers (e.g., complex organics) as part of the test are preferred. Technologies that support or enable the use of multiple techniques to investigate a single sample are of particular interest, both because of small sample sizes in planetary missions and the need to apply multiple independent tests to identify extant life. Proposed technologies should support miniaturization and design for low power and use in harsh environments.

S2.01 Proximity Glare Suppression for Astronomical Coronagraphy

Lead Center: MSFC

Participating Center(s): ARC, GSFC

Technology Area: TA15 Aeronautics

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: MSFC

Participating Center(s): GSFC, LaRC

Technology Area: TA15 Aeronautics

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 occulter 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

Technology Area: TA15 Aeronautics

This subtopic matures technologies needed to affordably manufacture, test or operate complete mirror systems or telescope assemblies. Solutions are solicited 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.

Specific needs are listed in the Technical Challenges Section. New for 2017 are two areas using additive manufacturing technology:

- Lightweight mirror substrates for Far-IR with < 100 nm rms cryo-deformation at 10K.
- Ultra-stable support structures for potential telescope assemblies: 0.5 meter LISA, 4-m monolithic HabEx, or 12-m segmented LUVOIR.

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.

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.

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. After performance, the most important metric for an advanced optical system is affordability or areal cost (cost per square meter of collecting aperture). Current normal incidence space mirrors cost \$4 million to \$6 million per square meter of optical surface area. This research effort seeks a cost reduction for precision optical components by 5 to 50 times, to between \$100K/m² to \$1M/m².

Specific metrics are defined for each wavelength application region:

Aperture Diameter for all wavelengths

- Monolithic: 1 to 8 meters
- Segmented: > 12 meters

For UV/Optical

- Areal Cost < \$500K/m²
- Wavefront Figure < 5 nm RMS
- Wavefront Stability < 10 pm/10 min
- First Mode Frequency 250 to 500 Hz
- Actuator Resolution < 1 nm RMS

For Far-IR

- Areal Cost for Far-IR < \$100K/m²
- Cryo-deformation for Far-IR < 100 nm RMS

For EUV

- Slope < 0.1 micro-radian

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

1. Optical Components and Systems for potential UV/Optical Missions

Large UV/Optical (LUVOIR) and Habitable Exoplanet (HabEx) Missions

Potential UV/Optical missions require 4 to 16 meter monolithic or segmented primary mirrors with < 5 nm RMS surface figures. Active or passive alignment and control is required to achieve system level diffraction limited performance at wavelengths less than 500 nm (< 40 nm RMS wavefront error, WFE). Additionally, potential Exoplanet mission, using an internal coronagraph, requires total telescope wavefront stability on order of 10 picometers 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 requirement requires active thermal control

systems, ultra-stable mirror support structures, and vibration compensation.

Mirror areal density depends upon available launch vehicle capacities to Sun-Earth L2 (i.e., 15 kg/m² for a 5 m fairing EELV vs. 150 kg/m² for a 10 m fairing SLS). Regarding areal cost, a good goal is to keep the total cost of the primary mirror at or below \$100M. Thus, an 8-m class mirror (with 50 m² of collecting area) should have an areal cost of less than \$2M/m². And, a 16-m class mirror (with 200 m² of collecting area) should have an areal cost of less than \$0.5M/m².

Key technologies to enable such a mirror include new and improved:

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

Also needed is ability to fully characterize surface errors and predict optical performance via integrated opto-mechanical modeling.

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

Ultra-Stable Balloon Telescopes and Telescope Structures

Multiple potential balloon and space missions to perform Astrophysics, Exoplanet and Planetary science investigations require a complete optical telescope system with 0.5 meter or larger of collecting aperture. 1-m class balloon-borne telescopes have flown successfully, however, the cost for design and construction of such telescopes can exceed \$6M, and the weight of these telescopes limits the scientific payload and duration of the balloon mission. A 4X reduction in cost and mass would enable missions which today are not feasible. Space-based gravitational wave observatories (eLISA) need a 0.5 meter class ultra-stable telescope with an optical path length stability of a picometer over periods of roughly one hour at temperatures near 230K in the presence of large applied thermal gradients. The telescope will be operated in simultaneous transmit and receive mode, so an unobstructed design is required to achieve extremely low backscatter light performance.

Exoplanet Balloon Mission Telescope

A potential exoplanet mission seeks a 1-m class wide-field telescope with diffraction-limited performance in the visible and a field of view > 0.5 degree. The telescope will operate over a temperature range of +10 to -70 C at an altitude of 35 km. It must survive temperatures as low as -80 C during ascent. The telescope should weigh less than 250 kg and is required to maintain diffraction-limited performance over:

- The entire temperature range.
- Pitch range from 25 to 55 degrees elevation.
- Azimuth range of 0 to 360 degrees.
- Roll range of -10 to +10 degrees.

The telescope will be used in conjunction with an existing high-performance pointing stabilization system.

Planetary Science Balloon Mission Telescope

A potential planetary balloon mission requires an optical telescope system with at least 1-meter aperture for UV, visible, near- and mid-IR imaging and multi/hyperspectral imaging, with the following optical, mechanical and operational requirements:

Optical Requirements:

- 1-meter clear aperture.
- Diffraction-limited performance at wavelengths $\geq 0.5 \mu\text{m}$ over entire FOV.
- System focal length: 14.052-meters.
- Wavelength range: 0.3 – 1.0 μm and 2.5 – 5.0 μm .
- Field of view: 60 arc-sec in 0.3 – 1.0 μm band, 180 arc-sec in 2.5 – 5.0 μm band.
- Straylight rejection ratio $\geq 1\text{e-}9$.

Mechanical/Operational Requirements:

- Overall length: ≥ 2.75 meters.
- Overall diameter: ≥ 1.25 meters.
- Mass: ≥ 250 kg.
- Temperature: -80 to +50°C.
- Humidity: $\geq 95\%$ RH (non-condensing).
- Pressure: sea level to 1 micron Hg.
- Shock: 10G without damage.
- Elevation angle range: 0° to 70° operating, -90° to + 90° non-operating.

Other Requirements:

- Must allow field disassembly with standard hand tools.
- Maximum mass of any sub-assembly < 90 kg.
- Largest sub-assembly must pass through rectangular opening 56 by 50 inches (1.42 by 1.27 meters).

2. Optical Components and Systems for potential Infrared/Far-IR missions

Large Aperture Far-IR Surveyor Mission

Potential Infrared and Far-IR missions require 8 m to 24 meter class monolithic or segmented primary mirrors with $\sim 1 \mu\text{m}$ RMS surface figure error which operates at < 10 K. There are three primary challenges for such a mirror system:

- Areal Cost of < \$100K per m^2 .
- Areal Mass of < 15 kg per m^2 substrate (< 30 kg per m^2 assembly).
- Cryogenic Figure Distortion < 100 nm RMS from 300K to <10K.

Infrared Interferometry Balloon Mission Telescope

A balloon-borne interferometry mission requires 0.5 meter class telescopes with siderostat steering flat mirror. There are several technologies which can be used for production of mirrors for balloon projects (aluminum, carbon fiber, glass, etc.), but they are high mass and high cost.

3. Fabrication, Test and Control of Advanced Optical Systems

While Sections 1 and 2 detail the capabilities need to enable potential future UVO and IR missions, it is important to note that this capability is made possible by the technology to fabricate, test, and control optical systems. Therefore, this subtopic also encourages proposals to develop such technology which will make a significant

advance of a measurable metric.

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

Lead Center: MSFC

Participating Center(s): JPL, MSFC

Technology Area: TA15 Aeronautics

This subtopic solicits proposals in the following areas:

- Components, Systems, and Technologies of potential X-Ray missions.
- Coating technologies for X-Ray, EUV (extreme ultraviolet), LUV (Lyman ultraviolet), VUV (vacuum ultraviolet), Visible, and IR (infrared) 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 including Carbon Nanotubes (CNT) for wide range of wavelengths from X-Ray to IR (X-Ray, EUV, LUV, VUV, Visible, and IR).
- Free-form Optics design, fabrication, and metrology for CubeSat, SmallSat and various coronagraphic instruments.

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, EUV, LUV, VUV, Visible and 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 coronagraphic instruments.

In a nutshell, a successful proposal demonstrates a low-cost ability to address NASA science mission needs and technical challenges specified under each category with feasible plan to develop the technology for infusion into NASA Decadal class missions and sub-orbital rockets and/or balloon for IR-class telescopes.

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 NASAs 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, LUV, UV, Visible, and IR Telescopes

The optical coating technology is a mission-enabling feature that enhances the optical performance and science return of a mission. Lowering the areal cost of coating determines if a proposed mission could be funded in the current cost environment. The most common forms of coating used on precision optics are anti-reflective (AR) coating and high reflective coating. The current coating technology of optical components needs to achieve TRL-6 by approximately 2018 to support the 2020 Astrophysics Decadal process. A number of optical coating metrics specific to each wavelength are desired such as:

The Optical Coating Metrics

The telescope optical coating needs to meet low temperature operation requirement. It's desirable to achieve 35° Kelvin in future.

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 90 nm and the ability to be applied onto a < 2 meter mirror substrate.

LUV/VOIR Metrics:

- Broadband reflectivity > 70% from 90 nm to 120 nm (LUV); > 90% from 120 nm to 2500 nm (VUV/Visible/IR); Reflectivity non-uniformity < 1% from 90 nm to 2500 nm. Induced polarization aberration < 1% from 400 nm to 2500 nm and depositable onto 1 to 8 m 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 at least 10 years.
- Withstand launch conditions such as vibration, acoustics, etc.
- Tolerate both high continuous wave (CW) and pulsed power and power densities without damage. ~10 W for 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.

S3.01 Power Generation and Conversion

Lead Center: GRC

Participating Center(s): ARC, JPL, JSC

Technology Area: TA15 Aeronautics

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

Technology Area: TA15 Aeronautics

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 [18]). Future spacecraft and constellations of spacecraft will have high-precision propulsion requirements, usually in volume- and power-limited envelopes. Also recently precise propulsion systems have been incorporated into disturbance reduction systems to demonstrate that a solid body can float freely in space completely undisturbed in order to explore the gravitational universe. However, technology limits to propulsion system life still exist which can ultimately limit mission duration for more ambitious follow-on formation flying applications.

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 [19]) and NASA's Office of the Chief Technologist (http://www.nasa.gov/pdf/501329main_TA02-InSpaceProp-DRAFT-Nov2010-A.pdf [20]).

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

Advanced Electric Propulsion Components

Towards that end, this solicitation seeks to mature and demonstrate iodine electric propulsion technologies. Iodine propellant has two key advantages over the state-of-the-art (SOA) xenon propellant: (i) increased storage density and (ii) reduced storage pressure. These key advantages permit iodine propulsion systems with conformal storage tanks, reduced structural mass, and reduced volume compared with the SOA xenon, while retaining similar thrust, specific impulse, and thruster efficiency.

This subtopic seeks proposals that mature iodine propulsion technologies, including:

- Iodine compatible Hall Effect Thruster cathodes with lifetimes greater than 10,000 hours.
- Robust and electrically efficient iodine storage and delivery system architectures (scalable 5 kg to 100 kg iodine):
 - Numerical modeling to guide system design and CONOPS, predicting power consumption, iodine mobility, thermal transport, sublimation rate, condensation, clogging, recovery time post-anomalies, etc.
 - Design and analysis of innovative iodine feed system architectures.
 - Experimental demonstration of promising feed system architectures under conditions of long-term iodine storage and dynamic thermal environments.
- Compact low-power iodine compatible feed system technologies, including high accuracy pressure sensors (<1 atm full scale), propellant flow control valves, latch valves, heaters, etc.
 - Feed system technologies utilizing innovative iodine resistant materials and coating.
 - Experimental and numerical demonstration of component operation in dynamic simulated mission environments.

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:

- Thruster components including, but not limited to, advanced cathodes, rf devices, advanced grids, lower-cost components enabled by novel manufacturing techniques.
- 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.

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 these satellite missions flown are often selected for concept or component demonstration activities as the primary objectives. Opportunities are anticipated to select future satellite missions based on application goals (i.e., science return). However, several technology limitations prevent high value science from low-cost 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.
- Improved operational life over SOA propulsion systems.

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

Solar/Electric Sail Propulsion

This subtopic seeks sail propulsion innovations in three areas for future robotic science and exploration missions:

- Large solar sail propulsion systems with at least 1000 square meters of deployed surface area for small (<150 kg) spacecraft to enable multiple Heliophysics missions of interest.
- Electric sail propulsion systems capable of achieving at least 1 mm/sec² characteristic acceleration to support Heliophysics missions of interest and rapid outer solar system exploration.
- Electrodynamic tether/sail propulsion systems capable generating from the Lorentz Force delta-V sufficient to de-orbit from altitudes up to 2,000 km and to maintain a small (< 500 kg) spacecraft in LEO at altitudes up to 400 km for 5 years enabling Earth ionospheric and plasmasphere investigations.

Design solutions must demonstrate high deployment reliability and predictability with minimum mass and launch volume and maximum strength, stiffness, stability, and durability.

Innovations are sought in the following areas:

- Novel design, packaging, and deployment concepts.
- Lightweight, compact components including booms, substrates, and mechanisms.
- Validated modeling, analysis, and simulation techniques.
- Ground and in-space test methods.
- High-fidelity, functioning laboratory models.

Note: Cubesat propulsion technologies have been moved to a new STMD subtopic: Z8.01 - Small Spacecraft Propulsion Systems.

S3.03 Power Electronics and Management, and Energy Storage

Lead Center: GRC

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

Technology Area: TA15 Aeronautics

NASA's science

vision (http://science.nasa.gov/media/medialibrary/2014/05/02/2014_Science_Plan-0501_tagged.pdf [21]) 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 [22]). 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, 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 shows 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 components 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.

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.
- 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.

Note to Proposers - Cubesat power technologies have been moved to a new STMD subtopic: Z8.03 Small Spacecraft Power and Thermal Control

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 Guidance, Navigation and Control

Lead Center: GSFC

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

Technology Area: TA15 Aeronautics

NASA seeks innovative, groundbreaking, and high impact developments in spacecraft guidance, navigation, and control technologies in support of future science and exploration mission requirements. This subtopic covers mission enabling technologies that have significant performance improvements (SWaP-C) over the state of the art COTS in the areas of Spacecraft Attitude Determination and Control Systems, Absolute and Relative Navigation Systems, and Pointing Control Systems, and Radiation-Hardened GN&C Hardware.

Component technology developments are sought for the range of flight sensors, actuators, and associated algorithms and software required to provide these improved capabilities. Technologies that apply to most spacecraft platform sizes will be considered. Cubesat GN&C technologies have been moved to a new STMD subtopic: Z8.05 Small Spacecraft Avionics and Control.

Advances in the following areas are sought:

- *Spacecraft Attitude Determination and Control Systems* - Sensors and actuators that enable <0.1 arcsecond level pointing knowledge and arcsecond level control capabilities for large space telescopes, with

improvements in size, weight, and power requirements.

- *Absolute and Relative Navigation Systems* - Autonomous onboard flight navigation sensors and algorithms incorporating both spaceborne and ground-based absolute and relative measurements. For relative navigation, machine vision technologies apply. Special considerations will be given to relative navigation sensors enabling precision formation flying, astrometric alignment of a formation of vehicles, robotic servicing and sample return capabilities, and other 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 technology that can be used to enable other areas within this subtopic applies.
- *Radiation-Hardened Hardware* - GN&C sensors that could operate in a high radiation environment, such as the Jovian environment

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.

S3.05 Terrestrial and Planetary Balloons

Lead Center: MSFC

Participating Center(s): JPL

Technology Area: TA15 Aeronautics

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 power storage and satellite communications bitrates as described below:

- *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.

Planetary Balloons

Innovations in materials, structures, and systems concepts have enabled buoyant vehicles to play an expanding role in planning NASA's future Solar System Exploration Program. Balloons are expected to carry scientific payloads at Venus that will perform in-situ investigations of the atmosphere. Venus features extreme environments that significantly impact the design of balloons. Proposals are sought in the following areas:

- *Floating Platforms for Venus* - 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 platforms at altitudes of between 50 and 60 km for periods in excess of 100 days. The temperature at 50 km is roughly 75°C; at 60 km it is about -10°C. Sulfuric acid aerosols are known to exist in this altitude range on Venus. A target payload mass of 100 kg shall be used for system sizing purposes. The primary focus should be on the design of the floating platform system and the materials for achieving long duration operation. Concepts may include fixed altitude and/or variable altitude (controlled) floating vehicles. Systems that use alternative lift gases such as ammonia, or phase change fluids should be considered. Traditional lift gases such as helium or hydrogen are acceptable. Additional areas of interest for developing floating platforms include:
 - Analytical tools for predicting vehicle dynamic behavior in the atmosphere.
 - Packaging and storage methods for inflatable components.
 - Methods for deployment, inflation, and component separation during descent in the atmosphere.

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.

S3.06 Thermal Control Systems

Lead Center: GSFC

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

Technology Area: TA15 Aeronautics

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:

- Advanced thermal devices capable of maintaining components within their specified temperature ranges are needed for future advanced spacecraft. 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.
 - Thermal coatings with low absorptance, high emittance, and good electrical conductivity.
 - Radiator heat rejection turndown devices (e.g., mini heat switches, mini louvers).
 - Miniature pumped fluid loop systems with passive valve for radiator heat rejection turndown, and consumes minimal power.
- 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. 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.

- Thermoelectric converts (TEC) have advantages of small size, long life, solid state design, and no moving parts or fluid operation, and have been used on many science instruments requiring dedicated/localized cooling to meet their stringent requirements. However, they have historically exhibited poor efficiency and have not been able to provide the cold temperatures needed by certain types of space science instruments. Research and development in areas of advanced materials, processes, and designs are needed in order to improve its efficiency, and extend its low temperature (<90K) capability for space science application.
- Water has been used in two-phase thermal control devices such as heat pipes due to its high heat transport capability. However, water has two main drawbacks that limit its use in many aerospace applications. Its expansion upon freezing creates a concern about rupture of the heat pipe and the concern for reliable startup from an initially frozen state. Water-containing azeotropes, which behave as a single-component working fluid, can offer substantial benefits as alternatives to use of pure water for applications where freeze/thaw and frozen startup concerns exist. High-performance water azeotropes which can lower the freezing point of water below -40°C while providing improved reliability for aerospace thermal control systems are needed.
- Three-dimensional (3D) integrated circuits (ICs) offer unprecedented functionality and efficiency in small form factors, but their operation is constrained by the current remote cooling paradigm that relies on conduction and heat spreading across multiple interfaces. An embedded approach, which facilitates in-situ cooling of the chip stack is needed. Such a cooling device must also accommodate high heat fluxes and minimize the thermal resistance between the heat source and sink.

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.

Note to Proposers - Cubesat thermal technologies have been moved to a new STMD subtopic: Z8.03 Small Spacecraft Power and Thermal Control

S3.07 Slow and Fast Light

Lead Center: MSFC

Technology Area: TA15 Aeronautics

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.

S3.08 Command, Data Handling, and Electronics

Lead Center: MSFC

Participating Center(s): JPL, LaRC

Technology Area: TA15 Aeronautics

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 2017 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.

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- 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> [23]).

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:

- *System-In-Package Integrated Assemblies* - Technologies enabling highly integrated System-In-Package (SIP) assemblies integrating multiple die from different processes and foundries, enabling implementation of miniaturized, highly-reliable embedded processing or sensor readout modules.
- *Printed Wiring Board Miniaturization* - Technologies enabling miniaturization of highly reliable printed wiring board assemblies and interconnect.
- *COTS Micropower/Ultra-Low Power Computing* - Technologies enabling the use of COTS micropower/ultra-low power computing devices in highly reliable spacecraft avionics systems.
- *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.

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

Lead Center: JPL

Participating Center(s): ARC, JSC, LaRC

Technology Area: TA15 Aeronautics

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:

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- 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.

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

Technology Area: TA15 Aeronautics

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. Application to Ocean Worlds is of increasing importance.

Mobility technologies are needed to enable access to steep and rough terrain for planetary bodies where gravity dominates, such as the Moon and Mars. Wheeled, legged, and aerial solutions are of interest. Wheel concepts with good tractive performance in loose sand while being robust to harsh rocky terrain are of interest. Technologies to enable mobility on small bodies and access to liquid 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. Design for planetary protection and contamination control is important for sample acquisition and handling systems.

Component technologies for low-mass and low-power systems tolerant to the in-situ environment 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:

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

S4.03 Spacecraft Technology for Sample Return Missions

Lead Center: MSFC

Participating Center(s): GRC

Technology Area: TA15 Aeronautics

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: MSFC

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

Technology Area: TA15 Aeronautics

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:

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- 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: MSFC

Technology Area: TA15 Aeronautics

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.

S4.06 Sample Collection For Life Detection in Outer Solar System Ocean World Plumes

Lead Center: JPL

Participating Center(s): GSFC, JPL

Technology Area: TA15 Aeronautics

This subtopic solicits development of in-situ instrument technologies and components to advance the maturity of instruments focused on the collection of samples for life detection from plumes in the Ocean Worlds (e.g., Europa, Enceladus, Titan, Ganymede, Callisto, Ceres, etc.). 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 allow collection during high speed (>1 km/sec) velocity passes through a plume are of interest as are technologies that can maximize total sample mass collected while passing through tenuous plumes. Technologies that reduce mass, power, volume, and data rates without loss of scientific capability are of particular importance.

For synergistic NASA technology solicitation, see ROSES 2016/C.20 Concepts for Ocean worlds Life Detection Technology (COLDTECH) call:

- <https://nspires.nasaprs.com/external/solicitations/summary.do?method=init&solId={5C43865B-0C93-6ECA-BCD2-A3783CB1AAC8}&path=init> [17].

For the NASA Roadmap for Ocean World Exploration see:

- <http://www.lpi.usra.edu/opag/ROW> [24].

The icy moons of the outer Solar System are of astrobiological interest. The most dramatic target for sampling from a plume is for Enceladus. Enceladus is a small icy moon of Saturn, with a radius of only 252km. Cassini data have revealed about a dozen or so jets of fine icy particles emerging from the south polar region of Enceladus. The jets have also been shown to contain organic compounds, and the south-polar region is warmed by heat flow coming from below.

As a target for future missions, Enceladus rates high because fresh samples of interest are jetting into space ready for collection. Indeed, Enceladus has been added to the current call for New Frontiers missions with a focus on habitability and life detection. Particles from Enceladus also form the E-ring around Saturn. The particles in the E-ring are known to contain organics and are thus also an important target for sample collection and analysis. Recent data have indicated a possible plume at Europa that may also be carrying ocean water from that world into space. In addition to plumes, there are other energetic processes that can spray material from the surface of these low-gravity worlds into space where they could also be collected in-flight and analyzed.

Collecting samples for a variety of science purposes is required. These include samples that allow for determination of the chemical and physical properties of the source ocean, samples for detailed characterization of the organics present in the gas and particle phases, and samples for analysis for biomarkers indicative of life. Thus these "Ocean Worlds" of the outer Solar System offer the opportunity for a conceptually new approach to life detection focusing on in-flight sample collection of material freshly injected into space. Technologies of particular interest include sample collection systems and subsystems capable of:

- Capture, containment, and/or transfer of gas, liquid, ice, and/or mineral phases from plumes to sample processing and/or instrument interfaces.
- Technologies for characterization of collected sample parameters including mass, volume, total dissolved solids in liquid samples, and insoluble solids.
- Sample collection and sample capture for in-situ imaging.
- Systems capable of high-velocity sample collection with minimal sample alteration to allow for habitability and life detection analyses.
- Microfluidic sample collection systems that enable sample concentration and other manipulations.
- Plume material collection technologies that minimize risk of terrestrial contamination, including organic chemical and microbial contaminants.

Proposers are strongly encouraged to relate their proposed development to NASA's future Ocean Worlds exploration goals. 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.

S5.01 Technologies for Large-Scale Numerical Simulation

Lead Center: JPL

Participating Center(s): GSFC

Technology Area: TA15 Aeronautics

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

- Decrease the barriers to entry for prospective supercomputing users.
- Minimize the supercomputer user's total time-to-solution (e.g., time to discover, understand, predict, or

design).

- Increase the achievable scale and complexity of computational analysis, data ingest, and data communications.
- Reduce the cost of providing a given level of supercomputing performance for NASA applications.
- Enhance the efficiency and effectiveness of NASA's supercomputing operations and services.

Expected outcomes are to improve the productivity of NASA's supercomputing users, broaden NASA's supercomputing user base, accelerate advancement of NASA science and engineering, and benefit the supercomputing community through dissemination of operational best practices.

The approach of this subtopic is to seek novel software and hardware technologies that provide notable benefits to NASA's supercomputing users and facilities, and to infuse these technologies into NASA supercomputing operations. Successful technology development efforts under this subtopic would be considered for follow-on funding by, and infusion into, NASA's high-end computing (HEC) projects - the High End Computing Capability project at Ames and the Scientific Computing project at Goddard. To assure maximum relevance to NASA, funded SBIR contracts under this subtopic should engage in direct interactions with one or both HEC projects, and with key HEC users where appropriate. Research should be conducted to demonstrate technical feasibility and NASA relevance during Phase I and show a path toward a Phase II prototype demonstration.

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

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

Projects need not benefit all NASA HEC users or application codes, but demonstrating applicability to an important NASA discipline, or even a key NASA application code, could provide significant value. For instance, a GPU accelerated (or multi-core) planetary accretion code such as LIPAD (Lagrangian Integrator for Planetary Accretion and Dynamics).

The three main technology areas of S5.01 are aligned with three objectives of NSCI, the National Strategic Computing Initiative, announced by the White House in July 2015. The overarching goal of NSCI is to coordinate and accelerate U.S. activities in HEC, including hardware, software, and workforce development, so that the U.S. remains the world leader in HEC technology and application. NSCI charges every agency that is a significant user of HEC to make a significant contribution to this goal. This SBIR subtopic is an important part of NASA's contribution to NSCI. See <https://www.nitrd.gov/nsci/index.aspx> [25] for more information about NSCI. The three main elements of S5.01 are:

- Many NASA science applications demand much faster supercomputers. This area seeks technologies to accelerate the development of an efficient and practical exascale computing system (10¹⁸ operations per second). Innovative file systems that leverage node memory and a new exascale operating system geared toward NASA applications are two possible technologies for this element. At the same time, this area calls for technology to support co-design (i.e., concurrent design) of NASA applications and exascale supercomputers, enabling application scaling to billion-fold parallelism while dramatically increasing memory access efficiency. This supports NSCI Objective 1 (Accelerating delivery of a capable exascale computing system that integrates hardware and software capability to deliver approximately 100 times the performance of current 10 petaflop systems across a range of applications representing government needs.).
- Data analytics is becoming a bigger part of the supercomputing workload, as computed and measured data expand dramatically, and the need grows to rapidly utilize and understand that data. This area calls for technologies that support convergence of computing systems optimized for modeling & simulation and those optimized for data analytics (e.g., data assimilation, data compression, image analysis, machine

learning, visualization, and data mining). In-situ data analytics that can run in-memory side-by-side with the model run is another possible technology for this element. This supports NSCI Objective 2 (Increasing coherence between the technology base used for modeling and simulation and that used for data analytic computing.).

- Presently it is difficult to integrate cyberinfrastructure elements (supercomputing system, data stores, distributed teams, instruments, mobile devices, etc.) into an efficient and productive science environment. This area seeks technologies to make elements of the supercomputing ecosystem much more accessible and composable, while maintaining security. Thus supports NSCI Objective 4 (Increasing the capacity and capability of an enduring national HPC ecosystem by employing a holistic approach that addresses relevant factors such as networking technology, workflow, downward scaling, foundational algorithms and software, accessibility, and workforce development.).

S5.02 Earth Science Applied Research and Decision Support

Lead Center: JPL

Participating Center(s): JPL

Technology Area: TA15 Aeronautics

The NASA Earth (<http://science.nasa.gov/earth-science/> [26]) and Applied Science (<http://appliedsciences.nasa.gov/> [27]) programs seeks innovative and unique approaches to increase the utilization and extend the benefit of Earth Science research data to better meet societal needs. The main focus of this subtopic is improving the pipeline from NASA Earth Science data and products to a range of end user communities to support decision making. To that end, one area of interest is new or improved decision support tools for a variety of applications areas (<http://appliedsciences.nasa.gov/sites/default/files/ar2014/index.html#/applications-areas> [28]), including but not limited to, disaster response, agricultural and food security, water resource management, land surface modeling, air quality and health.

This subtopic aims to connect and demonstrate the integration of NASA Earth science data and models into societal benefit areas with clear operational partners. This solicitation encourages project teams to consider products from recently-launched NASA Missions, as well as simulated products from upcoming, planned missions (e.g., SMAP, GPM, Landsat, GRACE, GRACE-FO, IceSat-2, SWOT), and field campaigns or other observatories (e.g., Airborne Snow Observatory (<http://aso.jpl.nasa.gov/> [29]), SnowEx (<https://snow.nasa.gov/snowex> [30])). Projects may consider connecting with NASA-sponsored activities including, but not limited to SPoRT (<http://weather.msfc.nasa.gov/sport/> [31]), NASA Earth Exchange – NEX (<https://nex.nasa.gov/nex/> [32]), and SERVIR (http://www.nasa.gov/mission_pages/servir/ [33]). NASA hosts a broad range of modeling systems and related that have been highly valuable to operational and end user communities, including MERRA-2 (<https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/> [34]), climate project information from GISS GCMs (<http://www.giss.nasa.gov/projects/gcm/> [35]) and Land Data Assimilation Systems (LDAS (<http://ldas.gsfc.nasa.gov/ldas/> [36])).

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. The goal of this solicitation is to directly link what is being done at NASA with the end user community to support decision making. The outcomes of this work could include new tools, integration systems, visualization interfaces, among others. Responsive proposals must include a clear identification of a data product(s), modeling tools, or NASA activities that will be used and a clear end user/stakeholder organization to which the tools, systems, etc. are intended to support for applied research and decision support. Proposals should explain how the proposed capabilities will address an end user need or

gap area in decision support capabilities. Proposals should also outline existing capabilities, including software, models, and data that are already implemented at NASA or through related NASA activities and how the proposed activities may leverage, complement, or expand from existing infrastructure. Projects must be mindful of NASA security restrictions in the development of new activities.

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

Lead Center: JPL

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

Technology Area: TA15 Aeronautics

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:

- Reanalysis data sets such as MERRA (200 TB) MERRA2 (400 TB), and emerging reanalysis data sets with chemistry components.
- 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, infrastructure, and/or algorithms to enable high performance analytics across large observational and model data sets.

Proposals MUST be in alignment with existing and/or future NASA programs and address or extend a specific need or question for those programs. It is therefore incumbent upon the proposers to have discussions with NASA scientists and engineers to receive feedback prior to submission and to adequately show the alignment of the proposed innovation to NASA.

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, methods, and/or algorithms for high performance analytics that scale to extremely large data sets – of specific interest are the following:
 - Preference to employ machine and deep learning methods

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- Other techniques to be considered could cover 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.).
 - New services, methods, and/or algorithms to enable in-situ, data proximal, parallel data analytics that will accelerate the access, analysis, and distribution of large Science datasets.
 - Use of open source data analytic tools to accelerate analytics is desired.
 - 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

Technology Area: TA15 Aeronautics

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

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- 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.