The overarching goal of the Sun–Earth Connection (SEC) theme in Space Science is an understanding of how the Sun, heliosphere, and planetary environments are connected in a single system. The three principal science objectives spring from this goal:

1. Understanding the changing flow of energy and matter throughout the Sun, heliosphere, and planetary environments;
2. Exploring the fundamental physical processes of plasma systems in the solar system; and
3. Defining the origins and societal impacts of variability in the Sun–Earth Connection.

SEC missions investigate the physics of the Sun, the heliosphere, the local interstellar medium, and all planetary environments within the heliosphere. They address problems such as solar variability, the responses of the planets to such variability, and the interaction of the heliosphere with the galaxy. Increasingly, SEC investigations have focused upon space weather, the diverse array of dynamic and interconnected space phenomena that affects life, society, and exploration systems. Technology plays an important role in maximizing the science return from all SEC missions.

Sub Topics:

S1.01 Technologies for Particles and Fields Measurements

Lead Center: GSFC

The SEC theme encompasses the Sun with its surrounding heliosphere carrying its photon and particle emissions and the subsequent responses of the Earth and planets. This requires remote and in situ sensing of upper atmospheres and ionospheres, magnetospheres and interfaces with the solar wind, the heliosphere, and the Sun. Improving our knowledge and understanding of these requires accurate in situ measurements of the composition, flow, and thermodynamic state of space plasmas and their interactions with atmospheres, as well as the physics and chemistry of the upper atmosphere and ionosphere systems. Remote sensing of neutral atoms are required for the physics and chemistry of the Sun, the heliosphere, magnetospheres, and planetary atmospheres and ionospheres. Because instrumentation is severely constrained by spacecraft resources, miniaturization, low power consumption, and autonomy are common technological challenges across this entire category of sensors. Specific technologies are sought in the following categories.
Plasma Remote Sensing (e.g, neutral atom cameras)

This may involve techniques for high-efficiency and robust imaging of energetic neutral atoms covering any part of the energy spectrum from 1 eV to 100 keV, within resource envelopes less than 5 kg and 5W.

- Miniaturized, radiation-tolerant, autonomous electronic systems for the above, within resource envelopes of 1–2 kg and 1–2 W.

In Situ Plasma Sensors

- Improved techniques for imaging of charged particle (electrons and ions) velocity distributions, as well as improvements in mass spectrometers in terms of smaller size or higher mass resolution.
- Improved techniques for the regulation of spacecraft floating potential near the local plasma potential, with minimal effects on the ambient plasma and field environment.
- Low power digital time-of-flight analyzer chips with subnanosecond resolution and multiple channels of parallel processing.
- Miniaturized, radiation-tolerant, autonomous electronic systems for the above, within resource envelopes of 1–2 kg and 1–2 W.

Fields Sensors

- Improved techniques for measurement of plasma floating potential and DC electric field (and by extension the plasma drift velocity), especially in the direction parallel to the spin axis of a spinning spacecraft.
- Measurement of the gradient of the electric field in space around a single spacecraft or cluster of spacecraft.
- Improved techniques for the measurement of the gradients (curl) of the magnetic field in space local to a single spacecraft or group of spacecraft.
- Direct measurement of the local electric current density at spatial and time resolutions typical of space plasma structures such as shocks, magnetopauses, and auroral arcs.
- Miniaturized, radiation-tolerant and autonomous electronic systems for the above, within resource envelopes of 1–2 kg and 1–2 W.

Electromagnetic Radiation Sensors

- Radar sounding and echo imaging of plasma density and field structures from orbiting spacecraft.
- Miniaturized, radiation-tolerant and autonomous electronic systems for the above, within resource envelopes of 1–2 kg and 1–2 W.
Spacecraft propulsion technology innovations are sought for upcoming deep space science missions. Propulsion system functions for these missions include primary propulsion, maneuvering, planetary injection, and planetary descent and ascent. Innovations are needed to reduce spacecraft propulsion system mass, volume, and/or cost. Applicable propulsion technologies include solar electric, chemical and thermal, solar sails, aeroassist and aerocapture and emerging technologies.

**Solar Electric Propulsion**

Innovations in electric propulsion system technologies are being sought for space science applications. One area of emphasis pertains to high-performance propulsion systems capable of delivering specific impulse (Isp) greater than 2000 s, using electrical power from radioisotope or solar energy sources. Thruster technologies include, but are not limited to, ion engines, Hall thrusters, and pulsed electromagnetic devices. Other areas of interest include propellant storage, direct drive and other innovative power processing, power management and distribution, heat-to-electrical power conversion, and waste heat disposal. Innovations considered here may focus on the component, subsystem or system level, and must ultimately result in significant improvements in spacecraft capability, longevity, mass, volume, and/or cost.

**Solar Sails**

Solar sails are envisioned as a low-cost, efficient transport system for future near-Earth and deep space missions. NASA mission's enabled and enhanced by solar sail propulsion include Tech Pull Missions such as Geotail, Comet Sample and Titan Flyby all to be launched between 2009 and 2012. Another category of NASA missions is the Particle Acceleration Solar Orbiter, including the L1-Diamond and the Solar Polar Imager, both to be launched between 2015 and 2028. Solar Sails are enabling for several strategic missions in the Sun-Earth Connection Space Science theme, including Solar Polar Imager and Interstellar Probe, the latter being a sail mission to explore interstellar space. Missions in the Exploration of the Solar System theme would be broadly enhanced by the availability of proven sail technology. Innovations are sought that will lower the cost and risk associated with sail development and application, and enhance sail delivery performance. Innovations are sought in the following areas: systems engineering, materials, structures, mechanical systems, fabrication, packaging and deployment, system control (attitude, etc.), maneuvering and navigation, operations, durability and survivability, and sail impact on science. Development of ultra-lightweight inflatable and deployable support structures is of significant interest, including rigidization approaches. Innovations in ultra-light reflective thin films are also sought. Three parameters have been used as sail performance metrics in mission applications: sail size, sail survivability for close solar approaches, and areal density (ratio of mass of the sail to area of the sail). In addition, important programmatic metrics are cost, benefit, and risk. Technologies of interest should be geared toward a wide range of sail sizes, solar closest approach distances, and aerial densities, and may be optimized for one portion of the range rather than trying to cover the whole range. Sail sizes may range from very small (meter-sized for use with very tiny picosat payloads or for use as auxiliary propulsion), to medium (50–100 m size for achieving high-inclination solar orbits or non-Keplerian near-Earth orbits) and ultimately to the very large (hundreds of meters for levitated orbits, high delta V, and for use in leaving the Solar System at high speed). Sail weight should include, but not be limited to, ultra-lightweight sail materials (
Chemical and Thermal Propulsion

Innovations in low-thrust chemical propulsion system technologies are being sought for Space Science missions applications. One area of interest is a bipropellant engine with Isp greater than 360 s. Component, subsystem, or system level technology development will be considered but work must ultimately result in significant reductions in spacecraft system mass, volume, and/or cost. Other areas to be considered include lightweight, compact and low-power propellant management components, such as valves, flow control/regulation, fluid isolation, dependable ignition systems, and lightweight tankage.

Aeroassist

Aeroassist is a general term given to various techniques to maneuver a space vehicle within an atmosphere, using aerodynamic forces in lieu of propulsion fuel. Aeroassist systems enable shorter interplanetary cruise times, increased payload mass, and reduced mission costs. Subsets of aeroassist are aerocapture and aerogravity assist. Aerocapture relies on the exchange of momentum with an atmosphere to achieve a decelerating thrust leading to orbit capture. This technique permits spacecraft to be launched from Earth at higher velocities, thus providing a shorter overall trip time. At the destination, the velocity is reduced by aerodynamic drag within the atmosphere. Without aerocapture, a substantial propulsion system would be needed on the spacecraft to perform the same reduction of velocity. Aerogravity assist is an extension of the established technique of gravity assist with a planetary body to achieve increases in interplanetary velocities. Aerogravity assist involves using propulsion in conjunction with aerodynamics through a planetary atmosphere to achieve a greater turning angle during planetary fly-by. In particular, this subtopic seeks technology innovations that are in the following areas:

Aerocapture

Thermal Protection Systems: Development of advanced thermal protection systems and insulators. Materials need high strength (modulus in the tens of GPa) and very low density (tens of kg/m$^3$). Improvements needed in materials include having highly anisotropic thermal properties, i.e., high thermal diffusivity tangential to the spacecraft shape and low thermal diffusivity normal to the spacecraft shape.

Sensors for Inflatable Decelerators: Health monitoring method for inflatable thin film systems.

Analytical Tools: Development of advanced tools to perform coupled aeroelastic and aerothermal analysis of inflatable decelerator systems.

Aerogravity Assist

Aerogravity Assist Technology Analysis: Research advancements in leading edge materials and provide CFD analysis of heating environment for aerogravity assist maneuvers at a small planet (e.g., Venus).

Emerging Propulsion Technologies

This effort will focus on technologies supporting innovative and advanced concepts for propellantless propulsion and other revolutionary transportation technologies. The categories under Emerging Propulsion Technologies include, but are not limited to: electrodynamic and momentum-exchange tether propulsion, beamed energy, ultra-light solar sails, bimodal sails, and low to medium power electric propulsion (including pulse inductive devices). The electrodynamic tether propulsion uses electromagnetic interaction with a planetary magnetic field to exchange angular momentum. Momentum exchange tethers (such as the MXER tether concept use a strong tether to transfer angular momentum and orbital energy to a payload. Beamed energy propulsion concepts include lasers or microwave energy to directly propel a spacecraft or to supply power that is utilized for propulsion onboard the...
spacecraft. Ultra-light or bimodal sail propulsion developing conventional solar sails into extremely high-performing systems. The low to medium electric propulsion is a general category for fresh variations of electric thrusters (Hall, MHD, PIT, etc.) that support near or mid-term solar powered spacecraft (e.g., below ~50 kW). Unique, innovative and novel propulsion ideas are sought but with reasonable expectations to progress to hardware prototypes. The concept must be above TRL 2 with rapid demonstration to TRL 4 expected. Distinctive variations of existing propulsion methods or chief subsystem component improvements are also suitable for submission. Proposals should provide development of specific innovative technologies or techniques supporting any of the above approaches. A clear plan for demonstrating feasibility, noting any test and experiment requirements, is also recommended. Key to each idea is an unambiguous knowledge of past research and concepts conducted on related work, and specifically, how this new proposal differs to the extent that it appears to offer a significant benefit. Identification of the fundamental technology to be developed is also crucial.

S1.03 Multifunctional Autonomous Robust Sensor Systems

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

NASA seeks innovative concepts for Multifunctional Autonomous Robust Sensor Systems (MARSS) to increase spacecraft autonomy and robustness. These concepts are intended to lower overall mission costs, reduce reliance on human control and monitoring, and allow for systems that are inherently robust and provide maximum flexibility of the space vehicles throughout mission lifecycle and for various space/planetary exploration missions. The systems should include the ability to couple the data from a variety of distributed sensor technologies to relevant response actuation systems of the vehicle. As we move from 10s of sensors to 1000s of sensors and beyond, new approaches must be investigated that will allow the vehicle to efficiently obtain “knowledge” about the health and optimization of its systems, and the ever changing environment it is in.

Robustness and autonomy in space vehicles are two of the keys to achieving maximum efficiency of missions and increasing the probability of success. Distributed, self-sufficient, reconfigurable sensors are at the heart of this capability. Technologies such as, but not limited to, MEMS, nanotechnology, integrated /distributed processors and fuzzy logic are potential elements of MARSS. These systems should be able to provide their own power by scavenging it from the environment and provide real-time knowledge from large numbers of sensors to various response systems to comprise “sense and respond” systems. In addition, methods are sought to improve radiation shielding of systems components. This includes, but are not limited to, metal and metal matrix materials that may offer better radiation protection properties than the current state-of-the-art aluminum alloys, and high atomic number intercalated graphite composites for light weight strong radiation shielding of electronics to improve their robustness.

Emphasis should be placed on technologies that provide a sense-and-respond capability using technologies that are small, reliable, low-cost, lightweight, and would allow space probes to adapt to a wide range of space missions. Sensing requirements include both intrinsic (relating to the performance and health of the vehicle itself) and extrinsic (relating to the performance of the mission and adapting to the operating environment).

 Evaluators will be looking for system concepts and not just individual pieces that could be used for a system. This requires multidiscipline collaboration on various proposals and clear explanations of system functionality, benefit, and improvement over existing technology. In addition, details of how systems will function in relevant space...
environments should be provided. The Technology Readiness Level (TRL) for submissions should be in the TRL 4-6 range. Please see the SBIR Web site for more details.

S1.04 Spacecraft Technology for Micro- and Nanosats
Lead Center: GSFC

NASA seeks research and development of components, subsystems and systems that enable inexpensive, highly capable small spacecraft for future SEC missions. The proposed technology must be compatible with spacecraft somewhere within the micro-to-nano range of 100 kg down to 1 kg. All proposed technology must have a potential for providing a function at current performance levels with significantly reduced mass, power, and cost, or have a potential for significant increase in performance without additional mass, power, and cost. These reduction and/or improvement factors should be significant and show a minimum factor of 2 with a goal of 10 or higher.

A proposed technology must state the type or types of expected improvements, (performance, mass, power, and cost), list the assumptions for the current state-of-the-art, and indicate the spacecraft range of sizes for which the technology is applicable.

The integration of multiple components into functional units and subsystems is desirable but not a requirement for consideration.

- Avionics and architectures that support command and data handling functions, including input and output, formatting, encoding, processing, storage, and analog-to-digital conversion. System level architecture, software operating systems, low voltage logic switching, radiation-tolerant design, and packaging techniques are also appropriate technologies for consideration.

- Sensors and actuators that support guidance, navigation, and control functions such as Sun–Earth sensors, star trackers, inertial reference units, navigation receivers, magnetometers, reaction wheels, magnetic torquers, and attitude thrusters. Technologies with applications to either spinning or three-axis stable spacecraft are sought.

- Power system elements including those that support the generation, storage, conversion, distribution regulation isolation, and switching functions for spacecraft power. System level architecture, low voltage buss design, radiation tolerant design, and novel packaging techniques are appropriate technologies for consideration.

- New and novel application of technologies for manufacturing, integration and test of micro and nano size spacecraft are sought. Limited production runs of up to several hundred spacecraft can be considered. Efficiencies can derive from increased reliability, flexibility in the end-to-end production process, as well as cost, labor, and schedule.

- Technologies that support passive and active thermal control suitable for micro and nano size spacecraft are sought. These functions include heat generation, storage, rejection, transport, and the control of these
functions. Efficient system level approaches for integrated small spacecraft that may see a wide range of thermal environments are desirable. These environments may range from low heliocentric orbits to 2 hr shadows.

- Elements that support Earth-to-space or space-to-space communications functions are sought. This includes receivers, transmitters, transceivers, transponders, antennas, RF amplifiers, and switches. S and X are the target communications bands.

- System architectures and hardware that lead to greater spacecraft and constellation autonomy and, therefore, reduce operational expenses are desired. Technologies that derive added capability for a fixed bandwidth, efficient utilization of ground systems, status analysis, and situation control or other enhancing performance for operations are sought.

- Structure and mechanism technologies and material applications that support the micro and nano class of spacecraft are desired. Exoskeleton structures, spin release mechanisms, and bi-stable deployment mechanisms are typical of the desired technology.

- Propulsion system elements that provide delta-V capability for spinning and/or three-axis stable spacecraft are sought. This includes solid, cold-gas, and liquid systems, and their components such as igniters, thrust vector control mechanisms, tanks, valves, nozzles, and system control functions.

**S1.05 Information Technology for Sun-Earth Connection Missions**

**Lead Center: GSFC**

A large number of multiple-spacecraft missions are planned for the future of SEC science. Cost-effective implementation of these missions will require new information technology: tools, systems and architectures for mission planning, implementation, and operations; and science data processing and analysis that facilitate scientific understanding. Specific research areas of interest for these SEC multi-spacecraft missions include the following items below.

**Information Technology for Cost-Effective Mission Planning and Implementation**

Tools or systems are needed that improve the system engineering, integration, test, and synchronous operations of semiautonomous multispacecraft missions with intermittent contact and large communication latencies; automated approaches to onboard science data processing and reactive onboard instrument management and control; and tools that capture and represent scientific objectives as preplanned and reactive onboard autonomous drivers.

**Data Analysis**

Items of interest in this area focus on innovative approaches and the tools necessary to support space and solar physics virtual observatories (physically distributed heterogeneous science data sources considered as a logical entity).
Tools are needed for enabling automated systematic identification, access, ad hoc science analysis, and distribution of large distributed heterogeneous data sets from space and solar physics data centers; and technologies and tools supporting inclusion of individual researcher provided, ad hoc, science analysis modules as a component of search criteria for remote data mining at space and solar physics data centers.

S1.06 UV and EUV Optics

Lead Center: GSFC
Participating Center(s): MSFC

From the Sun’s atmosphere to the Earth’s aurora, remote imaging, spectroscopy, and polarimetry at ultraviolet (UV) and extreme ultraviolet (EUV) wavelengths are important tools for studying the Sun-Earth connection. A far ultraviolet (FUV) range is sometimes interposed between UV and EUV, but the terminology is arbitrary: the pertinent full range of wavelength is approximately 20–300 nm.

Proposals should explain specifically how they intend to advance the state-of-the-art in one or more of the following areas.

Imaging Mirrors

- Large aperture: 1–4 m
- Low mass: 5–20 kg m\(^{-2}\)
- Accurate figure: \(~0.01\) wave rms or better at 632 nm. Figure accuracy must be maintained through launch and on orbit (including, for mirrors subjected to direct or concentrated solar radiation, the effects of differential heating)
- Low microroughness: \(~1\) nm rms or better on scales below 1 mm.

Optical Coatings and Transmission Filters

- Coatings (filters) with improved reflectivity (transmission) and selectivity (narrow bands, broad bands, or edges). Technologies include (but are not limited to) multilayer coatings, transmission gratings, and Fabry-Pérot étalons.

Diffraction Gratings

- High groove density (> 4000 mm\(^{-1}\)) for high spectral resolving power in conjunction with achievable focal
• High efficiency and low scatter (microroughness)
• Variable line spacing
• Echelle gratings
• Active gratings (replicated onto deformable surfaces)
• Aspherical concave substrates, such as toroids and ellipsoids

Proposals that address detector requirements of Sun-viewing instruments, such as large format, deep wells, fast readout, or "3-D" (spatial-spatial-energy) resolution, should be submitted to Topic S2.05.

Structure and Evolution of the Universe Topic S2

The goal of the Space Science Enterprise's Structure and Evolution of the Universe (SEU) Theme is to seek the answer to three fundamental questions:

1. What is the structure of the universe and what is our cosmic destiny?
2. What are the cycles of matter and energy in the evolving universe?
3. What are the ultimate limits of gravity and energy in the universe?

SEU's strategy for understanding this interactive system is organized around four fundamental Quests, designed to answer the following questions:

1. Identify dark matter and learn how it shapes galaxies and systems of galaxies,
2. Explore where and when chemical elements were made,
3. Understand the cycles in which matter, energy, and magnetic fields are exchanged between stars and the gas between stars,
4. Discover how gas flows in disks and how cosmic jets formed,

5. Identify the sources of gamma-ray bursts and high energy cosmic rays, and

6. Measure how strong gravity operates near black holes and how it affects the early universe.

Sub Topics:

S2.01 Sensors and Detectors for Astrophysics

Lead Center: JPL

Future NASA astrophysics missions like Sofia, Herschel, Planck, FAIR, MAXIM, EXIST, and ARISE (http://spacescience.nasa.gov/missions/index.htm [1]) need improvements in sensors and detectors. Beyond 2007, expected advances in detectors and other technologies may allow the Filled Aperture Infrared instrument (FAIR) to extend HST observations into the mid- and far-infrared (40–500 micron) region; the Micro-Arcsecond X-ray Imaging Mission Pathfinder (MAXIM) will demonstrate the feasibility of x-ray interferometry with a resolution of 100 micro-arc seconds, which is 5000 times better than the Chandra observatory; the Energetic X-ray Imaging Telescope (EXIST) will conduct the first high sensitivity, all-sky imaging survey at the predominantly thermal (x-ray) and non-thermal (gamma-ray) universe requiring a wide-field coded aperture telescope array; and the Advanced Radio Interferometry between Space and Earth (ARISE) mission will create an interferometer including radio telescopes in space and on Earth.

Space science sensor and detector technology innovations are sought in the following areas:

**Mid/Infrared, Far Infrared and Submillimeter**

Future space-based observatories in the 10-40 micron spectral regime will be passively cooled to about 30 K. They will make use of large sensitive detector arrays with low-power dissipation array readout electronics. Improvements in sensitivity, stability, array size, and power consumption are sought. In particular, novel doping approaches to extend wavelength response, lower dark current and readout noise, novel energy discrimination approaches, and low noise superconducting electronics are applicable areas. Future space observatories in the 40 micron to 1 mm spectral regime will be cooled to even lower temperatures, frequently 20 W Hz-1/2 over most of the spectral range in a 100x100 pixel detector array, with low-power dissipation array readout electronics. The ideal detector element would count individual photons and provide some energy discrimination. For detailed line mapping (e.g., C+ at 158 micron), heterodyne receiver arrays are desirable, operating in the same frequency range near the quantum limit.

**Space Very Long Baseline Interferometry (VLBI)**

The next generations of Very Long Baseline Interferometry (VLBI) missions in space will demand greatly improved sensitivity over current missions. These new missions will also operate at much higher frequencies (at first to 86 GHz and eventually to 600 GHz). These thrusts will require development of improved space-borne low-power ultra-low-noise amplifiers and mixers to serve as primary receiving instruments.
Innovations in materials, structures, and systems concepts have enabled buoyant vehicles to play an expanding role in NASA's Space and Earth Science Enterprises. A new generation of large, stratospheric balloons based on advanced balloon envelope technologies will be able to deliver payloads of several thousand kilograms to above 99.9% of the Earth's absorbing atmosphere and maintain them there for months of continuous observation. Smaller scale, but similarly designed, balloons and airships will also carry scientific payloads on Mars, Venus, Titan, and the outer planets in order to investigate their atmospheres in situ and their surfaces from close proximity. Their envelopes will be subject to extreme environments and must support missions with a range of durations. Robotic balloons, known as aerobots, have a wide range of potential applications both on Earth and on other solar system bodies. NASA is seeking innovative and cost-effective solutions in support of terrestrial and extraterrestrial balloons and aerobots in the following areas.

**Stratospheric Long Duration Balloon (LDB) Support**

**Materials**

- Innovative membranes for terrestrial applications to support the Long Duration Balloon (LDB) and Ultra-Long Duration Balloon (ULDB) development efforts. The material of interest shall meet all environmental, design, fabrication, and operational requirements and must be producible in large quantities in a lay-flat width of at least 1.6 m.

- Innovative concepts for reducing the UV degradation of flight components including balloon membranes, load carrying members, and parachute components.

**Support Systems**

- Innovative concepts for trajectory control and/or station-keeping for effectively maneuvering large terrestrial and small extraterrestrial aerobots in either the horizontal latitude or vertical altitude plane or both.

- Innovative low mass, high density, and high efficiency power systems for terrestrial balloons that produce 2 kW or more continuously.

- Innovative power systems that enable long duration, sunlight independent missions for a duration of 30 days or more.

- Innovative, low cost, low power, low mass, precision instrument pointing systems that permit arcsecond or better accuracy.

- Innovative sensor concepts for balloon gas or skin temperature measurements.

- Innovative floatation systems for water recovery of payloads.
Design and Fabrication

- Innovative, efficient, reliable and cost-effective balloon fabrication and inspection techniques to support the current ULDB development efforts.
- Innovative balloon design concepts for long duration missions which can provide any or all of the following:
  - Reduced material strength requirements;
  - Increased reliability;
  - Enhanced performance;
  - Reduced manufacturing time;
  - Reduced manufacturing cost; and
  - Improved mission flexibility.

Titan Missions Support

Titan is the second largest moon in the solar system and the only one that features a sufficiently dense atmosphere for buoyant vehicle flight. Targeted for exploration by Cassini-Huygens in 2004 and beyond, Titan is expected to be a geologically and chemically diverse world containing important clues on the nature of prebiotic chemistry. NASA is starting to lay the ground work for post-Cassini-Huygens exploration of Titan using highly autonomous, self-propelled aerobots capable of surveying many widely separated locations on the world and potentially including surface sampling and composition analysis. Innovative technologies are sought in the following areas:

- Concepts, devices and materials for sealing (repairing) of small holes in the balloon envelope material during flight at Titan. Repair of these holes may be required to enable the long mission lifetimes (6–12 months) desired at Titan. Although the balloon envelope material for Titan has not yet been specified, repair strategies should be generally compatible with polymer materials and the 90 K environment. It is imperative that proposed solutions be low mass (on the order of a few kilograms) and low power (a few Watts).

- Concepts and devices for the processing of atmospheric methane into hydrogen gas and its use as a makeup gas to compensate for leakage during operational flight at Titan. It is imperative that proposed solutions be low mass (on the order of a few kilograms) and low power (a few Watts).

Venus Missions Support

Venus is the second planet from the Sun and features a dense, CO₂ atmosphere completely covered by clouds. Although already explored by various orbiters and short-lived atmospheric probes and landers, Venus retains many secrets pertaining to its formation and evolution. One of NASA’s long-term objectives is to develop the technologies required for a surface sample return mission. A high temperature balloon is one key element that will be needed to loft the sample from the surface to a high altitude for launching a return rocket back to Earth. Innovative technologies are, therefore, sought in the following area:
• Designs, materials, and prototypes for surface-launched Venus balloons. Balloon volumes in the range of 0.5–5 m$^3$ are required when fully inflated. The balloon must be storable in a packaged condition for up to 1 year and have an areal density of less than 1000 g/m$^2$. Proposed concepts must include an automatic surface launch that will work in the Venus environment consisting of 460°C temperature, 90 atmosphere pressure, and surface winds of up to 1 m/s.

S2.03 Cryogenic Systems

Lead Center: GSFC
Participating Center(s): ARC, JPL, MSFC

Cryogenic systems have long been used to perform cutting edge space science, but at high cost and with limited lifetime. Improvements in cryogenic system technology enable further scientific advancement at lower cost and/or lower risk. Lifetime, reliability, mass, and power requirements of the cryogenic systems are critical performance concerns. Of interest are cryogenic coolers for cooling detectors, telescopes, and instruments. In addition, cryogenic coolers for lunar and interplanetary exploration are of interest. The coolers should have long life, low vibration, low mass, low cost, and high efficiency. Specific areas of interest include the following:

• Highly efficient coolers in the range of 4–10 K as well as 50 mK and below, and cryogen-free systems that integrate these coolers together;
• Low-mass, highly efficient coolers for gas sample collection and liquefaction of gases for use in propulsion systems;
• Essentially vibration-free cooling systems, such as reverse Brayton cycle cooler technologies;
• Highly reliable, efficient, low-cost Stirling and pulse tube cooler technologies in the 10 K, 15 K, and 35 K regions;
• Highly efficient magnetic and dilution cooling technologies, particularly at very low temperatures;
• Hybrid cooling systems that make optimal use of radiative coolers; and
• Miniature, MEMS, and solid-state cooler systems.

S2.04 Optical Technologies

Lead Center: GSFC
Participating Center(s): JPL

The NASA Space Science Enterprise is studying future missions to explore the Structure and Evolution of the
Universe (SEU). To understand the structure and evolution of the universe, a variety of large space-based observatories are necessary to observe cosmic phenomena from radio waves to the highest energy cosmic rays. It will be necessary to operate some of these observatories at cryogenic temperatures (to 4 K) beyond geosynchronous orbits. Apertures for normal incidence telescope optics are required up to 40 m in diameter, while grazing incidence optics are required to support apertures up to 10 m in diameter. For some missions, these apertures will form a constellation of telescopes operating as interferometers. These interferometric observatories may have effective apertures up to 1000 m diameter. Low mass of critical components such as the primary mirror, its support and/or deployment structure, is extremely important. In order to meet the stringent optical alignment and tolerances necessary for a high quality telescope and to provide a robust design, there are significant benefits possible from employing systems that can adaptively correct for image degrading sources from inside and outside the spacecraft. This includes correction systems for large aperture space telescopes that require control across the entire wavefront, typically at low temporal bandwidth. The following technologies are sought:

- Grazing incidence focusing mirrors with response up to 150 keV.
- Large, ultra-lightweight grazing incidence optics for x-ray mirrors with angular resolutions less than 5 arcsec.
- Wide field-of-view optics using square pore slumped microchannel plates or equivalent.
- Develop fabrication techniques for ultra-thin-flat silicon (or like material) for grating substrates for x-ray energies.
- Large area thin blocking filters with high efficiency at low energy x-ray energies.
- Ultraviolet filters with deep blocking.
- Develop novel materials and fabrication techniques for producing ultra-lightweight mirrors, high-performance diamond turned optics (including freeform optical surfaces), and ultra-smooth (2–3 angstroms rms) replicated optics that are both rigid and lightweight. Lightweight high modulus (e.g., silicon carbide) optics and structures are also desired.
- High-performance (e.g., high modulus, low density, high thermal conductivity) materials and fabrication processes for ultra-lightweight, high precision (e.g., subarcsecond resolution or
- Advanced, low-cost, high quality large optics fabrication processes and test methods including active metrology feedback systems during fabrication, and artificial intelligence controlled systems.
- Large, ultra-lightweight optical mirrors including membrane optics for very large aperture space telescopes and interferometers.
- Cryogenic optics, structures, and mechanisms for space telescopes and interferometers.
- Ultra-precise, low mass deployable structures to reduce launch volume for large-aperture space telescopes and interferometers.
- Segmented optical systems with high-precision controls; active and/or adaptive mirrors; shape control of deformable telescope mirrors; and image stabilization systems.
- Advanced, wavefront sensing and control systems including image based wavefront sensors.
- Wavefront correction techniques and optics for large aperture membrane mirrors and refractors (curved lenses, Fresnel lenses, diffractive lenses).
- Nanometer to sub-picometer metrology for space telescopes and interferometers.
- Develop ultra-stable optics over time periods from minutes to hours.
- Advanced analytical models, simulations, and evaluation techniques, and new integrations of suites of
existing software tools allowing a broader and more in-depth evaluation of design alternatives and identification of optimum system parameters including optical, thermal, structural, and dynamic performance of large space telescopes and interferometers.

- Develop portable and miniaturized state-of-the-art optical characterization instrumentation and rapid, large-area surface-roughness characterization techniques are needed. In addition, develop calibrated processes for determination of surface roughness using replicas made from the actual surface. Traceable surface roughness standards suitable for calibrating profilometers over sub-micron to millimeter wavelength ranges are needed.

- Develop instruments capable of rapidly determining the approximate surface roughness of an optical surface, allowing modification of process parameters to improve finish, without the need to remove the optics from the polishing machine. Techniques are needed for testing the figure of large, convex aspheric surfaces to fractional wave tolerances in the visible.

**S2.05 Advanced Photon Detectors**

Lead Center: GSFC

Participating Center(s): MSFC

The next generation of astrophysics observatories for the infrared, ultraviolet (UV), x-ray, and gamma-ray bands require order-of-magnitude performance advances in detectors, detector arrays, readout electronics, and other supporting and enabling technologies. Although the relative value of the improvements may differ among the four energy regions, many of the parameters where improvements are needed are present in all four bands. In particular, all bands need improvements in spatial and spectral resolutions, in the ability to cover large areas, and in the ability to support the readout of the thousands to millions of resultant spatial resolution elements.

Innovative technologies are sought to enhance the scope, efficiency, and resolution of instrument systems at all energies and wavelengths:

- The next generation of gravitational missions will require greatly improved inertial sensors. Such an inertial sensor must provide a carefully fabricated test mass which has interactions with external forces (i.e., low magnetic susceptibility, high degree of symmetry, low variation in electrostatic surface potential, etc.) below 10–16 of the Earth’s gravity, over time scales from several seconds to several hours. The inertial sensor must also provide a housing for containing the proof mass in a suitable environment (i.e., high vacuum, low magnetic and electrostatic potentials, etc.).

- Advanced charged couple device (CCD) detectors, including improvements in UV quantum efficiency and read noise, to increase the limiting sensitivity in long exposures and improved radiation tolerance. Electron-bombarded CCD detectors, including improvements in efficiency, resolution, and global and local count rate capability. In the x-ray, we seek to extend the response to lower energies in some CCDs, and to higher, perhaps up to 50 keV, in others.

- Significant improvements in wide band gap (such as GaN and AlGaN) materials, individual detectors, and arrays for UV applications.
• Improved microchannel plate detectors, including improvements to the plates themselves (smaller pores, greater lifetimes, alternative fabrication technologies, e.g., silicon), as well as improvements to the associated electronic readout systems (spatial resolution, signal-to-noise capability, dynamic range), and in sealed tube fabrication yield.

• Imaging from low-Earth orbit of air fluorescence UV light generated by giant airshowers by ultra-high energy (E > 1019 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 (~106), low noise, fast time response (2 to 10 x 10 mm2). Focal plane mass must be minimized (2 g/cm² goal). Individual pixel readout. The entire focal plane detector can be formed from smaller, individual sub-arrays.

• For advanced x-ray calorimetry improvements in several areas are needed, including:
  • Superconducting electronics for cryogenic x-ray detectors such as SQUID-based amplifiers and their multiplexers for low impedance cryogenic sensors and superconducting single-electron transistors and their multiplexers for high impedance cryogenic sensors;
  • Micromachining techniques that enhance the fabrication, energy resolution, or count rate capability of closely-packed arrays of x-ray calorimeters operating in the energy range from 0.1–10 keV; and
  • Surface micromachining techniques for improving integration of x-ray calorimeters with read-out electronics in large scale arrays.

• Improvements in readout electronics, including low power ASICs and the associated high density interconnects and component arrays to interface them to detector arrays.

• Superconducting tunnel junction devices and transition edge sensors for the UV and x-ray regions. For the UV, these offer a promising path to having “three-dimensional” arrays (spatial plus energy). Improvements in energy resolution, pixel count, count rate capability, and long wavelength rejection are of particular interest. We seek techniques for fabrication of close packed arrays, with any requisite thermal isolation, and sensitive (SQUID or single electron transistor), fast, readout schemes and/or multiplexers.

• Arrays of CZT detectors of thickness 5–10 mm to cover the 10–500 keV range, and hybrid detector systems with a Si CCD over a CZT pixelated detector operating in the 2–150 keV range.

• For improvements to detector systems for solar and night-time UV and EUV (approx. 20–300nm) observing the following areas are of interest: Large format (4 K x 4 K and larger); high quantum efficiency; small pixel size; large well depth; low read noise; fast readout; low power consumption (including readout); intrinsic energy and/or polarization discrimination (3d or 4d detector); active pixel sensors (back-illumination, UV sensitivity); and high-resolution image intensifiers, UV and EUV sensitive, insensitive to moisture.

• Space spectroscopic observations in the UV, visible and IR requiring long observations times would be much more sensitive with high quantum efficiency (QE) and zero read noise. Techniques are sought which improve the QE of photon counters, or eliminate the read noise of solid state detectors.

• X-ray and gamma-ray imaging with higher sensitivity, dynamic range, and angular resolution requires innovations in modulation collimators and detection devices. The energy range of interest is from a few kilo-electron Volts to hundreds of milli-electron Volts for observations of solar flares and cosmic sources. Collimators with size scales down to a few microns and thicknesses commensurate with photon absorption over a significant fraction of this energy range are required. Low-background detectors capable of
Instruments that detect low frequency gravity waves offer a new window on the universe, its origin, evolution and structure. Complementing ground-based experiments such as the Laser Interferometer Gravitational Wave Observatory (LIGO), the Laser Interferometer Space Antenna (LISA), and the follow on vision mission, Big Bang Observer, will implement ambitious systems to detect and characterize gravity waves associated with the Big Bang, mergers of black holes, and other significant astrophysical phenomena. The success of such investigations will largely depend on the technology building blocks that are needed to implement multiple spacecraft constellations with extremely precise laser interferometers and test masses which are actively decoupled from systematic and random disturbances.

The technology areas are organized into two subsystems, one dealing with the disturbance rejection subsystem, which houses the proof mass with active sensors and thrusters to cancel non-gravity wave disturbances, and the other implementing the network of laser interferometers with nanometer-level resolution of relative range between the test masses. Because the systems will be deployed in space, the technologies to be considered must be, or have, credible paths toward full space flight qualification, including thermal and radiation considerations.

Background information on LISA, along with preliminary technology discussions, can be found in the proceedings of the 4th International LISA Symposium, Penn State University, 19–24 July 2002, published in the Classical and Quantum Gravity Journal, Volume 20, Number 10, 21 May 2003.

**Disturbance Reduction System (DRS)**

- Vacuum system – non-magnetic vacuum pump for reaching pressures of $-6 \text{ Pa}$ with a pumping volume of 1 liter; with associated valves and electronics
- Vacuum gauge – read pressure down to $10^{-6} \text{ Pa}$ on orbit, must be non-magnetic
- Caging actuator – hold 2 kg mass $\sim 4 \text{ cm}^3$ against launch loads of $\sim 25 \text{ g rms}$, with the capability for moving caged test mass over $\sim 10 \text{ micron}$ range with $\sim 1 \text{ nm}$ precision during ground testing
- Test mass, $\sim 4 \text{ cm}^3$, mass $\sim 1–2 \text{ kg}$, magnetic susceptibility $-6$ (e.g., 73% gold/27% platinum)

**Laser Interferometer**

- Laser with exceptional power, frequency noise, amplitude noise, lifetime characteristics.
  - Fiber coupled output power (1 W) CW
  - A combination of a lower power master oscillator with suitable amplifier to yield 1 W of total fiber coupled output power may be acceptable
  - Frequency and amplitude noise characteristics: Frequency stability to (30 Hz/vHz at 1 mHz), and
power stability to \(2 \times 10^{-4} / \text{vHz at 1 mHz}\)

- Lifetime of 10 years or more.
- Wavelength is nominally 1.064 micron, but +/- 20% of that value is acceptable.
- Semiconductor diode pump laser with outstanding reliability to operate with a suitable solid-state laser (e.g., non-planar ring oscillator laser) is required.

- Electro-optical modulator – produce phase modulation of continuous laser beam with 10% (power) modulation depth at frequencies from 1.9–2.1 GHz with fiber coupled input and output. Baseline operation will be at 1.064 microns. In addition to the space qualification requirements, the modulator must be able to handle optical power levels at \(~1\ W\).

Research and technology development 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 to a participating NASA Center for testing at the completion of the Phase II contract.

Astronomical Search for Origins Topic S3

The questions “How did we get here?” and “Are we alone?” have driven mankind to explore and expand our understanding of the universe and our role in it since before recorded history. Today, we move our attention to the cosmos. Understanding of how galaxies, stars, and planetary systems formed in the early universe will provide a basis for future exploration. Are planetary systems and Earth-like planets typical? Is life beyond the Earth rare or non-existent? If life in the universe is robust, has it spread throughout the galaxy? Current missions using innovative technology research are Space Interferometer Mission (SIM) and Terrestrial Planet Finder (TPF). New missions in the planning phase, which requires innovative technology, are Space Astronomy Far Infrared Telescope (SAFIR), Life Finder and Planet Imager. The Origins technology program develops the means to achieve the most ambitious and technically challenging measurements ever made. New large space telescopes and instruments are required to detect the extremely faint signatures from the deep universe. Innovations are needed in these areas: Precision constellations for interferometry, advanced astronomical instrumentation, deployable precision structures, high-contrast astrophysical imaging, large aperture lightweight telescope mirrors, and wavefront sensing and control. These technologies will enable NASA to explore the early universe, find planets around other stars, and search for life beyond Earth.

Sub Topics:

**S3.01 Precision Constellations for Interferometry**

**Lead Center:** JPL

This subtopic seeks hardware and software technologies necessary to establish, maintain and operate hyper-
precision spacecraft constellations to a level that enables separated spacecraft optical interferometry. Also sought are technologies for analysis, modeling, and visualization of such constellations.

In a constellation for large effective telescope apertures, multiple, collaborative spacecraft in a precision formation collectively form a variable-baseline interferometer. These formations require the capability for autonomous precision alignment and synchronized maneuvers, reconfigurations, and collision avoidance. It is important that, in order to enable precision spacecraft formation keeping from coarse requirements (relative position control of any two spacecraft to less than 1 cm, and relative bearing of 1 arcmin over target range of separations from a few meters to tens of kilometers) to fine requirements (micron relative position control and relative bearing control of 0.1 arcsec), the interferometer payload would still need to provide at least 1–3 orders of magnitude improvement on top of the S/C control requirements. The spacecraft also require onboard capability for optimal path planning, and time optimal maneuver design and execution.

Innovations that address the above precision requirements are solicited for distributed constellation systems in the following areas:

- Integrated optical/formation/control simulation tools;
- Distributed, multitiming, high fidelity simulations;
- Formation modeling techniques;
- Precision guidance and control architectures and design methodologies;
- Centralized and decentralized formation estimation;
- Distributed sensor fusion;
- RF and optical precision metrology systems;
- Formation sensors;
- Precision microthrusters/actuators;
- Autonomous reconfigurable formation techniques;
- Optimal, synchronized, maneuver design methodologies;
- Collision avoidance mechanisms;
- Formation management and station keeping; and
- Six degrees of freedom precision formation testbeds.

S3.02 High Contrast Astrophysical Imaging
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 and the detailed inner structure of galaxies with very bright nuclei. Contrast ratios of one million to one billion over an angular spatial scale of 0.05–1.5 arcsec are typical of these objects. Achieving a very low background against which to detect a planet, 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 any starlight cancellation scheme.

This innovative research focuses on advances in coronagraphic instruments, interferometric starlight cancellation instruments, and potential occulting technologies that operate at visible and infrared wavelengths. The ultimate application of these instruments is to operate in space as part of a future observatory mission. Much of the scientific instrumentation used in future NASA observatories for the Origins Program theme will be similar in character to instruments used for present day space astrophysical observations. The performance and observing efficiency of these instruments, however, must be greatly enhanced. The instrument components are expected to offer much higher optical throughput, larger fields of view, and better detector performance. The wavelengths of primary interest extend from the visible to the thermal infrared. Measurement techniques include imaging, photometry, spectroscopy, coronography, and polarimetry. There is interest in component development, and innovative instrument design, as well as in the fabrication of subsystem devices to include, but are not limited to, the following areas:

### Starlight Suppression Technologies

- Advanced starlight canceling coronagraphic instrument concepts.
- Advanced aperture apodization and aperture shaping techniques.
- Pupil plane masks for interferometry.
- Advanced apodization mask or occulting spot fabrication technology controlling smooth density gradients to $10^{-4}$ with spatial resolutions ~1 µm.
- Metrology for detailed evaluation of compact, deep density apodizing masks, Lyot stops, and other types of graded and binary mask elements. Development of a system to measure spatial optical density, phase inhomogeneity, scattering, spectral dispersion, thermal variations, and to otherwise estimate the accuracy of masks and stops is needed.
- Interferometric starlight cancellation instruments and techniques to include aperture synthesis and single input beam combination strategies.
- Fiber optic spatial filter development for visible coronagraph wavelengths.
- Single mode fiber filtering from visible to 20 µm wavelength.
- Methods of polarization control and polarization apodization.
- Components and methods to insure amplitude uniformity in both coronographs and interferometers, specifically materials, processes, and metrology to insure coating uniformity.
Wavefront Control Technologies

- Development of small stroke, high precision deformable mirrors (DM) and associated driving electronics scalable to 104 or more actuators (both to further the state-of-the-art towards flight-like hardware, and to explore novel concepts). Multiple DM 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.

- Reliability and qualification of actuators and structures in deformable mirrors to eliminate or mitigate single actuator failures.

- Multiplexer development for electrical connection to deformable mirrors that has ultra-low power dissipation. The most promising DM technology may be sensitive to temperature, so developing a MUX that has very low thermal hot-spots, and very uniform temperature performance will improve the control of the mirror surface.

- High precision wavefront error sensing and control techniques to improve and advance coronagraphic imaging performance.

S3.03 Precision Deployable Lightweight Cryogenic Structures for Large Space Telescopes

Lead Center: JPL

Planned future NASA Origins Missions and Vision Missions such as the Single Aperture Far-IR (SAFIR) telescope, Life Finder, and Submillimeter Probe of the Evolution of Cosmic Structure (SPECs) require 10–30 m class telescopes that are diffraction limited at wavelengths between the visible and the near IR, and operate at temperatures from 4–300 K. The desired areal density is 3–10 kg/m². Wavefront control may be either passive (via a high stiffness system) or active control. Potential architecture implementations must package into an existing launch volume, deploy and be self-aligning to the micron level. The environment is expected to be L2.

This topic solicits proposals to develop enabling component and subsystem technology for these telescopes in the areas of precision deployable structures, i.e., large deployable optics manufacture and test; innovative concepts for packaging integrated actuation systems; metrology systems for direct measurement of the structure; deployment packaging and mechanisms; active control implemented on the structure (downstream corrective and adaptive optics are not included in this topic area); actuator systems for alignment (2 cm stroke actuators, lightweight, submicron dynamic range, nanometer stability); mechanical and inflatable deployable technologies; new thermally-stable materials for deployables; new approaches for achieving packagable structural depth; etc.

The goal for this effort is to mature technologies that can be used to fabricate 20 m class lightweight cryogenic flight-qualified telescope primary mirror systems. Proposals to fabricate demonstration components and subsystems with direct scalability to flight systems (concept described in the proposal) will be given preference. The target volume and disturbances, along with the estimate of system performance should be included in the discussion. A successful proposal shows a path toward a Phase II delivery of demonstration hardware on the scale of 3 m for characterization.
S3.04 Large-Aperture Lightweight Cryogenic Telescope Components & Systems

Lead Center: MSFC
Participating Center(s): GSFC, JPL

Planned future NASA infrared, far infrared and submillimeter missions such as the Single Aperture Far-IR (SAFIR) telescope, Space Infrared Interferometric Telescope (SPIRIT) and Submillimeter Probe of the Evolution of Cosmic Structure (SPECS) require both 10–30 m and 2–4 m class telescopes that are diffraction limited at 5–20 mm and operate at temperatures from 4–10 K. The desired areal density is 3–10 kg/m$^2$. Wavefront control may be either passive (via a high stiffness system) or active control. Potential architecture implementations include 2 m class segments, 4 m class mirrors, or membrane systems. It is anticipated that active cooling will be required. Potential telescope system architectures require transporting 1 W of heat at 15 K with 5 W/K, while others require 100 mW at 4 K with 1 W/K. This topic solicits proposals to develop enabling component and sub-system technology for cryogenic telescopes, including but not limited to: large-aperture lightweight cryogenic optic manufacture and test; thermal management, distributed cryogenic cooling, multiple heat lift; structure, deployment, and mechanisms; deployable cryogenic coolant lines; active wavefront control; etc. The goal for this effort is to mature technologies that can be used to fabricate 2–4 m and 10–30 m class lightweight cryogenic flight-qualified telescope primary mirror systems at a cost of less than $300,000 per square meter. Proposals to fabricate demonstration components and subsystems with direct scalability to flight will be given preference.

Exploration of the Solar System Topic S4

NASA’s program for Exploration of the Solar System seeks to answer fundamental questions about the Solar System and life: How do planets form? Why are planets different from one another? Where did the makings of life come from? Did life arise elsewhere in the solar system? What is the future habitability of Earth and other planets? The search for answers to these questions requires that we augment the current remote sensing approach to solar system exploration with a robust program that includes in situ measurements at key places in the solar system, and the return of materials from them for later study on the Earth. We envision a rich suite of missions to achieve this, including a comet nucleus sample return, a Europa lander, and a rover or balloon-borne experiment on Saturn’s moon Titan, to name a few. Numerous new technologies will be required to enable such ambitious missions.

Sub Topics:
This subtopic supports the development of advanced instruments and instrument technology to enable or enhance scientific investigations on future planetary missions. New measurement concepts, advances in existing instrument concepts, and advances in critical components are all of interest. Proposers are strongly encouraged to relate their proposed technology development to future planetary exploration goals.

Instruments for both remote sensing and in situ investigations are required for NASA’s planned and potential solar system exploration missions. Instruments are required for the characterization of the atmosphere, surface and subsurface regions of planets, satellites, and small bodies. These instruments may be deployed for remote sensing, on orbital or flyby spacecraft, or for in situ measurements, on surface landers and rovers, subsurface penetrators, and airborne platforms. In situ instruments cover spatial scales from surface reconnaissance to microscopic investigations. These instruments must be capable of withstanding operation in space and planetary environmental extremes, which include temperature, pressure, radiation, and impact stresses.

Examples of instruments that will meet the goals include, but are not limited to, the following:

- Instrumentation for definitive chemical, mineralogy, and isotopic analysis of surface materials: soils, dusts, rocks, liquids, and ices at all spatial scales, from planetary mapping to microscopic investigation. Examples include advanced techniques in reflectance spectroscopy, wet chemistry, laser-induced breakdown spectrometers, water and ice detectors, novel gas chromatograph and mass spectrometry, and age-dating systems.

- Instrumentation for the assessment of surface terrain and features. Examples include lidar systems and advanced imaging systems.

- Geophysical sensing systems to determine the near-surface and subsurface structure, textures, bulk components, and composition, such as seismic sensors, porosity measurement devices, permeameters, and surface penetrating radars.

- Instruments and components that will rely on, and take advantage of, high power capabilities, up to 100 kW, for measurements of planetary surfaces. The instruments may make direct or indirect use of the power, long duration observations, or extremely high data rates.

- Instrumentation focused on assessments of the identification and characterization of biomarkers of extinct or extant life, such as prebiotic molecules, complex organic molecules, biomolecules, or biominerals.

- Instrumentation for the chemical and isotopic analysis of planetary atmospheres.

- Advanced detectors for solar absorption spectrometry. One example is a detector that is fast and linear, i.e., does not saturate under high photon fluxes.

- Environmental sensing systems, such as meteorological sensors, humidity sensors, wind and particle size distribution sensors, and sounders for atmospheric profiling.

- Particles and fields measurements, such as magnetometers, and electric field monitors.

- Enabling instrument component and support technologies, such as laser sources, miniaturized pumps, sample inlet systems, valves, integrated bulk sample handling and processing systems, and fluidic
technologies for sample preparation.

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

S4.02 Extreme Environment & Aerial Mobility

Lead Center: JPL

This subtopic is composed of two elements: (1) Technologies for High Temperature/High Pressure Environments and (2) Technologies for Aerial Mobility. Both areas are focused on the future in situ exploration needs for Titan and Venus, worlds featuring dense atmospheres with low and high temperature extremes, respectively. Note that some technologies developed for the cryogenic environment of Titan will also be applicable to other severe low temperature destinations such as asteroids, comets, and Europa.

Titan is the second largest moon in the solar system and the only one that features a sufficiently dense atmosphere for buoyant vehicle flight. The atmosphere is predominantly nitrogen with a surface temperature of approximately 90 K. Targeted for exploration by Cassini-Huygens in 2004 and beyond, Titan is expected to be a geologically and chemically diverse world containing important clues on the nature of prebiotic chemistry. NASA is starting to lay the ground work for post-Cassini-Huygens exploration of Titan using autonomous, self-propelled aerobots capable of surveying many widely separated locations and potentially including surface sampling and composition analysis.

Venus is the second planet from the Sun and features a dense, CO$_2$ atmosphere completely covered by clouds with sulfuric acid aerosols, a surface temperature of 460°C and a surface pressure of 90 atmospheres. Although already explored by various orbiters and short-lived atmospheric probes and landers, Venus retains many secrets pertaining to its formation and evolution. NASA is interested in expanding its ability to explore the deep atmosphere and surface of Venus through use of long lived (days or weeks) balloons and landers.

Technologies for High Temperature and High Pressure Environments

- Advanced thermal control for Venus, including lightweight (50 kg/m$^3$), insulated pressure vessels able to protect the electronics and instruments enclosed inside for a few hours at 460°C and 100 bar; new lightweight thermal insulation materials (0.1 W/mK at 460°C), thermal storage (with 300–1000 kJ/kg energy density), thermal switches (over 1 W/K for “on” and 0.01 W/K for “off” mode), and high performance heat pipes (0.05 W/mK at 460 ºC and 100 bar).

- Science and engineering sensors able to operate at 460°C and 100 bar, including seismometers.

- High temperature electronics and electronic packaging for sensor and actuator interfaces at 460 °C, including low noise (10 nV/sqHz) preamplifiers, transmitters (S-band), drivers (with 0–100 V digital output for driving piezoelectric, electrostatic, or electromagnetic actuators), and high value (on the order of one to hundreds of micro Farad) capacitors.

- High temperature primary batteries (200 Whr/kg, 100 cycles) for operation at 460°C.
• Sample handling and acquisition systems including high temperature drills, motors, and actuators able to operate in the 460ºC, 90 atmosphere surface environment of Venus.

Technologies for Aerial Mobility

In addition to the severe environment technologies above, innovative technologies are also sought in the following areas of robotic technologies for aerial mobility:

• Concepts and devices for a low mass (~1–2 kg), high efficiency electric drive motor for the 90 K Titan environment. This motor needs to operate continuously for up to 12 months on Titan and drive the main propulsion propeller at up to 5 revolutions per second with a controllable power input across the range of 0–50 W.

• Concepts and devices for a low mass (Concepts and devices for surface sample acquisition from an aerobot in the 90 K surface environment of Titan. These can include, but are not limited to, station keeping, landed or anchored (tethered) aerobots. Both liquid and solid (ice or rock; loose particle or drilled core) samples are of interest.

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

S4.03 Advanced Flexible Electronics and Nanosensors

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

The strategic plan within the Office of Space Science at NASA calls for intense exploration of a wide variety of bodies in the solar system within a modest budget. To achieve this will require revolutionary advances over the capabilities of traditional spacecraft systems and a broadening of the tool set through the introduction of new kinds of space exploration systems. These systems will include, but are not limited to, orbiters, landers, atmospheric probes, rovers, penetrators, aerobots (balloons), planetary aircraft, subsurface vehicles (ice and soil), and submarines. Also of interest are delivery of distributed sensor systems consisting of networks of tiny (Nanosensors

The nanosensing and bio-nanotechnology for the sensing aspect of this subtopic seeks to leverage breakthroughs in the emerging fields of nano-technology and biotechnology to develop advanced sensors and actuators with increased sensitivity and small size for solar system exploration. Technologies should provide enhanced capabilities over the current state-of-the-art and be able to operate in an extreme environments. This harsh environment includes steady operation and cycling in the temperature range of -180°C to 100°C, and high radiation. Of particular interest are harsh environment-operable nanosystems for single molecule sensing and manipulation, on-chip biomolecular analysis, and semiconductor laser diodes in the 2–5 µm and detectors in the greater than 15 µm wavelength range.
Flexible Electronics

Electronically steerable L-band phased array antennas are needed for missions to the Moon, Mars, Titan and Venus. L-band provides the capability to detect surface and subsurface topology including ice or features hidden by the surface dust. Flexible, lightweight active arrays enable better packaging efficiency for the antenna and are critical for these missions. Currently, manufacturing reliable passive arrays with required tolerances is challenging and the only method for integration of the electronics is to attach and interconnect the electronic components on the surface. This method is expensive, unreliable and impractical for large arrays. Technologies enabling large area flexible antennas including flexible electronics are needed. State-of-the-art flexible, printable electronics have low switching frequencies. Innovative new materials or processes will be needed to enable devices that can handle the gigahertz frequencies needed for radar. In addition, large area manufacturing methods are needed to manufacture these passive and active antennas.

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

S4.04 Deep Space Power Systems

Lead Center: GRC
Participating Center(s): GSFC, JPL, JSC

Innovative concepts using advanced technology are solicited in the areas of energy conversion, storage, power electronics, and power system materials. Power levels of interest range from tens of milliwatts, to hundreds of watts. NASA Space Science missions in deep space environments require energy systems with long life capability, high energy density, high radiation tolerance, reliability, and low overall costs (including operations) which can operate in high and low temperatures and over wide temperature ranges. Advanced technologies are sought in the following areas:

Energy Conversion

Advances in photovoltaic technology are sought, including high power solar arrays and ultra lightweight thin and concentrator arrays with substantial increases in specific power watts per kilogram. Advances in radioisotope power conversion to electricity (tens of milliwatts to hundreds of watts with efficiencies >20 %) are sought. This includes advances in thermophotovoltaics, thermoelectrics, and Stirling. All proposed energy conversion technologies must be able to operate in deep-space environments with high radiation and wide-temperature operations.

Energy Storage

Includes advances in primary and secondary (rechargeable) battery technologies. Rechargeable technologies include lithium ion batteries, lithium polymer batteries, and other advanced concepts providing long life capability, and dramatic increases in mass and volume energy density watt hours per kilogram and watt hours per liter.
Primary battery technologies include Li-CFx and other high specific energy electrochemical systems. Must be able to operate in deep-space environments, including high radiation and low (-100°C) to high (400°C) temperature regimes.

For operation on planetary surfaces, the use of regenerative fuel cells, both conventional and unitized - passive designs, with substantial increases in mass and volume-specific energy for those situations where there are substantial time periods of charging and recharging (anywhere from hours to days).

**Power Electronics**

Advanced power electronic materials and devices for deep-space power systems are sought. The materials of interest include soft magnetics, dielectrics, insulation, and semiconductors. Devices of interest include transformers, inductors, electrostatic capacitors, high power semiconductor switches and diodes, and integrated control and driver circuits. Proposed technologies must improve upon the following characteristics: high temperature operation (>200°C), low-temperature (cryogenic) operation, wide-temperature operation (25–200°C), and/or high levels of space radiation (>150 krads) resistance.

**Electronics Packaging**

Advanced electronics packaging technologies that reduce volume and mass capable of either high temperature or wide temperature operation and space radiation resistance for use in space power systems are of interest. Also of interest are thermal control technologies of high heat flux capability which are integral to the electronic package.

**Power System Materials**

Advances are sought in materials, surfaces, and components that are durable for soft x-ray, electron, proton, and ultraviolet radiation and thermal cycling environments, lightweight electromagnetic interference shielding, and high-performance, environmentally-durable thermal control surfaces.

**S4.05 Astrobiology**

**Lead Center:** ARC  
**Participating Center(s):** JPL

Astrobiology includes the study of the origin, evolution, and distribution of life in the universe. New technologies are required to enable the search for extant or extinct life elsewhere in the solar system, to obtain an organic history of planetary bodies, to discover and explore water sources elsewhere in the solar system, and to detect microorganisms and biologically important molecular structures within complex chemical mixtures. Biomarkers produced by microbial communities are profoundly affected by internal biogeochemical cycling. The small spatial scales at which these biogeochemical processes operate necessitate measurements made using microsensors. The search for life on other planetary bodies will also require systems capable of moving and deploying instruments across, and through, varied terrain to access biologically important environments.
A second element of Astrobiology is the understanding of the evolutionary development of biological processes leading from single-cell organisms to multi-cell specimens and to complex ecological systems over multiple generations. Understanding of the effects of radiation and gravity on lower organisms, plants, humans and other animals (as well as elucidation of the basic mechanisms by which these effects occur) will be of direct benefit to the quality of life on Earth. These benefits will occur through applications in medicine, agriculture, industrial biotechnology, environmental management, and other activities dependent on understanding biological processes over multiple generations.

A third component of Astrobiology includes the study of evolution on ecological processes. Astrobiology intersects with NASA Earth Science studies through the highly accelerated rate of change in the biosphere being brought about by human actions. One particular area of study with direct links to Earth Science is microbe–environment interactions.

NASA seeks innovations in the following technology areas:

- For Mars exploration, technologies that would enable to provide a broad survey of areas in the vicinities of a rover or lander to narrow down a field of search for biomarkers.

- For Mars exploration, technologies that (using x-ray, neutron, ultrasonic, and other types of tomography) would enable a noninvasive, nondestructive analysis of the subsurface environment and areas inside rocks and ice to depths 10–20 cm with spatial resolutions of 2–10 micron. Such technologies should provide the capability for analysis of structures inside opaque matrices created by endolithic organisms or fossil structures, and possible elemental analysis of such structures.

- Technologies that would enable the aseptic acquisition of deep subsurface samples, the detection of aquifers, or enhance the performance of long distance ground roving, tunneling, or flight vehicles are required.

- For Europa exploration, technologies to enable the penetration of deep ice are required.

- Desirable features for both Mars and Europa exploration include the ability to carry an array of instruments and imaging systems, to provide aseptic operation mode, and to maintain a pristine research environment.

- Low-cost, lightweight systems to assist in the selection and acquisition of the most scientifically interesting samples are also of significant interest.

- High sensitivity, (femtomole or better) high resolution methods applicable to all biologically relevant classes of compounds for separation of complex mixtures into individual components.

- Advanced miniaturized sample acquisition and handling systems optimized for extreme environment applications.

- High sensitivity (femtomole or better) characterization of molecular structure, chirality, and isotopic composition of biogenic elements (H, C, N, O, S) embodied within individual compounds and structures.

- High spatial resolution (5 angstrom level) electron microscopy techniques to establish details of external morphology, internal structure, elemental composition, and mineralogical composition of potential biogenic structures.

- Innovative software to support studies of the origin and evolution of life. The areas of special interest are (1) biomolecular and cellular simulations, (2) evolutionary and phylogenetic algorithms and interfaces, (3) DNA computation, and (4) image reconstruction and enhancement for remote sensing.
- Technologies capable of measuring a range of volatile compounds at small spatial scales. Improved sensor designs for a wide range of analytes, including oxygen, pH, sulfide, carbon dioxide, hydrogen, and small molecular weight organic acids both on and near surfaces that could serve as habitats for microbes.

- Biotechnology – determining mutation rates and genetic stability in a variety of organisms, as well as accurately determining protein regulation changes in microgravity and radiation environments.

- Automated chemical analytical instrumentation for determining gross metabolic characteristics of individual organisms and ecologies, as well as chemical composition of environments.

- Spectral and imaging technology with high resolution and low power requirements.

- Habitat support – technologies for supporting miniature closed ecosystems, data collection, and transmission technologies in concert with the automated chemical instrumentation described above.

- Miniature-to-microscopic, high resolution, field worthy, smart sensors, or instrumentation for the accurate and unattended monitoring of environmental parameters that include, but are not limited to, solar radiation (190–800 nm at

- High resolution, high sensitivity (femtomole or better) methods for the isolation and characterization of nucleic acids (DNA and RNA) from a variety of organic and inorganic matrices.

- Mathematical models capable of predicting the combined effects of elevated pCO₂ (change in CO₂ over the eons) and solar UV radiation on carbon sequestration and N₂O emissions from experimental data obtained from field and laboratory studies of C-cycling rates, N-cycling rates, as well as diurnal and seasonal changes in solar UV.

- Microscopic techniques and technologies to study soil cores, microbial communities, pollen samples, etc., in a laboratory environment for the detailed spectroscopic analysis relevant to evolution as a function of climate changes.

- Robotic systems designed to provide access to environments such as deep-ocean hydrothermal vents.

Mars Exploration Topic S5

Technology enables us to answer our scientific questions. Without the continual development of new technologies, our thirst for knowledge will go unfulfilled. Our goal is to invent new technologies, rigorously test them here on Earth or in space and apply them to Mars Exploration. The technologies developed and tested in each mission will help enable even greater achievements in the missions that follow. See URL: [http://mars.jpl.nasa.gov/technology/] for [2] additional information.

Sub Topics:

S5.01 Detection and Reduction of Biological Contamination on Flight Hardware and in Return Sample Handling

Lead Center: JPL

Participating Center(s): ARC
As solar system exploration continues, NASA remains committed to the implementation of its planetary protection policy and regulations. Missions designed to return the first extraterrestrial samples since the Apollo moon landings are currently in space—the Stardust and Genesis spacecraft will return cometary and solar wind particles to Earth within this decade. A mission to return samples from Mars is being planned for the next decade. Other missions will seek evidence of life through in situ investigations far from Earth. One of the great challenges, therefore, is to develop or find the technologies or system approaches that will make compliance with planetary protection policy routine and affordable. Planetary protection is directed to 1) the control of terrestrial microbial contamination associated with robotic space vehicles intended to land, orbit, flyby, or otherwise be in the vicinity of extraterrestrial solar system bodies; and 2) the control of contamination of the Earth by extraterrestrial solar system material collected and returned by such missions. The implementation of these requirements will ensure that biological safeguards to maintain extraterrestrial bodies as biological preserves for scientific investigations are being followed in NASA’s space program. To fulfill its commitment, NASA seeks technologies and system approaches that will support compliance with planetary protection requirements.

Examples of such technologies include:

- Techniques for cleaning of organics to the nanogram per square centimeter level on complex surfaces (nondestructively and without residues) and validation of cleanliness at this level or better
- Nonabrasive cleaning techniques for narrow aperture occluded areas on spacecraft
- Techniques for in situ (i.e., at the exploration site) cleaning and sterilization to prevent cross-contamination between planetary surface samples
- A device or methodology for controlled measurement of microbial reduction at temperatures from 200–300°C to enable generation of microbial lethality curves.

Examples of systems approaches include:

- Containerization and encapsulation of samples to be returned to Earth, including innovative mechanisms for isolation, sealing, and leak detection
- System design concepts to enable facile and rapid use of cleaning and sterilization technologies during flight hardware assembly
- System design concepts to maintain the integrity of cleaned and sterilized complex flight systems and/or subsystems
- System concepts that would facilitate spacecraft sterilization at the system level just before launch or in flight

Research should be conducted to demonstrate technical feasibility during Phase I and show a path toward a Phase II hardware and software demonstration, and that will, when possible, deliver a demonstration unit or software package for JPL testing before the completion of the Phase II contract.
S5.02 Mars In Situ Robotics Technology

Lead Center: JPL

During future exploration of planets, moons, and small solar system bodies (such as comets and asteroids), developments are needed in new innovative robotic technologies for surface operations, subsurface access, and autonomous software for each. Because of limited spacecraft resources, elements must be robust and have low power, volume, mass, computation, telemetry bandwidth, and operational overhead requirements. Successful technologies will have to operate in environments characterized by extremes of temperatures, pressures, gravity, high-gravity landing impacts, vibration, and thermal cycling. In particular, this subtopic seeks technology innovations in the following areas:

Subsurface Access: Research should be conducted to develop complete, lightweight, dry drilling systems with a penetration depth of 10–50 m and have the capability of penetrating both regolith and rocks. The development should focus on significant reduction in mass from the currently available state-of-the-art interplanetary drilling systems as well as the automation required for real-time control and fault diagnosis and recovery. In addition, because of the lack of water in most of the environments of interest, the drilling should be performed without a lubricant between the bit and rock. Of interest also is the development of ice penetrators, designed with explicit consideration of limited computation and power, which use heat to melt their way through the surface.

Rover Technology: Long-range autonomous navigation systems that focus on long distance (greater than 5 km) traverses through natural terrain, using no a priori knowledge of the subject terrain. Inflatable rover technology with a focus on the development of low-mass, highly capable platforms for exploration of extreme terrain through innovations in novel mechanisms and the automation required for real-time control. Systems enabling navigation in very rough terrain with explicit consideration of limited sensing, computation, and power. Development of new sensor prototypes, with a clear path to flight-ready status within a short time span and at minimum cost. Concepts for new mobility systems or components, such as innovative wheel or suspension designs. Instrument placement with a focus on improved tools for the design of manipulation systems, to perform contact and noncontact operations such as drilling, grasping, sample acquisition, sample transfer, and contact and noncontact science instrument placement and pointing. Infrastructure for research, including low-cost, mass producible, research-quality rovers and supporting elements.

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

S5.03 Mars and Deep Space Telecommunications

Lead Center: JPL
This subtopic seeks innovative technologies for both RF and Free-Space Optical Communications supporting missions to Mars, including both planetary and proximity ranges, and for other planetary missions and local planetary networks.

### RF Communications

- Ultra-small, low-cost, low-power, innovative deep-space transponders and components, incorporating MMICs and Bi-CMOS circuits.
- MMIC modulators with drivers to provide large linear phase modulation (above 2.5 rad), high-data rate BPSK/QPSK modulation at X-band (8.4 GHz) and Ka-band.
- Sub-microradian antenna pointing techniques for Ka-band spacecraft antennas.
- High rate (10–200 Mbps) turbo-encoder and decoder and wavelet compression chips.
- Technologies for surface-to-surface communications in planetary environments.
- Fault-tolerant digital signal processing: Current space qualified DSP elements do not support high bandwidths because of the power consumption associated with radiation hardened manufacturing processes. Reconfigurable signal processing elements are sought that provide autonomous fault detection and correction with a graceful degradation in performance over the service life.
- Antenna systems: Novel materials and approaches are sought to construct large, inflatable reflective and RF focusing surfaces for use as large aperture antennas. Need to provide highly directional surface to orbit antenna patterns to maintain high rate data links.

### Optical Communications

- Efficient (greater than 20% wall plug), lightweight, flight-qualifiable, variable repetition-rate (1–60 MHz), pulsed lasers with greater than 1 kW of peak power per pulse (over the entire pulse-repetition rate), and potential for up to 10 W of average power.
- Photon counting 1064 nm and 1550 nm detectors with the gain greater than 1000, detection efficiency greater than 50%, very low additive noise, about 0.5 mm in diameter, bandwidth greater than 500 MHz, saturation levels > 50Mcounts/s.
- Lightweight, compact, high precision (less than 0.1 micro-radian), high bandwidth (0–2kHz), inertial reference sensors (angle sensors, gyros) for use onboard spacecraft.
- Novel schemes for stray-light control and sunlight mitigation, especially for large (> 5 m) ground-based optical antennae that must operate when pointed to within a few (about 3) degrees of the Sun.
- Low-cost, lightweight, efficient, compact, high precision (one micro-radian accuracy) star-trackers for spaceflight application.

Research should be conducted to demonstrate technical feasibility during Phase I and show a path toward a Phase II hardware and software demonstration, and that will, when possible, deliver a demonstration unit or software package for JPL testing before completion of the Phase II contract.
The SEC theme encompasses the Sun with its surrounding heliosphere carrying its photon and particle emissions and the subsequent responses of the Earth and planets. This requires remote and in situ sensing of upper atmospheres and ionospheres, magnetospheres and interfaces with the solar wind, the heliosphere, and the Sun. Improving our knowledge and understanding of these requires accurate in situ measurements of the composition, flow, and thermodynamic state of space plasmas and their interactions with atmospheres, as well as the physics and chemistry of the upper atmosphere and ionosphere systems. Remote sensing of neutral atoms are required for the physics and chemistry of the Sun, the heliosphere, magnetospheres, and planetary atmospheres and ionospheres. Because instrumentation is severely constrained by spacecraft resources, miniaturization, low power consumption, and autonomy are common technological challenges across this entire category of sensors. Specific technologies are sought in the following categories.

**Plasma Remote Sensing** (e.g, neutral atom cameras)

This may involve techniques for high-efficiency and robust imaging of energetic neutral atoms covering any part of the energy spectrum from 1 eV to 100 keV, within resource envelopes less than 5 kg and 5W.

- Miniaturized, radiation-tolerant, autonomous electronic systems for the above, within resource envelopes of 1–2 kg and 1–2 W.

**In Situ Plasma Sensors**

- Improved techniques for imaging of charged particle (electrons and ions) velocity distributions, as well as improvements in mass spectrometers in terms of smaller size or higher mass resolution.
- Improved techniques for the regulation of spacecraft floating potential near the local plasma potential, with minimal effects on the ambient plasma and field environment.
- Low power digital time-of-flight analyzer chips with subnanosecond resolution and multiple channels of parallel processing.
- Miniaturized, radiation-tolerant, autonomous electronic systems for the above, within resource envelopes of 1–2 kg and 1–2 W.
Fields Sensors

- Improved techniques for measurement of plasma floating potential and DC electric field (and by extension the plasma drift velocity), especially in the direction parallel to the spin axis of a spinning spacecraft.
- Measurement of the gradient of the electric field in space around a single spacecraft or cluster of spacecraft.
- Improved techniques for the measurement of the gradients (curl) of the magnetic field in space local to a single spacecraft or group of spacecraft.
- Direct measurement of the local electric current density at spatial and time resolutions typical of space plasma structures such as shocks, magnetopauses, and auroral arcs.
- Miniaturized, radiation-tolerant and autonomous electronic systems for the above, within resource envelopes of 1–2 kg and 1–2 W.

Electromagnetic Radiation Sensors

- Radar sounding and echo imaging of plasma density and field structures from orbiting spacecraft.
- Miniaturized, radiation-tolerant and autonomous electronic systems for the above, within resource envelopes of 1–2 kg and 1–2 W.

Sub Topics:
Deep Space Propulsion Topic S1.02

Spacecraft propulsion technology innovations are sought for upcoming deep space science missions. Propulsion system functions for these missions include primary propulsion, maneuvering, planetary injection, and planetary descent and ascent. Innovations are needed to reduce spacecraft propulsion system mass, volume, and/or cost. Applicable propulsion technologies include solar electric, chemical and thermal, solar sails, aeroassist and aerocapture and emerging technologies.

Solar Electric Propulsion

Innovations in electric propulsion system technologies are being sought for space science applications. One area of emphasis pertains to high-performance propulsion systems capable of delivering specific impulse (Isp) greater than 2000 s, using electrical power from radioisotope or solar energy sources. Thruster technologies include, but are not limited to, ion engines, Hall thrusters, and pulsed electromagnetic devices. Other areas of interest include propellant storage, direct drive and other innovative power processing, power management and distribution, heat-to-electrical power conversion, and waste heat disposal. Innovations considered here may focus on the component, subsystem or system level, and must ultimately result in significant improvements in spacecraft capability, longevity, mass, volume, and/or cost.

Solar Sails
Solar sails are envisioned as a low-cost, efficient transport system for future near-Earth and deep space missions. NASA mission's enabled and enhanced by solar sail propulsion include Tech Pull Missions such as Geotail, Comet Sample and Titan Flyby all to be launched between 2009 and 2012. Another category of NASA missions is the Particle Acceleration Solar Orbiter, including the L1-Diamond and the Solar Polar Imager, both to be launched between 2015 and 2028. Solar Sails are enabling for several strategic missions in the Sun-Earth Connection Space Science theme, including Solar Polar Imager and Interstellar Probe, the latter being a sail mission to explore interstellar space. Missions in the Exploration of the Solar System theme would be broadly enhanced by the availability of proven sail technology. Innovations are sought that will lower the cost and risk associated with sail development and application, and enhance sail delivery performance. Innovations are sought in the following areas: systems engineering, materials, structures, mechanical systems, fabrication, packaging and deployment, system control (attitude, etc.), maneuvering and navigation, operations, durability and survivability, and sail impact on science. Development of ultra-lightweight inflatable and deployable support structures is of significant interest, including rigidization approaches. Innovations in ultra-light reflective thin films are also sought. Three parameters have been used as sail performance metrics in mission applications: sail size, sail survivability for close solar approaches, and areal density (ratio of mass of the sail to area of the sail). In addition, important programmatic metrics are cost, benefit, and risk. Technologies of interest should be geared toward a wide range of sail sizes, solar closest approach distances, and aerial densities, and may be optimized for one portion of the range rather than trying to cover the whole range. Sail sizes may range from very small (meter-sized for use with very tiny picosat payloads or for use as auxiliary propulsion), to medium (50–100 m size for achieving high-inclination solar orbits or non-Keplerian near-Earth orbits) and ultimately to the very large (hundreds of meters for levitated orbits, high delta V, and for use in leaving the Solar System at high speed). Sail weight should include, but not be limited to, ultra-lightweight sail materials.

**Chemical and Thermal Propulsion**

Innovations in low-thrust chemical propulsion system technologies are being sought for Space Science missions applications. One area of interest is a bipropellant engine with Isp greater than 360 s. Component, subsystem, or system level technology development will be considered but work must ultimately result in significant reductions in spacecraft system mass, volume, and/or cost. Other areas to be considered include lightweight, compact and low-power propellant management components, such as valves, flow control/regulation, fluid isolation, dependable ignition systems, and lightweight tankage.

**Aeroassist**

Aeroassist is a general term given to various techniques to maneuver a space vehicle within an atmosphere, using aerodynamic forces in lieu of propulsion fuel. Aeroassist systems enable shorter interplanetary cruise times, increased payload mass, and reduced mission costs. Subsets of aeroassist are aerocapture and aerogravity assist. Aerocapture relies on the exchange of momentum with an atmosphere to achieve a decelerating thrust leading to orbit capture. This technique permits spacecraft to be launched from Earth at higher velocities, thus providing a shorter overall trip time. At the destination, the velocity is reduced by aerodynamic drag within the atmosphere. Without aerocapture, a substantial propulsion system would be needed on the spacecraft to perform the same reduction of velocity. Aerogravity assist is an extension of the established technique of gravity assist with a planetary body to achieve increases in interplanetary velocities. Aerogravity assist involves using propulsion in conjunction with aerodynamics through a planetary atmosphere to achieve a greater turning angle during planetary fly-by. In particular, this subtopic seeks technology innovations that are in the following areas:

**Aerocapture**

Thermal Protection Systems: Development of advanced thermal protection systems and insulators. Materials need high strength (modulus in the tens of GPa) and very low density (tens of kg/m$^3$). Improvements needed in materials include having highly anisotropic thermal properties, i.e., high thermal diffusivity tangential to the spacecraft shape and low thermal diffusivity normal to the spacecraft shape.
Sensors for Inflatable Decelerators: Health monitoring method for inflatable thin film systems.

Analytical Tools: Development of advanced tools to perform coupled aeroelastic and aerothermal analysis of inflatable decelerator systems.

Aerogravity Assist

Aerogravity Assist Technology Analysis: Research advancements in leading edge materials and provide CFD analysis of heating environment for aerogravity assist maneuvers at a small planet (e.g., Venus).

Emerging Propulsion Technologies

This effort will focus on technologies supporting innovative and advanced concepts for propellantless propulsion and other revolutionary transportation technologies. The categories under Emerging Propulsion Technologies include, but are not limited to: electrodynamic and momentum-exchange tether propulsion, beamed energy, ultra-light solar sails, bimodal sails, and low to medium power electric propulsion (including pulse inductive devices). The electrodynamic tether propulsion uses electromagnetic interaction with a planetary magnetic field to exchange angular momentum. Momentum exchange tethers (such as the MXER tether concept use a strong tether to transfer angular momentum and orbital energy to a payload. Beamed energy propulsion concepts include lasers or microwave energy to directly propel a spacecraft or to supply power that is utilized for propulsion onboard the spacecraft. Ultra-light or bimodal sail propulsion developing conventional solar sails into extremely high-performing systems. The low to medium electric propulsion is a general category for fresh variations of electric thrusters (Hall, MHD, PIT, etc.) that support near or mid-term solar powered spacecraft (e.g., below ~50 kW). Unique, innovative and novel propulsion ideas are sought but with reasonable expectations to progress to hardware prototypes. The concept must be above TRL 2 with rapid demonstration to TRL 4 expected. Distinctive variations of existing propulsion methods or chief subsystem component improvements are also suitable for submission. Proposals should provide development of specific innovative technologies or techniques supporting any of the above approaches. A clear plan for demonstrating feasibility, noting any test and experiment requirements, is also recommended. Key to each idea is an unambiguous knowledge of past research and concepts conducted on related work, and specifically, how this new proposal differs to the extent that it appears to offer a significant benefit. Identification of the fundamental technology to be developed is also crucial.

Sub Topics:
Multifunctional Autonomous Robust Sensor Systems Topic S1.03

NASA seeks innovative concepts for Multifunctional Autonomous Robust Sensor Systems (MARSS) to increase spacecraft autonomy and robustness. These concepts are intended to lower overall mission costs, reduce reliance on human control and monitoring, and allow for systems that are inherently robust and provide maximum flexibility of the space vehicles throughout mission lifecycle and for various space/planetary exploration missions. The systems should include the ability to couple the data from a variety of distributed sensor technologies to relevant response actuation systems of the vehicle. As we move from 10s of sensors to 1000s of sensors and beyond, new approaches must be investigated that will allow the vehicle to efficiently obtain “knowledge” about the health and optimization of its systems, and the ever changing environment it is in.

Robustness and autonomy in space vehicles are two of the keys to achieving maximum efficiency of missions and increasing the probability of success. Distributed, self-sufficient, reconfigurable sensors are at the heart of this capability. Technologies such as, but not limited to, MEMS, nanotechnology, integrated/distributed processors and fuzzy logic are potential elements of MARSS. These systems should be able to provide their own power by scavenging it from the environment and provide real-time knowledge from large numbers of sensors to various...
response systems to comprise “sense and respond” systems. In addition, methods are sought to improve radiation shielding of systems components. This includes, but are not limited to, metal and metal matrix materials that may offer better radiation protection properties than the current state-of-the-art aluminum alloys, and high atomic number intercalated graphite composites for lightweight strong radiation shielding of electronics to improve their robustness.

Emphasis should be placed on technologies that provide a sense-and-respond capability using technologies that are small, reliable, low-cost, lightweight, and would allow space probes to adapt to a wide range of space missions. Sensing requirements include both intrinsic (relating to the performance and health of the vehicle itself) and extrinsic (relating to the performance of the mission and adapting to the operating environment).

Evaluators will be looking for system concepts and not just individual pieces that could be used for a system. This requires multidiscipline collaboration on various proposals and clear explanations of system functionality, benefit, and improvement over existing technology. In addition, details of how systems will function in relevant space environments should be provided. The Technology Readiness Level (TRL) for submissions should be in the TRL 4-6 range. Please see the SBIR Web site for more details.

Sub Topics:
Spacecraft Technology for Micro- and Nanosats Topic S1.04
NASA seeks research and development of components, subsystems and systems that enable inexpensive, highly capable small spacecraft for future SEC missions. The proposed technology must be compatible with spacecraft somewhere within the micro-to-nano range of 100 kg down to 1 kg. All proposed technology must have a potential for providing a function at current performance levels with significantly reduced mass, power, and cost, or have a potential for significant increase in performance without additional mass, power, and cost. These reduction and/or improvement factors should be significant and show a minimum factor of 2 with a goal of 10 or higher.

A proposed technology must state the type or types of expected improvements, (performance, mass, power, and cost), list the assumptions for the current state-of-the-art, and indicate the spacecraft range of sizes for which the technology is applicable.

The integration of multiple components into functional units and subsystems is desirable but not a requirement for consideration.

- Avionics and architectures that support command and data handling functions, including input and output, formatting, encoding, processing, storage, and analog-to-digital conversion. System level architecture, software operating systems, low voltage logic switching, radiation-tolerant design, and packaging techniques are also appropriate technologies for consideration.

- Sensors and actuators that support guidance, navigation, and control functions such as Sun–Earth sensors, star trackers, inertial reference units, navigation receivers, magnetometers, reaction wheels, magnetic torquers, and attitude thrusters. Technologies with applications to either spinning or three-axis stable spacecraft are sought.
• Power system elements including those that support the generation, storage, conversion, distribution, regulation, isolation, and switching functions for spacecraft power. System level architecture, low voltage buss design, radiation tolerant design, and novel packaging techniques are appropriate technologies for consideration.

• New and novel application of technologies for manufacturing, integration and test of micro and nano size spacecraft are sought. Limited production runs of up to several hundred spacecraft can be considered. Efficiencies can derive from increased reliability, flexibility in the end-to-end production process, as well as cost, labor, and schedule.

• Technologies that support passive and active thermal control suitable for micro and nano size spacecraft are sought. These functions include heat generation, storage, rejection, transport, and the control of these functions. Efficient system level approaches for integrated small spacecraft that may see a wide range of thermal environments are desirable. These environments may range from low heliocentric orbits to 2 hr shadows.

• Elements that support Earth-to-space or space-to-space communications functions are sought. This includes receivers, transmitters, transceivers, transponders, antennas, RF amplifiers, and switches. S and X are the target communications bands.

• System architectures and hardware that lead to greater spacecraft and constellation autonomy and, therefore, reduce operational expenses are desired. Technologies that derive added capability for a fixed bandwidth, efficient utilization of ground systems, status analysis, and situation control or other enhancing performance for operations are sought.

• Structure and mechanism technologies and material applications that support the micro and nano class of spacecraft are desired. Exoskeleton structures, spin release mechanisms, and bi-stable deployment mechanisms are typical of the desired technology.

• Propulsion system elements that provide delta-V capability for spinning and/or three-axis stable spacecraft are sought. This includes solid, cold-gas, and liquid systems, and their components such as igniters, thrust vector control mechanisms, tanks, valves, nozzles, and system control functions.

Sub Topics:
Information Technology for Sun-Earth Connection Missions Topic S1.05

A large number of multiple-spacecraft missions are planned for the future of SEC science. Cost-effective implementation of these missions will require new information technology: tools, systems and architectures for mission planning, implementation, and operations; and science data processing and analysis that facilitate scientific understanding. Specific research areas of interest for these SEC multi-spacecraft missions include the following items below.

Information Technology for Cost-Effective Mission Planning and Implementation

Tools or systems are needed that improve the system engineering, integration, test, and synchronous operations of semiautonomous multiprobecraft missions with intermittent contact and large communication latencies; automated approaches to onboard science data processing and reactive onboard instrument management and control; and tools that capture and represent scientific objectives as preplanned and reactive onboard autonomous drivers.
Data Analysis

Items of interest in this area focus on innovative approaches and the tools necessary to support space and solar physics virtual observatories (physically distributed heterogeneous science data sources considered as a logical entity).

Tools are needed for enabling automated systematic identification, access, ad hoc science analysis, and distribution of large distributed heterogeneous data sets from space and solar physics data centers; and technologies and tools supporting inclusion of individual researcher provided, ad hoc, science analysis modules as a component of search criteria for remote data mining at space and solar physics data centers.

Sub Topics:
UV and EUV Optics Topic S1.06

From the Sun's atmosphere to the Earth's aurora, remote imaging, spectroscopy, and polarimetry at ultraviolet (UV) and extreme ultraviolet (EUV) wavelengths are important tools for studying the Sun-Earth connection. A far ultraviolet (FUV) range is sometimes interposed between UV and EUV, but the terminology is arbitrary: the pertinent full range of wavelength is approximately 20–300 nm.

Proposals should explain specifically how they intend to advance the state-of-the-art in one or more of the following areas.

Imaging Mirrors

- Large aperture: 1–4 m
- Low mass: 5–20 kg m\(^{-2}\)
- Accurate figure: ~0.01 wave rms or better at 632 nm. Figure accuracy must be maintained through launch and on orbit (including, for mirrors subjected to direct or concentrated solar radiation, the effects of differential heating)
- Low microroughness: ~1 nm rms or better on scales below 1 mm.

Optical Coatings and Transmission Filters

- Coatings (filters) with improved reflectivity (transmission) and selectivity (narrow bands, broad bands, or edges). Technologies include (but are not limited to) multilayer coatings, transmission gratings, and Fabry-Pérot étalons.

Diffraction Gratings
• High groove density (> 4000 mm\(^{-1}\)) for high spectral resolving power in conjunction with achievable focal lengths and pixel sizes

• High efficiency and low scatter (microroughness)

• Variable line spacing

• Echelle gratings

• Active gratings (replicated onto deformable surfaces)

• Aspherical concave substrates, such as toroids and ellipsoids

Proposals that address detector requirements of Sun-viewing instruments, such as large format, deep wells, fast readout, or “3-D” (spatial-spatial-energy) resolution, should be submitted to Topic S2.05.

Sub Topics:
Sensors and Detectors for Astrophysics Topic S2.01

Future NASA astrophysics missions like Sofia, Herschel, Planck, FAIR, MAXIM, EXIST, and ARISE (http://spacescience.nasa.gov/missions/index.htm [1]) need improvements in sensors and detectors. Beyond 2007, expected advances in detectors and other technologies may allow the Filled Aperture Infrared instrument (FAIR) to extend HST observations into the mid- and far-infrared (40–500 micron) region; the Micro-Arcsecond X-ray Imaging Mission Pathfinder (MAXIM) will demonstrate the feasibility of x-ray interferometry with a resolution of 100 micro-arc seconds, which is 5000 times better than the Chandra observatory; the Energetic X-ray Imaging Survey Telescope (EXIST) will conduct the first high sensitivity, all-sky imaging survey at the predominantly thermal (x-ray) and non-thermal (gamma-ray) universe requiring a wide-field coded aperture telescope array; and the Advanced Radio Interferometry between Space and Earth (ARISE) mission will create an interferometer including radio telescopes in space and on Earth.

Space science sensor and detector technology innovations are sought in the following areas:

**Mid/Infrared, Far Infrared and Submillimeter**

Future space-based observatories in the 10-40 micron spectral regime will be passively cooled to about 30 K. They will make use of large sensitive detector arrays with low-power dissipation array readout electronics. Improvements in sensitivity, stability, array size, and power consumption are sought. In particular, novel doping approaches to extend wavelength response, lower dark current and readout noise, novel energy discrimination approaches, and low noise superconducting electronics are applicable areas. Future space observatories in the 40 micron to 1 mm spectral regime will be cooled to even lower temperatures, frequently 20 W Hz\(^{-1/2}\) over most of the spectral range in a 100x100 pixel detector array, with low-power dissipation array readout electronics. The ideal detector element would count individual photons and provide some energy discrimination. For detailed line mapping (e.g., C\(^+\) at 158 micron), heterodyne receiver arrays are desirable, operating in the same frequency range near the quantum limit.
Space Very Long Baseline Interferometry (VLBI)

The next generations of Very Long Baseline Interferometry (VLBI) missions in space will demand greatly improved sensitivity over current missions. These new missions will also operate at much higher frequencies (at first to 86 GHz and eventually to 600 GHz). These thrusts will require development of improved space-borne low-power ultra-low-noise amplifiers and mixers to serve as primary receiving instruments.

Sub Topics:
Terrestrial and Extra-Terrestrial Balloons and Aerobots Topic S2.02

Innovations in materials, structures, and systems concepts have enabled buoyant vehicles to play an expanding role in NASA’s Space and Earth Science Enterprises. A new generation of large, stratospheric balloons based on advanced balloon envelope technologies will be able to deliver payloads of several thousand kilograms to above 99.9% of the Earth’s absorbing atmosphere and maintain them there for months of continuous observation. Smaller scale, but similarly designed, balloons and airships will also carry scientific payloads on Mars, Venus, Titan, and the outer planets in order to investigate their atmospheres in situ and their surfaces from close proximity. Their envelopes will be subject to extreme environments and must support missions with a range of durations. Robotic balloons, known as aerobots, have a wide range of potential applications both on Earth and on other solar system bodies. NASA is seeking innovative and cost-effective solutions in support of terrestrial and extraterrestrial balloons and aerobots in the following areas.

Stratospheric Long Duration Balloon (LDB) Support

Materials

- Innovative membranes for terrestrial applications to support the Long Duration Balloon (LDB) and Ultra-Long Duration Balloon (ULDB) development efforts. The material of interest shall meet all environmental, design, fabrication, and operational requirements and must be producible in large quantities in a lay-flat width of at least 1.6 m.

- Innovative concepts for reducing the UV degradation of flight components including balloon membranes, load carrying members, and parachute components.

Support Systems

- Innovative concepts for trajectory control and/or station-keeping for effectively maneuvering large terrestrial and small extraterrestrial aerobots in either the horizontal latitude or vertical altitude plane or both.

- Innovative low mass, high density, and high efficiency power systems for terrestrial balloons that produce 2 kW or more continuously.

- Innovative power systems that enable long duration, sunlight independent missions for a duration of 30 days or more.
• Innovative, low cost, low power, low mass, precision instrument pointing systems that permit arcsecond or better accuracy.

• Innovative sensor concepts for balloon gas or skin temperature measurements.

• Innovative floatation systems for water recovery of payloads.

**Design and Fabrication**

• Innovative, efficient, reliable and cost-effective balloon fabrication and inspection techniques to support the current ULDB development efforts.

• Innovative balloon design concepts for long duration missions which can provide any or all of the following:
  
  ○ Reduced material strength requirements;
  ○ Increased reliability;
  ○ Enhanced performance;
  ○ Reduced manufacturing time;
  ○ Reduced manufacturing cost; and
  ○ Improved mission flexibility.

**Titan Missions Support**

Titan is the second largest moon in the solar system and the only one that features a sufficiently dense atmosphere for buoyant vehicle flight. Targeted for exploration by Cassini-Huygens in 2004 and beyond, Titan is expected to be a geologically and chemically diverse world containing important clues on the nature of prebiotic chemistry. NASA is starting to lay the groundwork for post-Cassini-Huygens exploration of Titan using highly autonomous, self-propelled aerobots capable of surveying many widely separated locations on the world and potentially including surface sampling and composition analysis. Innovative technologies are sought in the following areas:

• Concepts, devices and materials for sealing (repairing) of small holes in the balloon envelope material during flight at Titan. Repair of these holes may be required to enable the long mission lifetimes (6–12 months) desired at Titan. Although the balloon envelope material for Titan has not yet been specified, repair strategies should be generally compatible with polymer materials and the 90 K environment. It is imperative that proposed solutions be low mass (on the order of a few kilograms) and low power (a few Watts).

• Concepts and devices for the processing of atmospheric methane into hydrogen gas and its use as a makeup gas to compensate for leakage during operational flight at Titan. It is imperative that proposed solutions be low mass (on the order of a few kilograms) and low power (a few Watts).

**Venus Missions Support**

Venus is the second planet from the Sun and features a dense, CO₂ atmosphere completely covered by clouds. Although already explored by various orbiters and short-lived atmospheric probes and landers, Venus retains many
secrets pertaining to its formation and evolution. One of NASA’s long-term objectives is to develop the technologies required for a surface sample return mission. A high temperature balloon is one key element that will be needed to loft the sample from the surface to a high altitude for launching a return rocket back to Earth. Innovative technologies are, therefore, sought in the following area:

- Designs, materials, and prototypes for surface-launched Venus balloons. Balloon volumes in the range of 0.5–5 m$^3$ are required when fully inflated. The balloon must be storable in a packaged condition for up to 1 year and have an areal density of less than 1000 g/m$^2$. Proposed concepts must include an automatic surface launch that will work in the Venus environment consisting of 460°C temperature, 90 atmosphere pressure, and surface winds of up to 1 m/s.

Sub Topics:
- Cryogenic Systems Topic S2.03
Cryogenic systems have long been used to perform cutting edge space science, but at high cost and with limited lifetime. Improvements in cryogenic system technology enable further scientific advancement at lower cost and/or lower risk. Lifetime, reliability, mass, and power requirements of the cryogenic systems are critical performance concerns. Of interest are cryogenic coolers for cooling detectors, telescopes, and instruments. In addition, cryogenic coolers for lunar and interplanetary exploration are of interest. The coolers should have long life, low vibration, low mass, low cost, and high efficiency. Specific areas of interest include the following:

- Highly efficient coolers in the range of 4–10 K as well as 50 mK and below, and cryogen-free systems that integrate these coolers together;
- Low-mass, highly efficient coolers for gas sample collection and liquefaction of gases for use in propulsion systems;
- Essentially vibration-free cooling systems, such as reverse Brayton cycle cooler technologies;
- Highly reliable, efficient, low-cost Stirling and pulse tube cooler technologies in the 10 K, 15 K, and 35 K regions;
- Highly efficient magnetic and dilution cooling technologies, particularly at very low temperatures;
- Hybrid cooling systems that make optimal use of radiative coolers; and
- Miniature, MEMS, and solid-state cooler systems.

Sub Topics:
- Optical Technologies Topic S2.04
The NASA Space Science Enterprise is studying future missions to explore the Structure and Evolution of the Universe (SEU). To understand the structure and evolution of the universe, a variety of large space-based observatories are necessary to observe cosmic phenomena from radio waves to the highest energy cosmic rays. It will be necessary to operate some of these observatories at cryogenic temperatures (to 4 K) beyond
geosynchronous orbits. Apertures for normal incidence telescope optics are required up to 40 m in diameter, while grazing incidence optics are required to support apertures up to 10 m in diameter. For some missions, these apertures will form a constellation of telescopes operating as interferometers. These interferometric observatories may have effective apertures up to 1000 m diameter. Low mass of critical components such as the primary mirror, its support and/or deployment structure, is extremely important. In order to meet the stringent optical alignment and tolerances necessary for a high quality telescope and to provide a robust design, there are significant benefits possible from employing systems that can adaptively correct for image degrading sources from inside and outside the spacecraft. This includes correction systems for large aperture space telescopes that require control across the entire wavefront, typically at low temporal bandwidth. The following technologies are sought:

- Grazing incidence focusing mirrors with response up to 150 keV.
- Large, ultra-lightweight grazing incidence optics for x-ray mirrors with angular resolutions less than 5 arcsec.
- Wide field-of-view optics using square pore slumped microchannel plates or equivalent.
- Develop fabrication techniques for ultra-thin-flat silicon (or like material) for grating substrates for x-ray energies
- Large area thin blocking filters with high efficiency at low energy x-ray energies
- Ultraviolet filters with deep blocking
- Develop novel materials and fabrication techniques for producing ultra-lightweight mirrors, high-performance diamond turned optics (including freeform optical surfaces), and ultra-smooth (2–3 angstroms rms) replicated optics that are both rigid and lightweight. Lightweight high modulus (e.g., silicon carbide) optics and structures are also desired.
- High-performance (e.g., high modulus, low density, high thermal conductivity) materials and fabrication processes for ultra-lightweight, high precision (e.g., subarcsecond resolution or
- Advanced, low-cost, high quality large optics fabrication processes and test methods including active metrology feedback systems during fabrication, and artificial intelligence controlled systems.
- Large, ultra-lightweight optical mirrors including membrane optics for very large aperture space telescopes and interferometers.
- Cryogenic optics, structures, and mechanisms for space telescopes and interferometers.
- Ultra-precise, low mass deployable structures to reduce launch volume for large-aperture space telescopes and interferometers.
- Segmented optical systems with high-precision controls; active and/or adaptive mirrors; shape control of deformable telescope mirrors; and image stabilization systems.
- Advanced, wavefront sensing and control systems including image based wavefront sensors.
- Wavefront correction techniques and optics for large aperture membrane mirrors and refractors (curved lenses, Fresnel lenses, diffractive lenses).
- Nanometer to sub-picometer metrology for space telescopes and interferometers.
- Develop ultra-stable optics over time periods from minutes to hours.
- Advanced analytical models, simulations, and evaluation techniques, and new integrations of suites of existing software tools allowing a broader and more in-depth evaluation of design alternatives and identification of optimum system parameters including optical, thermal, structural, and dynamic performance of large space telescopes and interferometers.
Develop portable and miniaturized state-of-the-art optical characterization instrumentation and rapid, large-area surface-roughness characterization techniques are needed. In addition, develop calibrated processes for determination of surface roughness using replicas made from the actual surface. Traceable surface roughness standards suitable for calibrating profilometers over sub-micron to millimeter wavelength ranges are needed.

Develop instruments capable of rapidly determining the approximate surface roughness of an optical surface, allowing modification of process parameters to improve finish, without the need to remove the optics from the polishing machine. Techniques are needed for testing the figure of large, convex aspheric surfaces to fractional wave tolerances in the visible.

Sub Topics:
Advanced Photon Detectors Topic S2.05

The next generation of astrophysics observatories for the infrared, ultraviolet (UV), x-ray, and gamma-ray bands require order-of-magnitude performance advances in detectors, detector arrays, readout electronics, and other supporting and enabling technologies. Although the relative value of the improvements may differ among the four energy regions, many of the parameters where improvements are needed are present in all four bands. In particular, all bands need improvements in spatial and spectral resolutions, in the ability to cover large areas, and in the ability to support the readout of the thousands to millions of resultant spatial resolution elements.

Innovative technologies are sought to enhance the scope, efficiency, and resolution of instrument systems at all energies and wavelengths:

- The next generation of gravitational missions will require greatly improved inertial sensors. Such an inertial sensor must provide a carefully fabricated test mass which has interactions with external forces (i.e., low magnetic susceptibility, high degree of symmetry, low variation in electrostatic surface potential, etc.) below 10–16 of the Earth’s gravity, over time scales from several seconds to several hours. The inertial sensor must also provide a housing for containing the proof mass in a suitable environment (i.e., high vacuum, low magnetic and electrostatic potentials, etc.).

- Advanced charged couple device (CCD) detectors, including improvements in UV quantum efficiency and read noise, to increase the limiting sensitivity in long exposures and improved radiation tolerance. Electron-bombarded CCD detectors, including improvements in efficiency, resolution, and global and local count rate capability. In the x-ray, we seek to extend the response to lower energies in some CCDs, and to higher, perhaps up to 50 keV, in others.

- Significant improvements in wide band gap (such as GaN and AlGaN) materials, individual detectors, and arrays for UV applications.

- Improved microchannel plate detectors, including improvements to the plates themselves (smaller pores, greater lifetimes, alternative fabrication technologies, e.g., silicon), as well as improvements to the associated electronic readout systems (spatial resolution, signal-to-noise capability, dynamic range), and in sealed tube fabrication yield.

- Imaging from low-Earth orbit of air fluorescence UV light generated by giant airshowers by ultra-high energy (E > 1019 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
For advanced x-ray calorimetry improvements in several areas are needed, including:

- Superconducting electronics for cryogenic x-ray detectors such as SQUID-based amplifiers and their multiplexers for low impedance cryogenic sensors and superconducting single-electron transistors and their multiplexers for high impedance cryogenic sensors;

- Micromachining techniques that enhance the fabrication, energy resolution, or count rate capability of closely-packed arrays of x-ray calorimeters operating in the energy range from 0.1–10 keV; and

- Surface micromachining techniques for improving integration of x-ray calorimeters with read-out electronics in large scale arrays.

- Improvements in readout electronics, including low power ASICs and the associated high density interconnects and component arrays to interface them to detector arrays.

- Superconducting tunnel junction devices and transition edge sensors for the UV and x-ray regions. For the UV, these offer a promising path to having "three-dimensional" arrays (spatial plus energy). Improvements in energy resolution, pixel count, count rate capability, and long wavelength rejection are of particular interest. We seek techniques for fabrication of close packed arrays, with any requisite thermal isolation, and sensitive (SQUID or single electron transistor), fast, readout schemes and/or multiplexers.

- Arrays of CZT detectors of thickness 5–10 mm to cover the 10–500 keV range, and hybrid detector systems with a Si CCD over a CZT pixelated detector operating in the 2–150 keV range.

- For improvements to detector systems for solar and night-time UV and EUV (approx. 20–300nm) observing the following areas are of interest: Large format (4 K x 4 K and larger); high quantum efficiency; small pixel size; large well depth; low read noise; fast readout; low power consumption (including readout); intrinsic energy and/or polarization discrimination (3d or 4d detector); active pixel sensors (back-illumination, UV sensitivity); and high-resolution image intensifiers, UV and EUV sensitive, insensitive to moisture.

- Space spectroscopic observations in the UV, visible and IR requiring long observations times would be much more sensitive with high quantum efficiency (QE) and zero read noise. Techniques are sought which improve the QE of photon counters, or eliminate the read noise of solid state detectors.

- X-ray and gamma-ray imaging with higher sensitivity, dynamic range, and angular resolution requires innovations in modulation collimators and detection devices. The energy range of interest is from a few kilo-electron Volts to hundreds of milli-electron Volts for observations of solar flares and cosmic sources. Collimators with size scales down to a few microns and thicknesses commensurate with photon absorption over a significant fraction of this energy range are required. Low-background detectors capable of...
with extremely precise laser interferometers and test masses which are actively decoupled from systematic and random disturbances.

The technology areas are organized into two subsystems, one dealing with the disturbance rejection subsystem, which houses the proof mass with active sensors and thrusters to cancel non-gravity wave disturbances, and the other implementing the network of laser interferometers with nanometer-level resolution of relative range between the test masses. Because the systems will be deployed in space, the technologies to be considered must be, or have, credible paths toward full space flight qualification, including thermal and radiation considerations. Background information on LISA, along with preliminary technology discussions, can be found in the proceedings of the 4th International LISA Symposium, Penn State University, 19–24 July 2002, published in the Classical and Quantum Gravity Journal, Volume 20, Number 10, 21 May 2003.

**Disturbance Reduction System (DRS)**

- Vacuum system – non-magnetic vacuum pump for reaching pressures of -6 Pa with a pumping volume of 1 liter; with associated valves and electronics
- Vacuum gauge – read pressure down to $10^{-6}$ Pa on orbit, must be non-magnetic
- Caging actuator – hold 2 kg mass $\sim 4 \text{ cm}^3$ against launch loads of $\sim 25$ g rms, with the capability for moving caged test mass over $\sim 10$ micron range with $\sim 1$ nm precision during ground testing
- Test mass, $\sim 4 \text{ cm}^3$, mass $\sim 1–2$ kg, magnetic susceptibility -6 (e.g., 73% gold/27% platinum)

**Laser Interferometer**

- Laser with exceptional power, frequency noise, amplitude noise, lifetime characteristics.
  - Fiber coupled output power (1 W) CW
  - A combination of a lower power master oscillator with suitable amplifier to yield 1 W of total fiber coupled output power may be acceptable
  - Frequency and amplitude noise characteristics: Frequency stability to $(30 \text{ Hz}$/$\text{vHz}$ at 1 mHz), and power stability to $(2 \times 10^{-4}$/$\text{vHz}$ at 1 mHz)
  - Lifetime of 10 years or more.
  - Wavelength is nominally 1.064 micron, but +/- 20% of that value is acceptable.
  - Semiconductor diode pump laser with outstanding reliability to operate with a suitable solid-state laser (e.g., non-planar ring oscillator laser) is required.
- Electro-optical modulator – produce phase modulation of continuous laser beam with 10% (power) modulation depth at frequencies from 1.9–2.1 GHz with fiber coupled input and output.Baseline operation will be at 1.064 microns. In addition to the space qualification requirements, the modulator must be able to handle optical power levels at $\sim 1$ W.
Research and technology development 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 to a participating NASA Center for testing at the completion of the Phase II contract.

Sub Topics:

   Precision Constellations for Interferometry Topic S3.01

This subtopic seeks hardware and software technologies necessary to establish, maintain and operate hyper-precision spacecraft constellations to a level that enables separated spacecraft optical interferometry. Also sought are technologies for analysis, modeling, and visualization of such constellations.

In a constellation for large effective telescope apertures, multiple, collaborative spacecraft in a precision formation collectively form a variable-baseline interferometer. These formations require the capability for autonomous precision alignment and synchronized maneuvers, reconfigurations, and collision avoidance. It is important that, in order to enable precision spacecraft formation keeping from coarse requirements (relative position control of any two spacecraft to less than 1 cm, and relative bearing of 1 arcmin over target range of separations from a few meters to tens of kilometers) to fine requirements (micron relative position control and relative bearing control of 0.1 arcsec), the interferometer payload would still need to provide at least 1–3 orders of magnitude improvement on top of the S/C control requirements. The spacecraft also require onboard capability for optimal path planning, and time optimal maneuver design and execution.

Innovations that address the above precision requirements are solicited for distributed constellation systems in the following areas:

- Integrated optical/formation/control simulation tools;
- Distributed, multitiming, high fidelity simulations;
- Formation modeling techniques;
- Precision guidance and control architectures and design methodologies;
- Centralized and decentralized formation estimation;
- Distributed sensor fusion;
- RF and optical precision metrology systems;
- Formation sensors;
- Precision microthrusters/actuators;
- Autonomous reconfigurable formation techniques;
Optimal, synchronized, maneuver design methodologies;

Collision avoidance mechanisms;

Formation management and station keeping; and

Six degrees of freedom precision formation testbeds.

Sub Topics:
High Contrast Astrophysical Imaging Topic S3.02

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 and the detailed inner structure of galaxies with very bright nuclei. Contrast ratios of one million to one billion over an angular spatial scale of 0.05–1.5 arcsec are typical of these objects. Achieving a very low background against which to detect a planet, 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 any starlight cancellation scheme.

This innovative research focuses on advances in coronagraphic instruments, interferometric starlight cancellation instruments, and potential occulting technologies that operate at visible and infrared wavelengths. The ultimate application of these instruments is to operate in space as part of a future observatory mission. Much of the scientific instrumentation used in future NASA observatories for the Origins Program theme will be similar in character to instruments used for present day space astrophysical observations. The performance and observing efficiency of these instruments, however, must be greatly enhanced. The instrument components are expected to offer much higher optical throughput, larger fields of view, and better detector performance. The wavelengths of primary interest extend from the visible to the thermal infrared. Measurement techniques include imaging, photometry, spectroscopy, coronography, and polarimetry. There is interest in component development, and innovative instrument design, as well as in the fabrication of subsystem devices to include, but are not limited to, the following areas:

**Starlight Suppression Technologies**

- Advanced starlight canceling coronagraphic instrument concepts.
- Advanced aperture apodization and aperture shaping techniques.
- Pupil plane masks for interferometry.
- Advanced apodization mask or occulting spot fabrication technology controlling smooth density gradients to $10^{-6}$ with spatial resolutions $\sim 1 \mu m$.
- Metrology for detailed evaluation of compact, deep density apodizing masks, Lyot stops, and other types of graded and binary mask elements. Development of a system to measure spatial optical density, phase inhomogeneity, scattering, spectral dispersion, thermal variations, and to otherwise estimate the accuracy of masks and stops is needed.
- Interferometric starlight cancellation instruments and techniques to include aperture synthesis and single input beam combination strategies.

- Fiber optic spatial filter development for visible coronagraph wavelengths.

- Single mode fiber filtering from visible to 20 µm wavelength.

- Methods of polarization control and polarization apodization.

- Components and methods to insure amplitude uniformity in both coronagraphs and interferometers, specifically materials, processes, and metrology to insure coating uniformity.

**Wavefront Control Technologies**

- Development of small stroke, high precision deformable mirrors (DM) and associated driving electronics scalable to 104 or more actuators (both to further the state-of-the-art towards flight-like hardware, and to explore novel concepts). Multiple DM 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.

- Reliability and qualification of actuators and structures in deformable mirrors to eliminate or mitigate single actuator failures.

- Multiplexer development for electrical connection to deformable mirrors that has ultra-low power dissipation. The most promising DM technology may be sensitive to temperature, so developing a MUX that has very low thermal hot-spots, and very uniform temperature performance will improve the control of the mirror surface.

- High precision wavefront error sensing and control techniques to improve and advance coronagraphic imaging performance.

**Sub Topics:**

**Precision Deployable Lightweight Cryogenic Structures for Large Space Telescopes Topic S3.03**

Planned future NASA Origins Missions and Vision Missions such as the Single Aperture Far-IR (SAFIR) telescope, Life Finder, and Submillimeter Probe of the Evolution of Cosmic Structure (SPECs) require 10–30 m class telescopes that are diffraction limited at wavelengths between the visible and the near IR, and operate at temperatures from 4–300 K. The desired areal density is 3–10 kg/m². Wavefront control may be either passive (via a high stiffness system) or active control. Potential architecture implementations must package into an existing launch volume, deploy and be self-aligning to the micron level. The environment is expected to be L2.

This topic solicits proposals to develop enabling component and subsystem technology for these telescopes in the areas of precision deployable structures, i.e., large deployable optics manufacture and test; innovative concepts for packaging integrated actuation systems; metrology systems for direct measurement of the structure; deployment packaging and mechanisms; active control implemented on the structure (downstream corrective and adaptive optics are not included in this topic area); actuator systems for alignment (2 cm stroke actuators, lightweight, submicron dynamic range, nanometer stability); mechanical and inflatable deployable technologies; new thermally-stable materials for deployables; new approaches for achieving packagable structural depth; etc.
The goal for this effort is to mature technologies that can be used to fabricate 20 m class lightweight cryogenic flight-qualified telescope primary mirror systems. Proposals to fabricate demonstration components and subsystems with direct scalability to flight systems (concept described in the proposal) will be given preference. The target volume and disturbances, along with the estimate of system performance should be included in the discussion. A successful proposal shows a path toward a Phase II delivery of demonstration hardware on the scale of 3 m for characterization.

Sub Topics:
Large-Aperture Lightweight Cryogenic Telescope Components & Systems Topic S3.04

Planned future NASA infrared, far infrared and submillimeter missions such as the Single Aperture Far-IR (SAFIR) telescope, Space Infrared Interferometric Telescope (SPIRIT) and Submillimeter Probe of the Evolution of Cosmic Structure (SPECS) require both 10–30 m and 2–4 m class telescopes that are diffraction limited at 5–20 mm and operate at temperatures from 4–10 K. The desired areal density is 3–10 kg/m². Wavefront control may be either passive (via a high stiffness system) or active control. Potential architecture implementations include 2 m class segments, 4 m class mirrors, or membrane systems. It is anticipated that active cooling will be required. Potential telescope system architectures require transporting 1 W of heat at 15 K with 5 W/K, while others require 100 mW at 4 K with 1 W/K. This topic solicits proposals to develop enabling component and sub-system technology for cryogenic telescopes, including but not limited to: large-aperture lightweight cryogenic optic manufacture and test; thermal management, distributed cryogenic cooling, multiple heat lift; structure, deployment, and mechanisms; deployable cryogenic coolant lines; active wavefront control; etc. The goal for this effort is to mature technologies that can be used to fabricate 2–4 m and 10–30 m class lightweight cryogenic flight-qualified telescope primary mirror systems at a cost of less than $300,000 per square meter. Proposals to fabricate demonstration components and subsystems with direct scalability to flight will be given preference.

Sub Topics:
Science Instruments for Conducting Solar System Exploration Topic S4.01

This subtopic supports the development of advanced instruments and instrument technology to enable or enhance scientific investigations on future planetary missions. New measurement concepts, advances in existing instrument concepts, and advances in critical components are all of interest. Proposers are strongly encouraged to relate their proposed technology development to future planetary exploration goals.

Instruments for both remote sensing and in situ investigations are required for NASA’s planned and potential solar system exploration missions. Instruments are required for the characterization of the atmosphere, surface and subsurface regions of planets, satellites, and small bodies. These instruments may be deployed for remote sensing, on orbital or flyby spacecraft, or for in situ measurements, on surface landers and rovers, subsurface
penetrators, and airborne platforms. *In situ* instruments cover spatial scales from surface reconnaissance to microscopic investigations. These instruments must be capable of withstanding operation in space and planetary environmental extremes, which include temperature, pressure, radiation, and impact stresses.

Examples of instruments that will meet the goals include, but are not limited to, the following:

- Instrumentation for definitive chemical, mineralogy, and isotopic analysis of surface materials: soils, dusts, rocks, liquids, and ices at all spatial scales, from planetary mapping to microscopic investigation. Examples include advanced techniques in reflectance spectroscopy, wet chemistry, laser-induced breakdown spectrometers, water and ice detectors, novel gas chromatograph and mass spectrometry, and age-dating systems.

- Instrumentation for the assessment of surface terrain and features. Examples include lidar systems and advanced imaging systems.

- Geophysical sensing systems to determine the near-surface and subsurface structure, textures, bulk components, and composition, such as seismic sensors, porosity measurement devices, permeameters, and surface penetrating radars.

- Instruments and components that will rely on, and take advantage of, high power capabilities, up to 100 kW, for measurements of planetary surfaces. The instruments may make direct or indirect use of the power, long duration observations, or extremely high data rates.

- Instrumentation focused on assessments of the identification and characterization of biomarkers of extinct or extant life, such as prebiotic molecules, complex organic molecules, biomolecules, or biominerals.

- Instrumentation for the chemical and isotopic analysis of planetary atmospheres.

- Advanced detectors for solar absorption spectrometry. One example is a detector that is fast and linear, i.e., does not saturate under high photon fluxes.

- Environmental sensing systems, such as meteorological sensors, humidity sensors, wind and particle size distribution sensors, and sounders for atmospheric profiling.

- Particles and fields measurements, such as magnetometers, and electric field monitors.

- Enabling instrument component and support technologies, such as laser sources, miniaturized pumps, sample inlet systems, valves, integrated bulk sample handling and processing systems, and fluidic technologies for sample preparation.

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

Sub Topics:

Extreme Environment & Aerial Mobility Topic S4.02

This subtopic is composed of two elements: (1) Technologies for High Temperature/High Pressure Environments and (2) Technologies for Aerial Mobility. Both areas are focused on the future *in situ* exploration needs for Titan and Venus, worlds featuring dense atmospheres with low and high temperature extremes, respectively. Note that
some technologies developed for the cryogenic environment of Titan will also be applicable to other severe low temperature destinations such as asteroids, comets, and Europa.

Titan is the second largest moon in the solar system and the only one that features a sufficiently dense atmosphere for buoyant vehicle flight. The atmosphere is predominantly nitrogen with a surface temperature of approximately 90 K. Targeted for exploration by Cassini-Huygens in 2004 and beyond, Titan is expected to be a geologically and chemically diverse world containing important clues on the nature of prebiotic chemistry. NASA is starting to lay the ground work for post-Cassini-Huygens exploration of Titan using autonomous, self-propelled aerobots capable of surveying many widely separated locations and potentially including surface sampling and composition analysis. Venus is the second planet from the Sun and features a dense, CO₂ atmosphere completely covered by clouds with sulfuric acid aerosols, a surface temperature of 460°C and a surface pressure of 90 atmospheres. Although already explored by various orbiters and short-lived atmospheric probes and landers, Venus retains many secrets pertaining to its formation and evolution. NASA is interested in expanding its ability to explore the deep atmosphere and surface of Venus through use of long lived (days or weeks) balloons and landers.

Technologies for High Temperature and High Pressure Environments

- Advanced thermal control for Venus, including lightweight (50 kg/m³), insulated pressure vessels able to protect the electronics and instruments enclosed inside for a few hours at 460°C and 100 bar; new lightweight thermal insulation materials (0.1 W/mK at 460°C), thermal storage (with 300–1000 kJ/kg energy density), thermal switches (over 1 W/K for “on” and 0.01 W/K for “off” mode), and high performance heat pipes (0.05 W/mK at 460 ºC and 100 bar).
- Science and engineering sensors able to operate at 460°C and 100 bar, including seismometers.
- High temperature electronics and electronic packaging for sensor and actuator interfaces at 460 °C, including low noise (10 nV/sqHz) preamplifiers, transmitters (S-band), drivers (with 0–100 V digital output for driving piezoelectric, electrostatic, or electromagnetic actuators), and high value (on the order of one to hundreds of micro Farad) capacitors.
- High temperature primary batteries (200 Whr/kg, 100 cycles) for operation at 460°C.
- Sample handling and acquisition systems including high temperature drills, motors, and actuators able to operate in the 460°C, 90 atmosphere surface environment of Venus.

Technologies for Aerial Mobility

In addition to the severe environment technologies above, innovative technologies are also sought in the following areas of robotic technologies for aerial mobility:

- Concepts and devices for a low mass (~1–2 kg), high efficiency electric drive motor for the 90 K Titan environment. This motor needs to operate continuously for up to 12 months on Titan and drive the main propulsion propeller at up to 5 revolutions per second with a controllable power input across the range of 0–50 W.
- Concepts and devices for surface sample acquisition from an aerobot in the 90 K surface environment of Titan. These can include, but are not limited to, station keeping, landed or anchored (tethered) aerobots. Both liquid and solid (ice or rock; loose particle or drilled core) samples are of interest.
Research should be conducted to demonstrate technical feasibility during Phase I and show a path toward a Phase II hardware/software demonstration, and when possible, deliver a demonstration unit or software package for JPL testing at the completion of the Phase II contract.

Sub Topics:
Advanced Flexible Electronics and Nanosensors Topic S4.03

The strategic plan within the Office of Space Science at NASA calls for intense exploration of a wide variety of bodies in the solar system within a modest budget. To achieve this will require revolutionary advances over the capabilities of traditional spacecraft systems and a broadening of the tool set through the introduction of new kinds of space exploration systems. These systems will include, but are not limited to, orbiters, landers, atmospheric probes, rovers, penetrators, aerobots (balloons), planetary aircraft, subsurface vehicles (ice and soil), and submarines. Also of interest are delivery of distributed sensor systems consisting of networks of tiny (Nanosensors)

The nanosensing and bio-nanotechnology for the sensing aspect of this subtopic seeks to leverage breakthroughs in the emerging fields of nano-technology and biotechnology to develop advanced sensors and actuators with increased sensitivity and small size for solar system exploration. Technologies should provide enhanced capabilities over the current state-of-the-art and be able to operate in an extreme environments. This harsh environment includes steady operation and cycling in the temperature range of -180°C to 100°C, and high radiation. Of particular interest are harsh environment-operable nanosystems for single molecule sensing and manipulation, on-chip biomolecular analysis, and semiconductor laser diodes in the 2–5 µm and detectors in the greater than 15 µm wavelength range.

Flexible Electronics

Electronically steerable L-band phased array antennas are needed for missions to the Moon, Mars, Titan and Venus. L-band provides the capability to detect surface and subsurface topology including ice or features hidden by the surface dust. Flexible, lightweight active arrays enable better packaging efficiency for the antenna and are critical for these missions. Currently, manufacturing reliable passive arrays with required tolerances is challenging and the only method for integration of the electronics is to attach and interconnect the electronic components on the surface. This method is expensive, unreliable and impractical for large arrays. Technologies enabling large area flexible antennas including flexible electronics are needed. State-of-the-art flexible, printable electronics have low switching frequencies. Innovative new materials or processes will be needed to enable devices that can handle the gigahertz frequencies needed for radar. In addition, large area manufacturing methods are needed to manufacture these passive and active antennas.

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

Sub Topics:
Deep Space Power Systems Topic S4.04

Innovative concepts using advanced technology are solicited in the areas of energy conversion, storage, power
electronics, and power system materials. Power levels of interest range from tens of milliwatts, to hundreds of watts. NASA Space Science missions in deep space environments require energy systems with long life capability, high energy density, high radiation tolerance, reliability, and low overall costs (including operations) which can operate in high and low temperatures and over wide temperature ranges. Advanced technologies are sought in the following areas:

**Energy Conversion**
Advances in photovoltaic technology are sought, including high power solar arrays and ultra lightweight thin and concentrator arrays with substantial increases in specific power watts per kilogram. Advances in radioisotope power conversion to electricity (tens of milliwatts to hundreds of watts with efficiencies >20 %) are sought. This includes advances in thermophotovoltaics, thermoelectrics, and Stirling. All proposed energy conversion technologies must be able to operate in deep-space environments with high radiation and wide-temperature operations.

**Energy Storage**
Includes advances in primary and secondary (rechargeable) battery technologies. Rechargeable technologies include lithium ion batteries, lithium polymer batteries, and other advanced concepts providing long life capability, and dramatic increases in mass and volume energy density watt hours per kilogram and watt hours per liter. Primary battery technologies include Li-CFx and other high specific energy electrochemical systems. Must be able to operate in deep-space environments, including high radiation and low (-100°C) to high (400°C) temperature regimes.

For operation on planetary surfaces, the use of regenerative fuel cells, both conventional and unitized - passive designs, with substantial increases in mass and volume-specific energy for those situations where there are substantial time periods of charging and recharging (anywhere from hours to days).

**Power Electronics**
Advanced power electronic materials and devices for deep-space power systems are sought. The materials of interest include soft magnetics, dielectrics, insulation, and semiconductors. Devices of interest include transformers, inductors, electrostatic capacitors, high power semiconductor switches and diodes, and integrated control and driver circuits. Proposed technologies must improve upon the following characteristics: high temperature operation (>200°C), low-temperature (cryogenic) operation, wide-temperature operation (25–200°C), and/or high levels of space radiation (>150 krad) resistance.

**Electronics Packaging**
Advanced electronics packaging technologies that reduce volume and mass capable of either high temperature or wide temperature operation and space radiation resistance for use in space power systems are of interest. Also of interest are thermal control technologies of high heat flux capability which are integral to the electronic package.

**Power System Materials**
Advances are sought in materials, surfaces, and components that are durable for soft x-ray, electron, proton, and ultraviolet radiation and thermal cycling environments, lightweight electromagnetic interference shielding, and high-
performance, environmentally-durable thermal control surfaces.

Sub Topics:

Astrobiology Topic S4.05

Astrobiology includes the study of the origin, evolution, and distribution of life in the universe. New technologies are required to enable the search for extant or extinct life elsewhere in the solar system, to obtain an organic history of planetary bodies, to discover and explore water sources elsewhere in the solar system, and to detect microorganisms and biologically important molecular structures within complex chemical mixtures. Biomarkers produced by microbial communities are profoundly affected by internal biogeochemical cycling. The small spatial scales at which these biogeochemical processes operate necessitate measurements made using microsensors. The search for life on other planetary bodies will also require systems capable of moving and deploying instruments across, and through, varied terrain to access biologically important environments.

A second element of Astrobiology is the understanding of the evolutionary development of biological processes leading from single-cell organisms to multi-cell specimens and to complex ecological systems over multiple generations. Understanding of the effects of radiation and gravity on lower organisms, plants, humans and other animals (as well as elucidation of the basic mechanisms by which these effects occur) will be of direct benefit to the quality of life on Earth. These benefits will occur through applications in medicine, agriculture, industrial biotechnology, environmental management, and other activities dependent on understanding biological processes over multiple generations.

A third component of Astrobiology includes the study of evolution on ecological processes. Astrobiology intersects with NASA Earth Science studies through the highly accelerated rate of change in the biosphere being brought about by human actions. One particular area of study with direct links to Earth Science is microbe–environment interactions.

NASA seeks innovations in the following technology areas:

- For Mars exploration, technologies that would enable to provide a broad survey of areas in the vicinities of a rover or lander to narrow down a field of search for biomarkers.

- For Mars exploration, technologies that (using x-ray, neutron, ultrasonic, and other types of tomography) would enable a noninvasive, nondestructive analysis of the subsurface environment and areas inside rocks and ice to depths 10–20 cm with spatial resolutions of 2–10 micron. Such technologies should provide the capability for analysis of structures inside opaque matrices created by endolithic organisms or fossil structures, and possible elemental analysis of such structures.

- Technologies that would enable the aseptic acquisition of deep subsurface samples, the detection of aquifers, or enhance the performance of long distance ground roving, tunneling, or flight vehicles are required.

- For Europa exploration, technologies to enable the penetration of deep ice are required.

- Desirable features for both Mars and Europa exploration include the ability to carry an array of instruments and imaging systems, to provide aseptic operation mode, and to maintain a pristine research environment.

- Low-cost, lightweight systems to assist in the selection and acquisition of the most scientifically interesting samples are also of significant interest.
• High sensitivity, femtomole or better high resolution methods applicable to all biologically relevant classes of compounds for separation of complex mixtures into individual components.

• Advanced miniaturized sample acquisition and handling systems optimized for extreme environment applications.

• High sensitivity (femtomole or better) characterization of molecular structure, chirality, and isotopic composition of biogenic elements (H, C, N, O, S) embodied within individual compounds and structures.

• High spatial resolution (5 angstrom level) electron microscopy techniques to establish details of external morphology, internal structure, elemental composition, and mineralogical composition of potential biogenic structures.

• Innovative software to support studies of the origin and evolution of life. The areas of special interest are (1) biomolecular and cellular simulations, (2) evolutionary and phylogenetic algorithms and interfaces, (3) DNA computation, and (4) image reconstruction and enhancement for remote sensing.

• Technologies capable of measuring a range of volatile compounds at small spatial scales. Improved sensor designs for a wide range of analytes, including oxygen, pH, sulfide, carbon dioxide, hydrogen, and small molecular weight organic acids both on and near surfaces that could serve as habitats for microbes.

• Biotechnology – determining mutation rates and genetic stability in a variety of organisms, as well as accurately determining protein regulation changes in microgravity and radiation environments.

• Automated chemical analytical instrumentation for determining gross metabolic characteristics of individual organisms and ecologies, as well as chemical composition of environments.

• Spectral and imaging technology with high resolution and low power requirements.

• Habitat support – technologies for supporting miniature closed ecosystems, data collection, and transmission technologies in concert with the automated chemical instrumentation described above.

• Miniature-to-microscopic, high resolution, field worthy, smart sensors, or instrumentation for the accurate and unattended monitoring of environmental parameters that include, but are not limited to, solar radiation (190–800 nm at

• High resolution, high sensitivity (femtomole or better) methods for the isolation and characterization of nucleic acids (DNA and RNA) from a variety of organic and inorganic matrices.

• Mathematical models capable of predicting the combined effects of elevated pCO₂ (change in CO₂ over the eons) and solar UV radiation on carbon sequestration and N₂O emissions from experimental data obtained from field and laboratory studies of C-cycling rates, N-cycling rates, as well as diurnal and seasonal changes in solar UV.

• Microscopic techniques and technologies to study soil cores, microbial communities, pollen samples, etc., in a laboratory environment for the detailed spectroscopic analysis relevant to evolution as a function of climate changes.

• Robotic systems designed to provide access to environments such as deep-ocean hydrothermal vents.
As solar system exploration continues, NASA remains committed to the implementation of its planetary protection policy and regulations. Missions designed to return the first extraterrestrial samples since the Apollo moon landings are currently in space—the Stardust and Genesis spacecraft will return cometary and solar wind particles to Earth within this decade. A mission to return samples from Mars is being planned for the next decade. Other missions will seek evidence of life through in situ investigations far from Earth. One of the great challenges, therefore, is to develop or find the technologies or system approaches that will make compliance with planetary protection policy routine and affordable. Planetary protection is directed to 1) the control of terrestrial microbial contamination associated with robotic space vehicles intended to land, orbit, flyby, or otherwise be in the vicinity of extraterrestrial solar system bodies; and 2) the control of contamination of the Earth by extraterrestrial solar system material collected and returned by such missions. The implementation of these requirements will ensure that biological safeguards to maintain extraterrestrial bodies as biological preserves for scientific investigations are being followed in NASA’s space program. To fulfill its commitment, NASA seeks technologies and system approaches that will support compliance with planetary protection requirements.

Examples of such technologies include:

- Techniques for cleaning of organics to the nanogram per square centimeter level on complex surfaces (nondestructively and without residues) and validation of cleanliness at this level or better
- Nonabrasive cleaning techniques for narrow aperture occluded areas on spacecraft
- Techniques for in situ (i.e., at the exploration site) cleaning and sterilization to prevent cross-contamination between planetary surface samples
- A device or methodology for controlled measurement of microbial reduction at temperatures from 200–300°C to enable generation of microbial lethality curves.

Examples of systems approaches include:

- Containerization and encapsulation of samples to be returned to Earth, including innovative mechanisms for isolation, sealing, and leak detection
- System design concepts to enable facile and rapid use of cleaning and sterilization technologies during flight hardware assembly
- System design concepts to maintain the integrity of cleaned and sterilized complex flight systems and/or subsystems
- System concepts that would facilitate spacecraft sterilization at the system level just before launch or in flight

Research should be conducted to demonstrate technical feasibility during Phase I and show a path toward a Phase II hardware and software demonstration, and that will, when possible, deliver a demonstration unit or software package for JPL testing before the completion of the Phase II contract.
Sub Topics:
Mars In Situ Robotics Technology Topic S5.02
During future exploration of planets, moons, and small solar system bodies (such as comets and asteroids), developments are needed in new innovative robotic technologies for surface operations, subsurface access, and autonomous software for each. Because of limited spacecraft resources, elements must be robust and have low power, volume, mass, computation, telemetry bandwidth, and operational overhead requirements. Successful technologies will have to operate in environments characterized by extremes of temperatures, pressures, gravity, high-gravity landing impacts, vibration, and thermal cycling. In particular, this subtopic seeks technology innovations in the following areas:

Subsurface Access: Research should be conducted to develop complete, lightweight, dry drilling systems with a penetration depth of 10–50 m and have the capability of penetrating both regolith and rocks. The development should focus on significant reduction in mass from the currently available state-of-the-art interplanetary drilling systems as well as the automation required for real-time control and fault diagnosis and recovery. In addition, because of the lack of water in most of the environments of interest, the drilling should be performed without a lubricant between the bit and rock. Of interest also is the development of ice penetrators, designed with explicit consideration of limited computation and power, which use heat to melt their way through the surface.

Rover Technology: Long-range autonomous navigation systems that focus on long distance (greater than 5 km) traverses through natural terrain, using no a priori knowledge of the subject terrain. Inflatable rover technology with a focus on the development of low-mass, highly capable platforms for exploration of extreme terrain through innovations in novel mechanisms and the automation required for real-time control. Systems enabling navigation in very rough terrain with explicit consideration of limited sensing, computation, and power. Development of new sensor prototypes, with a clear path to flight-ready status within a short time span and at minimum cost. Concepts for new mobility systems or components, such as innovative wheel or suspension designs. Instrument placement with a focus on improved tools for the design of manipulation systems, to perform contact and noncontact operations such as drilling, grasping, sample acquisition, sample transfer, and contact and noncontact science instrument placement and pointing. Infrastructure for research, including low-cost, mass producible, research-quality rovers and supporting elements.

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

Sub Topics:
Mars and Deep Space Telecommunications Topic S5.03
This subtopic seeks innovative technologies for both RF and Free-Space Optical Communications supporting missions to Mars, including both planetary and proximity ranges, and for other planetary missions and local planetary networks.

RF Communications
• Ultra-small, low-cost, low-power, innovative deep-space transponders and components, incorporating MMICs and Bi-CMOS circuits.

• MMIC modulators with drivers to provide large linear phase modulation (above 2.5 rad), high-data rate BPSK/QPSK modulation at X-band (8.4 GHz) and Ka-band.

• Sub-microradian antenna pointing techniques for Ka-band spacecraft antennas.

• High rate (10–200 Mbps) turbo-encoder and decoder and wavelet compression chips.

• Technologies for surface-to-surface communications in planetary environments.

• Fault-tolerant digital signal processing: Current space qualified DSP elements do not support high bandwidths because of the power consumption associated with radiation hardened manufacturing processes. Reconfigurable signal processing elements are sought that provide autonomous fault detection and correction with a graceful degradation in performance over the service life.

• Antenna systems: Novel materials and approaches are sought to construct large, inflatable reflective and RF focusing surfaces for use as large aperture antennas. Need to provide highly directional surface to orbit antenna patterns to maintain high rate data links.

Optical Communications

• Efficient (greater than 20% wall plug), lightweight, flight-qualifiable, variable repetition-rate (1–60 MHz), pulsed lasers with greater than 1 kW of peak power per pulse (over the entire pulse-repetition rate), and potential for up to 10 W of average power.

• Photon counting 1064 nm and 1550 nm detectors with the gain greater than 1000, detection efficiency greater than 50%, very low additive noise, about 0.5 mm in diameter, bandwidth greater than 500 MHz, saturation levels > 50Mcounts/s.

• Lightweight, compact, high precision (less than 0.1 micro-radian), high bandwidth (0–2kHz), inertial reference sensors (angle sensors, gyros) for use onboard spacecraft.

• Novel schemes for stray-light control and sunlight mitigation, especially for large (> 5 m) ground-based optical antennae that must operate when pointed to within a few (about 3) degrees of the Sun.

• Low-cost, lightweight, efficient, compact, high precision (one micro-radian accuracy) star-trackers for spaceflight application.

Research should be conducted to demonstrate technical feasibility during Phase I and show a path toward a Phase II hardware and software demonstration, and that will, when possible, deliver a demonstration unit or software package for JPL testing before completion of the Phase II contract.