NASA's program for Solar System Exploration 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. These robotic explorers will pursue compelling scientific questions, demonstrate breakthrough technologies, identify space resources, and extend an advanced telepresence that will send stunning imagery back to Earth. Numerous new technologies will be required to enable such ambitious missions. This topic includes investments in technology to enable the delivery and access of scientific instruments to planetary surfaces and atmospheres. This includes landing, flying, roving, and digging, as well as sample acquisition for delivery to instruments. This topic will also address Earth entry vehicles for sample return missions, planetary protection, and contamination control for in situ missions. The planetary bodies of interest are the Moon, Mars, Venus, Titan, and the icy satellites of the outer planets.

Subtopics

S2.01 Science Instruments for Conducting Solar System Exploration

Lead Center: JPL
Participating Center(s): ARC

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; and

- 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 1 and show a path toward a Phase 2 hardware and software demonstration, and when possible, deliver a demonstration unit or software package for JPL testing at the completion of the Phase 2 contract.
Proposals are sought for technologies to enable operation and survivability in high-temperature/high-pressure space environments. These technologies service the needs of the future in situ exploration of Venus as well as the atmospheric probes for giant planets.

Venus features a dense, CO$_2$ atmosphere completely covered by clouds with sulfuric acid aerosols, a surface temperature of 486ºC, 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 the use of long-lived (days or weeks) balloons and landers. Survivability in extreme high temperatures (380ºC) and high pressures (>100 bar) is also required for deep atmospheric probes to giant planets.

Technology needs for high-temperature and high-pressure environments include:

- Advanced passive and active thermal control for Venus missions, including lightweight (50 kg/m$^3$), high strength/stiffness, high buckling stress resistant pressure vessels to protect the electronics and instruments for several hours; new lightweight thermal insulation materials with conductivity less than 0.1 W/mK at 486ºC, thermal storage systems with 300-1000 kJ/kg energy density, thermal switches with a switching ratio of at least 100:1 between "On" and "Off" modes, and high temperature heat pipe systems operating over a temperature range of 25 to 500ºC. Refrigeration systems capable of pumping heat from a 25 to 75ºC source to the Venus sink temperature of 486ºC;

- Science and engineering sensors able to operate at 486ºC and 100 bar, including for example, high temperature imagers, hybrid imaging system that utilizes high temperature fiber optics, seismometers, and pressure sensors;

- High-temperature, low-power, and ultra-low-power electronics and electronic packaging technology for sensor and actuator interfaces at 486ºC, including low-noise (10 nV/sqHz) preamplifiers, power amplifiers and transmitters (S-band), temperature stable oscillators, 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;

- Computer Aided Design (CAD) tools for predicting the performance, reliability, and life cycle for high-temperature electronic systems and components;

- High-temperature primary batteries (200 Whr/kg)) for operation at 380ºC and 486ºC;

- Actuators for sample handling and acquisition systems including high-temperature drills, motors, and actuators able to operate in the 486ºC, 90 atmosphere surface environment of Venus; and

- Anticorrosive coatings to protect optical systems and spacecraft structures from corrosive agents present in the upper levels of Venus’ atmosphere (sulfuric acid clouds) or near surface (besides carbon oxide and nitrogen, the atmosphere contains sulfuric acid, hydrochloric acid, and hydrofluoric acid).

Research should be conducted to demonstrate technical feasibility during Phase 1 and show a path toward a Phase 2 hardware/software demonstration, and when possible, deliver a demonstration unit or software package for JPL testing at the completion of the Phase 2 contract.
S2.03 Nanosensors

Lead Center: JPL
Participating Center(s): ARC

The 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 environment. This harsh environment includes steady operation and cycling in the temperature range of -180 degrees Centigrade to 100 degrees Centigrade, 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 um wavelength range, and detectors in the greater than 15 um wavelength range.

S2.04 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, power electronics, and power system materials. Power levels of interest range from milliwatts to 1 KW. NASA Space Science missions in deep space environments require energy systems with long life capability, 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

All proposed energy conversion technologies must be able to show substantial increases over state-of-the-art in efficiency and specific power (W/kg) and to operate in deep-space environments with high radiation and wide-temperature operations (-200°C to 300°C). Long-life (>14 years), highly reliable advanced energy conversion technologies are sought that keep manufacturability in mind. Advances in photovoltaic technology are sought, including high power solar arrays and ultra lightweight, thin film, and concentrator arrays. Advances in radioisotope thermal to electric power conversion technology (milliwatt/multiwatt and 100W-1KW classes with efficiencies (state-of-the-art) are sought. This includes advances in thermophotovoltaics, thermoelectrics, Brayton, Rankine, and Stirling technologies as well as compact heat exchangers. Innovative control methods are also sought.

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 (-125°C to 200°C), and/or high levels of space radiation (>150 krad) resistance.

Electronics Packaging and Materials

Advanced electronics packaging technologies that reduce volume and mass capable of either high temperature, cryogenic, wide temperature operation, and/or space radiation resistance for use in space power systems are of interest. Advances are sought in power electronics packaging materials, surfaces, and components that are durable for soft X-ray, electron, proton, and ultraviolet radiation and thermal cycling environments.

S2.05 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 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 microns. 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 pCO$_2$ (change in CO$_2$ over the eons) and solar UV radiation on carbon sequestration and N$_2$O 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; and

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

**S2.06 Advanced Flexible Electronics**

**Lead Center:** JPL

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 1 and show a path toward a Phase 2 hardware and software demonstration, and when possible, deliver a demonstration unit or software package for JPL testing at the completion of the Phase 2 contract.

**S2.07 Risk Modeling and Analysis**

**Lead Center:** JPL

**Participating Center(s):** LaRC

The purpose of this subtopic is to advance the state-of-the-art in risk modeling and analysis, particularly for use in early design (formulation) phases. Of particular interest would be methods for risk characterization and modeling that extend beyond typical technical aspects, including software, programmatic, operations, organization, and management elements. This subtopic includes tools and methods, visualization techniques, and process enhancements. Technical areas to address include:
• Uncertainty modeling including both epistemic and aleatory uncertainties;
• Attribute-driven risk identification;
• Risk reduction modeling that includes both preventative and mitigative activities;
• Methods for aggregation and/or integration of quantitative and qualitative risks;
• Methods for characterization and integration of software, organizational, operations, and other non-physics based risks;
• Integration of risks and risk insights into the trade and formal design processes, including new techniques for risk visualization and new methods for directly trading risk against other design aspects;
• Development of risk model library elements and techniques for selecting, maintaining, and integrating the elements;
• Methods for cost-effective adaptation and utilization of PRA and other probabilistic methods in early design (e.g., conceptual design) which can be integrated directly into the design process (i.e., can be utilized directly by the system designers without additional analyst support); and
• Methods for risk-based margin determination and management.