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.

Subtopics

S4.01 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.

- 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 groundwork 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 460ºC 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 460ºC and 100 bar; new lightweight thermal insulation materials (0.1 W/mK at 460ºC), 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 460ºC and 100 bar, including seismometers.
- High temperature electronics and electronic packaging for sensor and actuator interfaces at 460 ºC, 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 460ºC.
- 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 (
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.
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.

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 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.

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