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 Astrobiology and Atmospheric Instruments for Planetary Exploration

Lead Center: JPL
Participating Center(s): ARC

This subtopic supports the development of advanced instruments and instrument technologies 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. These goals include geochemical, geophysical and astrobiological objectives.

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.

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;
- Instrumentation focused on 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.

Instruments specific to astrobiology include:
For Mars or Venus exploration, technologies that (using X-ray, neutron, ultrasonic, and other types of tomography) would enable a noninvasive, nondestructive analysis of biomarkers inside rocks and ice to depths 10 - 20 cm with spatial resolutions of 2 - 10 microns;

- Technologies that would enable the aseptic acquisition of samples under conditions of extreme environments;

- For Europa and Enceladus exploration, technologies to enable the penetration of ice and/or access to subsurface vents are required;

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

- 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;

- 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;

- 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; and

- 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.

S2.02 In Situ Planetary Atmospheric Measurement Technologies

Lead Center: JPL

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

Proposals are sought for technologies that enable the in situ exploration of the surface and deep atmosphere of Venus and the deep atmospheres of Jupiter or Saturn for future NASA missions. Venus features a dense, CO$_2$ atmosphere completely covered by clouds with sulfuric acid aerosols, a surface temperature of 486°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 the use of long-lived (days or weeks) balloons and landers. Survivability in extreme high temperatures (~480°C) and high pressures (~100 atmospheres) is also required for deep atmospheric probes to giant planets. Technology advancements to permit operation and survivability in high-temperature/high-pressure planetary environments are sought in the following areas:

Pressure Vessels and Structural Shells

Historically, titanium and aluminum have been used as structural shells or pressure vessels for extreme environment planetary probes and landers. Improvements in the state-of-the-art of pressure vessel materials are sought to reduce the mass of such components by 20 to 50% over titanium shells. New structural shell materials
shall exhibit high strength and stiffness at elevated temperatures and shall be resistant to creep and buckling under high external pressures.

**Thermal Control Systems**

Survivability of electronic components in high temperature environments relies on three basic areas of thermal control: isolation, thermal capacitance and/or refrigeration. Specific improvements in are sought in the development of:

- Lightweight and stable insulation materials with a conductivity less than 0.1 W/m-K at 486ºC and 90 atm pressure;
- Thermal energy storage systems with 300 - 1000 kJ/kg energy density through either phase changes or chemical heat absorption;
- High performance, low mass refrigeration cooling systems capable of pumping on the order of 100 Watts of heat from a 100ºC source to the Venus sink temperature of 486ºC. In this area, particular attention must be paid to the power source for such a system. A total systems approach must be considered as opposed to development of a particular component.

**High Temperature Electronics**

- 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 simulation tools for predicting the performance, reliability, and life cycle for high-temperature electronic systems and components.

**High Temperature Motors and Actuators**

- 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.

**S2.03 Energy Conversion and Power Electronics for Deep Space Missions**

Lead Center: GRC
Participating Center(s): GSFC, JPL, JSC
Proposals are solicited to develop advanced energy conversion and power electronics to enable or enhance the capabilities of next decadal deep space missions, with potential missions to Europa, Venus, Titan, and primitive bodies. These missions require power systems with long life capability and high reliability and offering significant mass and volume savings and improved efficiency compared to the state of practice (SOP) devices. Other desired capabilities are high radiation tolerance, and ability to operate in extreme environments (high and low temperatures and over wide temperature ranges).

**Extreme Photovoltaics Energy Conversion**

NASA has an increasing interest in solar array technology for deep space missions. The science community is currently pushing for solar missions that go as far as Saturn. PV proposals are sought to develop advanced photovoltaic devices and systems that can operate in extreme environments and offer significant mass and volume savings over the SOP systems. Photovoltaic cell and array technologies should also have significant improvements in efficiency, specific power, cost, and ability to operate in high-radiation, extreme-temperature environments such as near sun (high-intensity, high-temperature - HIHT) environment or deep space (low-intensity, low-temperature - LILT) environments. Extreme Photovoltaic technologies of interest are:

- Solar cells that can function effectively under LILT conditions and high radiation environments for deep space missions beyond 4 AU;
- Solar cells that can operate high temperatures (up to 450°C) for near sun missions;
- Solar arrays with high specific power (> 250 W/kg) and low stowage volume for solar electric propulsion missions.

**RPS Energy Conversion**

Radioisotope power systems (RPS) are presently used in some planetary surface missions and deep space science missions that go beyond 4 AU. Proposals are sought to develop advanced RPS technologies that would contribute to a system with long life capability (> 14 years), high conversion efficiency (> 20%), and high specific power (> 8 - 10 W/kg). The radioisotope power conversion systems of interest are, Stirling, Thermoelectrics (TE), and Thermophotovoltaics (TPV). All proposed energy conversion technologies must be able to operate in deep space environments with high radiation and wide-temperature operations (-200°C to >300°C). A high priority for NASA is the development of advanced static power conversion technologies (TPV or TE) that offer greater than 20% thermal-to-electric conversion efficiency for an RPS system, as well as power conversion approaches that can operate in the extreme environments of Venus and Europa.

Thermophotovoltaic technologies should focus on demonstrating converter component technologies that offer improved performance parameters:

- Photovoltaic devices capable of operating at high temperature (> 50°C) and high current density for extended durations (> 14 yr) while maintaining high performance;
- Optical filters that offer high spectral efficiency and high temperature survivability (> 150°C);
- Emitter materials that offer high efficiency as well as low evaporative losses suitable for extended (14 yr) operation;
Solar concentrator based TPV systems with concepts for thermal energy storage and their integration with the emitter systems.

Thermoelectric technologies should focus on:

- High temperature and performance thermoelectric materials. NASA is interested in nanostructured thermoelectric materials with potential for ZT > 2 and ability to operate at temperatures and lifetimes compatible with RPS systems;
- Innovative packaging of thermoelectric elements in closed or compact arrays;
- Sublimation coatings or methods.

Stirling power conversion technologies should focus on:

- Novel methods or approaches for radiation-tolerant, sensorless, autonomous control of the Stirling converters with very low vibration and having low mass, size, and electromagnetic interference (EMI);
- Advanced regenerators with improved durability and high temperature capability while maintaining high performance;
- Lightweight, high-efficiency linear alternators with low EMI and capable of high-temperature operation;
- High temperature heater heads (> 850°C) and joining techniques.

Advanced Photovoltaics Energy Conversion

Photovoltaic cell and array technologies with significant improvements in efficiency, mass specific power, stowed volume, cost, radiation resistance, and wide operating conditions are solicited. Photovoltaic cell technologies for wide temperature operation and radiation environments are solicited. Potential array technologies of interest include:

- Rigid and deployable arrays;
- Concentrators (rigid or inflatable, primary or secondary);
- Ultra-lightweight arrays for lightweight, flexible;
- Thin-film photovoltaic cells;
- Electrostatically clean spacecraft solar arrays.
**Energy Conversion Thermal Management**

Thermal technology areas include heat rejection, composite materials, heat pipes, pumped loop systems, packaging and deployment, including integration with the power conversion technology. Highly integrated systems are sought that combine elements of the above subsystems to show system level benefits.

**S2.04 Flexible Antennas and Electronics for L-Band Remote Sensing**

**Lead Center:** JPL

Electronically steerable L-band, phased array antennas are needed for missions to the Moon, Mars, Titan, Europa and Venus for remote sensing applications and support of communications. Flexible, lightweight active arrays enable better packaging efficiency for the antenna and are critical for these missions. These antennas will be deployed on orbiting spacecraft and on rovers or aerial platforms such as lighter than atmospheres (LTA) vehicles or airplanes.

When used for active remote sensing, L-band also provides the capability to detect surface and subsurface topology including density contrasts within the ice or dust and subsurface water or warm ice. In addition, the use of L-band frequencies enables proximity communications between the in situ vehicle and a spacecraft in orbit or on a flyby trajectory.

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.

**S2.05 Planetary Balloons and Aerobots**

**Lead Center:** JPL

**Participating Center(s):** GSFC

Innovations in materials, structures, and systems concepts have enabled buoyant vehicles to play an expanding role in NASA’s Solar System Exploration Program. Balloons and airships will 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. Proposals are sought in the following areas:
Hot Air (Montgolfiere) Balloons for Titan

NASA is considering the use of hot air (Montgolfiere) balloons for Titan using waste heat from the radioisotope power source (RPS). Proposals are sought for concepts and prototypes for this balloon that have the following nominal characteristics: 2000 Watts of available RPS waste heat, a 100 gm/m² balloon envelope material, 160 kg of payload mass (including the RPS but excluding the balloon), and a controllable altitude over the range of 0 to 10 km with the ability to maintain a +/- 20 m tolerance near the surface (93K, 1.46 bar). It is important that the balloon be storable in a typical entry vehicle for transport to Titan and be deployed and inflated upon arrival. Preference will be given to proposals that include cryogenic testing to validate the thermal performance models upon which the design is based.

Apex Valve for Montgolfiere Balloons

Solar-heated Montgolfiere balloons are an attractive platform for the exploration of Mars, particularly the polar regions which experience long periods of solar illumination during summer solstice. These balloons can be altitude controlled through selective venting of the heated gas through a valve located at the apex of the balloon. Proposals are sought for concepts and prototypes for this valve to be used on a solar-heated balloon on Mars. Typical specifications include large flow area (10 m²), low mass (few kilograms), packaged into a small volume for transport to Mars (3) and consume minimal electrical energy.

Aerial Deployment Modeling Tool

Planetary aerobots at Mars, Titan, and Venus will likely be aerially deployed and inflated during parachute descent after arrival at the destination. Proposals are sought that would provide computer modeling tools that can simulate this complex process. Of particular importance is the ability to model the balloon shape and material stresses as a function of time, taking into account the aerodynamic forces generated by the parachute and by the uninflated or partially inflated balloon, as well as transient loads during balloon deployment from its storage container. The balloons can be either polymer film or polymer film plus reinforcing fabric laminates.

Metal Bellows for High Temperature Venus Balloons

Cylindrically-shaped metal bellows are a potential solution to the problem of making balloons that can tolerate the 460°C temperatures near the surface of Venus. Commercial off-the-shelf metal bellows are limited in diameter to approximately 0.4 m. NASA seeks proposals for metal bellows technology that can produce prototypes in the range of 1 - 2 m in diameter and 5 - 10 m long; tolerant of sulfuric acid; good fatigue properties at 460°C; and areal densities of up to 1 kg/m².