The Science Mission Directorate will carry out the scientific exploration of our Earth, and the planets, moons, comets, and asteroids of our Solar System and beyond; chart the best route of discovery; and reap the benefits of Earth and space exploration for society. A major objective of the NASA science spacecraft systems development programs is to implement science measurement capabilities with small or more affordable spacecraft so development programs can meet multiple mission needs and therefore, make the best use of limited resources. NASA is fostering innovations in cross-cutting technologies that can be leveraged by spacecraft and other platforms to enable new investigations of Earth space, the solar system, and the universe. These missions all require propulsion, power, and guidance and navigation systems that must be implemented at minimal mass and cost to maximize the scientific return for a given budget. To this end, innovations are sought in the areas of Guidance, Navigation and Control, Command and Data Handling, Electric Propulsion, Advanced Chemical and Propellantless Propulsion, Platform Power Management and Distribution (including power electronics and packaging), and Thermal Control Technologies for Science Spacecraft. These technologies need not be limited to spacecraft, but can also be applicable to other platforms such as piloted and unpiloted aircraft, balloons, drop sondes, and sounding rockets. These application examples are given to illustrate the wide diversity of possibilities for acquiring Earth and Space Science data consistent with the future vision of the Science Mission Directorate for which technology development is required. For this solicitation, related science spacecraft system technologies like energy conversion, energy storage, and extreme environment electronics can be found under S2 Robotic Exploration Throughout the Solar System and X8 Energy Generation and Storage.

**Subtopics**

**S7.01 Guidance, Navigation and Control Beyond Low Earth Orbit (LEO)**

*Lead Center: GSFC*

*Participating Center(s): JPL*

Envisioned NASA science missions will increasingly use large, and/or distributed, observatories in orbits beyond LEO. Advanced Guidance Navigation and Control (GN&C) technology is required for these platforms to address high performance and reliability requirements while simultaneously satisfying low power, mass, volume and affordability constraints. In particular, there are many technology gaps in challenging orbital environments, including highly elliptical Earth orbits, libration point orbits, and lunar and planetary orbits. A vigorous effort is needed to develop guidance, navigation and control methodologies, algorithms, and sensor-actuator technologies to enable revolutionary science missions. Of particular interest are highly innovative GN&C technology proposals directed towards enabling scientific investigators to exploit new vantage points, develop new sensing strategies, and implement new system-level observational concepts that promote agility, adaptability, evolvability, scalability, and...
affordability. Specific areas of research include:

**Precision Pointing**

Innovative GN&C solutions for scientific instrument and laser communication system pointing, tracking, and stabilization are sought. Proposals that exploit and combine recent advances in attitude determination and control, lasers, advanced electro-mechanical packaging are encouraged. Proposed NASA science missions provide applications with pointing accuracies of 3 microradians or less with jitter of 30 nanoradians or less.

**Formation Flying**

Novel approaches to autonomous sensing and navigation of multiple distributed space platforms are sought. Of particular interest are sensing systems for formation, relative navigation and attitude. Proposed NASA science missions provide applications with relative range accuracies of 1 cm or less over formation scales of several km.

**Low Impact Sensors and Actuators**

GN&C sensors and actuators such as Sun sensors, Earth sensors, star/celestial object trackers, fine guidance sensors, gyroscopes, accelerometers, magnetometers, reaction/momentum wheels, control-moment gyros, magnetic torquers, tethers, attitude control thrusters, etc are sought. Of particular interest are technologies that will provide a sensing or actuation function, having performance (e.g., dynamic range, stability, accuracy, noise, sensitivity, bandwidth, control authority, etc.) consistent with the state-of-the-art, but with significantly reduced impact (mass, power, volume, and cost) to the host spacecraft. These resource reduction improvement factors should be quantified in the proposal and show a minimum factor of 2 with a goal of 10 or greater.

**S7.02 Long Duration Command and Data Handling for Harsh Environments**

**Lead Center: GSFC**

NASA’s space based observatories, fly by spacecraft, orbiters, landers, and robotic and sample return missions, require robust command and data handling system capabilities. Advances in command and data handling technologies are sought to support the NASA's goals for improved investigations of Earth space, the solar system, and the universe.

The subtopic goal is to develop high-performance processors and architectures and reliable electronic systems that can operate effectively for long periods of time in harsh environments. The subtopic objective is to elicit novel architectural concepts and component technologies that are realistic and have credible applications to NASA missions.

A proposal's ideas should reflect (1) that the final end product(s) lead to usable hardware that can be integrated into NASA programs within 5 to 7 years, (2) effective and sustainable hardware and software development environments, (3) sustainability (affordable, reliable and effective), and (4) applicability to deep space missions (i.e., resource efficient and reliable over extreme environments of temperature and radiation), and will significantly
advance solutions to the challenges of high performance processing, reconfiguration, and fault tolerant operations.

Technology priorities:

**High Performance Processing**

- Distributed or multi-core processing, with math co-processor or floating point capability that significantly exceeds the present state of the art;
- FPGA-based processing, targeting performance and fault tolerance, based on voting processors implemented as part of a rad-tolerant FPGA fabric

**Onboard Networks**

- Rad-hard Ethernet physical layer components, fully compatible with the current ground based 10/100 Ethernet. The board side interface would have the Ethernet MII and RMII interface standards;
- Rad-hard multi gigabit fiber optic transceiver to support high data rate network protocols.

**Data System Support Electronics**

- Radiation hard oscillators (greater than 150 MHz with equal duty cycles);
- Models for analysis of interplanetary radiation and radiation belts, and technologies that enable in-flight radiation measurements such as total dose and single event effects in computing systems.

**S7.03 Electric Propulsion**

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

Innovations in propulsion technologies are needed to support the Science Mission Directorate (SMD) goals of better understanding the Earth-Sun system, exploring our solar system, and investigating the nature of the universe beyond our solar system. Planetary spacecraft need ever-increasing propulsive performance and flexibility for ambitious missions requiring high duty cycles and years of operation. Satellites and satellite constellations have high-precision propulsion requirements, usually in volume- and power-limited envelopes. Electric propulsion systems also present challenging plasma plume and contamination environments to the host spacecraft and payloads. This subtopic seeks innovations in propulsion technologies to increase the capabilities of SMD spacecraft.
Specifically, technology innovations are sought to improve the capability of low- to medium-power electric propulsion systems, including ion, Hall, and advanced plasma thrusters. Areas where innovations are sought include power processing, long-life, high-efficiency cathodes and neutralizers, electrode-less plasma production, low-erosion materials for ion optics and Hall discharge chambers, high-temperature magnetic circuits, plume mitigation, and next generation thrusters. Innovations sought include, but are not limited to those that improve performance, increase lifetime, reduce mass, decrease cost, and facilitate electric propulsion integration. Improvements are also sought for propellant management system components including storage, distribution, and flow control to support solar electric propulsion applications. Innovations in miniature electrostatic and electromagnetic propulsion devices are sought for miniature (less than 10 kg) spacecraft and for high-precision (impulse bit

S7.04 Chemical and Propellantless Propulsion for Deep Space

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

Spacecraft propulsion technology innovations are sought for future 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 advanced chemical, emerging technologies, and aerocapture.

Advanced Chemical Propulsion

Innovations in low-thrust chemical propulsion system technologies are sought for robotic, deep-space, scientific, mission applications. Delta Vs for the missions of interest range from 1000 m/sec to 3000 m/sec. Advanced chemical propulsion technologies of interest are:

- Advanced material and component technology to enable development of bipropellant engines with Isp greater than 360 seconds, both pressure-fed and pump-fed, with chamber pressures ranging from 100 to 500 psia systems;
- Non-catalytic ignition technology and critical component materials (e.g., tank bladders, valve seats, and filters) for power-limited spacecraft using high-performance (Isp >275 s), high-density (>1 g/cc) monopropellant formulations.

Tether Technologies

Focus on technologies that support the development of tethers that can survive in the space environment. The near-Earth environment contains a significant amount of atomic oxygen (AO) formed by photo-dissociation of atmospheric oxygen. This AO attacks the chemical bonds of polymeric materials, which are desirable for their high specific tensile strength. Furthermore, ultraviolet radiation also attacks tether materials. A coating for a polymeric tether must be able to protect the tether against both effects. Coatings that can be uniformly applied after the fabrication of a multi-strand tether structure are especially desirable, because of the requirement that a space
tether have a multitude of separate load paths in the event of a cut by an orbital debris particle. Certain materials (such as titanium oxide/zinc oxide) offer both ultraviolet radiation protection as well as atomic oxygen resistance. Tether technologies of interest are:

- Techniques and processes to coat and protect polymeric tether materials from offer both ultraviolet radiation protection as well as atomic oxygen resistance effects. Such coatings must be as thin as possible because of the importance in maintaining a high specific tensile strength in tether materials, although they must be able to adhere uniformly and reliably to tether materials, even in the face of winding and ground handling. Degradation to the strength characteristics of the tether generated by the coating process must be absolutely minimized.

**Aeroassist (Aerocapture)**

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. The aerocapture maneuver can be accomplished by utilizing either rigid or inflatable deceleration systems.

Preliminary analysis has shown that the inflatable decelerator concepts may provide mass reduction and improved packaging efficiency over a rigid aeroshell system. However, the TRL for these inflatable decelerators must be increased before an adequate comparison to traditional rigid aeroshells can be made. Current inflatable decelerator concepts are expected to be manufactured from thin film materials, elastomeric materials, and/or high temperature fabrics, stowed during transport and inflated prior to atmospheric entry for aerocapture applications at planetary destinations. Materials of particular interest include: polyimide thin films, polybenzobisoxazole (PBO) thin films, and ceramic fabrics. Prior to the aerocapture maneuver, the inflatable decelerator will be tightly stowed for many years (up to 10 years) in an uncontrolled space environment (-130°C) during transport to outer solar system destination. Before final atmospheric entry, the inflatable decelerator will be unstowed and inflated (cold GN₂). During the aerocapture maneuver, up to 24 hours after the inflation process is initiated, the inflatable decelerator will experience temperatures to 500°C (or higher).

**Low Temperature/High Temperature Structural Materials/Adhesives**

Development for Inflatable Deceleration Systems: This task focuses on the development and testing of structural materials/adhesives that can be utilized for aerocapture inflatable decelerator systems. This task should include:

- A thorough survey of the thin film polymer, elastomeric;
- A high temperature fabric trade space for materials that will maintain structural properties during the temperature extremes and long term space exposure experienced by inflatable decelerators.;
- Investigation of the effects of various coatings, surface treatments, or impregnation processes to enhance material properties, which may include optical, mechanical, thermal or physical properties;
- A thorough survey of the adhesives trade space for materials that will maintain bond strength during the temperature extremes of long term space exposure and atmospheric entry experienced by inflatable decelerator systems must also be included.
Final deliverables should include selection criteria for final materials/adhesives, an evaluation of technology readiness levels (TRL) of candidates, technology development and testing of candidates that require further TRL advancement.

S7.05 Power Electronic Devices, Components and Packaging

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

NASA science missions employ Earth orbit and planetary spacecraft, along with terrestrial balloons, surface assets, aircraft, and marine craft as observation platforms. Advanced electrical power technologies are required for the electrical components and systems on these platforms to address the issues of size, mass, efficiency, capacity, durability, and reliability. Advancements are sought in power electronic devices, components, and packaging.

Power Electronic Components

Advanced inductors, transformers, capacitors, micro batteries, semiconductor switches, diodes, and current sensors are of interest. Proposals must address improvements in energy density, speed, efficiency, or wide temperature operation (-125°C to 200°C) with a high number of thermal cycles.

Power Conversion, Motor Drive, Protection, and Distribution

Technologies that provide significant improvements in mass, size, power quality, reliability, or efficiency in electrical power conversion, motor drives, and protective switchgear components are of interest. Candidate applications include solar array regulators, battery charge and discharge regulators, battery by-pass switches, power conversion, power distribution, fault protection, high-speed motors/generators, magnetic bearing drivers, and integrated flywheel energy storage and attitude control electronics.

Electrical Packaging

Thermal control technologies are sought that are integral to electrical devices with high heat flux capability and advanced electronic packaging technologies which reduce volume and mass or combine electromagnetic shielding with thermal control.
Future Spacecraft and instruments for NASA's Science Mission Directorate will require increasingly sophisticated thermal control technology. Innovative proposals for thermal control technologies are sought in the following areas:

1. Optical systems, lasers, and detectors require tight temperature control, often to better than +/- 1°C. Some new missions require thermal gradients held to micro-degree levels. Methods of precise temperature measurement and control to this level are needed.

2. Heat flux levels from lasers and other high power devices are increasing, with some projected to go as high as 100 W/cm². They will require thermal technologies such as spray and jet impingement cooling. Also, high conductivity, vacuum-compatible interface materials will be needed to minimize losses across make/break interfaces.

3. Future missions will use large structures, like mirrors and detector arrays, at both ambient and cryogenic temperatures. Some anticipated technology needs include: advanced thermoelectric coolers capable of providing cooling at ambient and cryogenic temperatures, high conductivity materials to minimize temperature gradients and provide high efficiency light-weight radiators, and advanced thermal control coatings such as variable emittance surfaces and coatings with a high emissivity at ambient and cryogenic temperatures.

4. The push for miniaturization also drives the need for new thermal technologies approaching the MEMS level. Miniaturized heat transport devices, especially those suitable for cooling small sensors, devices and electronics are of interest.

5. Future robotic missions and reconfigurable spacecraft present engineering challenges requiring systems which are more self-sufficient.

Some of the technology needs are:

- Single and two-phase mechanically pumped fluid loop systems which accommodate multiple heat sources and sinks, and long life, lightweight pumps for these systems;
- Efficient, lightweight vapor compression systems for cooling up to 2 KW;
- Advanced thermal modeling techniques that can be easily integrated into existing codes, emphasizing inclusion of two-phase system and mechanically pumped system models;
- Integration of standardized formats into existing codes for the representation and exchange of Thermal Network Models and Thermal Geometric Models and results.