NASA is fostering innovations that support implementation of the Earth Science (ES) Enterprise program, an integrated international undertaking to study the Earth system. ES uses the unique perspective available from orbit to study land cover and land use changes, short and long term climate variability, natural hazards, and environmental changes. Additionally, ES uses terrestrial and airborne measurements to complement those acquired from Earth orbit. ES has a parallel development effort to these platforms that includes the largest ground and data system ever undertaken, which will provide the facility for command and control of flight segments and for data processing, distribution, storage, and archival of vast amounts of Earth science research data. The Earth Science Program defines platforms as the host systems for ES instruments, i.e., they provide the infrastructure for an instrument or suite of instruments. Traditionally, the term 'platform' would be synonymous with 'spacecraft,' and it certainly does include spacecraft. 'Platform,' however, is intended to be much broader in application than spacecraft and is intended to include non-traditional hosts for sensors and instruments such as airborne platforms (piloted and unpiloted aircraft, balloons, and drop sondes), terrestrial platforms, sea surface and subsurface platforms, and even surface penetrators. These application examples are given to illustrate the wide diversity of possibilities for acquiring ES data consistent with the future vision of the Earth Science Program and indicate types of platforms for which technology development is required.

Subtopics

**E2.01 Guidance, Navigation and Control**

*Lead Center: GSFC*

*Participating Center(s): JPL*

Future ES architectures will include platforms of varying size and complexity in a number of mission trajectories and orbits. These platforms will include spacecraft, sounding rockets, balloons, and Unmanned Aerial Vehicles (UAVs). 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, and volume resource constraints. A vigorous effort is needed to develop guidance, navigation and control methodologies, algorithms, and sensor–actuator technologies to enable revolutionary Earth science missions. Of particular interest are highly innovative GN&C technology proposals directed towards enabling ES 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. Novel approaches for the autonomous control of distributed ES spacecraft and/or the management of large fleets of heterogeneous and/or homogeneous ES assets are desired. Specific areas of research include:

**GN&C System Technologies**

Innovative GN&C solutions for ES instrument pointing and stabilization. Advanced GN&C solutions for the Microsat attitude determination and control problem. Of special interest are low cost (at high production volumes) and highly integrated Microsat GN&C subsystems suitable for enabling both spin stabilized and three-axis stabilized Microsats. GN&C proposals that exploit and combine recent advances in miniature spacecraft subsystem architectures, spacecraft attitude determination and control theory, advanced electro-mechanical packaging, MEMS technology, ultra-low power microelectronics are encouraged. Proposals of special interest are ones that address the technologies needed to implement closed-loop spacecraft control system architectures which provide the "Drag-Free" precision orbit determination and maintenance capabilities needed for future ES Low Earth Orbit (LEO) formation-flying applications. Technology solutions are encouraged that employ Drag-Free sensors (similar to accelerometers), high specific impulse (Isp) thrusters, and low-cost processors with appropriate closed-loop filtering and control algorithms to implement a complete Drag-Free spacecraft control system module.

Vision-based GN&C system concepts, subsystems, hardware components, and supporting algorithms/flight software. Applications of interest are of high performance video image processing technology to provide alternative solutions to challenging GN&C problems such as spacecraft relative range and attitude determination while in close formation and/or during proximity operations.

Advanced GN&C solutions for balloon-borne stratospheric science payloads, including sub-arc second pointing control, sub-arcsecond attitude knowledge determination and trajectory guidance for individual balloon-borne payloads. Innovative techniques are of interest for modeling, simulating, and analyzing the inherent dynamics and control of balloon-borne payloads. Also of interest are innovative concepts, strategies, techniques, and methods for modeling, simulating, and analyzing formations, constellations, and/or networks of multiple balloon-borne stratospheric science payloads.

**GN&C Sensors and Actuators**

Advanced sensors and actuators with enhanced capabilities and performance, as well as reduced cost, mass, power, volume, and reduced complexity for all spacecraft GN&C system elements. Emphasis is placed on improved stability, accuracy, and noise performance. Nontraditional multifunctional sensor/actuator technology proposals are of particular interest.

Innovations in Global Positioning System (GPS) receiver hardware and algorithms that use GPS code and carrier signals to provide spacecraft navigation, attitude, and time. Of particular interest are GPS-based navigation techniques that may employ Wide Area Augmentation System (WAAS) corrections.

Novel approaches to autonomous sensing and navigation of multiple distributed space platforms. Of particular interest are specialized sensors and measurement systems for formation sensing and navigations functions.
Advancing science with reduced levels of mission funding, shorter mission development schedules and reduced availability of flight electronic components creates new requirements for spacecraft Command and Data Handling (C&DH) systems. There are specific areas for which proposals are being sought.

Onboard Processing

- General purpose data processing: higher levels of spacecraft autonomy require higher levels of general purpose CISC (Complex Instruction Set Computer) and RISC (Reduced Instruction Set Computer) processing with fault tolerance and error correction (system and application).
- Special purpose data processing: higher levels of automated onboard science data processing to complement the data gathering capabilities of future instruments. Reduce the processed data volume to remain within the limits of spacecraft to Earth communications.
- Reconfigurable computing hardware: achieving pure hardware processing capabilities with the flexibility of reprogrammability to allow different science objectives to be met with the same hardware platform. Development of technologies such as radiation hardened Field Programmable Gate Arrays (FPGAs) and similar components for data communications and processing.
- Low-power electronics: in order to provide higher capabilities on smaller and/or less expensive spacecraft. Electronics that consume less power decrease overall thermal load, and decrease battery size and solar panel size.

Command and Data Transfer

- Subsystem data transfer: communications between various spacecraft subsystems in order to realize higher autonomy. Development of technologies and architectures that increase the rate of data transfer above 20 Mbits/s are necessary to achieve the self-diagnosis, autonomous control, and science data transfer requirements.
- Intra-system data transfer: communications within the spacecraft subsystem, between cards within a box to replace the conventional passive backplanes.

Protocols and Architectures

- Internet-based protocol modules and extensions that will support seamless connectivity between terrestrial and aerospace platforms by mitigating variable latencies and bit error rates among distributed air and spacecraft to terrestrial gateways.
- Novel methodologies for performing medium to large-scale simulations of space Internet architectures,
protocols, and applications.

- Network security technologies to assure integrity and authentication of data from the public Internet to protected space-based networks.
- Ad hoc and innovative, lightweight networking protocols to support spacecraft constellation, formation flying, satellite clusters, proximity, and sensor based networks.

E2.03 Advanced Communication Technologies for Near-Earth Missions

Lead Center: GSFC
Participating Center(s): GRC

Programmable Analog Devices

A technology is desired to provide a software programmable analog component. This “programmable analog array” would consist of basic elements including filters, amplifiers, couplers and mixers whose frequency of operation, bandwidths and gains can be changed by software command. The signal flow in the component itself will be reconfigurable by software and firmware loads in a manner similar to that of Field Programmable Gate-Array (FPGA) digital devices. Desired components will be capable of operating in the S- and Ku-bands. Maximum flexibility in configuration is also desired with the goal of producing a generic “sea of elements” rather than an integrated system on a chip.

Low-Overhead Software-Defined Radio (SDR) Implementations

NASA is interested in SDR architectures and implementations that optimize flexibility and interoperability between different SDRs, but are based on extremely efficient core architectures and low processor overheads. Algorithms that can be implemented in current space flight capable hardware are especially encouraged.

RF Component Technology

A wide variety of general advances in component, material and manufacturing technologies are required to support future NASA mission requirements. These technologies include innovative approaches to enable higher frequency, miniature, power efficient Traveling Wave Tube Amplifiers (TWTAs) operating at millimeter wave frequencies and at data rates of 10 Gbps or higher. Wide band-gap semiconductor (WBGS) based devices for high power, high efficiency microwave and millimeter wave solid-state power amplifiers (SSPAs), as well as low noise amplifiers in the same ranges. MEMS-based RF switches are needed for use in reconfigurable antennas, phase shifters, amplifiers, oscillators and in-flight reconfigurable filters. Frequencies of interest include S-, Ku-, Ka-, and V-band (60 GHz).

Bandwidth Efficient Channel Coding

To support extremely high data rates in a limited frequency spectrum, bandwidth-efficient channel coding is required. NASA is interested in algorithms that provide lossless data compression and efficient error correction at data rates greater than 1 Gbps for links between Earth orbit and Earth ground stations.
RF Materials and Structures

NASA is interested in materials that can be efficiently manufactured and effectively used in the construction and deployment of thin-film based RF antenna systems. Methods for deploying very large, lightweight, aperture structures on-orbit are needed. Inflatable structures, as well as “shape memory” alloy-based implementations, capable of withstanding launch and deployment forces are encouraged.

E2.04 Onboard Propulsion

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

This subtopic seeks technologies that will significantly increase capabilities and reduce costs for Earth science spacecraft. Propulsion functions include orbit insertion, orbit maintenance, constellation maintenance, precision positioning, in-space maneuvering, and de-orbit. Propulsion technologies are sought that will provide platforms with larger scientific payloads, longer-life missions, and increased operational flexibility during missions. To accomplish these goals, innovations are needed in low-thrust chemical and low-power electric propulsion technology, including thruster components, advanced propellants, power processing units, and feed system components. Of particular interest are innovations in propulsion technology that lead to smaller-sized, integrated, autonomous spacecraft. The following specific areas are of interest:

Miniature and Precision Propulsion

Propulsion technologies for miniature (less than 10 kg) spacecraft and for high-precision (impulse bit

Thruster Technology

Electric and chemical propulsion technologies that provide increased capability (mass and volume) and/or flexibility (duty cycle and life) for small, power-limited spacecraft, including:

- Electrostatic and electromagnetic propulsion technologies;
- High-performance (specific impulse > 250 s), high-density monopropellant thruster technology;
- High-performance (specific impulse > 350 s), space storable bipropellant thruster technology; and
- Propellant gelation technology.

Propulsion System Components

Innovative electric and chemical propulsion system components for small spacecraft are sought including:
• Materials compatible with high-temperature, oxidizing, and reactive environments;
• Components for fluid isolation, pressure and mass flow regulation, relief quick disconnect, and flow control;
• Technologies for metering, injection, and ignition of fluids in combustion devices;
• Gaseous storage and pressurization system; and
• Components for xenon storage and flow control.

E2.05 Energy Storage Technologies

Lead Center: GRC

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

Advanced energy storage technologies are required for Earth science observation platforms. These platforms are defined as host systems that include traditional spacecraft, airborne platforms, such as piloted and unpiloted aircraft and balloons, terrestrial platforms, micro-spacecraft, and surface penetrators.

The energy storage technologies solicited include both primary and secondary batteries, primary and regenerative fuel cells, and flywheels. The desired technology advances common to all of the storage devices of interest include the following elements:

• Improvements in energy density and specific energy;
• Improvement in cycle life, run time, and calendar life;
• Performance over a wide temperature range;
• Reduction in device size, to the micro-scale;
• Reduction in system complexity; and
• Integration into, and with, other spacecraft structures.

A vigorous effort is needed to develop energy storage technologies that will enable the revolutionary ES missions.

Specific technology advances that contribute to achieving the following performance goals are of interest.

Advanced Battery Technology
• Specific energy: >150 Wh/kg for secondary batteries >400 Wh/kg for primary batteries

• Low-Earth-Orbit (LEO) cycle life >60,000 cycles for secondary batteries

• Calendar life >15 years

• Operating temperature range -100°C to 100°C

  ○ Systems capable of delivering 30–50% of the capacity available at ambient temperatures at temperatures as low as -100°C

Primary and rechargeable lithium-based batteries with advanced anode and cathode materials and advanced liquid and polymer electrolytes are of particular interest. Proposals addressing structural and microbatteries are sought.

**Fuel cell (FC) and Regenerative Fuel Cell (RFC) Technologies**

• Specific energy: FC >1500 W/kg, RFC >600 Wh/kg

• Efficiency: FC>70% at 1500 W/kg, RFC >60% at 600 Wh/kg

• Life FC >10,000 hours, RFC > 1500 cycles

Advances to PEM, Direct methanol and solid oxide fuel cell systems are of particular interest.

**Flywheel Energy Storage**

• Specific energy > 100 Wh/kg

• LEO cycle life > 60,000 cycles

Micro-flywheels with a high number of watt hours per kilogram and highly integrated components are of particular interest.

**E2.06 Energy Conversion for Space Applications**

Lead Center: GRC
Participating Center(s): GSFC

Earth science observation missions will employ spacecraft, balloons, sounding rockets, surface assets, and piloted
and robotic aircraft and marine craft. Advanced power technologies are required for each of these platforms that address issues of size, mass, capacity, reliability, and operational costs. A vigorous effort is needed to develop energy conversion technologies that will enable the revolutionary Earth science missions. Exploiting innovative technological opportunities, developing power systems for adverse environments, and implementing system-wide techniques that promote scalability, adaptability, flexibility, and affordability are characteristic of the technological challenges to be faced and are representative of the type of developments required beyond the current state-of-the-art.

The energy conversion technologies solicited include photovoltaics, Brayton, Rankine, Stirling, and thermophotovoltaic, as well as related technologies such as concentrators and thermal technologies. Specific areas of interest follow.

- Photovoltaic cell and array technologies with significant improvements in efficiencies, cost, radiation resistance, and wide operating conditions are solicited. Potential concepts include rigid arrays, concentrator configurations, and ultra-lightweight array technologies that exploit the properties of lightweight, flexible thin-film photovoltaic cells. Photovoltaic cell and array technologies for extreme environments such as high- or low-temperature operation are solicited. Technologies for electrostatically-clean spacecraft solar arrays are also of interest.

- Future micro-spacecraft require distributed power sources that are integrated with microelectronics devices/instruments. These microelectronic devices/instruments integrate energy conversion and storage into a hybrid structure.

- Thermal power conversion technologies for Earth orbiting spacecraft and/or orbit transfer vehicles are sought.

- Advances may be in solar concentrators (rigid or inflatable, primary or secondary) and receivers to improve specific power and reduce mass.

- Topics of interest in power conversion include heat cycles (Brayton, Rankine, and Stirling), compact heat exchangers, advanced materials and fabrication techniques, and control methods, as they relate to life, reliability and manufacturability.

- 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.

**E2.07 Platform Power Management and Distribution**

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

Earth science missions employ spacecraft, balloons, sounding rockets, surface assets, aircraft, and marine craft as observation platforms. Advanced 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 materials, devices, components, packaging, and coatings.
Power Electronic Materials and Components

Advanced magnetic, dielectric, semiconductor, and superconductor materials, devices, and circuits are of interest. Proposals must address improvements in energy density, speed, or efficiency. Candidate devices and applications include transformers, inductors, semiconductor switches and diodes, electrostatic capacitors, current sensors, and cables.

Power Conversion, Protection, and Distribution

Technologies that provide significant improvements in mass, size, power quality, reliability, or efficiency in electrical power conversion and protective switchgear components are of interest. Candidate applications include solar array regulators, battery charge and discharge regulators, power conversion, power distribution, and fault protection.

Environmentally Durable Technologies

Technologies that enable materials, surfaces, coatings, and components to be durable in a space environment, in atomic oxygen, soft x-ray, electron, proton, ultraviolet radiation, and thermal cycling environments are of interest to NASA. Environmentally durable coatings for radiators and lightweight electromagnetic shielding are sought.

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.