

Develop Technologies, Data, and Knowledge Systems to Improve Future Operational Systems

Innovation is the engine that drives scientific progress, through development of new theories, invention of new technologies that lead to improved measurements, and emergence of entirely new capabilities. SSSC must embrace the development, infusion, and study of new technology, both for its stimulating effect on science (enabling and enhancing new missions), and because of the key role that understanding and predicting the space environment presents for the safety and productivity of our global infrastructure that is increasingly space-based and of other NASA missions.

Continuing progress in the characterization, modeling, and prediction of the Sun-Solar System Connection (SSSC) will require technological development in a number of key areas.

Highly desirable capabilities include:

- Simultaneously sampling space plasmas at multiple points with cost-effective means (e.g., MMS, LWS Storm Probes, and Sentinels); measuring phenomena at a higher resolution and coverage in order to answer specific scientific questions (e.g, GEC);
- Achieving unique vantage points such as upstream of the Earth-Sun L1, polar orbit around the Sun, or even beyond the heliosphere;
- Developing the next generation of capable, affordable instrumentation;
- Enabling the return of vast new data sets from anywhere in the solar system;
- Synthesizing understanding from system-wide measurements using new data analysis and visualization techniques.

The highest priority SSSC technology needs follow these key focus areas:

1. Developing compact, low-cost spacecraft and launch systems;
2. Achieving high ΔV propulsion (solar sails);
3. Designing, building, testing, and validating the next generation of SSSC instrumentation;
4. Returning and assimilating large data sets from throughout the solar system;
5. Analysis, data synthesis, modeling, and visualization of plasma and neutral space environments throughout the solar system.

Table 4.1 shows enabling and enhancing technologies for Sun-Solar System Connection missions. The table traces the dependence of these key technologies to high-priority missions and also outlines the importance of other areas such as avionics, formation flying, structures & materials, power, and low cost access to space. The number of spacecraft required versus time is displayed in Figure 4.1 entitled “Sun-Solar System Connection Cluster and Constellation Missions.” Missions with “clusters” of spacecraft (in the range of 2-6 spacecraft) seek lower unit costs, while constellation missions such as Magnetospheric Constellation (30-36) and Solar Wind Buoys (12-15) could be enabled by ST-5 nanosats.

The following sections give more detail for each of the high-priority technology needs.

1. Developing compact, low-cost spacecraft and launch systems

Because of the complexity and large scale of solar system plasmas, progress requires clusters or constellations of spacecraft making simultaneous multi-point measurements (e.g., Inner Heliospheric Sentinels, MMS, MagCon, and GEC). For multi-spacecraft missions enabling and enhancing technologies include the development of low mass, power, and volume instrumentation as well as low mass, economical spacecraft. These two developments are linked in the sense that smaller, better integrated, spaceflight instrumentation packages could be accommodated on smaller, less expensive launch platforms.

Reducing the unit cost of multiple space systems will require efforts on multiple fronts. Many system issues are wholly unrelated to typical performance-driven technology development. One important area of technology is the development of low-power electronics for space systems and instruments. Flight validation of one LPE component and technique, the CULPRIT Reed-Solomon Encoder on ST5, is scheduled for 2006. Support for further development was provided by the NASA' Exploration Systems Directorate in 2004 (ECT NRA). Power dissipation at the component level can be reduced by factors of 50-100 over conventional technology. If LPE technology were available system-wide, power consumption on satellite systems could be reduced by up to 70%, enabling system-wide benefits and providing spacecraft designers with greater flexibility reducing weight, size, and cost.

2. Enabling high ΔV propulsion (solar sails)

Progress in key areas of SSSC science requires access to unique vantage points both inside and outside the heliosphere. One key vantage point is high-inclination, heliocentric orbit, which would enable unprecedented imaging of the Sun's polar regions. Mission concepts relying on existing technology use either 5 years of solar

electric propulsion to reach just a 38° inclination in the inner heliosphere (Solar Orbiter) or rely on a Jovian gravity assist and conventional propulsion to provide an eccentric 0.25 x 2.5 AU polar orbit (Telemachus).

The solar sail is envisioned as a cost-effective means of propelling spacecraft in the inner solar system to very high velocity ($\Delta v > 50$ km/s). Because sails rely on the Sun's continuous supply of photons to provide low-thrust propulsion, solar sails also enable missions in non-Keplerian orbits that are currently not feasible by other means. Solar sails would enable three important SSSC missions:

- Heliostorm, providing significantly greater warning of energetic particles accelerated by CME's via measurements upstream of the Earth-Sun L1 point;
- Solar Polar Imager, providing remote sensing of solar poles from a near-optimal vantage point--circular, 0.5-AU, 75° inclination heliocentric orbit;
- Interstellar Probe, a cost-effective means of sampling interstellar space.

A solar sail consists of a reflective membrane and supporting structure that is deployed or constructed in space. As a result of development by the In-Space Propulsion Technologies Project, sail technology has advanced considerably in recent years. In 2004, two 10-m systems were tested in vacuum on the ground, followed by two 20-m systems in 2005. This recent development has moved the solar sail from the realm of science fiction to science fact.

Because of the nature of a solar sail—a gossamer and reflective membrane meant for deployment and to fly in space—there are fundamental limits to further validation and maturation on the ground. Building, deploying and flying a hundred-meter-class solar sail for a strategic science mission will first require a solar sail flight validation or “Sail Demo” mission. The sail demo will develop and operate in space a deployable solar sail, one that provides measurable acceleration and that can be steered. The flight experiment will test and validate the models and processes for solar sail design, fabrication, deployment, and flight. Such models and processes can then be used with confidence to design, fabricate, and operate the larger solar sails needed for strategic missions.

A sail demo is a candidate concept for the New Millennium Program's ST9 mission scheduled for 2010. Scale-up of the technology to 100-m lengths needed by Heliostorm could occur 5-6 years after a successful sail demo. After flight of a 100-m-class solar sail and a few years additional development, scale-up to still larger sails such as for Solar Polar Imager (~160-m edge length) are imaginable from there. Three decades hence, the deployment of a truly monumental, high-temperature sail required by a mission like Interstellar Probe (200-m radius) could be facilitated by human crews operating near libration points.

3. Enabling the development of the next generation of SSSC instrumentation

SSSC missions carry a wide range of instrumentation, some designed to make *in-situ* measurements within space plasmas while others make remote sensing measurements of plasma processes occurring at the Sun, near the planets, or out to the edge of the heliosphere. The development of new instruments and instrument concepts is crucial to the future of SSSC science, driven by the need to refine and improve instruments, reduce their mass and power consumption and enable new measurement techniques. Progress in instrument technology development is needed at all technology readiness (TRL) levels, from basic concepts for new detectors (e.g. MEMS-based (microelectro-mechanical systems) plasma detectors that could be used on MagCon) to system level demonstration of improved instruments (e.g. Compact Doppler/Magnetographs for missions such as Doppler). The development of these instruments will proceed from formulation of new ideas and designs (perhaps based on technologies developed in other fields), basic proof of concept, fabrication of test models, laboratory testing, and finally flight validation. It is important to maintain a balanced program that supports all levels of this development, particularly the final stages that enable instruments to be used in-flight. The most costly and time consuming development stages are those directly preceding flight on science missions, largely because of the specialized equipment required. In order to continue to lead the world in space science research, NASA must support the development and maintenance of space-quality test facilities, including those capable of simulating the particle and radiation environments encountered during spaceflight missions. For some of these applications, NASA's low-cost access to space (LCAS) program provides an ideal avenue for testing and validation. A prime example of this paradigm is the development of top-hat style plasma detectors. These were first conceived for studies of the Earth's auroral regions, and were first flown on sounding rockets. Their successes in this area led directly to instruments being flown on highly successful magnetospheric missions. Another important avenue for assessing the effects of the variable space environment on potential flight instruments (and other technologies) is the LWS Space Environment Testbed (SET) Program.

Specific component technologies that would benefit SSSC missions include: large area, deep well CCDs, active pixel sensors, low-noise micro-channel plates, foil technology for ENA imagers, high performance EUV mirrors, UV blind ENA imagers, low-mass high-voltage power supplies advanced X-ray optics and detectors, thin solid-state energetic particle detectors, compact, accurate magnetic sensors and small dead-layer solid state detectors. At the system level, many payloads on future SSSC missions will be severely mass and power constrained (MagCon and Solar Weather Buoys, for example): Technologies that reduce sensor and electronics mass and power

would be particularly useful. In addition to these focused technology needs, missions may benefit from serendipitous use of technologies developed in other fields. For example, the incredible shear strength and impressive electronic properties of carbon nanotubes may lead to the development of stronger, lighter materials and more power efficient ionization sources.

4. Enabling the return of large data sets from throughout the solar system

As our exploration of the Sun-Solar System connection proceeds, SSSC missions will place an increasing demand on NASA's communication resources. Many missions would be significantly enhanced by increased communications bandwidth. High bandwidth communication would benefit missions that image the Sun, such as Solar Polar Imager or Doppler, by allowing high cadence, high resolution imaging in multiple spectral channels. As solar remote sensing missions are deployed beyond Earth orbit, these benefits become more critical: missions such as SHIELDS or the Farside Sentinel will study the Sun from multiple distant vantage points, requiring spacecraft to be operated up to 2 AU from the Earth. Closer to Earth, missions will require multiple spacecraft to explore the geospace environment, separating the effects of variations in time and space and examining the structure of complex boundaries. Large numbers of individual spacecraft (in MagCon, for example) distributed throughout geospace will stretch the capabilities of the current communications infrastructure. As we venture further out in the solar system, with missions such as Jupiter Polar Orbiter (Juno), HIGO and Interstellar Probe, returning the required data places an increasing burden on spacecraft, driving cost and complexity. Considered individually, the above missions may be achievable with current technology, however pursuing system-wide SSSC science goals will be enabled by enhancements to our communications technology.

Several technologies will contribute to the solution to this problem. Planned enhancements to the Deep Space Network (DSN), replacing outdated 70m and 34m antenna with arrays of smaller antenna working at Ka-band, will increase the available bandwidth substantially, while also providing the flexibility to communicate with multiple spacecraft simultaneously. Using 200 such antennas, for example, would enable kilobit per second communications from an Interstellar Probe at 100 AU, providing the type of data provided by the ACE or Ulysses missions throughout the solar system to the edge of the heliosphere. Optical communication would also provide a substantial increase in communication bandwidth and additionally provide the capability for high-bandwidth point-to-point communication for missions monitoring the interplanetary radiation environment. The next generation DSN is expected to provide both enhanced RF and optical communications. Arrays of small antennas plus other RF improvements (transmitters, inflatable antennas, transponders, for example) together with optical

communication would provide orders of magnitude increase in science data rates. RF arrays would also enable a significant increase in the number of spacecraft that can be supported, particularly in closely spaced clusters.

5. Enabling the analysis, modeling, and visualization of solar system plasmas

As we continue to explore Sun-Solar System connections, the requirement to effectively model the vast systems we study using sparsely sampled observations becomes more critical. Remote space weather predictive capabilities may even be required for explorers far from Earth. In many missions (e.g. the Inner Heliosphere Sentinels, MagCon, or SEPM) modeling will be a critical element of the mission itself, while other modeling efforts will be required to assimilate the data collected by multiple missions into coherent models. The necessary groundwork for these activities has already begun - examples include NASA's Information Power Grid, a joint effort between government, academia, and industry to provide large scale, distributed computing resources to the scientific and engineering communities. The Columbia supercomputer, uses 10,240 Intel Itanium 2 processors and provides an order of magnitude increase in NASA's computing capability. The goal of producing integrated models, and software frameworks that link these models, is also being addressed, with organizations such as NASA's Coordinated Community Modeling Center (CCMC), the NSF-funded Center for Integrated Space Weather Modeling (CISM) and the Center for Space Environment Modeling at the University of Michigan. These efforts are by definition cross-disciplinary, requiring expertise in numerical analysis, high-performance computational science, and solar, interplanetary, magnetospheric, ionospheric and atmospheric physics. Future modeling and theory programs will need to be expanded to handle the demands of increasingly complex data sets and simulations that encompass the entire solar, heliospheric and geospace environments. As new computer capabilities emerge, SSSC scientists will construct broader ranging and more complex models that will allow us to predict the behavior of solar system plasmas based on the assimilation of data from our SSSC Great Observatory.

One of the great challenges faced by current and future SSSC missions is visualization of complex data sets measured by multiple spacecraft in a simultaneous, coherent fashion. Current efforts include the VisBARD project, funded by NASA's Applied Information Systems Research Program. In this project, space science data are displayed three-dimensionally along spacecraft orbits that may be presented as either connected lines or as individual points. The data display allows the rapid determination of vector configurations, correlations between many measurements at multiple points, and global relationships. Events such as vector field rotation and dozens of simultaneous variables that are difficult to see in traditional time-series line-

plots are more easily visualized with such a tool. Future data sets will be even more extensive requiring ever more sophisticated visualization tools.

In analyzing future spacecraft data and comparing them with data available from the rest of the SSSC Great Observatory, pattern and feature recognition will become increasingly valuable, allowing large datasets to be mined for events, particularly those detected by multiple platforms. Data structures like the Virtual Solar Observatory and Virtual Heliospheric Observatory will allow such mining, enhancing the value of our data repository and making data more accessible to the science community. Visual representation of imaging data is also critical to its analysis and interpretation, as well as providing a ready means to engage the public. A wide range of SSSC image data will be produced: gamma-ray, X-ray, ultraviolet, visible, infrared, radio, and neutral atom instruments will all produce data requiring image visualization. Tools aimed at producing images of these data are an important part of our current technology, however future missions (STEREO, SDO, IBEX, and GEMINI, for example) will continue to place demands on technological capabilities, as image formats increase in size and more complex multi-dimensional data sets need to be visualized.