NASA'S LIVING WITH A STAR PROGRAM

Dana A. Brewer
NASA Headquarters, Washington, DC 20546 USA, dbrewer@hq.nasa.gov
Janet L. Barth
NASA Goddard Space Flight Center, Greenbelt, MD 20771 USA, Janet.L.Barth.1@gsfc.nasa.gov
Kenneth A. LaBel
NASA Goddard Space Flight Center, Greenbelt, MD 20771 USA, klabel@pop700.gsfc.nasa.gov
William J. Kauffman
NASA Marshall Space Flight Center, Huntsville, AL 35812 USA, Billy.Kauffman@msfc.nasa.gov

ABSTRACT

NASA has initiated the Living with a Star (LWS) Program to develop the scientific understanding to address the aspects of the connected Sun-Earth system that affect life and society. A goal of the program is to bridge the gap between science, engineering, and user application communities by addressing scientific questions that pertain to human radiation exposure, climate change, and technological systems. This will enable future science, operational, and commercial objectives in space and atmospheric environments by improving engineering approaches to the accommodation and/or mitigation of the effects of solar variability on these systems.

The formulation of the LWS Program architecture and implementation plan is currently in progress with inputs from the science and engineering communities. There are plans for two groups of science spacecraft: (a) solar dynamics elements that observe the Sun and track disturbances originating there and (b) geospace elements located between the Sun and the Earth and around the Earth to measure downstream effects the geospace response to changes in solar activity. Plans also include a data analysis component to improve scientific understanding and a series of Space Environment Testbeds to provide infusion of the improved understanding to the design and operations of future missions.

The LWS Program is developing partnerships with other U.S. and International agencies and industry to augment existing capabilities. This paper will give an overview of the program architecture and the implementation and partnering plan for LWS.

1. INTRODUCTION

The Sun is our nearest star. It contains magnetic fields, plasmas, and energetic particles that interact with each other with an eleven-year periodicity. It produces the solar wind, electromagnetic radiation, and energetic particles, and this production also varies as a function of the time in the eleven-year solar cycle. These phenomena (solar wind, electromagnetic radiation, and energetic particles) interact with the Earth's magnetic fields and atmosphere to produce:

- Changes to the Earth's fields;
- Atmospheric photochemistry responsible for the climate and its change; and,
- Atmospheric ionization responsible for plasmas, auroras, and scintillation effects.

The effects of these changes on humanity increase every day due to the increased reliance on new technology and systems that have critical space-based components and the increased or changed use of existing technology (increasing the probability of failure of a unit). For example,

- Commercial communications and high frequency radio communications increasingly have critical space (satellite) links.
- The use of the Global Positioning System (GPS), a space asset, to provide assistance in navigation and location is increasing.
- The use of emerging and commercial off-the-shelf (COTS) microelectronics technology with better capability is increasing in space, in aircraft, and on the ground. These technologies tend to be more vulnerable to the effects of solar varying environments.
- The increase in air travel, particularly over the polar regions (where ionizing radiation is higher than at lower latitudes), may have implications for the occupational safety and health for flight crews.

Minimizing the impacts of the effects on technology, life, and society requires that we improve the scientific understanding for how and why the changes occur on the Sun as well as how the Sun and Earth interact as a system. We can then use the results to enable engineering applications that may improve future science. This connection is depicted in Figure 1.

NASA initiated the Living With a Star (LWS) Program in its Office of Space Science (OSS) to develop the scientific understanding to address the aspects of the connected Sun-Earth system that affect life and society. Three fundamental questions will be addressed to develop this understanding, as follows:

- How and why does the Sun vary?
- How does the Earth respond?
- What are the implications for humanity?

The LWS Program objectives are based upon these questions and are as follows:

- Understand solar variability and its effects on the space and Earth environments with an ultimate goal of a reliable predictive capability of solar variability on long and short term time scales (i.e., space weather);
- Obtain scientific knowledge relevant to mitigation or accommodation of undesirable effects of solar variability on humans and human technology; and,
- Understand how solar variability affects hardware performance and operations in space.

The LWS Program requirements were developed using a series of community workshops [1], results of the Space Science strategic planning process [2,3], interagency discussions, and reports by the National Space Weather Program [4] and National Research Council/National Academy of Sciences [5]. Participants were from U.S. industry, universities, and government agencies. They are customers for the understanding and knowledge resulting from the Program.

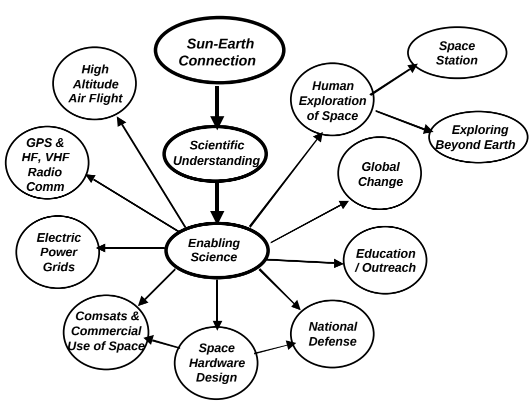

Figure 1. Schematic of the Sun-Earth connections.

The approach to addressing these questions has three components. The first component is a distributed network of research spacecraft to quantify the physics, dynamics, and behavior of the Sun-Earth connected system through the range of conditions occurring during the eleven-year solar cycle. The science missions gather basic science data to achieve the understanding of the connected Sun-Earth system.

Data mining and analysis in a Theory, Modeling, and Data Analysis (TMDA) component will improve knowledge of space environmental conditions and variations over the solar cycle, develop new techniques and models for predicting solar/geospace disturbances, and develop cost-effective techniques for assimilating data from networks of spacecraft. The TMDA defines the environment in the absence of a spacecraft.

The sequence of Space Environment Testbeds (SET) [6] will reduce the uncertainty in the space environment definition as functions of location and time in the solar cycle and will characterize the space environment effects on space hardware. The SET tasks are restricted to the interactions that change with solar variability.

Techniques to accommodate and mitigate the effects of solar variability can be developed and implemented using products from all three components, thereby minimizing the impact of space weather on technology and human space flight.

These components are integrated into an LWS Program in the OSS's Sun Earth Connection (SEC) Division and implemented through an LWS Program Office at the NASA Goddard Space Flight Center. They are described in the following sections of this paper. The SEC science community provides advice to the OSS through the Sun Earth Connection Advisory Subcommittee (SECAS), a subcommittee of the Space Science Advisory Committee [7]. The SET Steering Committee provides advice to the SET and the SECAS. A schematic of this LWS program architecture is given in Figure 2.

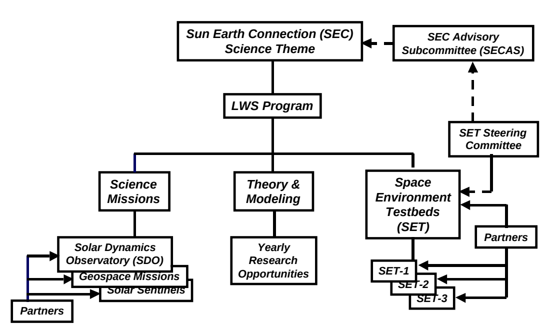

Figure 2. LWS Program architecture.

Participation in the LWS Program is open to U.S. and international investigators from industry, government, and academia. International investigators may participate based upon no exchange of funds. Partnering in investigations, in space flights, and in the development of complementary initiatives that maximize the utility of the LWS Program and resources is encouraged.

2. LWS SCIENCE MISSIONS

The mission pre-concepts are developed in Science and Technology Definition Teams (STDTs) with membership from the scientific and user communities. The system of spacecraft missions can be sub-divided into three categories based upon the area of the Sun-Earth system being characterized. They are (1) the area immediately around the Sun that is used to investigate solar variability, (2) the area between the Sun and the Earth used to investigate the effects of the variability on the space environment, and (3) the Earth's space environment used to investigate the Earth's atmospheric response to the effects of solar variability.

Science requirements from the STDT reports form the basis for the Headquarters-issued open, peer-reviewed competitions for science investigations for each mission. These competitions are open to both U.S. and non-U.S. participants. The investigations have two segments, a segment where a science instrument collects data in space and a segment where the collected data are analyzed to advance scientific knowledge. The formulation of each mission begins when Headquarters awards the science investigations, assigns the lead center for the project, and authorizes mission concept definition. Implementation, launch, and operations follow.

A first LWS system science campaign is planned for the next solar maximum that will peak in approximately 2010. Three missions are planned, and two of them have more than one spacecraft. They are the Solar Dynamics Observatory (SDO), the Geospace Missions, and the Solar Sentinels. The notional locations of these and other desired spacecraft are given in Figure 3. The Geospace Missions are the combination of the Radiation Belt Mappers and the Ionospheric Mappers that were defined in the LWS pre-formulation plan..

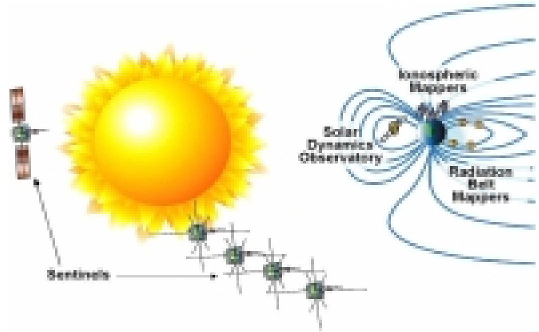

Figure 3. Sun-Earth Connection system of LWS science missions for the next solar maximum.

2.1 The SDO Mission

The SDO mission will observe the Sun's dynamics to increase understanding of the nature and sources of the Sun's variations [8]. The areas of the Sun that will be included are the changes in the magnetic fields and the relationships between the Sun's magnetic fields and mass and energy releases from the Sun.

The SDO mission concept employs a three-axis stabilized spacecraft with a complement of solar-pointed instruments to perform the investigations. A spacecraft concept is given in Figure 4. The mission has a 5-year primary lifetime. The spacecraft is planned for launch into geosynchronous Earth orbit in 2007.

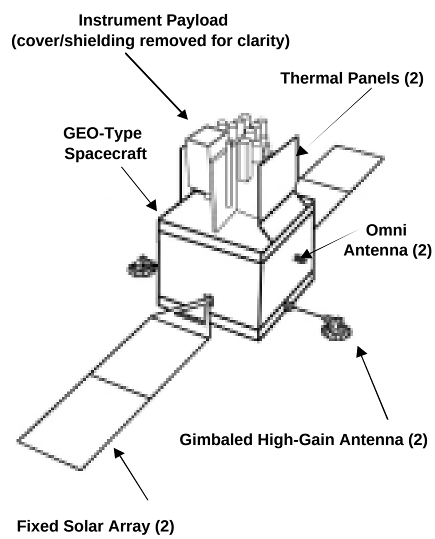

Figure 4. The spacecraft concept for the Solar Dynamic Observatory mission.

2.2 Geospace Missions

The goal of the Geospace Missions is to increase scientific understanding of how the Earth's ionosphere and magnetosphere respond to changes due to solar variability [9]. The focus areas for investigations are the ionizing radiation belts, the ionosphere, and the effects of changes in the ionizing radiation on the ionosphere. These focus areas require simultaneous measurements from several vantage points in the Earth's space environment.

The investigations of the radiation belts will focus on understanding the origin and dynamics of the radiation belts and the evolution of radiation during magnetic storms. An array of measurement platforms in low-inclination elliptical orbits will characterize particles and fields in the Earth's inner magnetosphere.

The ionospheric investigations will collect data to enable the creation of space-time maps for neutral density and drag, plasma density and drifts, scintillations, auroras, and winds. They will require polar orbit and low inclination vantage points.

In the Geospace Mission pre-concept, each measurement platform has a primary design lifetime of two years. Opportunities for vantage points as secondary or piggyback measurement platforms are being investigated. Launch is planned for 2008, and the mission pre-concept will be refined during 2002.

2.3 Solar Sentinel Missions

The Solar Sentinel missions will provide views of the Sun and the area in space between the Sun and the Earth (i.e., the heliosphere) to improve the description of the transition and evolution of eruptions and flares from the Sun to Earth [10]. The heliosphere is very inhomogeneous. That is, the propagation of transients is not uniform, and the transients could evolve significantly before reaching Earth. The single Farside Sentinel spacecraft will observe the formation and evolution of activity on the Sun from the backside of the Sun, the area not visible from Earth. The array of Inner Sentinels will characterize the transport and transformation of the mass and energy through the area of space between the Sun and the Earth. Analysis of data from the Sentinels will be coupled with data from other LWS missions to answer the fundamental LWS science questions. Launch is planned for the time frame of the next solar maximum.

Data Policy

Data collected in space will be treated as a public resource and will be made available for public access as soon as is practical. After the initial check out and calibration period of approximately three months after initial operation, the data and requisite basic analysis software will be made available to the international community through the project-designated facility with no more than a two-month delay.

3. LWS THEORY, MODELING, AND DATA ANALYSIS (TMDA)

The TMDA is a ground-based set of analyses that are performed using data from past and present space missions [11]. The analysis tasks are selected using a peer reviewed competition. The types of investigations that are appropriate for TMDA funding are broadly applicable to one or more NASA Enterprises (or business units). They include:

- Developing new instrument techniques, models, and concepts for investigating solar and geospace disturbances;
- Enhancing the understanding of the role of solar influences in terrestrial global climate change;
- Improving our scientific knowledge of space environment conditions and variations over the solar cycle; and,
- Developing models and ideas for the investigations that may result in future LWS missions.

Specific tasks that might be proposed include: discovery of a signature in soft X-ray images of solar regions that indicates a high probability for coronal mass ejections; models of the near real-time latitudinal cut-off of solar energetic particles; and developing cost-effective techniques for assimilating data from networks of research spacecraft, or providing scientific rationale for the locations of constellations of LWS spacecraft.

The NASA science Enterprises will use the scientific results of these investigations in different ways. The Space Science Enterprise will use the results to improve the understanding of the physics, dynamics, and behavior of the Sun-Earth system over the 11-year solar cycle. The Earth Science Enterprise will use the improvements in the description of the effects of solar variability in models that describe terrestrial climate change. The Human Exploration and Development of Space Enterprise will use the improvements in the advanced warning capabilities for solar energetic particles to improve the safety of space flight crews. The Aeronautics and Space Transportation Enterprise will use improved descriptions of the ionizing radiation environment and its variations to design more reliable avionics for air and space transportation systems and assess crew health affects from prolonged air transportation.

Participants in the TMDA and SET parts of the LWS Program may be selected from industry, universities, government agencies, and international partners. Products and data resulting from these segments of the LWS Program will be made available for public access consistent with International Traffic in Arms Regulations and Export Administration Regulations.

4. LWS SPACE ENVIRONMENT TESTBEDS

The LWS SETs are a series of testbeds and analyses that focus on improving the engineering approach to accommodate and/or mitigate the effects of solar variability on spacecraft design and operations [6,12,13]. They bridge the gap between the science, engineering, and user application communities by directly infusing new results from science missions into engineering products that are used to improve the design and operation of existing and future missions. The LWS SETs address the space environment in the presence of a spacecraft and only those environment effects that change due to solar variability with the goal of reducing the effects of space weather. The approach is to:

1. Define space environment effects and mechanisms:
    - Define detector/sensor degradation and failure mechanisms
    - Develop methods to control/eliminate plasma effects,
    - Develop methods to control/eliminate deep dielectric charging effects,
    - Understand materials degradation mechanisms and rates, and
    - Develop methodologies to improve microelectronics performance.

2. Reduce design margins
    - Increase use of space environment "tolerant" technologies
    - Increase the fraction of resources for payload
    - Reduce launch vehicle requirements
    - Enable routine operations above Low Earth Orbit (LEO) (above 2000 km) for LEO cost

3. Improve operational guidelines
    - Reduce unnecessary shutdowns
    - Lower the risk of anomalies
    - Reduce the number of failures

The data collection and analysis products from the SETs can then be used to enable science in non-spacecraft applications (see Figure 1).

4.1 Define Space Environment Effects and Mechanisms

The lack of understanding of space environment effects and mechanisms on new technologies is a major impediment to infusing enabling technologies into missions. Figure 5 shows that three elements are necessary to understand how a technology will perform in space environments:

- "All weather" environment models,
- Ground test data obtained with validated ground test protocols that simulate the actual space environment, and
- Effects models that simulate the basic physics mechanisms of the interaction of the environment with the component.

To develop highly capable systems with new technologies that are tolerant of all space weather conditions, ground test protocols and effects methods must be validated and made available.

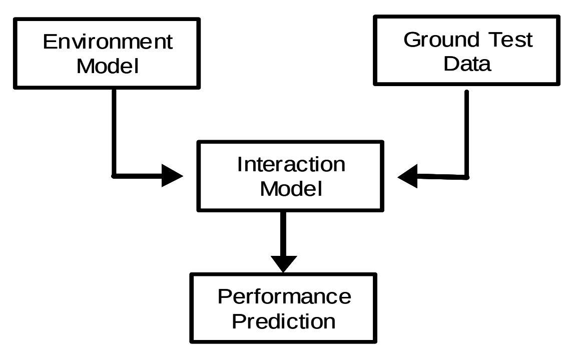

Figure 5: Inputs required for accurate performance predictions.

Simulated conditions on the ground do not correlate to actual flight conditions. The accuracy of a ground test is only as good as the correlation of the test protocol used for flight validation. In addition, test protocols and technology models are often technology specific. Table 1 illustrates the state of knowledge for technology models in the microelectronics and photonics regimes. Increased accuracy of ground testing and the induced environment (the environment that effects technology) clearly requires a correlation with actual space performance.

In some cases, environment tolerance means the use of mitigation techniques. One of the SET objectives is focused on validating these technologies and techniques. A relevant example is the plasma-induced charging issue in spacecraft that traverse energetic electrons during the course of their orbits [14]. Orbits such as GEO and Geo-Transfer (GTO) are particularly vulnerable to these effects. In the past, large spacecraft with a Faraday cage-like structure were used to mitigate this issue. With today's movement towards small, lightweight spacecraft, the unwieldy structures of the past are simply not feasible. New and novel approaches to mitigation of charging are required. Due to complexities of environment and to design complications, flight validation of these technologies is required.

Table 1: The state of microelectronic and photonic radiation effects models

Technology	***State of radiation effects models***
Standard CMOS	Adequate
Bipolar	Insufficient - Many unanswered questions still exist on enhancements from dose rate and particle source
Emerging CMOS, e.g., deep sub-micron and ultra-low power	Insufficient - New effects are being discovered that have not been modeled or flight validated
Emerging microelectronics e.g., SiGe, InP	Limited to nonexistent
Detectors, e.g., CCDs and focal plane arrays	Limited flight validation, Some novel detectors have not yet been modeled; new issues are constantly surfacing
Photonics	Under development with limited flight validation

4.2 Reduce Uncertainty Margins

Spacecraft design and operations requirements contain uncertainty margins that can either add large overhead on design and operations or even preclude the use of commercial off-the-shelf (COTS) and emerging technologies that enable missions. The margins can be grouped into three categories (see Figure 6). Margins due to the variations in the environment definitions and their associated effects that cannot be changed are in the first category. They form the statistical basis for the environments design and operations requirements.

Uncertainty due to the lack of complete knowledge of the either the definition of the environment or its effects on spacecraft operations comprises the second category of margin. This category is also associated with the inability to accurately test the spacecraft performance on the ground due to an inability to accurately simulate the in-space natural or induced environment on the ground. By improving the accuracy of both elements, design margins can be significantly reduced. The number of available choices in electronics and materials that meet the requirement is increased, including potentially less expensive, higher performing, and reduced mass technologies.

The third category of margin is the program manager's margin. It is added to account for (1) the use of technologies that have not been completely validated in the environment where they will be used; (2) the requirement to validate performance through analysis or similarity; and, (3) unanticipated performance during mission-specific technology applications.

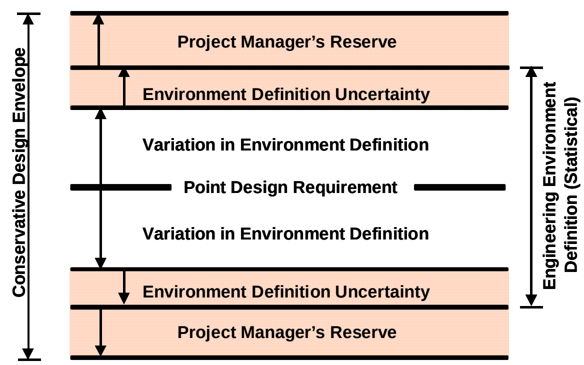

Figure 6. State of practice for spacecraft design requirements and operations planning margins.

Products from the SET Program seek to minimize the requirements for margins in the second and third categories, because eliminating them will either increase the payload fraction of the spacecraft or permit the use of a smaller launch vehicle (thereby reducing the spacecraft cost). They will also enable routine operation in new segments of the environment (such as middle Earth orbit) for costs similar to those for low Earth orbit operations and validate ground test protocols and design guidelines.

4.3 Improve Operational Guidelines

The demise of the space qualified component market, the commercial demand for electronics, shorter development times, use of smaller and lighter spacecraft, more demanding mission requirements, and the desire to operate in all regions of space all contribute to the use of more sensitive commercial off the shelf (COTS) components and emerging technologies in more severe space environments. In other words, component choices are driven by capability and availability and not by qualification for use in space and atmospheric environments. For the most part, these technologies are not space-qualified by manufacturers, and they tend to be increasingly sensitive to the environment. The trend toward using more sensitive technologies in technological systems implies that we can no longer completely avoid risk but must rely on managing risk. Risk avoidance and management for space systems are traditionally achieved through system design and component screening. However, increasingly, designing capable spacecraft that are 100% free from environment-induced effects cannot be accomplished within reasonable costs. As a result, systems must be designed to accommodate space environment effects during on-orbit operations. Discussion of design and operational strategies for mitigation of radiation effects can be found in References 15 and 16.

4.3.1 Data Collection in Space

The approach to achieving these objectives starts with data collection in space frequently and at a variety of locations. Flight experiments are developed and operated to assess the space environment in the presence of a spacecraft and its effects on spacecraft design and operation, and to characterize or validate the performance of new sensors and technologies. This may include experiments intended to fly on the SET experiment carriers and flights of opportunity on other commercial, international, or government missions.

The SET concept contains three types of investigation components based upon customer requirements: collateral environments measuring instruments, box experiments, and board experiments. Collateral environment measurements are performed to support the flight validation and performance characterization experiments. Box experiments are independent, self-contained experiments in separate packages. They interface directly to the testbed for power and data. Board experiments are modular card experiments that connect to a central board through a simple and common interface for analysis, storage and transfer of data and power conditioning.

A concept for a common experiment interface to a testbed and a simple interface between a testbed and a host spacecraft has been developed and is shown in Figure 7. In the figure, the microelectronics testbed is shown as an embedded testbed that interfaces to the central SET testbed and contains card experiments. The testbed provides a central processing unit (CPU) to the experiments. Stand-alone (box) and card experiments are shown.

Opportunities for experiment data collection can be maximized when opportunities for access to space and partnering for instruments, experiments, and access to space are maximized. Accordingly, the SET Program is seeking partners at three levels of participation: the Program, the testbed, and the experiment.

4.3.2 Data Analysis

Predictions of hardware performance in space are made using a combination of the engineering environment definition models and results from ground tests of devices. Data from the in-space performance characterization and correlative environment measurements will be analyzed to develop and validate engineering environment prediction and specification models, tools, & databases. The data can also be used to improve the ground test protocols when data are collected on the ground prior to characterizing their performance in space.

5. SUMMARY

The LWS Program is a funded program that includes science and applications to facilitate the scientific understanding to address pure science and applied science aspects of the connected Sun-Earth system that affect life and society. The Program is in formulation and is actively seeking partners in all three aspects of the Program: science missions, science data analysis, and applied science/engineering. Implementation of the LWS Program will provide data that will enable future objectives in space.

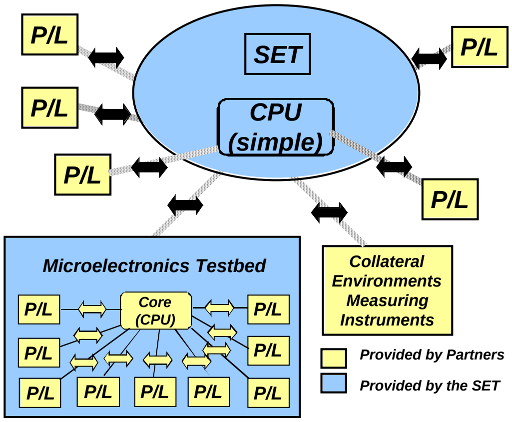

Figure 7. The Living With a Star (LWS) Space Environment Testbed (SET) concept showing experiments (or payloads, P/L), collateral environment measuring instruments, and two nested testbeds.

REFERENCES

1. Anon., Living with a Star (LWS) Pre-Formulation Study, Internet address http://lws.gsfc.nasa.gov/lws.htm, NASA Goddard Space Flight Center, Greenbelt, MD, Aug. 2000.

2. Anon., The Space Science Enterprise Strategic Plan, Doc. No. NP-2000-08-258-HQ. NASA Headquarters, Washington, DC, Nov. 2000. Avail. http://spacescience.nasa.gov.

3. Anon., Sun-Earth Connection Roadmap: Strategic Planning for 2005-2025. NASA Headquarters, Washington, DC, Jan. 2000. Avail. http://www.lmsal.com/sec/.

4. Anon., National Space Weather Program: Implementation Plan. Doc. No. FCM-P31-1997, Office of the Federal Coordinator for Meteorological Services and Supporting Research, Washington, DC, Jan. 1997. Avail. http://www.ofcm.gov/nswp-ip/text/cover.htm.

5. National Research Council, Radiation and the International Space Station: Recommendations to Reduce Risk. Space Studies Board and Board on Atmospheric Sciences and Climate, National Academy Press, Washington, DC, 2000.

6. J. L. Barth, K. A. LaBel, D. Brewer, G. Withbroe, and B. Kauffman, "The Living with a Star Program, NASA's Role in Assuring Performance in Space and Atmospheric Environments," Presented at AIAA Aerospace Conference, Reno, NV, January 8-11, 2001.

7. See http://www.hq.nasa.gov/office/ codez/new/ for the charter of the Space Science Advisory Committee.

8. The SDO mission is described at the following web sites: http://lws.gsfc.nasa.gov/thompson_commworkshop.ppt, http://lws.gsfc.nasa.gov/sdo_splinter_commworkshop.ppt, and http://lws.gsfc.nasa.gov/esa_so_commworkshop.ppt.

9. The Geospace Misisons are described at the following web sites: http://lws.gsfc.nasa.gov/im_commworkshop.ppt, http://lws.gsfc.nasa.gov/im_splinter_commworkshop.ppt, and http://lws.gsfc.nasa.gov/rbm_commworkshop.ppt.

10. The Sentinel Missions are described at the following web sites: http://lws.gsfc.nasa.gov/sentinels_commworkshop.ppt and http://lws.gsfc.nasa.gov/sentinels_splinter_commworkshop.ppt.

11. The Theory, Modeling, and Data Analysis are described at the following web sites: http://lws.gsfc.nasa.gov/tm_splinter_commworkshop.ppt and http://lws.gsfc.nasa.gov/da_splinter_commworkshop.ppt.

12. D. A. Brewer, K. A. LaBel, J. C. Ritter, J. L. Barth, K. S. Clifton, S.D. Pearson, J. Peden A. Campbell, and R. Liang, "The Orbiting Technology Testbed (OTTI) Space Experiments," Proc. IEEE RADECS 99, 11-17, 1999.

13. Orbiting Technology Testbed Initiative (OTTI) Final Report available at: http://see.msfc.nasa.gov/otti/Final_Report.htm, July 1998.

14. M.S. Gussenhoven, E.G. Mullen, and D.H. Brautigam, "Improved Understanding of the Earth's Radiation Belts from the CRRES Satellite," *IEEE Trans. Nucl. Sci., NS-43, 2, 353-369,* April 1996.

15. J. D. Kinnison, IEEE Nuclear and Space Radiation Effects Conference Short Course, "Achieving Reliable, Affordable Systems," Newport Beach, CA, July 20, 1998.

16. W. F. Heidergott, IEEE Nuclear and Space Radiation Effects Conference Short Course, "System Level Mitigation Strategies," Norfolk, VA, July 12, 1999.