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NASA's Sun-Earth Connection Program Strategic Planning, Missions & Technology Needs (2003-2028)[1,2]

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Abstract—Our variable star, the Sun, is the source of varying solar wind, electromagnetic fields, and particles that interact with the planets and the galaxy. The Earth's magnetic field and upper atmosphere provide the shielding from the Sun's external influences, and they also form a coupled system with the Sun and the heliosphere. The Sun-Earth Connection (SEC) [1] theme in the NASA Office of Space Science (OSS) has a goal to understand the Sun, heliosphere, and planetary environments as a single connected system.

The SEC Roadmap [2] strategy is to develop a synergistic set of missions that will allow us to discover and understand the connected Sun-Earth system in the spatial, temporal, and spectral domain from optimal vantage points in space. These missions will provide the remote and multipoint in situ measurements from unique vantages to support the primary SEC scientific goals and objectives. These missions will image the Sun's atmosphere in three dimensions by including high latitude and polar regions; explore the heliosphere from very near the Sun to the interstellar medium; and determine the connections in the magnetosphere and ionosphere with multisatellite measurements.

The first of a series of missions is under way and is being formulated and implemented in two flight programs: the Solar Terrestrial Probes (STP) [3], and the new Living With a Star [LWS] Program [4]. These programs build on the first truly coordinated investigations conducted by the International Solar Terrestrial Physics Program (ISTP) and SEC missions in the 1990s and early 2000s. These earlier missions identified the importance of a system that understands the variable Sun and its interaction with the Earth's geospace.

This paper provides an overview of the SEC strategic missions planned for the period 2003-2028 and their technology needs. These missions range from single to multiple spacecraft and even constellations of small

[2] Paper number 1162

satellites. Important technologies include those that enable economical multispacecraft missions, information technology for system-wide measurement and understanding, solar sail propulsion for reduced flight times, and improved scientific instrumentation to provide in situ and imaging observations. Enhancing technology related to systems and instruments are described that can improve payload mass-fraction, performance, and/or lower mission cost.

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1. SEC STRATEGIC PERSPECTIVE

The strategic perspective of the Sun-Earth Connection theme is derived from the NASA Sun-Earth Connection Roadmap 2003-2028 and the National Research Council Decadal Research Strategy in Solar and Space Physics [5]. The NASA Office of Space Science Strategic 2003 Plan is being prepared from the roadmaps and decadal studies from OSS science themes including SEC, Solar System Exploration (SSE), Astronomical Search for Origins (ASO), and Structure and Evolution of the Universe (SEU).

The 2002 SEC Roadmap (Figure 1) describes the wide-ranging science, missions, and technology needs for the period 2003-2028. The SEC theme has a goal to understand the Sun, heliosphere, and planetary environments as a single connected system. The flowdown from the science goal to science objectives, research focus areas (RFAs), investigations, missions, and technologies is shown in Figure 2. The primary SEC scientific goals and objectives are to:

- Understand the changing flow of energy and matter throughout the Sun, heliosphere, and planetary environments
- Explore the fundamental physical processes of space plasma systems
- Define the origins and societal impacts of variability in the Sun-Earth connection

Each of these primary science objectives is divided into RFAs. The decadal study utilized challenges that map reasonably close to these RFAs.

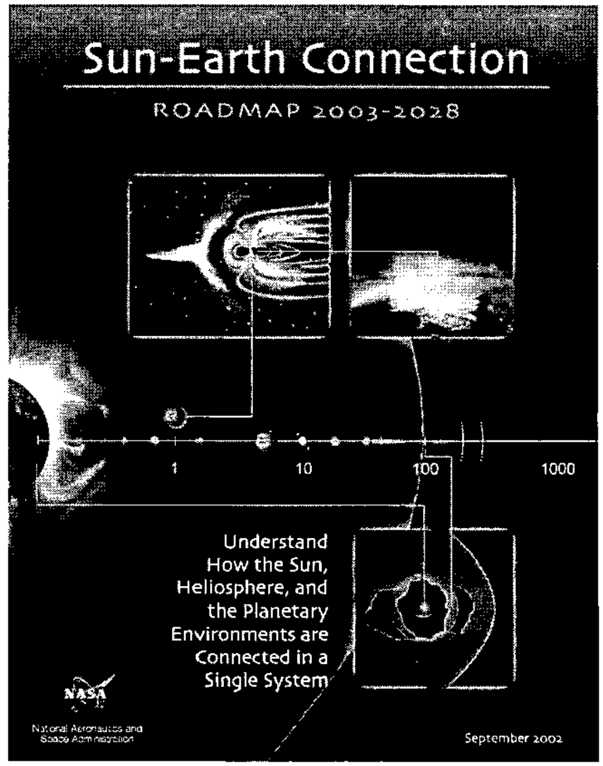


Figure 1 - 2002 SEC Roadmap cover

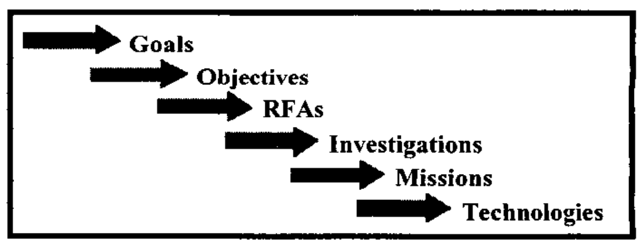


Figure 2 - SEC strategic flowdown

2. SEC ROADMAP MISSIONS

The missions studied in support of the SEC Roadmap cover a broad spectrum of sizes, complexities, and vantage points. From simple near-Earth orbiters to long-duration surveys throughout and beyond our solar system, the potential missions that answer the SEC objectives will need to take advantage of projected engineering capability and enhancing technologies. Some will require enabling technologies to meet mission requirements.

The missions generally fit into one of the four areas of the SEC domain: the Sun; the heliosphere or region of space influenced by the Sun; the magnetosphere or region of space influenced by Earth's magnetic field; and the ITM (ionosphere, thermosphere, magnetosphere) region that couples the Earth's upper atmosphere to the Sun.

The mission concepts directed at each of these areas are driven by focused science objectives and can be characterized by their similarities and differences in mission-level parameters. These parameters may include total mission mass, number of flight elements, mission data volume, and kinetic energy or delta-V. Representative missions that illustrate some of the general characteristics of concepts within the SEC domain include Magnetospheric Constellation and Dayside Boundary Constellation (large numbers of flight elements); Magnetic TRAnsition Region Probe (high data throughput and volume); Solar Polar Imager and Interstellar Probe (high-mission delta-V); and Jupiter Polar Orbiter and Telemachus (extreme or widely varying environment). It is intended that this mission characterization will assist in developing roadmaps for the implementation of synergistic missions that will improve our understanding and long-term monitoring requirements of the Sun–Earth system. These roadmaps, in turn, provide the strategic science objectives and supporting missions from which an OSS Strategic Plan can be developed.

The mapping of roadmap missions into SEC primary science objectives in the near, intermediate, and long term are shown in Figure 3 [2]. These missions address solar energy processes, the heliosphere or region of space influenced by the Sun, the magnetosphere or region of space influenced by the Earth's magnetic field, and the ITM region that couples the Earth's upper atmosphere to the Sun. Note that the near and intermediate term missions under a particular objective are listed in chronological order. The larger number of long term missions under a particular science objective are listed in alphabetical order to support a wider range of future mission concepts commensurate with a roadmap. The aggregation of these missions into Program areas for the near, intermediate, and long term is shown in Figure 4. These Program areas include STP, LWS, Other Missions, European Space Agency (ESA) Cooperative, and Solar System Exploration Joint.

Finally, a near and intermediate term mission timeline is shown in Figure 5 which includes on-going missions plus those derived from the roadmap. The timeline highlights the approval, launch, and prime operations of STP [4], LWS [5], and Other Missions.

Goal	Understand the Sun, heliosphere, and planetary environments as a single connected system		
Strategic Science Objectives	1) Understand the changing flow of energy and matter throughout the Sun, heliosphere, and planetary environments.	2) Explore the fundamental physical processes of space plasma systems.	3) Define the origins and societal impacts of variability in the Sun-Earth connection.
Near Term Missions Start Implementation (2003-2008)	• Solar-B • Solar-Terrestrial RElations Observatory (STEREO) • Geospace Electrodynamics Connections (GEC) • Solar Probe	• Magnetospheric Multiscale (MMS) • Bepi-Columbo	• Solar Dynamics Observatory (SDO) • Geospace Storm Probes - Radiation Belt Storm Probes - Ionosphere-Thermosphere Storm Probes
Intermediate Term Missions Start Implementation (2009-2014)	• Magnetospheric Constellation (MC) • Telemachus • Ionosphere-Thermosphere-Mesosphere Waves Coupler • Heliospheric Imager and Galactic Observer (HIGO)	• Reconnection Microscale (RAM) • Jupiter Polar Orbiter (JPO)	• Inner Heliospheric Sentinels (IHS) • Solar Orbiter • Inner Magnetospheric Constellation (IMC) • Tropical ITM Coupler • Magnetic TRAnsition region Probe (MTRAP)
Long Term Missions Start Implementation (2015-2028)	• Auroral Multi-Scale (AMS) • Geospace System Response Imager (GSRI) • Interstellar Probe • Neptune Orbiter • Solar Connection Observatory for Planetary Environments (SCOPE) • Solar Polar Imager (SPI)	• Dayside Boundary Layer Constellation (DBC) • Io Electrodynamics • Magnetosphere-Ionosphere Observatory (MIO) • Mars Aeronomy Probe • Particle Acceleration Solar Orbiter (PASO) • Venus Aeronomy Probe	• L1-Diamond • Solar Imaging Radio Array (SIRA) • Stellar Imager • Sun-Earth Energy Connector (SEEC) • Sun-Heliosphere-Earth Constellation

Figure 3 - SEC goal and strategic science objectives and their links to near, intermediate, and long term missions
- Near and intermediate term missions under a particular objective are listed in chronological order
- Long-term missions under a particular science objective are listed in alphabetical order

Theme	Near Term Start Implementation (2003-2008)	Intermediate Term Start Implementation (2009-2014)	Long Term Start Implementation (2015-2028)
SEC	*Solar Terrestrial Probes:* **Solar B** (w/ISAS) **STEREO** (Solar TErrestrial RElations Observatory) **MMS** (Magnetospheric Multiscale) **GEC** (Geospace Electrodynamics Connections) ***LWS Missions:*** **SDO** (Solar Dynamics Observatory) *The Geospace Storm Probes:* **ITSP** (Ionosphere-Thermosphere Storm Probes) **RBSP** (Radiation Belt Storm Probes) ***Other Missions:*** **Solar Probe** ***ESA Cooperative Missions:*** Bepi-Colombo (Mercury)	*Solar Terrestrial Probes:* **MagCon** (Magnetospheric Constellation) **Telemachus** (High Latitude Heliosphere [son of Ulysses]) **ITM Waves Coupler** (iono/thermo/meso-sphere) **RAM** (Solar Reconnection and Microscale) **HIGO** (Heliospheric Imager and Galactic Observer) ***LWS Missions:*** **IHS** (Inner Heliospheric Sentinels) **IMC** (Inner Magnetosphere Constellation) **Tropical ITM Coupler** **MTRAP** (Magnetic TRAnsition region Probe) ***ESA Cooperative Missions:*** **SoLo** (Solar Orbiter) ***SSE Joint Missions:*** **JPO** (Jupiter Polar Orbiter)	*Solar Terrestrial Probes:* **AMS** (Auroral Multiscale) **DBC** (Dayside Boundary layer Constellation) **GSRI** (Geospace System Response Imager) **MIO** (Magnetosphere-Ionosphere Observatory) **PASO** (Particle Acceleration Solar Orbiter) **SCOPE** (Solar Connection Observatory for Planetary Environments) **SPI** (Solar Polar Imager) ***LWS Missions:*** **L1-Diamond** **SIRA** (Solar Imaging Radio Array) **SEEC** (Sun-Earth Energy Connector) **SHECon** (Sun-Heliosphere-Earth Constellation) ***Other Missions:*** **ISP** (Interstellar Probes) **Stellar Imager** ***SSE Joint Missions:*** **IO Electrodynamics** **Mars Aeronomy Probe** **Neptune Orbiter** **Venus Aeronomy Probe**

Figure 4 - SEC program areas and their links to near, intermediate, and long term mission plans
Missions are listed in order by program areas for near term and intermediate term missions, and alphabetically by program areas for long-term missions.

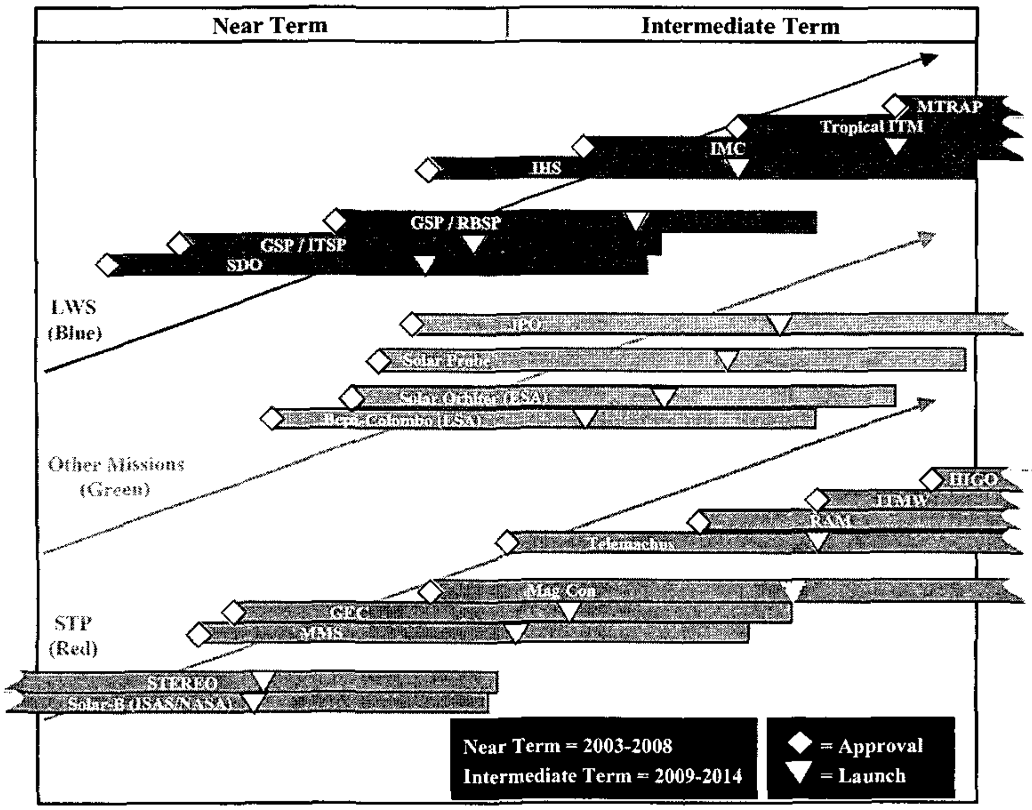


Figure 5 – SEC near and intermediate term mission timeline

3. On-going Programs

The SEC Program Strategic Flight Missions are being formulated and implemented in the Solar Terrestrial Probes (STP) and Living With a Star (LWS) programs. The goal of the STP program is to manage and execute a continuous sequence of SEC-defined strategic projects that provide in situ and remote sensing observations from multiple platforms for the sustained study of the Sun-Earth system. The goal of the LWS program is to develop the scientific understanding necessary to address effectively those aspects of the connected Sun-Earth system that directly affect life and society. The STP program emphasizes fundamental research through mission cadence and synergism, while the LWS program emphasizes a systems approach to research that would enable a predictive space weather system relevant to life and society. These programs relate to the SEC primary science objectives shown in Figure 6. The missions in these programs utilize vantages from which to obtain multipoint remote and in situ measurements in the connected Sun-Earth system aimed at a continuum of investigations ranging from fundamental research in STP to applied research in LWS.

3.1 Solar Terrestrial Probes

The present STP missions include two solar missions, Solar-B and STEREO; two magnetospheric missions, MMS and MC; and two ITM missions, TIMED and GEC. The STP mission suite and the primary science goal that each mission addresses are shown in Figure 7. The first, the Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics (TIMED) mission, was launched in December 2001 and is in its prime mission phase. TIMED will provide the first exploration of the basic structure and energy budget of the mesosphere, lower thermosphere, and ionosphere. The next two missions are planned to be launched in 2005. Solar-B is a collaboration in which the STP program is providing instruments for a mission led by the Japanese Institute of Space and Astronautical Science (ISAS). Solar-B science is aimed at determining how the photosphere is magnetically coupled to the corona. Solar-B will be placed in a sun-synchronous 600 km circular orbit for continuous 24 hour coverage. The Solar Terrestrial Relations Observatory (STEREO) will use a lunar flyby to insert a pair of spacecraft in orbit around the sun, one leading the Earth and one behind. STEREO will provide a three-dimensional view of the Sun to understand the origins and consequences of coronal mass ejections (CMEs).

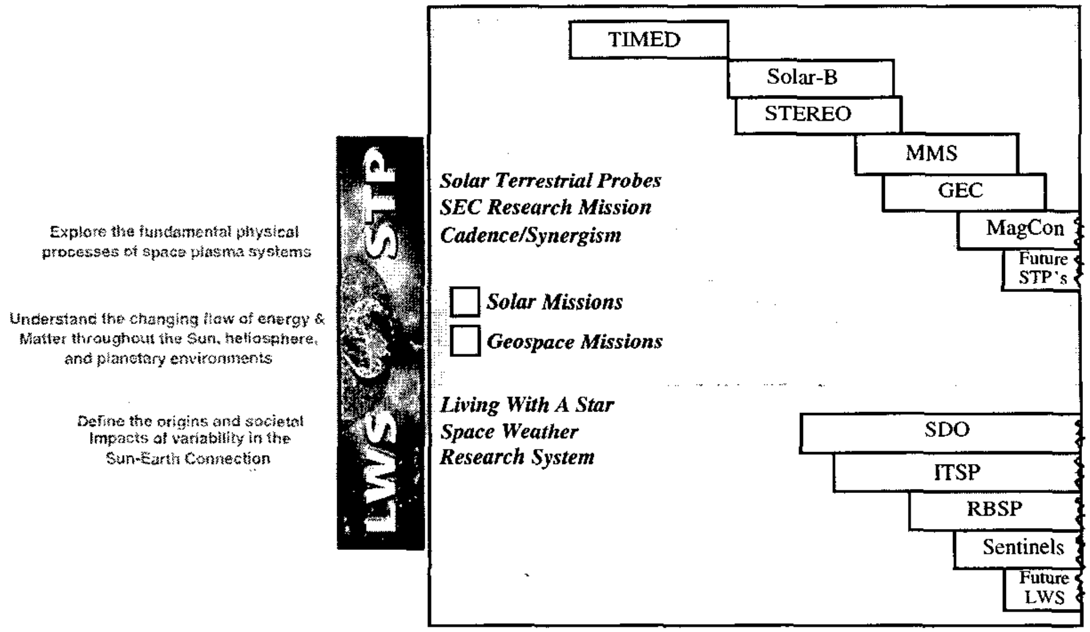


Figure 6 - SEC primary science objectives and their relationship to the STP and LWS strategic programs

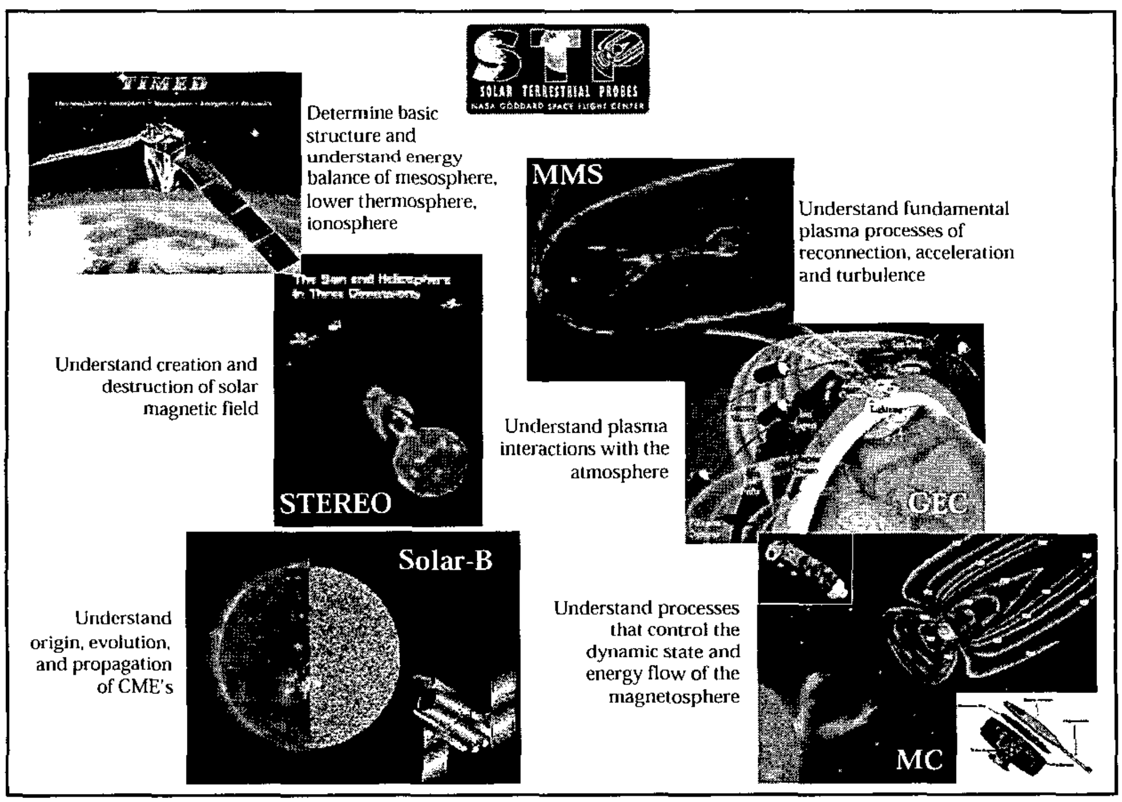


Figure 7 – STP programs

The remainder of the missions are in an earlier phase of development and are planned to be launched during the period between 2008 and 2012. Magnetospheric MultiScale (MMS) will utilize a cluster of four spacecraft in a tetrahedron constellation, with four orbital phases ranging from 1.2 x 12 Re at 10 degrees inclination to 10 x 40 Re at 90 degrees inclination. MMS science is aimed at understanding the plasma physics processes of reconnection, particle acceleration, and turbulence on the microscale and mesoscale in the Earth's magnetosphere. Geospace Electrodynamic Connections (GEC) will utilize a cluster of four spacecraft flying in formation (pearls on a string), at 185 x 2000 km at 83 degrees inclination, with maneuvers to lower perigee to 130 km, lasting up to a week. GEC science is aimed at improving our understanding of the response of the ITM system to magnetosphere forcing. Magnetospheric Constellation (MC) will fly a constellation of between 50 and 100 nanosat spacecraft in 3 x 7 Re to 3 x 40 Re nested orbits at low inclination. MC will provide systematic multipoint measurements of the magnetic field, bulk plasma, and energetic particle parameters that will define and characterize the magnetotail responses to external and internal drivers.

With missions ranging from individual spacecraft to couplets, clusters, and constellations, each mission presents its own technical challenges for spacecraft design, radiation environment, mission operations, constellation management, propulsion, and aerodynamics. The technology needs for MMS, GEC, and MC are shown in Figure 11 and are described in Section 5, Technology.

The STP line provides a cadence of missions at optimal vantage points that evolves from the SEC Roadmap and supports improved measurements enabling investigations aimed at increasing the level of understanding of fundamental SEC processes.

3.2 Living With a Star

The space that surrounds the Earth — geospace — is neither empty nor quiescent. It is populated by electrically charged particles whose motions are controlled by the Earth's magnetic field and driven by energy extracted from the solar wind, the Sun's supersonically expanding atmosphere. These populations of charged particles (or plasmas) form a medium in which storm-like disturbances occur, disturbances that drive powerful electrical currents into the Earth's upper atmosphere and accelerate charged particles to extremely high energies. Such disturbances, which are triggered by storms on the Sun, are known as geomagnetic storms and represent an extreme form of what has come to be known as "space weather." Like the more familiar weather on Earth, space weather can be mild, moderate, or severe. And like severe weather on Earth, the severe weather in space can adversely affect human activities. Indeed, as society becomes increasingly dependent on space-based technologies, our vulnerability to space weather becomes more obvious, and the need to understand it and mitigate its effects becomes more urgent.

NASA's Living With a Star (LWS) program is a space weather-focused and applications-driven research program within the Sun-Earth Connection (SEC) theme of the OSS. LWS utilizes a systems approach to develop the scientific understanding necessary to address effectively those aspects of the connected Sun-Earth system that directly affect life and society. This approach is accomplished by implementing a series of interrelated strategic missions. The LWS program elements are shown in Figure 8. Three mission elements are defined at present.

The first, the Solar Dynamics Observatory (SDO) mission, will employ a Sun-pointing spacecraft in geosynchronous orbit that NASA intends to launch in August 2007 for a prime mission of five years. The primary goal is to understand and, ideally, predict the solar variations that influence life on Earth and humanity's technological systems. SDO will accomplish this by determining how the Sun's magnetic field is generated and structured, and how this stored magnetic energy is converted and released into the heliosphere and geospace in the form of solar wind (a magnetized plasma), energetic particles, and variations in solar brightness.

The next two missions form the Geospace Missions Network. The Ionosphere-Thermosphere Storm Probes (ITSP) and Radiation Belt Storm Probes (RBSP) missions are designed to study those regions of the Earth's space environment in which solar variability produces disturbances that can adversely affect important communications and navigation technologies and that pose a potential threat to astronaut safety. ITSP consists of two small spacecraft that planned to be launched in 2008 into identical 450 km, 60° inclination circular orbits. The three-year ITSP prime mission is focused on characterizing and understanding mid-latitude ionospheric variability and the irregularities that affect communications, navigation, and radar systems. RBSP will employ two small spacecraft planned to be launched in 2010 into nearly identical low inclination, highly elliptical (500 km x 5.5 earth radii) orbits, with one leading and the other following, for a prime mission of two years. RBSP's science payload will be configured to characterize and understand the acceleration, global distribution, and variability of the radiation belt electrons and ions that produce the harsh environment for spacecraft and humans.

Finally, the Inner Heliospheric Sentinels (IHS) mission, which is very early in its formulation and scheduled for launch no earlier than 2012, will utilize solar orbiting spacecraft to understand the connection between eruptions and flares on the Sun and geospace disturbances. One possible implementation would launch four identical

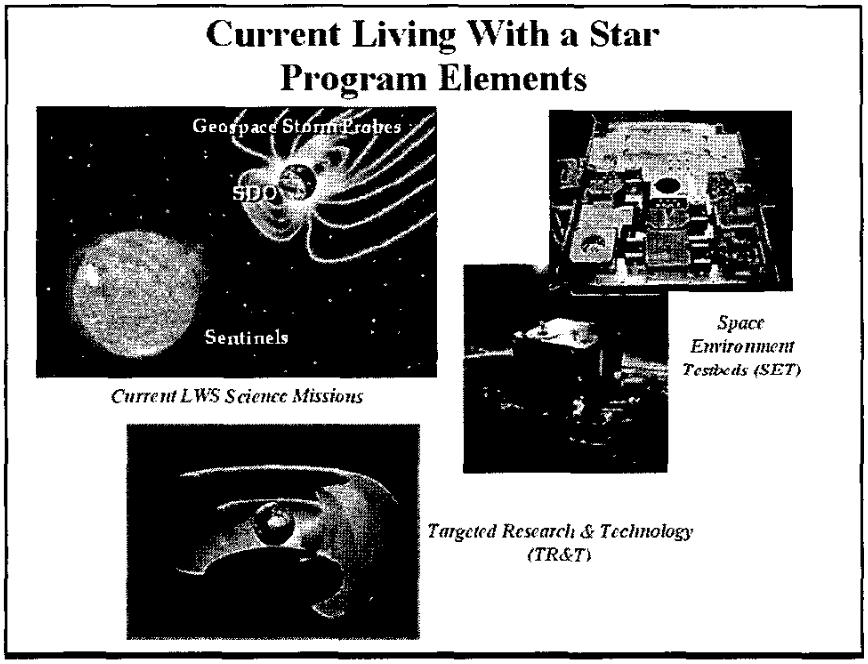


Figure 8 - Current Living With a Star Programs Elements

spacecraft into different heliocentric elliptical (0.5-0.95 x 0.72 AU) orbits for a prime mission of five years. This configuration would enable observations at various radial distances and longitudinal separation to trace geospace events back to the Sun.

The LWS science missions are augmented by two other program elements: Space Environment Testbeds (SET) and Targeted Research & Technology (TR&T). If the LWS science missions are designed to develop the scientific understanding necessary to characterize space weather, then SET is designed to characterize and understand the effects of space weather on advanced technologies. SET will provide flight opportunities on host spacecraft to evaluate the performance of new technologies and instruments in the space environment and to validate new and existing ground test protocols for the effects of solar variability on emerging technologies. The objective of the TR&T program is to develop new modeling tools and concepts for understanding solar and geospace disturbances and the connection between them. TR&T is key to integrating the various LWS program elements and fulfilling the broader program objectives.

The LWS program employs a systems approach directed at improving our understanding of space weather and the connected Sun-Earth system. Implementation of this program involves the deployment of individual spacecraft and small constellations into hostile orbits and radiation environments. Each mission presents unique technical challenges in mission and spacecraft design.

4. Other Missions

In the near and intermediate term, the category of Other Missions under study includes Solar Probe, ESA Cooperative Missions (Bepi-Columbo/Mercury, and Solar Orbiter), and SSE Joint Missions (Jupiter Polar Orbiter). These missions are described in the SEC 2002 Roadmap [2]. Solar Probe is featured in this paper resulting from its high priority in both the SEC 2002 Roadmap and Decadal Study and the demanding technology requirements.

4.1 Solar Probe

Sending a Solar Probe [6] to the inner frontier of the heliosphere is under study as a high priority mission that accomplishes SEC science that is not possible with any other mission. A NASA-appointed Science Definition Team has defined a solar probe mission and its scientific objectives. These objectives include making measurements to understand the processes that heat the solar corona and produce the solar wind, subjects of continuing scientific debate. The Solar Probe mission will accomplish these objectives with a combination of in situ measurements designed to characterize the local heating and acceleration of plasma near the Sun and high-resolution images to detect small-scale, transient magnetic structures at and around the Sun. To sample the solar corona acceleration region, Solar Probe will use a Jupiter gravity assist to fly to four solar radii from the center of the Sun in an orbit inclined 90° to the plane of the ecliptic. The probe will pass the poles at

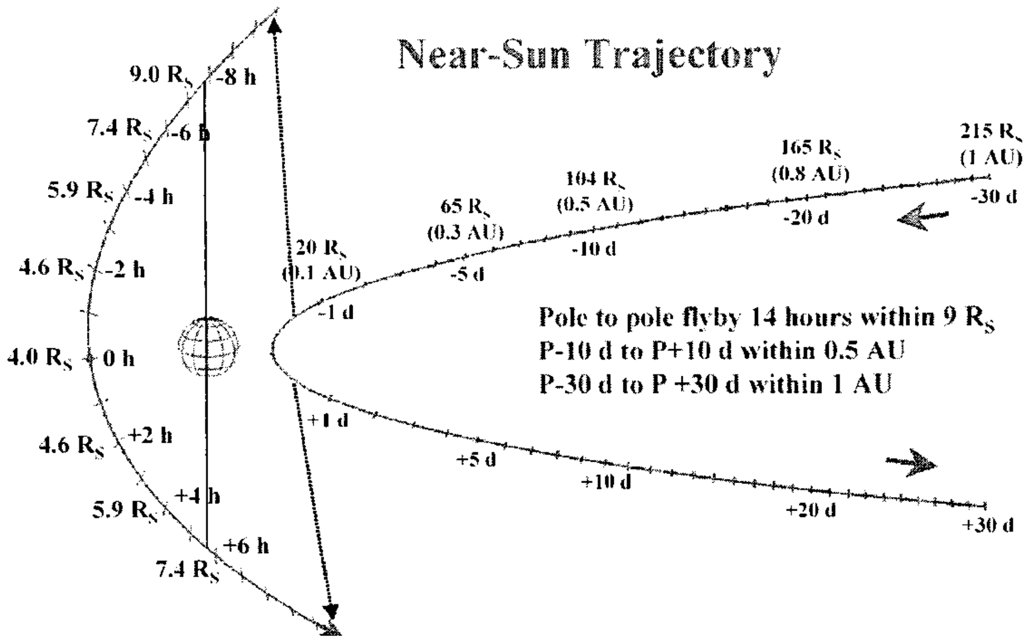


Figure 9 – Solar probe perihelion trajectory

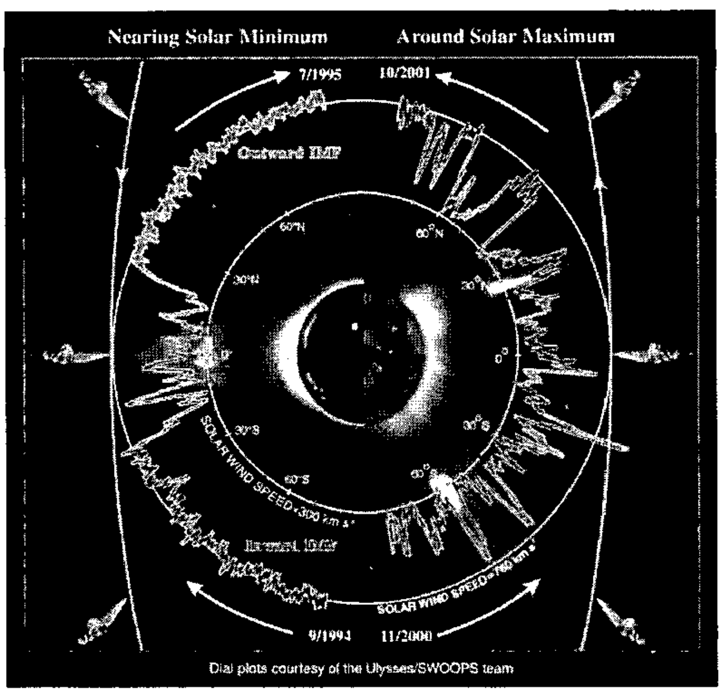


Figure 10 – Ulysses/SWOOPS solar wind measurements

eight solar radii, within the region where the wind acceleration occurs (Figure 9). Two perihelion passes at different solar phase are part of the mission design. This allows measurement of the coronal holes, which persist at the poles during solar minimum and through much of the solar cycle, as well as the transient wind flow at solar maximum. These solar wind characteristics are shown in the Ulysses/SWOOPS fast-latitude scans shown in Figure 10.

This mission will provide significant technical challenges: to survive the 3000-Sun intensity at perihelion; to maintain reliable power over the mission life; to protect against the hostile near-Sun dust environment; to control spacecraft attitude during the flyby for survival and imaging; to minimize coronal scintillation effects on communications; and to accommodate the in situ and imaging instrument requirements. The current engineering design philosophy will use new materials and aerogels for the thermal protection system; apply radioisotopic thermonuclear power sources to accommodate the cold flight and hot solar flyby requirements; use Ka-band telecommunications to mitigate solar noise and coronal scintillation concerns; and leverage advances in compact, low-power, high-radiation-tolerant electronics developed in other programs. This mission design approach will enable the Solar Probe mission to be one of totally new discovery.

5. Technology Needs

Virtually all future Sun-Earth Connection missions will be made possible or improved through the development of advanced technology. Development of new *enabling* technologies may provide a currently unavailable sensor or propulsion system critical for mission implementation. Alternatively, enabling technologies might offer cost savings vital to complete missions within fixed costs, such as technologies aimed at manufacturability and operations of multiple spacecraft. Similarly every mission can also cite examples of *enhancing* technology that significantly improves mission performance in some manner. While such enhancing technology does not enable new missions, a healthy portfolio of enhancing technologies is important for continual and steady advancement in the capabilities of space science missions.

The technology section of the 2003 SEC Roadmap identifies the critical enabling and vital enhancing technologies required for the complete set of strategic Sun-Earth Connection missions. Figure 11 shows the mapping of the technology focus areas against the Roadmap missions separated by time and program. The highest priority technologies are:

"Economical" spacecraft: SEC has a number of multiple spacecraft missions in the near and intermediate term, such as MMS, GEC, MagCon, Ionosphere-Thermosphere Storm Probe and Radiation Belt Storm Probe, and IHS. One of the most significant challenges these missions confront is the high unit cost of spacecraft. As this is generally a cost driver to mission implementation, cost-effective design and manufacturability of spacecraft is considered to be the most significant technology area that SEC needs to address. Technologies that might contribute to more economical spacecraft include ultra-low-power electronics, advanced packaging, and new architectures that could yield dramatic reductions in power and mass requirements. The challenge of economical spacecraft for clusters and constellations is shown in Figure 12.

Information technology (IT): In the near term, SEC will need flight and ground systems able to handle data volumes unprecedented within the OSS. In particular, SDO will have a data rate of ~150 Mb/s and a daily data volume >1 TB. The effective management of this and other data streams, management that leads to scientific discovery and understanding, must take into account a diverse set of requirements, customers, and systems while maximizing reliance on a dynamic commercial market. Optimizing the return from our missions means that investment in information technology must become a high priority for the Sun-Earth Connection. An anticipated four-fold increase in operational spacecraft will certainly affect how spacecraft are operated in the future. Technologies that lead to dramatically lower operations cost will be required.

Solar sails: The SEC strategic plan projects that solar sails will be the only propulsive technique with sufficient performance yet be affordable for strategic missions such as Solar Polar Imager and PASO. The early flight validation of solar sail technology is a high priority for SEC. The solar sail roadmap is shown in Figure 13.

Scientific Instrumentation: SEC scientific instrumentation performs both in situ and remote sensing measurements. The principal technology challenges in the in situ instrumentation concerns the development of highly integrated and compact instrument electronics, especially needed for multispacecraft missions. Aspects of this technology may be addressed by the development of low power electronics for spacecraft sub-systems, and most certainly will be aided by recently instituted, instrument development programs.

Remote sensing instruments have two specific technology requirements. These are large format array detectors and lightweight, precision optics and coatings.

Technology Summary: Until quite recently, technology investment in SEC largely has been managed and funded on a mission-by-mission basis. Our ambitious new missions require a new approach to technology development. Advancement of SEC-specific technology requires a broad and sustained program with a cross-mission perspective. NASA technology programs that will contribute to development are shown in Figure 14.

Category	Technology Focus area	Near- and Intermediate-Term Missions														Joint SSE/SEC Missions				Long-Term Missions												
		STP Missions							LWS Missions						*					STP Missions							LWS Missions				*	
		MMS	GEC	MC	Telemachus	RAM	ITM Waves Coupler	HIGO	SDO	Geospace Probes	IHS	IMC	Tropical ITM Coupler	MTRAP	Solar Probe	JPO	Io Electrodynamics	Neptune Orbiter†	Mars Aeronomy	Venus Aeronomy	DBC	MIO	PASO	AMS	GSRI	SCOPE	Solar Polar Imager	L1-Diamond	SIRA	SEEC	Sun-Helio-Earth Const.	Interstellar Probe	Stellar Imager
Spacecraft	Multi-spacecraft Issues (# of s/c)	4	4	50			2			4+	4	6	3								30	3		4	4			4	>10		5-10		30
	Avionics			Y	+			+	+	Y	+	R		R		R	R	+			+		+	+			+						
	Communications	+		Y	+	+		+	G		+			Y	Y	R	+	Y	+	+	Y		+	+		+	+	+				+	R
	Guidance, Navigation, Control	+	+	Y	Y		+			+	+	+	+	Y	+						+	+	R	+		R	R	R					R
	Power	+	+	Y	Y		+	+		+	+	+	+		Y	+	Y	R			Y	+	R	+		+						R	
	Structures/Materials		+	+		Y	+							R	Y						+		R			+	R	R				R	+
	Thermal Control		+		+	G	+				+		+	R	Y			+					R			+						R	+
Propulsion	Solar Sails																	R†					R				R	R				R	
	Conventional	+	+				+			+	+	+	+		+		+		+		+			+		+							R
IT/Autonomy	Information Technology	+		Y		+	+	+	Y	+	+	+	+	R	+	+					Y		+	+	+	+	+			R		+	R
	Autonomy	+		Y		+	+	+		+	+	+	+	R	+	+		+		+	Y		R	+	+	+	R	R				+	R
Instrumentation	Sensors/Instruments			G		G	+	R	Y	+	+	+	+	R	+	R	+	+	+		+	+	+				+	+				R	R
	Space-based Optics					R			+					R	+	+							+			R	+			R			R

6-Dec-2002

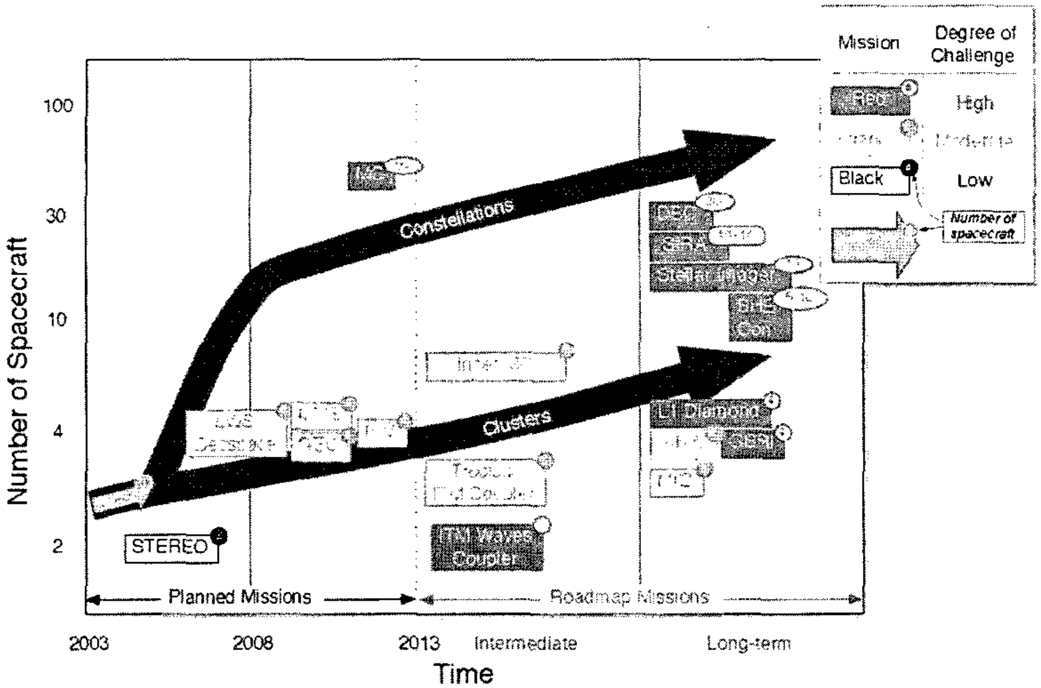
Legend

Enabling Technology, Development In Place	→
Enabling Technology, Development Pending	→ Y
Enabling Technology, Gap Apparent	→ R
Enhancing Technology	→ +

Notes

	Table does not include Solar Orbiter, Bepi-Columbo (ESA missions); nor STP missions such as STEREO, Solar-B (which are in implementation).
XYZ	Approved missions are underlined.
*	Other missions.
†	Neptune Orbiter: Solar Sails (or other advanced Propulsion) & aerocapture required.

Figure 11 – Enabling and enhancing technologies for SEC missions



The Challenge of "Economical" Spacecraft: *Develop affordable clusters and constellations of spacecraft for multi-point measurements of the connected Sun-Earth System.*

Figure 12 – The challenge of economical spacecraft

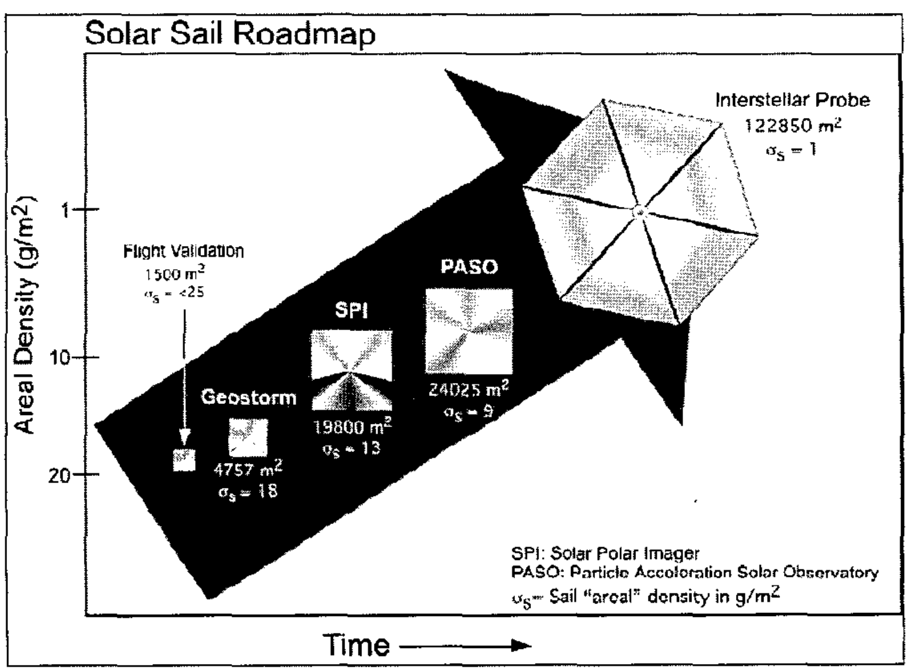


Figure 13 – Solar Sail Roadmap

Category	Technology Focus Area	Small Business Innovative Research (SBIR)	Office of Aerospace Technology (Code R)	In-Space Propulsion (ISP)	Nuclear Systems Initiative (NSI)	New Millennium Program (NMP)	Space Environment Testbed (SET)	SEC & LWS Instrument Development	Program-focused technology (proposed)	Mission-focused technology
Spacecraft	Multi-spacecraft Issues	✓	☆			★	✓	✓	☆	✓
	Avionics	✓	☆			✓	✓		☆	✓
	Communications	✓	★			✔				★
	Guidance, Navigation, Control	✓				✔				✔
	Power	✓	★		★	✓			☆	✓
	Structures/Materials	✓	✓				✓			
	Thermal Control	✓	☆			✓				✔
Propulsion	Solar Sails	✓	✓	★	☆*	★				
	Conventional	✓	✓	★						
IT/Autonomy	Information Technology		✓			✓			☆	★
	Autonomy	✓	✓			✔				✔
Instrumentation	Sensors/Instruments	✓	✔				✓	★		✓
	Space-based Optics	✓	☆							

Legend
- ✓ contributor
- ✔ important contributor
- ★ critical contributor
- ☆ potential gap-filling contributor

*Alternative advanced propulsion such as NEP

Figure 14 – SEC Technology Implementation Programs

6. Summary

The Sun-Earth Connection science theme in space science encompasses an enormous system driven by our variable Sun that encompasses the Earth's ITM and magnetosphere; the Sun's interior, corona and solar wind; the heliosphere; and the planets and our solar system and interstellar space. The vantages needed to obtain the required remote and in situ measurements drive an ever evolving suite of missions enabled by the advanced technology development needs described in this paper. The confluence of these advanced technologies and missions provides the opportunity for improved fundamental understanding of the Sun-Earth connected system and the enabling of improved future predictive systems that support life and society.

7. Acknowledgments

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8. References

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