4.0 Technology Introduction

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 presently unavailable sensor or propulsion system necessary for mission implementation. Enabling technologies may also be vital for cost reduction, e.g., technologies aimed at manufacturability and operation of multiple spacecraft. These technologies are vital for both intermediate- and long-term SEC missions and the technology program discussed below addresses both these demands.

Missions can also use *enhancing* technology. This type of technology significantly improves mission performance in some manner: e.g., increasing sensitivity, spatial or temporal resolution; improving data return; or simply reducing the cost of a particular capability. All of these enhancements provide more resources for more mission-critical elements. By definition, such enhancing technology does not enable these new missions. Nevertheless, enhancing technologies are important for continued and steady advancement in the capabilities of SEC missions.

This section of the 2003 Roadmap first identifies the vital enabling and critical enhancing technologies required for the entire suite of STP and LWS missions defined and described in Section 3. The technologies fall into four, cross-cutting focus areas; Spacecraft, IT/Autonomy, Scientific Instrumentation, and Propulsion. Within each cross-cutting focus area, the highest priority technology is discussed. Finally an implementation plan is recommended.

4.1 Enabling and Enhancing Technologies

Teams of scientists, system engineers, and technologists reviewed every mission in the SEC Roadmap. From each mission review there emerged mission-specific technologies assessed to be either enabling or enhancing. The mission enabling technologies were then further qualified. Enabling technologies were classified as “in place” if technology development programs were already firmly implemented and sufficiently funded. Other enabling technologies were classified as “planned” if development programs were planned but not yet implemented or were in place but considered insufficient. Finally, technologies were classified as “needed” if no current development plan existed. A summary of that technology identification and assessment is presented in Table 4.1.

The mission-specific technologies in Table 4.1 are shown in rows and grouped into the four broad technology areas. Red boxes indicate “needed” enabling technologies; yellow indicates “planned”; green indicates “in place.” The stippled boxes indicate mission-enhancing technologies. Under the “multiple spacecraft challenges” technology, the number in the box indicates the number of spacecraft desired for that mission.

4.2 Technology Prioritization

The review teams determined what technologies were needed to enable and enhance its mission set. Within each technology area, the individual technologies were then prioritized. The overriding factors in the prioritization of a needed technology were mission impact if the technology was not available, position in the mission queue, and cross-mission applicability. Technologies that were cross-cutting, critical for mission implementation, and needed for near- or intermediate- term missions received highest ranking. The four technology areas, the highest priority technologies requiring a concurrent technology program, and a representative mission that these technologies support are listed in Table 4.2.

Table 4.2 SEC Technology Needs and Supporting NASA Technology Programs

Technology Area	Highest Priority Need	Representative Mission
Spacecraft	Multiple spacecraft – low power electronics	Magnetospheric Constellation
IT/autonomy	Data management and assimilation	Solar Dynamics Observatory
Scientific Instrumentation	Detectors	Reconnection and Microscale
Propulsion	Solar Sails	Technology Demonstration

Table 4.1 Enabling and Enhancing Technologies for SEC Roadmap Missions

Category	Technology Focus area	MMS	GEC	MC	Telemachus	RAM	ITM Waves Coupler	HIGO	SDO	Geospace Probes	IHS	IMC	Tropical ITM Coupler	MTRAP	Solar Probe	JPO
		Near- and Intermediate-Term Missions														
		STP Missions							LWS Missions						*	oint SSE/SEC Missio
Spacecraft	Multi-spacecraft Issues (# of s/c	4	4	50			2			4	4	6	3			
	Avionics			Y	+			+	+	Y	+	R		R		R
	Communications	+		Y	+	+		+	G	+	+			Y	Y	R
	Guidance, Navigation, Control	G	+	Y	Y		+			+	+	+	+	Y	+	
	Power	+	+	Y	Y		+	+		+	+	+	+		Y	+
	Structures/Materials	+	+	+		Y	+							R	Y	
	Thermal Control		+		+	G	+			+	+		+	R	Y	
Propulsion	Solar Sails															
	Conventional	+	+	+			+				+	+	+		+	
IT/Autonomy	Information Technology	+		Y		+	+	+	Y	+	+	+	+	R	+	+
	Autonomy	+		Y		+	+	+		+	+	+	+	R	+	+
Instrumentation	Sensors/Instruments		+	G		G	+	R	Y	+	+	+	+	R	+	R
	Space-based Optics					R			+					R	+	+

Category	Technology Focus area	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
		Long-Term Missions																
		oint SSE/SEC Missio				STP Missions							LWS missions				*	
Spacecraft	Multi-spacecraft Issues (# of s/c					30	3		4	4			4	>10		5-10		30
	Avionics	R	+			+		+	+			+						
	Communications	+	Y	+	+	Y		+	+		+	+	+				+	R
	Guidance, Navigation, Control					+	+	R	+		R	R	R					R
	Power	Y	R			Y	+	R	+		+						R	
	Structures/Materials					+		R			+	R	R				R	+
	Thermal Control		+					R			+						R	+
Propulsion	Solar Sails		R=					R				R	R				R	
	Conventional	+		+		+			+		+							R
IT/Autonomy	Information Technology					Y		+	+	+	+	+			R		+	R
	Autonomy		+		+	Y		R	+	+	+	R	R				+	R
Instrumentation	Sensors/Instruments	+	+	+		+	+	+				+	+				R	R
	Space-based Optics							+			R	+			R			R

31-Jan-2003

Legend		
	Enabling Technology, Development In P	G
	Enabling Technology, Development Pen	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.

The next-tier priority technology development needs are spacecraft power systems, and communication systems. The specific details of these highest priority and next-tier technologies are provided below.

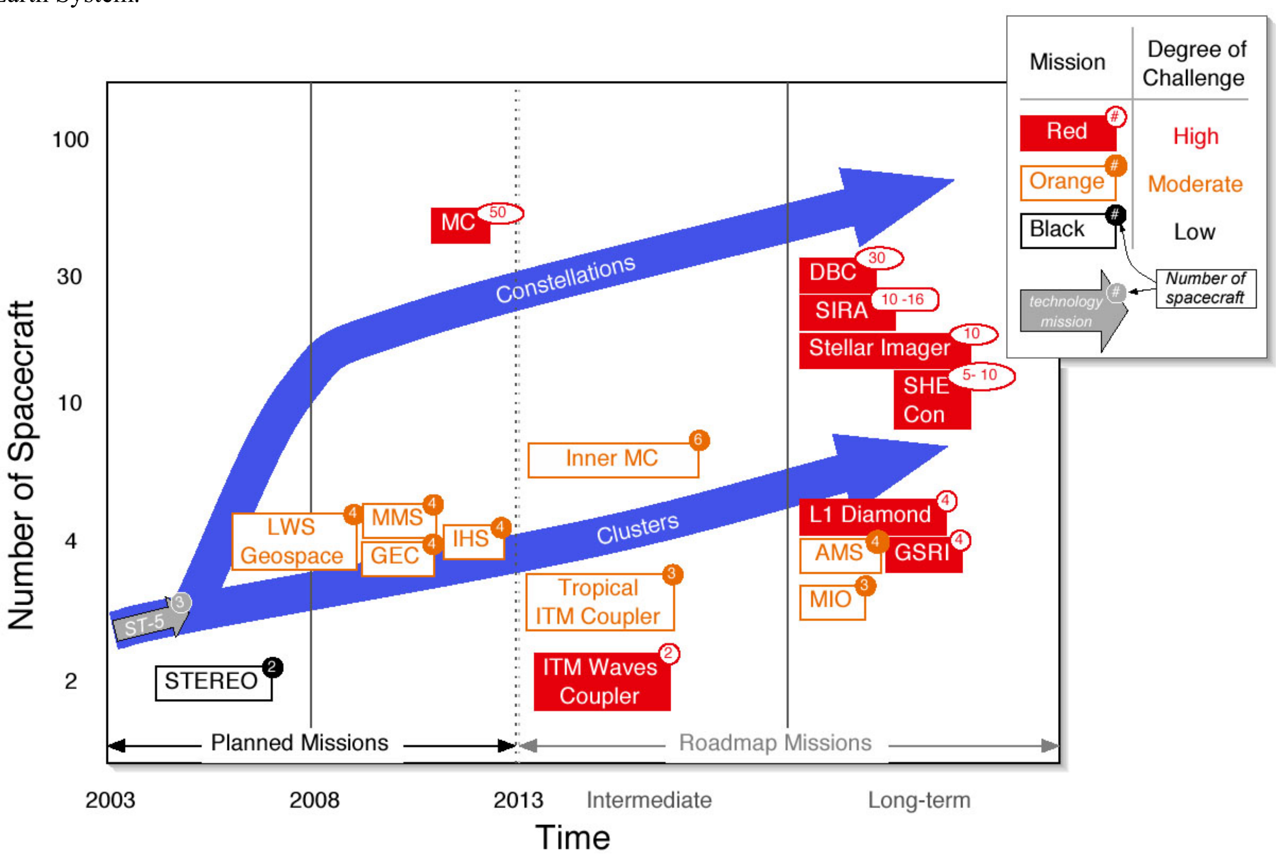
4.2.1 Spacecraft - Multiple Spacecraft Challenges and Ultra-Low Power Electronics

A large number of multiple-spacecraft missions are mandated for the future of SEC science. Cost-effective implementation of these missions could incorporate emerging technologies into highly integrated designs that are less expensive to build, test, and operate. First steps are underway to assure this vision, one example being the 3-spacecraft ST-5 mission. However, more investment will be required, and additional study will likely be needed to develop the specific aspects of a coherent theme or Enterprise investment strategy.

The multiple spacecraft challenge is motivated in the near- and intermediate-term by missions such as MMS, GEC, MagCon, GeoProbes, and IHS. Each mission has its own specific needs, but many of the challenges are cross cutting. All space missions would benefit from the availability of lower-cost platforms that provide essential spacecraft services for scientific instruments. SEC confronts the urgent requirement to reduce the unit cost of spacecraft, especially after the first one has been built. Figure 4.1 depicts this pervasive and vital need for economical spacecraft that could enable strategic SEC missions from the near to the far-term.

As part of the mission studies for this SEC roadmap, an analysis assessed the potential of enabling technologies to reduce spacecraft mass and power. Results indicate that 10 to 20% of the spacecraft cost could be saved through the evolution and application of technologies aimed at lowering spacecraft mass and power. Lower mass to orbit, in some cases multiplied by many spacecraft, can allow the use of a smaller launch vehicle, resulting then in even more substantial cost savings.

Figure 4.1 Demonstration of the overarching need for economical spacecraft. The Challenge of "Economical" Spacecraft: Develop affordable clusters and constellations of spacecraft for multi-point measurements of the connected Sun-Earth System.



System-level technologies such as ultra low power electronics and advanced packaging could bring dramatic reductions since they are applicable to both instruments and spacecraft bus. Generally, there is a direct relation between the electrical power needs of a spacecraft and total system mass. This relation is particularly important for *in situ* missions that employ body-mounted solar panel arrays. These missions often are severely power constrained because solar panel area is directly related to spacecraft size.

Ultra Low Power (ULP) electronics has the potential to dramatically reduce power requirements for flight avionics and instruments. The reduction in the voltage of logic from 5 V to 0.5 V can result in a power reduction for specific parts by a factor of 100. Early application of the technology is likely to focus on power "tall-poles" in digital logic. System-wide availability of the technology could reduce power consumption by 70% compared with conventional systems. Such power savings could be traded for reduced mass or greater data architectural flexibility (via redundancy). The first OSS flight experiment of this technology will likely be the ULP Reed-Solomon Encoder on ST-5. ULP electronics is a high priority technology with great potential. It addresses an important aspect of the multi-spacecraft challenge, and SEC should track and support its progress robustly.

4.2.2 Information Technology/Autonomy

The SEC mission set is comprised of coordinated scientific observations from spacecraft operating throughout the heliosphere. These missions are characterized by: multiple spacecraft making system-spanning measurements; instrument sets on platforms at unique vantage points; or missions making measurements with unprecedented spatial, temporal or spectral resolution. In the near-term, SEC will need flight systems able to handle data volumes unprecedented within OSS. It is vital that flight systems be developed that are capable of cost-effectively managing this data stream. Systems that loosely compress and encode high data-rate streams (thus maximizing the science return from limited bandwidth downlinks) will be needed.

SEC missions in the very near future will generate huge quantities of scientific data that will require processing, analysis, and information extraction. Thus far, data volume has kept pace with data storage capabilities, but new data volumes may tax future storage capabilities. However, data storage capacity is largely driven by needs outside of the SEC Division. Therefore, developing larger storage capacity may not hold out the promise of significant return on the investment. Instead of investing in increased storage capacity, a technology program is needed that develops the tools necessary for systematic and automatic access to large and distributed data sets and the ability to synthesize quite disparate data sets. To address all of these diverse requirements, early investments in information technology will be a high priority, in particular to promote the system understanding sought by LWS and STP missions.

In 2002, the number of spacecraft operated by SEC is 19. In 2012, it is reasonable that this number could approach 75. Much of the anticipated increase is due to the proposed fifty spacecraft of MC. Given recent history, it is safe to presume there will not be a concomitant four-fold increase in resources but rather that downward pressure on operations budgets will persist, if not intensify. For SEC to handle the increase in coming years, a technology program aimed to produce a steady and in some cases dramatic decrease in the operations cost per spacecraft is required.

4.2.3 Scientific Instrumentation

SEC scientific instrumentation performs *in situ* and remote sensing measurements. Technology challenges in the *in situ* instrumentation are largely related to the multi-spacecraft requirements of a large number of SEC missions. In particular, the development of highly integrated and compact instrument electronics is important for multi-spacecraft missions. However, 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 (see implementation section). Therefore, within the scientific instrumentation technology area, the remote sensing instrumentation should be accorded higher priority.

Remote sensing instruments have two specific technology requirements. These are large format array detectors and lightweight, precision optics and coatings. Of these two technology requirements, technology development of detector arrays derives the most benefit and is the highest priority.

Large format, fast-readout detectors offer enormous potential for performance enhancement of current remote sensing instrumentation. In particular, fast-readout, 4k x 4k, thinned, backside-illuminated CCDs are needed for SDO and ultimately 16k x 16k format CCDs will be needed for MTRAP. Active Pixel Sensor (APS) arrays offer enormous potential savings in mass, power and radiation hardness as well as variable gain readout capability, making them ideally suited for missions such as Solar Probe and RAM. Large format, energy resolved array detectors, such as microcalorimeter arrays, also offer exciting promise for soft x-ray spectroscopy on missions such as RAM, providing the ability to make simultaneous two dimensional spectral imaging observations of high temperature plasmas. Included in the technology necessary to develop these arrays are improved mechanical cryo-coolers for extended operational life.

Technology development in lightweight, precision optics and coatings also offers the potential for exciting enhancements in future remote sensing missions. In particular, large (>1 meter), lightweight, precision optics are required for MTRAP and precision, super-polished UV optics are needed for RAM and other missions. New, innovative coating technologies continue to be needed to expand spectral observing domains in the UV, EUV, X-ray and Gamma-ray, and enhance instrument efficiency on essentially all future remote sensing missions.

4.2.4 Propulsion - Solar Sails

For geospace missions, chemical propulsion will likely remain the standard means of achieving an observational station. However, solar sails remain a high technology priority for SEC, enabling unique vantage points in and outside the heliosphere wholly unavailable by other means. Such vantage points include: observing the Sun from high-inclination, heliocentric orbit (Solar Polar Imager); leaving the heliosphere to determine the nature of interstellar space (Interstellar Probe); observing the origin of high-energy solar particles from heliosynchronous orbit (Particle Acceleration Solar Orbiter); and making sustained measurements from otherwise inaccessible, non-Keplerian, near-Earth orbits (L1 Diamond). Furthermore, solar sails offer a unique advantage over other propulsion systems. These sails can be used as an active element in a spacecraft sensor array. For example, wire imbedded in the solar sail could be used as the antennae for an electric field instrument. Other propulsion systems (e.g., nuclear-powered propulsion) may be studied for other applications (e.g., planetary missions, where the ability to decelerate a spacecraft is as important as the ability to accelerate it). With the advent of the In-Space Propulsion and Nuclear Systems Initiatives, SEC should continue to closely monitor developments in nuclear electric and solar electric propulsion, and periodically assess whether these technologies could enable our deep-space missions. However, solar sails remain the highest technical priority for spacecraft propulsion for the SEC Division.

Given the challenge inherent in deploying and controlling a large, gossamer solar sail, a technology demonstration mission will be required. Successful demonstration of a 50-m class (root-area) solar sail would enable measurements upstream of L1 (such as NOAA's Geostorm concept or SEC's L1 Diamond) and by straight-forward scale-up to sizes in the 100-m class, such a demonstration would make Solar Polar Imager possible. Following this development, the technology would have to be adapted for application to the near-solar environment for missions like PASO (0.17 AU). This would likely require use of advanced thermal control techniques for the lightweight structure and membrane materials suitable for high-temperature use. Meeting the challenge of flying close to the Sun would feed in naturally to the next sail mission: Interstellar Probe. It will require the development of a 300-m-class solar sail, and likely incorporating technology from PASO, will use a solar gravity assist (perihelion ~ 0.25 AU).

4.3 Next-tier Priority Technologies – Power and Communication Systems

Power Systems

Exploration of the outer heliosphere in practice is contingent on the availability of radioactive power sources. While the SEC Division supports renewed prospects for advanced radioactive power sources, the vast majority of SEC missions will continue to rely on photovoltaic systems. Operations with photovoltaics as far as Jovian orbit require deployable, low-intensity, low-temperature solar arrays. In addition, photovoltaic systems able to cope with the high-temperature, high flux of the near-solar environment (< 0.4 AU from the Sun) will be needed. The theme has unique interest in the development of new lower-cost, electrostatically clean solar arrays.

Communications

Because of the large link distances, spacecraft in deep-space face communications challenges. SEC has some unique needs in this regard such as systems that provide for high data rate communications from spinning spacecraft in deep space. Specific technology needs include: Hi-EIRP telecom "cloverleaf", adaptive feed/uplink Beacon, Ka-band transmit network, and DSN 70-m equivalent with Ka-band downlink.

4.4 Other Notable Technologies

The SEC identifies other notable technologies that are mission enhancing. These include:

Avionics

High-performance flight avionics will play an increasingly important role in SEC missions. A number of factors contribute to this development: progressively higher-resolution and higher-cadence imaging of the Sun; multi-spacecraft missions making complex, system-wide measurements of dynamic phenomena at affordable cost; missions that must cope with severe environments; and those operating far from the Earth that face severe limits on communications.

Guidance, Navigation, and Control

Future SEC missions have some distinctive characteristics: single spacecraft operating at unique vantage points (often in severe environments); multiple spacecraft making coordinated measurements of a region of interest; or an instrument platform (or set of platforms) with unprecedented sensitivity, and/or temporal, spatial or spectral resolution. Each class of mission will require advances in the art and practice of guidance, navigation, and control.

Structures & Materials, Thermal Control

Materials, devices, and schemes for near-solar thermal management will be needed to enable *in-situ* measurements near the Sun. Solar Probe will need a phenomenally robust, carbon-carbon thermal shield, able to withstand temperatures up to 1,800°C with no appreciable sublimation of material. Solar sails and other spacecraft structures must be able to withstand thermal environments near and far from the Sun (the solar thermal input ranges from 0.04 Suns at 5 AU to 2800 Suns at 0.02 AU).

4.5 Technology Implementation Plan

Until quite recently, technology investment in SEC largely has been managed and funded on a mission-by-mission basis. However, the resources and time available to a mission in formulation is quite limited, and leads to focus on one or two key challenges. This approach yields a frustratingly low rate of technology infusion in general and cross-mission infusion of technology in particular. Our ambitious new missions require a new approach to technology development. Advancement of SEC-specific technology requires a broad and sustainable program with a cross-mission perspective.

Recently, two elements of ROSS NRAs have helped to bolster SEC technology investment, namely the SEC and LWS Instrument Development programs. These opportunities provide resources to the science community for the enabling scientific instrumentation demanded by future missions. However, this new program is relatively small and at present unproven given that the first funding cycle is still underway. No such parallel program exits for systems-level technology development, although NMP does play a significant role in many ways (e.g., development of nanosatellite technologies through ST-5). Other traditional and new sources of technology development programs for supporting SEC needs are: LWS Space Environment Testbed (SET), In-Space Propulsion, PRT, and SBIR.

LWS Space Environment Testbeds will provide flight opportunities for new hardware and design/operations tools whose performance is sensitive to solar variations. The testbeds will also fly instrument technologies of interest to SEC. Technologies will be competitively selected, with flight opportunities beginning in 2004 and recurring every two years thereafter. The experimental nature of the testbeds and potential for frequent access to space, make it a valuable resource for SEC strategic missions.

Continued advocacy within the agency for developing technology for SEC needs should focus on several different fronts. One area needing promotion is the publication of technology requirements as a means of facilitating dialog and improving alignment of technology providers. Another is in the area of partnering – competitively selected technologies are strongly preferred with directed efforts used solely to guide adaptation of technology previously selected through competition. Another area of significant impact would be the moderation of the current technology-averse policy in place for mission development.

A new theme technology program should be small and focused, serving clear, persistent technology needs within our program lines. Technology selected and developed within these programs must have potential for reasonable near-term return on investment but also high programmatic impact. Because such funds will always be vulnerable and have alternative usages, implementation will require impeccable Enterprise focus, competitive procurements, partnering, periodic assessment of the program, and the ability make periodic adjustments.