JPL Publication 2003-XX

Space Science Enterprise Technology Blueprint

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National Aeronautics and Space Administration

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Pasadena, California

January 2003

The research described in this publication was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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Acknowledgement

The editor would like to thank the many people who provided assistance and data for this report. Wayne Schober provided a great deal of help by greatly improving the assignment of products and requirements to various elements of the product breakdown structure. He also provided valuable help in using the TSG Database. Giulio Varsi had a number of valuable suggestions. Craig Peterson (JPL), Jim Cutts (JPL), B. M. Levine (JPL), Chris Schwartz (GSFC) and Tim Van Sant (GSFC) provided important data. Technical reviews and revisions to the draft were obtained from a number of individuals in the NASA community including (but not limited to) Wayne Zimmerman (JPL), Daniel Clancy (ARL), Paul Schenker (JPL), James Lesh (JPL), Jamie Bock (Caltech), Carol Carroll (ARC), Juan Roman (GSFC), Stand Ollendorf (GSFC), Theodore Swanson (GSFC), Mark Matsumura (GSFC), Greg Schmidt (ARC), Kul Bhasin (GRC), Jesse Leitner (GSFC), and David Content (GSFC).

Steve Prusha provided support for this effort via the Office of the Technology Director.

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EXECUTIVE SUMMARY

INTRODUCTION

The purpose of this Blueprint is to document the technologies required to implement the future missions of the NASA Space Science Enterprise (SSE). The Blueprint provides a synoptic view of technology needs and gaps in present programs addressing these needs, offering a good perspective for guiding investment in new and evolving technologies for future missions. It also offers a vehicle for coordinating and integrating of technology needs of the various NASA Office of Space Science (OSS) Themes.

The NASA Office of Space Science has five major Themes: Astronomical Search for Origins (ASO), Structure and Evolution of the Universe (SEU), the Sun-Earth Connection (SEC), the Mars Exploration program, and Exploration of the Solar System (ESS). The Themes have revised and updated their mission roadmaps in late summer 2002; missions are summarized in Section 2 of this report. In this process, the Themes identified needs for new technology to implement their often challenging proposed missions. The gap between these needs and the current state of the art in each technology area represents the challenge that lies ahead for NASA OSS technology development.

The Blueprint organizes technology under three major technology categories:

1. Space Observatories
2. In Situ Exploration Technology
3. Multi-Mission Spacecraft Technology.

For each of these technology categories, there are several subordinate technologies. The Blueprint lists technology requirements and state of the art for each major subordinate technology across the five themes. Gaps are identified, and the probability that ongoing programs will fill these gaps is assessed.

The primary content of this Blueprint is embodied in the Master Tables listing technology needs of future NASA Space Science missions and comparing them with state of the art and ongoing programs to discern gaps wherever they may exist. These Tables are provided in Section 6.

Technologies are organized in the Blueprint according to the NASA OSS TSG Taxonomy. For the Blueprint, it is useful to segregate the technologies into groups that serve specific interests. We have therefore organized them into three categories: observatory technologies, in situ technologies, and multi-mission technologies.

OBSERVATORY TECHNOLOGIES

Constellation Control

Increased resolution can be achieved alternately by utilizing multiple spacecraft, each supporting a moderate aperture, to create the resolution of an equivalent large aperture. Several of the envisioned future ASO, SEU and SEC missions incorporate interferometric systems on separate spacecraft that involve precision formation flying systems. Stringent requirements on relative positional accuracy and pointing are beyond the state of the art. Micro-Newton thruster technologies, currently under development for Laser Interferometer Space Antenna (LISA), will demand further study to determine their applicability to other missions. In addition, other future SEC missions will involve multiple spacecraft, although in these cases, the SEC needs revolve about orbit insertion, telecommunications, and low-cost replicated spacecraft and instruments. There are two substantial integrated programs working on the end-to-end challenges for formation flying. The first is at Goddard Space Flight Center (GSFC), focusing on the challenges from low-Earth-orbit out to the L2-Lagrange point, including the specialized sensors, relative navigation, and formation algorithms needed for the particular range of gravity and navigation signal availability (such as the Global Positioning System (GPS) or Deep Space Network (DSN)). The second formation flying activity is at Jet Propulsion Laboratory (JPL) focusing on the challenges from deep space down in to L2, including efforts investigating nanometer-class spacecraft-to-spacecraft metrology. Both efforts include high-fidelity hardware-in-the-loop testbeds to support technology development, validate end-to-end system performance, and transition the technologies into missions.

Cryocoolers

The principal need for cryocoolers is for infrared (IR)-observing instruments on future observatories. Cryocoolers that function in the temperature range 4 K to 20 K are needed for various IR applications. These could also function as upper stages for sub-Kelvin coolers for detectors that operate as low as 0.05 K. In the longer run, cryocoolers are also needed for large aperture IR reflectors such as Single Aperture Far Infrared (SAFIR).

The NASA Technology Program has a rich variety of small technology tasks exploring various new concepts for cryogenic cooling of detectors. But the Advanced Cryocooler Technology Development Program (ACTDP) is overwhelmingly most relevant to upcoming mission needs. This program will develop prototype coolers for Terrestrial Planet Finder (TPF), Constellation-X (Con-X) and Next Generation Space Telescope (NGST), and will also explore extensions of the technology to other temperatures and heat loads. It is expected that this program will be a source for most of the cryocoolers that will be used on future OSS missions in the near and intermediate terms and possibly beyond.

Space Optics

In order to launch larger and larger telescopes into space we require new precision materials and structures that allow the areal density of large optical elements to be reduced. This challenge applies equally to normal and grazing incidence optical systems.

The NGST Program embarked on a program called the Advanced Mirror System Development (AMSD) Program to develop the next generation primary reflector (6.5 m, density 20-25 kg/m^2). Recently, NASA selected TRW to build this telescope. A number of observatories that come after NGST depend on this telescope design, either to be used directly, or as a starting point for modifying the design. In addition to the anticipated impact on strategic missions, advances in lightweight optics will likely lead to significant new capabilities for missions in the Discovery and Explorer Programs.

A number of other smaller technology development activities continue to explore new approaches for lightweight reflectors for missions beyond NGST. Of particular interest are gossamer technologies.

A technology that has been explored in greater depth is the buildup of thin lightweight curved reflector sheets by laying them up on a very accurate glass mold. A considerable amount of development work has been done on creating carbon-fiber-reinforced plastic (CFRP) reflectors by this method. Another variant is known as nano-laminates. It lays down a sequence of thin layers of a metal alloy by sputtering onto a rotating mold. Thin reflectors created on a mold require a backing structure, and this presents significant technical challenges as well.

IN SITU TECHNOLOGIES

Avionics in Extreme Environments

Survivability and operation in extreme environments are very challenging for some future ESS missions. Some missions deploying only X2000-like hardware will not be able to survive under their environmental conditions. Hence such missions need to use additional measures (e.g., passive and active thermal control) to compensate for the mismatch between the hardware operating parameters and environmental conditions, or to develop hardware components that can reliably operate and survive in extreme temperature.

Guidance, Navigation, and Control – Rendezvous and Sample Capture/ Earth Return of Samples

For a Mars sample return, an autonomous sample rendezvous and capture system must be developed with the ability to autonomously locate, track, and capture a small sample canister in Mars orbit or deep space for return to Earth.

Rendezvous and sample capture technology is also needed for other sample return missions such as SPASR, Venus Surface Sample Return (VSSR) and Comet Nucleus Sample Return (CNSR). Some of these requirements are quite different from those of the

Mars Sample Return (MSR) mission, although the SPASR mission could be used to verify techniques to be used at a later date for the MSR mission.

Rendezvous technology is unlikely to take major steps forward until a mission proceeds to develop it.

Entry, Descent, and Landing/Aeroassist

Entry, descent and landing (EDL) technology is needed for a number of future ESS missions in several planetary contexts. The most pressing and well-defined need is for EDL for missions that land on Mars. The object is to land safely within a short distance (5-10 km) of any targeted science site so that a rover can reach it for exploration. Present capabilities for EDL lead to a landing error ellipse of 30 x 100 km.

EDL is also required for other missions, notably CNSR, VSSR, Europa Lander (EL), and Titan Organic Explorer (TE). These EDL systems are quite different from the Mars case and have to be developed to a large degree separately. The EDL process will be fundamentally different for landing on small bodies such as comets, as compared to large bodies such as planets. Also, there is a significant difference between large bodies with and without an atmosphere, because aeroassist, parachutes and aerobots can only be used if there is an atmosphere.

A key difficulty common to all these missions is that Earth-to-spacecraft communication delays are too long to perform EDL maneuvers via ground control. Hence, EDL must be accomplished autonomously with no human intervention.

Aerocapture has a high potential payoff for orbit insertion around distant planets, whether as part of an orbiter mission, or as a step in the process of launching a probe or lander for an in-situ mission.

Robotics and Planetary Access

Despite the highly successful Mars rover on the Mars Pathfinder mission, and the much more capable rovers developed for the forthcoming Mars Exploration Rovers (MER) mission, planetary mobility remains the key limiting factor on the scope, longevity and extent of Mars surface missions. Increasing autonomy is the key to longer traverses with rovers.

New approaches based on inflatable wheel rovers, legged rovers, and hoppers have not been studied to any great depth. It is possible that such approaches could provide significant gains over capabilities of articulated wheel rovers for terrain accessibility or range.

Aerial systems are enabling for missions to Titan and Venus. Titan and Venus have dense high molecular weight atmospheres. Aerial systems could augment other methods of exploration of Mars to cover large areas of rugged terrain where strata are exposed and rovers would be at a severe disadvantage. Technology for such aerial systems (balloons, aircraft, etc.) needs to be developed.

One of the key goals of Mars exploration is to locate water. Subsurface access is vital to this quest. In addition to depth, other requirements are mission-dependent and may involve the ability to bring up samples or cores in pristine condition, or the operation of instruments down in the hole.

Subsurface access will also be important for Europa, Titan, Venus and most other sample-return missions.

Planetary Protection and Sample Handling

Forward planetary protection must avoid transporting Earth-organisms to planetary bodies that could (1) contaminate the planet, or (2) appear in returned samples, or (3) interfere with in-situ instruments attempting to detect life. Technologies are needed to detect organisms at extremely low levels as well as for robust cleaning methods which preserve spacecraft instrument integrity.

After samples are returned to Earth, they must be secured to prevent inadvertent release of possible exogenous organisms, and the samples must be protected from contamination by Earth organisms.

MULTI-MISSION SPACECRAFT TECHNOLOGIES

Avionics

Technology needs in avionics divide into the following categories:

- Processors
- Memory
- Sensor interfaces
- Data bus and architecture
- Packaging and interconnects.

The X2000 avionics will be optimized for NASA, and will satisfy the needs of many NASA missions. However, X2000 appears to fall short of some of the requirements for missions that encounter harsh atmospheres. The ESS Space Science Enterprise Technical Advisory Group (SSETAG) has recommended that NASA complete the ongoing seven-year (1998–2005) X2000 campaign, but with significant enhancements from 2003 through 2005 and with development of a next-generation avionics system from 2004 to 2009.

Communications

Trunkline Communications to Earth

Technological limits on communications capabilities are a principal constraint on the science return of every science mission. By comparison with Earth-orbiting missions, the achievable quality of science data return is orders-of-magnitude less at planetary distances. However, the science community appears to feel that it must live with whatever capabilities the engineers have currently created. The problem is that development of advanced communications systems is too expensive to be developed by individual missions, and only makes economic sense when amortized over all the missions that utilize it.

SEC missions face some clear technical challenges in the course of the next decade: managing high data flows from geosynchronous solar-observing spacecraft, communications for multi-spacecraft missions, and missions in deep space, and relaying real-time data from near-solar encounters or from the far reaches of the heliosphere. Spacecraft exploring interstellar space will require communication links with Earth from distances of many hundreds or even thousands of astonomical units (AU). At the other end of the scale, communication with near-solar spacecraft is complicated by solar radio frequency (RF) emission and frequent conjunction with the Sun. Lastly, constellations in the geospace environment will require communications compatible with nanosats.

Several approaches can be taken to increase the data rates to the outer planets. These ideas can be grouped into the following categories: utilizing higher RF frequencies (Ka or W band), developing new apertures (distributed DSN or inflatable antennas for spacecraft), exploiting optical communications, and increased transmitter power.

The advantage of changing to higher frequencies is well understood and the technical maturity of switching from X-Band to Ka-Band is quite high. Adding antennas to the DSN will increase its capability in proportion to the added area. Another way to improve communications performance is to increase the transmit-antenna aperture size on the spacecraft with some form of deployable or inflatable antenna.

Another technology being considered for near-Earth and deep space communications is optical communications. The gains resulting from shorter wavelengths can be tens of dBs initially, with more improvements possible as the technology matures.

Tools that effectively compress data are vital to maximizing the science return from SEC missions.

Communication Relays

There are needs for local communications infrastructures between multiple exploration vehicles on or near distant targets.

Guidance and Control

Needs for GNC technology include trajectory design, flight path estimation, metrology, and attitude control. Trajectory design technology is particularly needed for solar electric propulsion missions that involve low thrust over long time periods. Flight path estimation is needed for in situ missions involving aerobots or landers, particularly where a rendezvous is planned between an ascending vehicle and an orbiter. Metrology is an adjunct of constellation control. Tethers offer a means of constellation control reducing the need for large quantities of fuel used for spacecraft orbital manuevers.

Attitude control is a challenging technology on SEC nanosats where mass and power are strictly limited.

Information Technology and Autonomy

There are many needs for information and autonomy technology on various missions. Ultimately, many of these involve shifting details of execution to the spacecraft, with uplink commands from Earth relegated to higher-level goals. There is also a need for more responsibility in housekeeping (monitoring, diagnosis, and response) to be relegated to the spacecraft. This is particularly true for in situ spacecraft and probes.

Because in situ missions may encounter difficulties or opportunities that were not predicted or imagined by mission planners, they need the capability to avoid problems and also to take advantage of science opportunities. Feature recognition is a critical element of hazard avoidance for landers.

Infusion of information technology (IT) technology into SSE missions has been slow. To remedy this, the Office of Aerospace Technology (OAT) is planning a significant increase in allocations for infusion and OSS is placing increasing emphasis on IT in its priorities. We anticipate that the volume of data returned from Code S missions will dramatically increase in the next decade. Advances in data mining and agent-assisted analysis must be brought to bear if we are to wring the maximum understanding from our rich and complex data sets.

Missions such as Magnetospheric Constellation with 50 to 100 spacecraft need very high autonomy. This must be accomplished with minimal mass, power, and cost.

Autonomy implies that the ability to make decisions based on analysis of sensor data is imparted to an onboard or ground computer via software without human intervention. As in the case of IT, although the needs for autonomy can be defined at a high level, the lack of quantitative metrics makes it difficult to assess the relative merits of different pathways of getting from where we are to where we want to be, or to even know when we have arrived. The ongoing OSS process for assessing the roles of relevant IT will also provide important insights in regard to autonomy. As the next phase evolves, important data and policy directions for autonomous systems technology should unfold.

Power

Photovoltaic (PV) arrays are the power source of choice for most space missions within 2 AU of the sun because of their high specific power (50–100 W/kg), efficiency (~26%) and reliability. Higher efficiency cells will become available as a natural outcome of the push toward higher efficiency for commercial Earth-orbiting satellites.

However, NASA is planning missions with unique requirements or environments for which the present and projected future state of solar power technology is inadequate. This includes missions that:

- Require very high power levels and high voltages with lightweight deployable arrays for SEP
- Carry sensitive instruments that require solar arrays to be electrostatically clean
- Approach the Sun and endure high temperatures.
- Go far from the Sun (low intensity/low temperature) (LILT)
- Endure strong radiation fields, such as at Jupiter or Europa
- Operate in the dusty environment of Mars (or comets).

If solar power is chosen for any of these scenarios, specialized solar cell and array technologies must be developed that go beyond the needs of conventional Earth-orbiting satellites.

Radioisotope power systems (RPS) are appropriate for missions that venture far from the Sun, or for which solar power is difficult due to problematic environments. Several converter technologies are under development with the potential to increase the thermal-to-electrical conversion efficiency and the specific power of RPS. Of these, the Stirling converter has the highest maturity. Such a device is ideal for Mars applications (which may have lifetimes of a few years) but it is not yet proven to have a sufficiently long life for long-duration outer planet missions. The Alkali Metal Thermal Electric Converter (AMTEC) converter and segmented thermoelectric technology are longer-term possibilities.

At a second level, NASA indicates a strong interest in developing a nuclear reactor for nuclear electric propulsion (NEP) and power, as a means of opening up the possibility of very ambitious space missions that could not be carried out with RPS or solar power.

Outer planetary missions require low mass, radiation-tolerant compact batteries that have a long operational life of 10–15 years. Venus missions require batteries that can operate at temperatures as high as 735 K. Some planetary surface and subsurface missions require batteries that can operate at temperatures as low as $\leq$ 175 K. Mars orbital missions require low-mass rechargeable batteries with long cycle- and calendar-life capabilities. Mars landers and rovers require batteries with low-mass and volume that operate at low temperatures ($\leq$ 235 K).

Rechargeable lithium-ion batteries have been developed by the joint efforts of the Air Force Research Laboratory (AFRL) and NASA. Flight hardware is presently under fabrication for the Mars Exploration Rover and ST-5 missions. There still remains the need to improve cycle life and calendar life, develop electrolytes that can enable operation at very low temperatures, and a need to improve the radiation tolerance of these batteries.

Propulsion

Needs for advanced chemical propulsion can be divided into several areas:

- Micro-thrusters for precision control of formation flying spacecraft
- Ascent propulsion for sample return from Mars or other planetary bodies
- Improved chemical propulsion for general space mission applications.

The requirements for solar electrical power (SEP) include scaled-up thrusters and very large deployable, lightweight solar arrays to provide power. At this point, the mass, packageability, and cost of high-power arrays appears to be the most serious constraint on SEP.

A solar sail is a propulsion concept that makes use of a flat surface of very thin reflective material that accelerates under the pressure from solar radiation (essentially a momentum transfer from reflected solar photons), thus requiring no propellant. Solar sails are deemed of great importance for several SEC missions but are at an early stage of evolution.

NASA recently announced a space Nuclear Systems Initiative, which will include development of space nuclear reactors that may eventually enable nuclear electric propulsion (NEP). Clearly, it will take many years and considerable funding to develop such a system. In the interim, solar electric propulsion is a viable technology. NEP will have major advantages for major missions that have multiple planetary targets. However, SEP will likely remain as a viable technology for moderate missions.

Structures and Materials

Needs include balloon materials for harsh environments at Venus and Titan, multi-function spacecraft structures, extra-terrestrial materials simulation, and multiple low-cost spacecraft for SEC constellations. SEC missions with multiple spacecraft require high-performance nanosats with three instruments at a unit cost of just several million dollars.

Thermal Control and Environmental Effects

Thermal control needs include more than a dozen categories (see Section 4.3.8). These run the gamut from protection of spacecraft and instruments in hot environment such as Venus or approaching the Sun, to cold environments at outer planets or near comets.

Environmental effects include maintenance of uniform spacecraft potential, dust mitigation for dusty environments, and environmental effects associated with use of solar sails and control of outgassing products as they affect space optics.

Sensors/Instruments

Detectors and instruments are central critical technology needs of SEU and ASO observatories. These run the gamut from sub-mm, far-IR, near IR, optical, UV, X-ray and gamma-ray instruments. Auxiliary technologies include read-out electronics, digital processing units, and detector cooling systems. The demands of upcoming missions will require major engineering advances in all of these areas.

The development of large format detector arrays is critical for the sub-mm and far IR astronomy. Both direct detectors (such as bolometers and photoconductive devices) and heterodyne instruments are required.

In the near IR and optical bands, extremely large arrays of imaging detectors based on charge coupled devices (CCDs), and low band-gap array detectors (e.g., HgCdTe) are needed, providing new challenges in production yield, detector uniformity, detector packaging, high-speed readout, and onboard data storage.

Novel photo-cathode materials may achieve significant improvements in UV detector quantum efficiency. UV-sensitive CCDs with lower read noise would be very valuable. So-called 3-D energy-resolving detectors offer tremendous promise, but the currently available array sizes are too small for the anticipated applications.

The development of cryogenic X-ray micro-calorimeter arrays has revolutionized the field in recent years. For future missions, much larger array sizes (e.g., 1000 × 1000) are required.

A factor of 25–100 improvement in sensitivity of gamma-ray detectors is required for an advanced Compton telescope.

Development of instrument technologies and instruments of mass and power commensurate with small, multiple satellite class missions is an imperative.

Needs for missions to explore the Solar System include instruments: mini-gas chromatograph/mass spectrometer (GC/MS), biotic/prebiotic detection and analysis, in situ sample collection and delivery mechanisms, geophysical systems, mineralogic characterization, and imaging systems.

TECHNOLOGIES: STATE OF ART VERSUS REQUIREMENTS; ONGOING EFFORTS; GAPS

There remains a great deal of work to assess how completely we understand the technology requirements for future missions, and also it is important to develop approximate time scales for when these requirements need to be met. At present, we have assembled all the requirements that are known, but it is likely that others have been missed. The required time scales will be included in the next edition of the Blueprint.

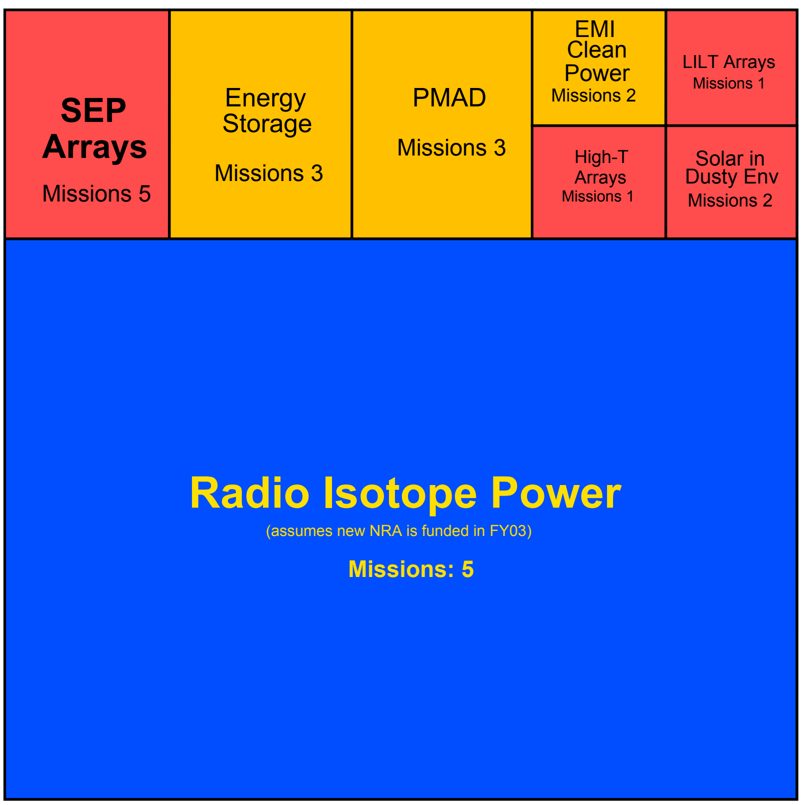
Rigorous gap analysis requires knowledge of requirements and state of the art. While requirements are known to a considerable extent, the state of the art remains uncertain in most instances, and therefore it is not possible to carry out a satisfactory gap analysis at this time. The gap analysis in the Blueprint is not presented as an accomplished result. Instead it is a rather subjectively assembled set of educated guesses. Its main value is to serve as an indication of what a later edition of the Blueprint might look like, after such a valid gap analysis is completed.

The major tables in Section 6 of this report provide details on requirements, state of the art, and adequacy of ongoing programs to meet requirements, for the wide diversity of NASA OSS mission needs, but many entries are still missing.

Ultimately, it is intended that the Blueprint will produce graphic displays that show the most important aspects of each major technology area. One approach that we have explored is tiling diagrams. For each technology, these show (1) the cost to develop, (2) the effectiveness of ongoing programs, and (3) the importance to future missions. The figure below shows an exploratory tiling diagram for power technologies. This will be reviewed and validated for the next edition of the Blueprint. In later editions of the Blueprint, validated tiling diagrams will be presented for a wider range of technologies.

The code used in this diagram is:

- **Size of Box** represents expected cost to develop technology to TRL 6
- **Color of Box** denotes adequacy of ongoing and planned technology programs for needs of missions: (**Red** = least adequate; **Yellow** = incomplete; **Blue** = most adequate)
- **Mission number** denotes importance of technology to NASA missions: (5 = most important to missions; 1 = least important)



Exploratory Tiling Diagram for Power Technology

SSE TECHNOLOGY BLUEPRINT

1. INTRODUCTION

1.1 Rationale

The purpose of this Blueprint is to document to the degree possible, the technologies required to implement the future missions of the NASA Space Science Enterprise (SSE). It provides the development status of these technologies both within and outside the Agency, and the adequacy of ongoing programs within the Enterprise and elsewhere to develop these technologies to maturation on an appropriate time scale. The Blueprint also identifies the areas that are insufficiently funded and those that are inadequately defined. The Blueprint provides a synoptic view of the technology needs and gaps in present programs addressing these needs, providing a good perspective for guiding investment in new and evolving technologies for future missions. It also offers a vehicle for coordination and integration of technology needs of the various NASA Office of Space Science (OSS) Themes.

The Blueprint is intended primarily as an internal document to assist the NASA Space Science Enterprise (SSE) management in prioritizing, planning, and advocating technology programs, and should be an important reference in preparing the technology portion of the NASA Code S Strategic Plan. The Blueprint is also expected to provide a technical reference and basis for external documents (e.g., testimonies, budget requests).

The NASA Office of Space Science has five major Themes:

- Astronomical Search for Origins (ASO)
- Structure and Evolution of the Universe (SEU)
- The Sun-Earth Connection (SEC)
- Mars Exploration Program (MEP)
- Exploration of the Solar System (ESS).

In late summer of 2002, each Theme prepared a roadmap of future missions to carry out their science goals; these missions are summarized in Section 2. The Themes have also identified needs for new technology required to implement these (often challenging) proposed missions. The gap between these needs and the current state of the art in each technology area represents the challenge that lies ahead for NASA OSS Technology.

The Blueprint organizes technology under three major technology categories:

- Space Observatories
- In Situ Exploration Technology
- Multi-Mission Spacecraft Technology.

For each of these technology categories, there are several subordinate technologies. The Blueprint lists technology requirements and state of the art for each subordinate technology across the five themes. It lists the key performance parameters and the rough time-frame in which the capability is expected to be ready for mission use. The Blueprint also addresses the current state–of–the–art performance, a reference to the efforts underway to meet the needed performance levels, and an identification of the current responsibility for the efforts (e.g., sponsoring office, performing organization – when known) if they are presently being addressed. In doing this, there was particular interest in identifying similar or related technology needs in different Themes for which some degree of cooperation could be effective in reducing cost and expanding capability.

It should be recognized that a document of this sort is never complete, and must be periodically updated to reflect changes that inevitably occur. As a work in progress, this edition of the Blueprint necessarily leaves some work to be done in the future.

1.2 Technology Hierarchical Structure

The SSE Strategic Plan 2000 summarized the strategic mission set and the planned launch priorities as of that time. Since then, some evolution of mission plans has taken place and these have been documented in Roadmaps prepared by the OSS Themes in the second half of CY2002. The ESS Theme has made some significant revisions in mission plans based on the recently issued report by the National Academy of Sciences Decadal Study of the NASA Solar System Exploration Program.

Many of these missions require various technological advances in order to be feasible and/or affordable. The OSS Themes have assessed the need for new technologies in their various missions. These technologies are organized in the Blueprint according to the NASA OSS TSG Taxonomy:

1.0 Avionics
2.0 Communications
3.0 GNC (Guidance and Control)
4.0 Information Technology/ Autonomy
5.0 Power
6.0 Propulsion
7.0 Structures/Materials
8.0 Thermal Control and Environmental Effects
9.0 Sensors/Instruments
10.0 Space Optics
11.0 Entry, Descent and Landing/Aeroassist
12.0 Robotics and Planetary Access
13.0 Planetary Protection and Sample Handling
14.0 Other

For our purposes in the Blueprint, it is useful (where possible) to segregate the technologies into groups that serve specific interests. We have therefore decided to organize them as follows:

Observatory Technologies

3.5 GNC - Constellation control/ metrology
8.1 Cryocoolers
10.0 Space Optics

In Situ Technologies

1.2 Avionics in Extreme Environments
3.6 GNC - Rendezvous and sample capture/ Earth Return of Samples
11.0 Entry, Descent and Landing/Aeroassist
12.0 Robotics and Planetary Access
13.0 Planetary Protection and Sample Handling

Multi-Mission Spacecraft Technologies

1.0 Avionics (other than 1.2)
2.0 Communications
3.0 GNC (other than 3.5 and 3.6)
4.0 Information Technology/ Autonomy
5.0 Power
6.0 Propulsion
7.0 Structures/Materials
8.0 Thermal Control and Environmental Effects (other than 8.1)
9.0 Sensors/Instruments

In doing this, we have segregated a few technologies from the second level in the taxonomy, where appropriate.

The taxonomy to level 3 is given in Appendix A.

1.3 Approach

The Blueprint is concerned with future OSS missions, and the needs and opportunities for new technology to enable and enhance these missions. Some technologies are enabling; without them the mission simply cannot function—these are imperative. There are also multi-mission spacecraft technologies that should be thought of not so much as needs but rather as opportunities. It might be possible to carry out future missions with present day technologies in these areas, but it would be inefficient. By developing advanced versions of these multi-mission spacecraft technologies to enhance future missions, future missions can be made to produce more, higher quality data, often with cost savings.

The approach used in this Blueprint was based on the ultimate goals of:

- Identifying (and wherever possible, quantifying) critical technology needs and opportunities to enable and enhance future OSS missions.
- For each important technology need or opportunity, quantitatively comparing the state of the art with the requirements and identifying gaps.
- For each important technology need or opportunity, assessing whether ongoing technology development programs are on a path toward bridging the gaps in an appropriate time-scale.

To accomplish these goals, the work was broken down as follows:

- The planned future missions of the Themes were summarized. (Section 2)
- The technology needs and opportunities of the future missions were identified, and where possible, quantified on a Theme-by-Theme basis. (Section 3)
- The various technology needs and opportunities from the Themes were combined into a unified set of needs for OSS. (Section 4)
- For each major need or opportunity, a comparison was made between the state of the art (to the extent it is known) and the requirement, and gaps were quantified wherever possible. An assessment was then made of whether ongoing technology development programs are on a course to fill this gap in a timely manner. (Section 5)

The Master Tables provided in Section 6 list the technology needs of future NASA Space Science missions, comparing them with state of the art and ongoing programs to discern gaps wherever they may exist.

2. OVERVIEW OF THEME MISSION ROADMAPS

During the fall of 2002, each of the five Themes documented their updated future mission plans and the needs for new technology to implement these missions in the near-, intermediate-, and long term. This Section provides a brief summary of these Theme Roadmaps.

2.1 Structure and Evolution of the Universe Missions

The charter of the Structure and Evolution of the Universe Theme is to:

- Explain structure in the Universe and forecast our cosmic destiny
- Explore the cycles of matter and energy in the evolving Universe
- Examine the ultimate limits of gravity and energy in the Universe ranging from the closest stars to the most distant quasars.

The SEU Theme is divided into two major branches:

- <u>Primary Emphasis</u>: *Beyond Einstein*: The Big Bang and the Search for Black Holes
- <u>Secondary Emphasis</u>: *Cycles of Matter and Energy* in the Universe.

2.1.1 Beyond Einstein

The SEU plan for the mid-term includes "Einstein Flagships" that are strategic missions in the 2010-2012 era:

Constellation-X (Con-X) and Laser Interferometer Space Antenna (LISA) are facility class missions that will use the complementary techniques of X-ray spectroscopy and gravitational waves to study black holes. They will investigate the extreme environment found in the vicinity of black holes and track their evolution with cosmic time.

Constellation-X increases the capability for high resolution X-ray spectroscopy by 25 to 100 times over the Chandra X-ray observatory with a key goal to observe in detail spectral features emitted close to the event horizon of a black hole, and obtain detailed spectra of the faint quasars at high redshift detected by Chandra. The mission is optimized for this challenge, but also provides the ability to observe other objects with unprecedented sensitivity, such as the formation of the first clusters of galaxies or supernovae in nearby galaxies.

LISA will provide the first capability to observe long-wavelength gravitational waves. Opening up this new window on the universe will allow observations of the merger of black holes anywhere in the universe and set important limits on any background radiation from the early universe.

The SEU plan also calls for “Einstein Probes” that are competed peer-reviewed missions (in the $300M- $450M cost range) that are launched every three years starting around 2010 in order to:

- Determine the nature of the dark energy which dominates the universe.
- Search for the signature of inflation imprinted in the microwave background.
- Survey the universe for black holes.

These will answer sharply focused critical questions. Three probes are planned at this point.

Dark Energy Probe will range from probing the dark energy amounts to measuring the evolution of the expansion rate of the universe over time. There are a number of different plausible strategies toward this goal, including using supernovae or other standard candles as a direct test of the distance/redshift relation; probing the evolution of linear growth of cosmological perturbations through observations of clusters and large-scale structure; or measurements of the number density of objects (whose evolution must be understood) in a given volume as a function of redshift. A common feature of these strategies is the need for an optical/infrared telescope with a wide field of view and large-scale detector arrays. A mission in space is crucial to obtain high-quality data at the large redshifts ($z \sim 0.5$ - 2) necessary to probe cosmological evolution.

Inflation Probe will search for the imprint of gravitational waves produced during inflation on the Cosmic Microwave Background (CMB) radiation. One promising approach to the mission would comprise a 2-m cooled telescope located at L2 and equipped with large arrays of polarization-sensitive detectors operating between 50 and 500 GHz.

Black Hole Finder Probe will perform the first all-sky imaging survey for black holes of all masses: from supermassive black holes in the nuclei of galaxies, to intermediate mass (~100-1000 solar mass) holes likely produced by the very first stars, to stellar mass holes in our Galaxy. A wide-field telescope operating in the hard X-ray band is a promising approach since hard X-rays penetrate the veil of dust and gas which currently hide most black holes from our view.

In the longer run, two visionary missions have been conceived:

Big Bang Observatory (BBO) is an evolution of the LISA concept for space-based gravitational wave observation. The goal of the mission is to fully decode the beginning of time, by directly measuring graviton quanta coherently amplified from inflation and still present in the universe today, with periods of order 1 second.

Black Hole Imager will provide direct imaging of supermassive black holes, on an angular scale comparable to the event horizon, will have a major impact on our understanding of the exotic physics and astrophysics at work in these systems. A black hole imaging mission, MicroArcsecond X-ray Imaging Mission Pathfinder (MAXIM) with an angular resolution of 0.1 micro arc second is required to resolve the event horizon of accreting black holes at the center of nearby galaxies (e.g., M87). Obtaining a simple image, while exciting in concept, is ultimately not sufficient to study the dynamics of the inner regions. To better disentangle the complicated dynamics near the black hole will ultimately require spectroscopic features that can be used to map the speeds as well as positions of gas in the accretion flow close to the event horizon.

2.1.2 Cycles of Matter and Energy

In the 2000 Roadmap, specific missions were listed for both branches. However, in the 2003 Roadmap, it was felt that the missions listed under "Beyond Einstein" were ambitious enough that they would require all the funds that might become available in the next decade or so. Therefore, the 2003 Roadmap provides the science rationale and goals for "Cycles of Matter and Energy" but does not list specific missions because such listed missions would likely remain on the books for many years without implementation. In the meanwhile, with the evolution of knowledge and technology, the plans for these Cycles missions will be continually refined and strengthened. At some appropriate future date, specific missions for Cycles will be defined. However some missions (Space Ultraviolet-Visible Observatory (SUVO), Single Aperture Far Infrared (SAFIR), Gen-X, Advanced Compton Telescope (ACT), High Resolution X-ray Spectroscopy Mission (HSI), and Advanced Radio Interferometry between Space and Earth (iARISE)), previously defined in the 2000 Roadmap, are mentioned briefly as illustrations of the types of missions that might someday be implemented for Cycles.

The objectives of the Cycles activity include:

- Exploring where and when the chemical elements were made
- Understanding how matter, energy and magnetic fields are exchanged between stars
- Studying the gas and dust between stars
- Discovering how gas flows in disks and how cosmic jets are formed
- Identifying the sources of gamma-ray bursts and cosmic rays
- Understanding the development of structure in the Universe
- Learning what physical processes gave rise to galaxies and systems of galaxies
- Exploring the behavior of matter in extreme astrophysical environments.

The following Cycles missions are mentioned as examples rather than specific proposals.

A cryogenic, large aperture infrared observatory like the SAFIR observatory would offer a unique window into galaxy collapse before stars form and cosmic nucleosynthesis begins.

ACT could be used to measure the explosion mechanisms in core-collapse supernovae, giving their use as a tracer of cosmic nucleosynthesis a more secure foundation.

Achievable baselines for proposed new missions such as the international i-ARISE telescope, would resolve accretion disks out to almost 200 Mpc, and probe the inner disk that surrounds the closest supermassive black hole -- in the galaxy M87. Such measurements will supplement the more complete dynamical picture provided by “Beyond Einstein” missions such as Constellation-X, and especially the vision mission

Black Hole Imager, which would provide monochromatic images of hot gas near the event horizon.

2.1.3 SEU Environments

The environments encountered by SEU spacecraft are typified by the representative missions listed in Table 2-1.

Table 2-1. Environments encountered by SEU Spacecraft

Mission	Trajectory/Location	Radiation
Constellation-X (Con-X)	L2	Moderate
Laser Interferometer Space Antenna (LISA)	Heliocentric 1 AU	Moderate
MicroArcsecond X-ray Imaging Mission (MAXIM)	Heliocentric 1 AU	Moderate
Cosmic Microwave Background Polarization (CMB-Pol)	L2	Moderate
SNAP	3 day sync	Moderate
Energetic X-ray Imaging Survey Telescope (EXIST)	500 km Earth orbit	Low
Gen-X	L2	Moderate
Advanced Compton Telescope (ACT)	LEO	Low
Submillimeter Probe of the Evolution of Cosmic Structure (SPECS)	L2	Moderate

2.2 Astronomical Search for Origins Missions

2.2.1 Near-Term Missions

The Space Interferometer Mission (SIM), Kepler, and Next Generation Space Telescope (NGST) are the only near-term missions planned for ASO, and Terrestrial Planet Finder (TPF) is a high priority intermediate-term mission. While the temptation exists to look at these missions as precursors to even more challenging far-term missions, there remain significant challenges in implementing NGST, SIM, and TPF.

The SIM instrument is a set of long-baseline optical Michelson stellar interferometers on a stable platform that acquire and track fringe patterns resulting from the interference of starlight directed along different paths. The SIM design uses three collinear interferometers mounted on a 10-meter boom. SIM will be the first observatory capable of detecting planetary bodies with a few times the mass of the Earth in orbit around nearby stars. In addition to its scientific goals, SIM will develop key technologies for future missions, including precision location of optical elements to picometers and the precise, active control of optical pathlengths to less than a thousandth the diameter of a human hair. SIM's extraordinary astrometric capabilities will permit determination of accurate positions throughout the Milky Way galaxy.

NGST is the nearest term new general observatory. It will be celestial-background-limited between 0.6 and 10+ microns, with imaging and spectroscopic instruments that will cover this entire wavelength regime. It will provide very high resolution in the near infrared. The primary mirror is about 2.5 times the diameter of the Hubble Space Telescope (HST) primary mirror with an areal density of less than 1/8 of that of HST.

The need to develop a 6.5-m reflector with areal density of 20-25 kg/m^2 remains a significant challenge in the near term. The NGST also requires advanced cryogenic actuators for segmented mirror alignment and deformable mirror control. Further advances in detector technology are also required for NGST.

Kepler is a Discovery Mission designed to conduct a census of extrasolar planets by using a telescope in heliocentric orbit to observe the periodic dimming in starlight caused by planetary transits. The instrument is a 0.95-m aperture differential photometer with a 113 square degree field of view, which continuously monitors the brightness of 100,000 main-sequence stars. The Kepler Mission is specifically designed to photometrically survey the extended solar neighborhood to detect and characterize hundreds of terrestrial and larger planets. These results will be instrumental in determining how deep TPF will have to look to gather an adequate sample of planetary systems to find and characterize habitable planets.

2.2.2 Intermediate-Term Missions

TPF has the goal of direct detection of planetary systems around stars as far away as 15 parsec (nearly 50 light-years). TPF also uses spectroscopy to measure planetary atmosphere composition in order to assess whether conditions might exist that could conceivably support life. In order to resolve relatively dim planets from a nearby bright star, very high angular resolution is required (~0.001 arc-sec). The TPF observatory will likely take the form of either a coronagraph operating at visible wavelengths or a large-baseline interferometer operating in the infrared. The visible-light coronagraph concept might use a single telescope with an effective diameter of 8-10 m operating at room temperature and required to achieve a billion-to-one image contrast. The infrared interferometer concept would use multiple (≈4), smaller 3-4 m diameter telescopes configured as an array and spread out over a large boom of up to 40 m, or operated on separated spacecraft over distances of a few hundred meters. The telescopes would operate at extremely low temperatures of ≈ 40K, and the observatory would necessarily be large. However, the image contrast requirement is only a million to one at infrared wavelengths and thus the required system optical quality would be much easier to achieve than the visible-light coronograph.

2.2.3 Far-Term Missions

SAFIR, consisting of a single 8~10 m telescope, could probe the epoch of energetic star formation in the redshift range $1 < z < 10$ at a wavelength regime, make high spatial resolution maps of the distribution of ices and minerals in the Kuiper Belts surrounding nearby stars, and study the nature of the recently discovered objects in the Kuiper Belt of our own Solar System which may be remnants of our own planet formation process.

A successor to HST operating at ultraviolet and optical wavelengths, SUVO, would produce forefront science in all areas of modern astronomy and would be focused on the era from redshifts $0 < z < 3$, which occupies over 80% of cosmic time and beginning after the first galaxies, quasars, and stars emerged into their present form. SUVO will demand greatly improved ultraviolet (UV) light detector capabilities. The UV spectrograph and associated cameras will need to deliver better than a 100-fold increase in both throughput and multiplex efficiency over current instruments.

Two missions even further in the future because of their demanding technologies have strong relevance to Origins goals. The first is the Life Finder, which would provide high resolution spectroscopy on habitable planets identified by TPF. The second mission concept that appears promising is a Far-IR Interferometer capable of detecting the far-infrared and submillimeter light from the youngest galaxies. An interferometer consisting of three 3-5 m telescopes with a 1 km baseline would have the sensitivity and angular resolution (0.02 arcseconds at 100 microns) needed to study the physical conditions in these young galaxies.

2.3 Sun-Earth Connection Missions

The Sun-Earth Connection has placed primary emphasis on missions to understand how the Sun, heliosphere, and planetary environments are connected in a single system. This, in turn, requires:

1) Understanding the changing flow of energy and matter throughout the Sun, heliosphere, and planetary environments
2) Exploring the fundamental physical processes of plasma systems in the Solar System
3) Defining the origins and societal impacts of variability in the Sun-Earth Connection.

The SEC Roadmap defines a series of missions listed in Tables 2-2, 2-3, and 2–4. Technology state of the art for SEC missions is shown in Tables 2-5 and 2-6.

Table 2-2. SEC missions for understanding the changing flow of energy and matter throughout the Sun, heliosphere, and planetary environments.

Near-Term Missions (2003 – 2008)	
Solar B - How is the photosphere magnetically coupled to the corona? **Solar-TErrestrial REIations Observatory (STEREO)** - What are the origins and consequences of coronal mass ejections (CME)? - What processes control CME dynamics and evolution? - How and where are energetic particles accelerated in CMEs?	**Geospace Electrodynamic Connections (GEC)** - How does the Earth's ionosphere-thermosphere (I-T) system respond to magnetospheric forcing? - How is the I-T system coupled to the magnetosphere? **Solar Probe** - What are the origins of the fast and slow solar wind? - Why is the Sun's corona hot?
Intermediate-Term Missions (2009-2014)	
Magnetospheric Constellation (MC) - How does the magnetotail control energy flow in the magnetosphere? - What processes control magnetotail structure and dynamics? - How do physical processes and regions of the magnetosphere couple over the hierarchy of scales? **Telemachus** - What is the large scale, 3-d structure of the heliosphere? - How is the heliosphere reconfigured over the course of single and multiple solar cycles?	**Ionosphere-Thermosphere-Mesosphere (ITM) Waves Coupler** - What are the global characteristics, variability, and sources of small-scale waves in the Earth's upper atmosphere? - What are the consequences of wave-induced transport between the upper and lower atmosphere? **Heliospheric Imager and Galactic Observer (HIGO)** - What is the nature, size, and variability of the heliospheric boundaries? - What is the composition of interstellar gas?
Long-Term Missions (2015 – 2028)	
Auroral Multiscale (AMS) - How is the Earth's high latitude ionosphere electrodynamically coupled to the magnetosphere? **Geospace System Response Imager (GSRI)** - How is mass and energy transported between the ionosphere and magnetosphere under both quiescent and active conditions? **Interstellar Probe (ISP)** - What is the nature of the interstellar dust and gas that interacts with the solar system? - How is the composition of the interstellar medium distributed between solid (dust), neutral (gas), and plasma (ionized gas) states?	**Neptune Orbiter** - What are the structure and solar wind interactions of a planetary magnetosphere whose spin axis and magnetic dipole axis are in very different directions? **SCOPE** - How are processes in the magnetospheres and upper atmospheres of the planets similar to those observed at Earth? **Solar Polar Imager (SPI)** - How do active regions on the Sun form and evolve at high latitudes? - What is the nature of the velocity vector field below the surface of the poles of the Sun?

Table 2-3. SEC missions that explore fundamental properties of plasmas.

Near Term Missions (2003 – 2008)	
Magnetospheric Multiscale (MMS) - Why do magnetic fields reconnect? - What is the nature of turbulence in geospace? - How are magnetospheric particles accelerated?	**Bepi-Colombo** -How do planetary magnetic fields interact with the solar wind in the absence of an ionosphere?
Intermediate Term Missions (2009-2014)	
Reconnection and Microscale (RAM) - What mechanisms lead to reconnection in the solar corona? - Where are regions of particle acceleration? - What micro-scale instabilities lead to global effects?	**Jupiter Polar Orbiter (JPO)** - How similar and different are fundamental auroral acceleration processes at Jupiter and Earth? - How does auroral coupling moderate the transfer of momentum by magnetic fields in astrophysical systems?
Long-Term Missions (2015 – 2028)	
Dayside Boundary Layer Constellation (DBC) - What is the global magnetic field topology of the Earth's dayside magnetopause? - How does turbulence in the magnetosheath or at the magnetopause modify plasma transfer across the magnetopause boundary? **Io Electrodynamics** - What are the energy coupling processes operating in a magnetosphere with an active moon? **Magnetosphere-Ionosphere Observatory (MIO)** - How is energy tapped from the Earth's magnetosphere to power auroral arcs in the high-latitude ionosphere?	**Mars Aeronomy** - How is the upper atmosphere of Mars electromagnetically coupled to the solar wind? **Particle Acceleration Solar Orbiter (PASO)** - How are the most energetic particles accelerated and transported in and around the Sun? **Venus Aeronomy** - What are the electrondyamic interactions of the solar wind with a planet without an intrinsic magnetic field?

Table 2-4. Missions that define origins and societal impacts of variability in the SEC.

Near Term Missions (2003 – 2008)	
Solar Dynamics Observatory (SDO) - What mechanisms drive the quasi-periodic 11-year cycle of solar activity? - What solar magnetic field configurations lead to CMEs, filament eruptions, and flares and can these events be forecasted? - Where do variations in the Sun's total and spectral irradiance arise? **Radiation Belt Storm Probes** - Which physical processes produce radiation belt enhancements? - What are the dominant mechanisms for relativistic electron loss? - How does the ring current affect radiation belt dynamics?	**Ionosphere Thermosphere (I-T) Storm Probes** - What is the contribution of solar EUV to ionospheric variability? - How does the middle- and low-latitude I-T system respond to geomagnetic storms? - How do ionospheric storms develop, evolve, and recover? - How are ionospheric irregularities produced?
Intermediate Term Missions (2009-2014)	
Inner Heliosphere Sentinels (IHS) - How does the global character of the solar wind and energetic particles in the inner heliosphere change with time? - What is the distinction between flare and shock accelerated particles? **Solar Orbiter** - What are the links between the solar corona and the heliosphere? - What is the nature of the inner heliosphere solar wind?	**Inner Magnetospheric Constellation (IMC)** - How do the radiation belts, ring current, and plasmasphere couple to produce changing energetic particle populations? - What is the origin, dynamics, and consequences of day/ night and dawn/dusk asymmetries in the inner magnetosphere? **Tropical ITM Coupler** - How are the mesosphere, thermosphere, ionosphere and plasmasphere coupled? - How does the ionosphere and thermosphere respond to forcing from the lower atmosphere?
Long-Term Missions (2015 – 2028)	
L1-Diamond - How does large-scale turbulence modify the "geoeffectiveness" of solar disturbances? - Can in situ forecasting of solar disturbances be extended to regions closer to the Sun than L1? **Magnetic Transition Region Probe (MTRAP)** - What are the dynamics of the Sun's magnetic transition region between the photosphere and upper chromosphere? - What processes control the stability of large-scale coronal structures and high density filaments that result in CMEs? **SIRA** - What is the global structure of CMEs and other transient and co-rotating regions in the outer corona?	**Stellar Imager** - What are the characteristics of stellar activity in stars like the Sun? - What are the signatures of solar activity on time-scales of years to decades? **Sun Earth Energy Connector (SEEC)** - How do solar irradiance variations affect geospace? **Sun-Heliosphere-Earth Constellation (SHE-Con)** - What are the end-to-end links of solar variability in the Sun-heliosphere-Earth system?

Table 2-5. Near and Intermediate Term SEC Missions Technology State of the Art.

Category	Focus area	Solar-Terrestrial Probe Missions									Living With a Star Missions				
		MMS	GEC	Solar Probe	MC	Telemachus	RAM	JPO	ITM Waves Coupler	HIGO	SDO	Geospace Probes	IHS	IMC	Trop. ITM Coup.
Spacecraft	Multi-spacecraft Issues (number of s/c)	4	4		50				2			4+	4	6	3
	Avionics				Y	+		R		+	+	Y	+	R	
	Communications	+		Y	Y	+	+	R		+	G		+		
	Guidance, Navigation, Control	+	+	+	Y	Y			+			+	+	+	+
	Power	+	+	Y	Y	Y		+	+	+		+	+	+	+
	Structures/Materials		+	Y	+		Y		+						
	Thermal Control		+	Y		+	G		+				+		+
Propulsion	Solar Sails														
	Conventional	+	+	+					+			+	+	+	+
IT/Autonomy	Information Technology	+		+	Y		+	+	+	+	Y	+	+	+	+
	Autonomy	+		+	Y		+	+	+	+		+	+	+	+
Instrumentation	Sensors/Instruments			+	G		G	R	+	R	Y	+	+	+	+
	Space-based Optics			+			R	+			+				

(Green = enabling technology in place; Yellow = enabling technology pending; Red = enabling technology with gap; + = enhancing technology)

Table 2-6. Long Term SEC Missions Technology State of the Art.

Category	Focus area	STP Missions										Living With a Star Missions							
		DBC	Io Electrodynamics	MIO	PASO	AMS	GSRI	Interstellar Probe	Neptune Orbiter	Mars Aeronomy	Venus Aeronomy	SCOPE	Solar Polar Imager	L1-Diamond	MTRAP	SIRA	Stellar Imager	SEEC	*Sun-Helio-Earth Con.*
Spacecraft	Multi-spacecraft Issues (no. of s/c)	30		3		4	4							4		>10	10		5-10
	Avionics	+	R		+	+			+				+		R				
	Communications	Y	+		+	+		R	R	+	+	Y	+	+	Y		R		
	Guidance, Navigation, Control	+		+	R	+							R	R	Y		R		
	Power	Y	Y	+	R	+		R	R			+							
	Structures/Materials	+			R			R				+	R	R	R		+		
	Thermal Control				R			R	+			+			R		+		
Propulsion	Solar Sails				R			R	R				R	R					
	Conventional	+	+			+				+		+					R		
IT/Autonomy	Information Technology	Y			+	+	+	+				+	+		R		R	R	
	Autonomy	Y			R	+	+	+	+		+	+	R	R	R		R		
Instrument-ation	Sensors/Instruments	+	+	+	+			R	+	+			+	+	R		R		
	Space-based Optics				+							R	+		R		R	R	

(Green = enabling technology in place; Yellow = enabling technology pending; Red = enabling technology with gap; + = enhancing technology)

2.4 Exploration of the Solar System and Mars Missions

The Exploration of the Solar System Theme was recently reviewed by the National Research Council (NRC) as a "decadal study." It is likely that the ESS Theme will adopt many of the recommendations of this study, and this will be assumed here in this Blueprint. The primary emphasis of the decadal study was the period 2003 - 2013. However, brief consideration was given to potential missions beyond 2013.

ESS will carry out Discovery and Scout missions (< $325M) at frequent intervals, while other high-priority science issues will require larger, more capable projects, to be called New Frontiers ($325M to $650M). About once per decade, Flagship missions (> $650M) will be necessary for sample return or comprehensive investigations of particularly worthy targets.

The primary missions recommended by the NRC are listed in Tables 2-7 and 2-8.

Table 2-7. Prioritized List of Non-Mars ESS Flight Missions for the Decade 2003-2013

Priority in Cost Class	Mission Concept Name	Description
Small (< $325 million)		
1	Discovery missions at one launch every 18 months	Small, innovative, principal investigator-led exploration missions
2	Cassini Extended	Orbiter mission at Saturn
Medium (< $650 million)		
1	Kuiper Belt-Pluto Explorer	A flyby mission of several Kuiper Belt objects, including Pluto/Charon, to discover their physical nature and understand their endowment of volatiles
2	South Pole-Aitken Basin Sample Return	A mission to return samples from the Solar System's deepest crater, which pierces the lunar mantle
3	Jupiter Polar Orbiter with Probes	A close-orbiting polar spacecraft equipped with various instruments and a relay for three probes that make measurements below the 100+ bar level
4	Venus In-Situ Explorer	A core sample of Venus to be lifted into the atmosphere for compositional analysis; simultaneous atmospheric measurements
5	Comet Surface Sample Return	Several pieces of a comet's surface to be returned to Earth for organic analysis
Large (>$650 million)		
1	Europa Geophysical Explorer	An orbiter of Jupiter's ice-encrusted satellite to seek the nature and depth of its ocean

A complete set of missions, including those of secondary priority for the post-2013 era, is provided in Table 2-9. The missions shown in italics are the second priority missions.

Table 2-8. Prioritized List of Mars Flight Missions for the Decade 2003-2013

Priority in Cost Class	Mission Concept Name	Description
Small (< $325 million)		
1	Mars Scout Line	A competitively selected line of Mars missions similar in concept to Discovery
2	Mars Upper-Atmosphere Orbiter	A spacecraft dedicated to studies of Mars's upper atmosphere and plasma environment
Medium (< $650 million)		
1	Mars Science Laboratory	A lander to carry out sophisticated surface observations and to validate sample return technologies
2	Mars Long-Lived Lander Network	A globally distributed suite of landers equipped to make comprehensive measurements of the planet's interior, surface, and atmosphere
Large (> $650 million)		
1	Mars Sample Return	A program to return several samples of the Red Planet to search for life, develop chronology, and define ground-truth.

Table 2-9. Complete List of Missions for post-2013 era (including those of secondary priority shown in italics).

Mission	Cost Class	Mission	Cost Class
Inner Planets		**Large Satellites**	
Venus In-Situ Explorer	Medium	Europa Geophysical Explorer	Large
South Pole-Aitken Basin SR	Medium	Europa Lander	Large
Geophysical Network Science	*Medium*	Titan Explorer	Large
Venus Sample Return	*Large*	*Neptune Orbiter/Triton Explorer*	*Large*
Mercury Sample Return	*Large*	*Io Observer*	*Medium*
Discovery missions	Small	*Ganymede Orbiter*	*Medium*
Primitive Bodies		Discovery missions	Small
Kuiper Belt-Pluto Explorer	Medium	**Mars**	
Comet Surface Sample Return	Medium	Mars Sample Return	Large
Trojan/Centaur Recon. Flyby	*Medium*	Mars Science Laboratory	Medium
Asteroid Rover/Sample Return	*Medium*	Mar Long-Lived Lander Network	Medium
Comet Cryogenic SR	*Large*	Mars Upper-Atmosphere Orbiter	Small
Discovery missions	Small	Mars Scouts	Small
Giant Planets			
Cassini Extended	Small		
Jupiter Polar Orbiter with Probes	Medium		
Neptune Orbiter with Probes	*Large*		
Saturn Ring Observer	*Large*		
Uranus Orbiter with Probes	*Large*		
Discovery missions	Small		

3. THEME TECHNOLOGY NEEDS

This section summarizes technology needs provided by the Themes in their 2003 Roadmaps.

3.1 Structure and Evolution of the Universe Technologies

3.1.1 Space Optics

The next-generation SEU space telescopes need to double in size. This challenge applies equally to normal and grazing incidence optical systems. Technology and processes must be developed to increase apertures, lower areal density, lower operating temperatures, and improve diffraction limited surface quality. But most importantly, this must all be accomplished rapidly and cost effectively and requires continuous effort in:

- Materials - Stiffer materials with smaller coefficients of thermal expansion, particularly at cryogenic temperatures - and stress free material deposition and/or curing enable low cost replication for mass production.
- Design Architectures - Must be developed and validated to take maximum advantage of the new materials such as mirror substrates made of glass or silicon foam.
- Fabrication Processes - How to physically handle and manipulate large and more fragile optical components - how to obtain the desired surface figure quality.
- Performance Characterization - As optics become larger and lighter, it may not be possible to test them on the ground. Soon, a telescope may be launched that has been completely validated by analysis.
- Mechanisms - The ability of hinges, latches, actuators, etc. to function in a cryogenic space environment is a critical enabling technology.

3.1.2 Detectors

Advances in detector technologies, in all wavebands have been dramatic in recent years, and have directly enabled most of the SEU missions that are currently flying or nearing launch (e.g., Chandra, Space Infrared Telescope Facility (SIRTF), Gamma Ray Large Area Space Telescope (GLAST)). In general, a detector is categorized by its quantum efficiency, its spectral band-pass, and in some cases, its intrinsic spatial and spectral resolution. Auxiliary technologies include read-out electronics, digital processing units, and detector cooling systems. The demands of upcoming missions will require major engineering advances in all of these areas. Some specifics are given below:

- <u>Submillimeter/Far Infrared</u>. The development of large format detector arrays is critical for the sub-mm and far infrared. Both direct detectors (such as bolometers and photoconductive devices) and heterodyne instruments are required. There are challenges in improving sensitivity, scalability to large arrays, and, for heterodyne systems, local oscillators and backend electronics, especially at the highest frequencies. Nevertheless, large leaps in sensitivity are anticipated.

- Near Infrared/Optical. In the near IR and optical bands, extremely large arrays of imaging detectors based on charge coupled devices (CCDs), and low band-gap array detectors (e.g., HgCdTe) are needed which provide new challenges in production yield, detector uniformity, detector packaging, high-speed readout, and onboard data storage. In addition, improvements in readout noise, quantum efficiency, spectral coverage, charge transfer efficiency, and radiation hardness will be necessary.
- Ultraviolet. Photocathode-based photon counting detectors, like micro-channel plates (MCPs) offer high counting rates and good background rejection, but suffer from low quantum efficiency (typically below 25 %). Further developments in novel photo-cathode materials may achieve significant improvements in quantum efficiency. For some applications, solar blindness is important. UV-sensitive CCDs have higher quantum efficiency, but the read noise is currently too high to make such devices useful for faint source spectroscopy, given the low photon fluxes in the UV band. So-called "3-D" energy-resolving detectors like super-conducting tunnel-junction arrays or transition-edge sensors with SQUID readout offer tremendous promise, but the currently available array sizes are too small for the anticipated applications.
- X-Ray. The development of cryogenic X-ray micro-calorimeter arrays has revolutionized the field in recent years. 30x30 arrays are envisioned as the principal focal plane detectors for Con-X. However, such small arrays yield very limited fields of view when implemented behind conventional grazing incidence telescopes. For future missions, such as Gen-X, much larger array sizes (e.g., 1000×1000) are required.
- Gamma-Ray. A factor of 25-100 improvement in sensitivity is required for an advanced Compton telescope compared to the MeV instruments flown on Compton Gamma Ray Observatory (CGRO) and International Gamma Ray Astrophysics Laboratory (INTEGRAL). The increase in sensitivity requires major improvements in angular resolution (achieved through position and energy resolution), detector effective area and field of view, and background rejection. The Compton telescope relies on gamma-ray tracking to determine the incident direction of the incoming photon. If only the interaction event locations and energies are determined, the direction is only localized to a ring on the sky. However, if the direction of the recoil electron can be determined, the ring can be reduced to a much smaller arc, thereby yielding a tremendous increase in source detection sensitivity.
- Cryocoolers. An ultimate temperature of 50 mK must be provided by an ADR operating from a 6 K heat sink of an intermediate cryocooler.

3.1.3 Spacecraft Systems and Formation Flying

Continued advances in enabling spacecraft technologies will be crucial to meeting the SEU science goals. Several of the envisioned missions (Black Hole Imager, SPECS, iARISE) incorporate interferometric systems on separate spacecraft that involve precision formation flying systems. Stringent requirements on relative positional accuracy and pointing are beyond the state of the art. Micro-Newton thruster technologies, currently under development for LISA, will demand further study to determine their applicability to these other missions. Thermal and mechanical stability tolerances are very tight. The development of advanced inertial reference systems may be applicable. Cryogenic technology is important, especially for the sub-mm and far IR systems where a cooled primary mirror may be required. Tethers may provide dramatic savings in fuel when used in interferometric telecopes flown in formation.

3.2 Astronomical Search for Origins Technologies

Detector Technologies. The single most important ASO technology issue is detector capability. The most dramatic gains in detector performance will be found at far infrared wavelengths where large format imaging arrays have yet to be perfected, and in the ultraviolet where new solid state devices must allow simultaneous detection of the both the intensity and wavelength of the light.

Cryocoolers. To achieve their ultimate performance, new detectors will require improvements in small, very low temperature, cryocoolers. In fact, the detector and its cryocooler should be viewed as an inseparable technological pair.

Space Optics Technologies. Usually, the largest and most massive component of a telescope is its primary mirror. In order to launch larger and larger telescopes into space with our current launch vehicles, we must find a way to keep the mass constant as the size increases. This requires new precision materials and structures that allow the areal density of large optical elements to be reduced. The NGST mirror technology program hopes to achieve 20 kg/m^2 over a 33-square-meter aperture. A 10-meter mirror that has the same total mass requires an areal density about 8 kg/m^2. Ultimately, areal densities as low as 1 kg/m^2 may be required for future missions.

Active Wavefront Error Control. As the areal density of the optical elements is reduced, they become more flexible and prone to distortions induced from external disturbances. However, the performance requirement on the overall optical system will remain close to perfect in order to achieve the benefits of going to space. This is true even for NGST. As the telescope size increases, there will be a growing need to actively sense and control (or correct for) the shape of the optical surfaces. This will be the only way to insure the required optical performance as the thermal, gravitational, and mechanical disturbance environment changes in orbit.

Full Aperture Cryocooling. The largest of the Origins observatories will operate at infrared wavelengths. In order to achieve the highest possible performance, the telescope's optics must be cooled to prevent them from being a brighter source of infrared energy than the astronomical targets. Cooling huge telescopes to deep cryogenic temperatures represents an enormous challenge. Observatories that are located at the Earth's distance from the Sun require some form of active cooling to reach the desired temperature of < 15K. If the telescope could be placed beyond the orbit of Mars, it could naturally cool to the required temperature. NASA's new nuclear power and propulsion initiative may produce new flight options that will allow space observatories to operate successfully in the outer Solar System. Most likely, cooling to these deep cryogenic temperatures will require new developments in passive (capillary and loop heat pipes) and active (cryocoolers) thermal control devices.

A trade-off would have to be made as to cost and risk when considering the alternative of operating in the outer Solar System to achieve low aperture temperatures.

Preserving Unique Space Science Technologies. As new technologies appear, we often lose sight of the important and continuing role of the older ones. It is easy to assume that reliable devices will always be there—reality has proven to be different. For example, scientific CCD detectors are no longer always available, optical filter technology was recently threatened by competing pressure for the same manufacturing capabilities, and other spacecraft components are no longer made. Where mature technologies exist that are still critical components of space science missions, NASA must take active steps to ensure that the manufacturing and testing capabilities are preserved. The single-most import area is preservation of technology base for high performance detectors that operate in the visible and infrared. These devices are near their theoretical limits and the capability to produce them must be retained.

3.3 Sun-Earth Connection Technologies

Implementation of the SEC strategic plan requires a prudent and timely investment in four broad technology areas:

- Advanced Propulsion (e.g., solar sails)
- Spacecraft Technology (e.g., cost-effective microsats, high data- rate communications, autonomous spacecraft, and robust long-lived spacecraft)
- Scientific Instrumentation (e.g., advanced imaging and miniaturized in situ instruments)
- Information Architecture (e.g., data synthesis, modeling, and visualization).

Solar sails are a high technology priority for SEC and, indeed, the enabling means envisioned for attaining unique vantage points inside 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).

3.3.1 Solar Sails

In the long term, many SEC missions (e.g., Interstellar Probe (ISP) and Solar Polar Imager (SPI)) are enabled only with advanced propulsion technologies that can deliver velocity changes (Δv) of greater than ~50 km/s in a cost-effective, high-performance system. Such performance is not possible with chemical propulsion. Trade studies suggest that only solar sails appear to offer this performance for overall low system mass. Of the more than 20 SEC Roadmap missions, nine are considered enabled by sail technology.

Recent technology advances have given new promise to the application of solar sail propulsion. Three metrics help define solar sail technology advances:

- Sail size
- Areal density
- Thermal characteristics.

Solar sail propulsion does not require any propellant. Payloads can be delivered to previously inaccessible regions of space in reasonable flight times. Access to the entire heliosphere and beyond is available with solar sail technology.

Given the challenge inherent in deploying and controlling a large, gossamer solar sail, it has long been presumed that a technology demonstration mission will be required. One can also imagine an alternative scenario in which sail performance might be first demonstrated and then even employed to enhance a mission, but was not itself a critical or enabling element. If a solar sail in the 50-m class (root-area) was successfully demonstrated, it would immediately enable measurements upstream of L1 and by straightforward scale-up to sizes in the 100-m class, and make possible Solar Polar Imager. The path to this development is illustrated in Table 3-1. After this point of development, the technology would have to be adapted for application to the near-solar environment for missions like Particle Acceleration Solar Observatory (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).

Table 3-1. Development Path for Solar Sails

Time Sequence	Mission	Sail Area (m^2)	Sail Density (g/m^2)	Comments
First	Technology flight validation	1500	>25	
Second	Geostorm	4760	18	
Third	SPI	19,800	13	
Fourth	PASO	24,000	9	
Fifth	ISP	122,900	1	Must pass within 0.25 AU of Sun for solar gravity assist

3.3.2 Spacecraft Technology

Significant advances in SEC science require multiple measurements from many satellites flying in a time-synchronized loose formation. To implement these measurements with affordable launch vehicles, the unit spacecraft mass, power, and cost must be significantly reduced. These reductions require miniaturizing all spacecraft subsystems as well as relevant scientific instrumentation while maintaining science measurement requirements. These resource reductions require timely infusion of new technology, primarily in specialized high performance electronics that are resistant to radiation. Microsats (100 kg > spacecraft mass> 10 kg) will be enhanced with these developments, while nanosats (10 kg > spacecraft mass > 1 kg) are enabled by such technology. Picosats, envisioned as spacecraft with masses less than 1 kg, are considered for the distant future.

Other required spacecraft technologies include:

- High-data-rate communications (burst mode from near-Earth constellations as well as continuous imaging from deep space).
- Spacecraft autonomy, in order to manage missions in a cost-efficient manner.
- Robust, long-lived (sometimes called "immortal") spacecraft to enable long-life missions, as well as missions into harsh environments such as near the Sun, dipping deep into the upper atmosphere of the Earth, and through multiple passes of terrestrial and planetary radiation belts.
- Inter-spacecraft communications, to enable autonomous coordination and synchronization of multi-spacecraft activities, event triggering, inter-spacecraft position measurement, and, in some cases, in-space distributed data processing.

The associated technology developments are required for both single spacecraft and constellation missions. In the near term, multi-spacecraft missions will generally involve a handful of highly capable spacecraft that will fly in loose formation.

The next level of understanding of geospace will require simultaneous in situ measurements that span the entire system under study. This suggests the need for 100 spacecraft to study the spatial-temporal dynamics of the magnetosphere (MagCon). Although constellations of spacecraft are now commonplace for telecommunications and global positioning, MagCon presents at least an order-of-magnitude increase in the number of spacecraft for a space science mission. There will be many technical challenges in making the leap from Magnetospheric Multi-Scale (MMS) (four spacecraft) to MagCon (~100). Dispensing 100 spacecraft into orbits where the science return of their measurements is maximized will probably require a low-mass dispenser spacecraft or propulsion-capable spacecraft, and mechanisms for dispensing nanosats will be needed. Figure 3-1 shows the evolution of SEC missions that require multiple spacecraft with time.

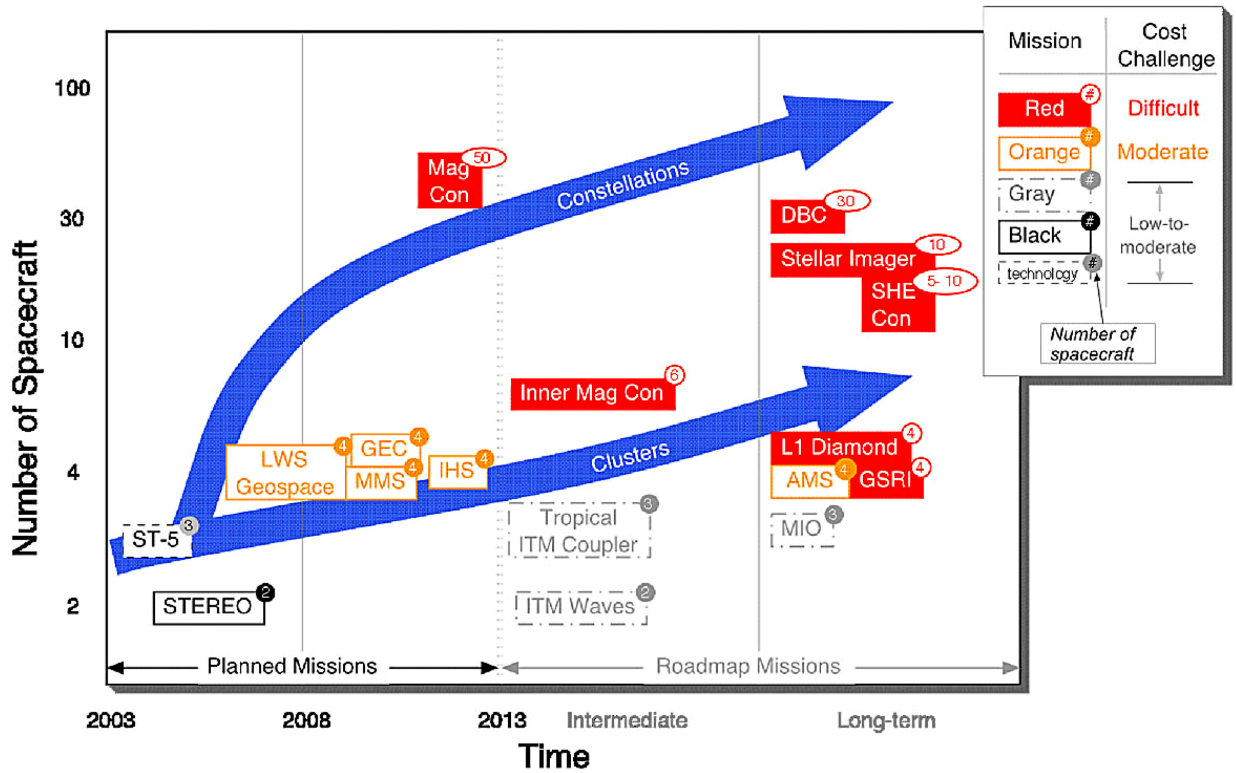


Figure 3-1. The need for ultra-low-cost multiple spacecraft in future SEC missions. (The projected number of spacecraft is given in the small circle at the upper right of the mission box.)

The number of discrete spacecraft and available launch vehicles suggests the need for nanosats outfitted with a few key instruments, for example, a plasma analyzer, an energetic-particle spectrometer, and a magnetometer. One instrument alone on previous SEC spacecraft may have weighed 10 kg or more. Instruments compatible with nanosats will have to be low-mass, low-volume, and low-power in nature. They will have to be inexpensive and readily manufactured in numbers up to 100. SEC missions will probably meet their low-mass requirements by using structures that serve multiple functions, such as thermal and power. Multifunctional structures that incorporate the spacecraft battery or thermal control devices will enable significant mass reductions. Systems for spacecraft power, energy storage, attitude, and thermal control will have to be developed to meet nanosat cost and manufacturing constraints.

Constellations exploring the magnetosphere will be constantly flying through radiation belts. Spacecraft electronics will have to be radiation-tolerant, as the number of spacecraft will necessitate highly autonomous spacecraft able to routinely operate independently of ground operators. Communication limits will probably require smart management of the downlink bandwidth and adaptive data management. Nanosat autonomy will thus be needed not only for system health, maintenance, and fault correction but also for adaptive control of instruments. Using existing architectures, data flowing from a 100-spacecraft constellation will be cumbersome and unwieldy.

New synthesis methods will be needed for the near-real-time incorporation of data into models and visualization tools. Substantial qualitative improvements in the capability of nanosats and microsats will be needed.

“Dipping” (temporary excursions into the high-atmospheric-drag region at <150 km) microsats will study the Ionosphere-Thermosphere-Mesosphere (ITM) regions (e.g., Tropical ITM Coupler). These microsats will require highly aerodynamic, low-drag structures and booms, as well as mass-efficient propulsion systems to enable sustained dipping campaigns into the ITM.

Solar Flotilla will require deep-space flying microsats, integrated with solar sail-equipped dispensing craft. These microsats will also have to cope with the severe thermal and radiation environment encountered in near-solar orbits (~0.2 AU).

Communications with microsats in deep space will be complicated by the proximity of the Sun, a problem that may require inter-spacecraft communications or even a near-solar relay network. The addition of solar imaging (envisioned for Inner Heliospheric Constellation) will require three-axis-stabilized microsats. Although the proximity to the Sun will produce some gains in sensitivity and resolution, lightweight optics for Sun-observing microsats will be needed.

3.3.2.1 High Data Rate Communications

The new SEC missions will pose several challenges to the existing state of the art in spacecraft communications. Spacecraft exploring interstellar space will require communication links with Earth from distances of many hundreds or even thousands of AU. At the other end of the scale, communication with near-solar spacecraft is complicated by solar RF emission and frequent conjunction with the Sun. Lastly, constellations in the geospace environment will require communications compatible with nanosats. Interstellar Probe is slated to reach 200 AU distance from Earth in less than 15 years of flight time, 2.5 times the distance from Earth of the Voyager 1 spacecraft in January 2000. Its suite of instruments will have significantly greater downlink requirements than the Voyager Interstellar Mission (~160 bps) spacecraft. Ka-Band, or possibly optical communications is expected to replace X-Band as the preferred method of communicating with spacecraft in interstellar space. Communication with near-solar spacecraft is problematic and subject to frequent interruption due to solar conjunction. Future SEC solar missions such as PASO, Solar Polar Imager, Solar Farside Observer, Solar Flotilla, and Inner Heliospheric Constellation may provide critical support to interplanetary manned missions with real-time solar monitoring. Substantial onboard storage, as well as autonomous, onboard processing will be needed for such missions. Innovations that involve inter-spacecraft relay networks will be required. Microsats will pose a substantial challenge for communications technology. Geospace constellations will have to balance downlink data with nanosat power, mass, and volume constraints. A miniature, low-voltage, high-efficiency, X-Band transmitter will have to be developed for use on high-perigee nanosats. General communication technology needs include:

- Autonomous onboard processing
- Onboard data storage
- Large, lightweight deployable antennae
- Lightweight, high-density power sources
- Deep-space/near-solar communications
- Optical communications
- Ground stations (e.g., improved antennae, receivers, and processors)
- Lossless data compression.

3.3.2.2 Autonomous Spacecraft

In August 1999, there were 15 operating spacecraft in the SEC Theme. By 2011, it is anticipated that an additional 120 discrete spacecraft will have been launched. Constellation missions in the SEC Roadmap conservatively suggest an increase of 10 spacecraft/year after 2011. Future SEC missions will require much more spacecraft autonomy. Constellation spacecraft in very-high-perigee orbits will be out of communications range for nearly a week at a time and will fly through radiation belts known to cause upsets. Faults that require intervention from ground controllers could result in loss of data and in degradation of a constellation's science return. Spacecraft in deep space (near-solar or interstellar space) will have to manage science return given the limits of bandwidth. Long-lifetime missions will require autonomous management of degrading subsystems. Autonomous spacecraft that employ technologies such as onboard software agents and automated decision making are necessary to detect, diagnose, and recover from faults. These must also interact intelligently with the payload to allow autonomous operation and management of the mission's science return. Testing and flight validation of autonomous agents will be challenging but necessary. Routine autonomous operation, data collection, and data synthesis are required to make mission operations manageable and cost-effective.

3.3.2.3 Robust, Long-Lived Spacecraft

SEC spacecraft will go where no other human-developed objects have gone, and they will return groundbreaking scientific data. In the future, they will pass blazingly close to the Sun (Solar Probe), explore the farthest reaches of the heliosphere, and even probe interstellar space. They will dip into the upper atmosphere of the Earth and other planets and will measure the trapped radiation of the Van Allen belts. To ensure successful missions, they will have to withstand these severe environments and, in some instances, have mission lifetimes measured in decades. All of this will be achieved at a cost equal to or less than that of previous comparable NASA missions. In some instances, the substantial reductions in mission cost are vital enabling factors. While all SEC missions will benefit from anticipated advances in low-cost, high-performance avionics, the impact of the radiation environment will constrain the incorporation of new information technology. Seven missions in the SEC Roadmap anticipate flying through the Earth's (or Jupiter's) radiation belts. Rad-tolerant avionics systems will be required for many of these missions (e.g., Jupiter Polar Orbiter and Io Electrodynamics).

Thermal management for the near-solar environment will be an issue since eight missions will pass within 0.5 AU of the Sun. Some of these will be for brief perihelion encounters, but others will orbit within 0.2 AU of the Sun and thus will require high-temperature solar arrays. Thermal control structures, materials, capillary-pumped loops, diamond substrates, and advanced packaging will be needed for nanosats and microsats. Measurement of the ITM will require spacecraft capable of sustained dipping into the upper atmosphere. These spacecraft will require mass-efficient, aerodynamic structures and booms. They will also require advanced coatings to withstand atomic oxygen erosion and the thermal environment induced by atmospheric heating. Advances in propulsion are urgently needed, since this is a life-limiting factor for all dipping spacecraft. Long-lifetime cryocoolers will enable long-duration study of the mesosphere in the infrared and thus contribute to an understanding of the planet's water cycle (knowledge with possibly profound implications for life on Earth and Mars). Quest III missions will pose significant challenges; they must be especially long-lived spacecraft. Interstellar Probe has a minimum lifetime of 15 years, and so this is a minimum requirement for spacecraft probing interstellar space. New missions must achieve this with quality approaches and programs that are in keeping with present-day financial realities. They will be designed to cope with the extreme heat of velocity-boosting perihelion approaches at ~ 0.25 AU and to withstand the cold of interstellar space. Advanced radioisotope power sources (ARPS) will be needed to provide power for 30 years or more and must meet evolving requirements for system safety.

3.3.2.4 Scientific Instrumentation

The SEC roadmap requires advanced imaging and miniaturized in situ instrumentation technologies that further divide structurally into electronics, mechanisms, detector heads (including collimators, guiding fields, and stray light rejection), and detectors (including detection physics as well as focal-plane conditions and operational constraints). These structural element technologies are all candidates for miniaturization, reduction of mass, power, and volume consistent with achieving science goals while enabling deployment on nanosat constellations or microsats with low-thrust solar sails. All identified instrumentation can benefit, in some instances in enabling ways, from miniaturization.

3.3.2.5 Power

The severe environments endured by SEC spacecraft pose a particular challenge for power systems. Exploration of the outer heliosphere in practice is contingent on the availability of radioactive power sources. However, the vast majority of SEC missions will continue to rely on photovoltaic systems. Operations with photovoltaics as far out as Jovian orbit require deployable, low-intensity, low temperature solar arrays. At the other end of the scale, 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 SEC theme has particular interest in the development of new lower-cost, electro-statically clean solar arrays.

The planned investment in nuclear fission reactors could some day result in high-performance, deep-space platforms able to contribute mightily to SEC science goals of exploring the outer heliosphere.

3.4 Exploration of the Solar System and Mars Technologies

3.4.1 Multi-Mission Spacecraft Technologies

The two most constrained resources in the current generation of ESS spacecraft are onboard power and propulsion. It is in these two areas where improvements will enable the greatest leaps forward in capability. Solar power is generally insufficient beyond the asteroid belt, provides limited power for spacecraft systems, and limits the lifetime of landed spacecraft. In-space chemical propulsion has limited capability, especially for missions to the outer planets, resulting in long flight-times and often limiting missions to rare launch windows requiring multi-planet flybys to gain the necessary energy.

The solutions to the power and propulsion problems include the following:

(1) Development of improved solar electric propulsion (SEP) by improving the performance (thrust, throughput, and specific impulse) of ion engines, and developing large lightweight deployable solar arrays that can deliver 15 to 30 kW with a specific power > 150 W/kg. Use of SEP on Titan and Comet Nucleus Sample Return (CNSR) missions reduces trip time from 10 years to 5. Use of SEP on Venus Surface Sample Return (VSSR) permits the orbiter and lander to be carried on a single launch vehicle. SEP has great benefits for a Neptune Orbiter because use of chemical propulsion requires rare gravity assists. SEP also has important benefits for most other inner planet missions.

(2) Development of advanced radioisotope power systems to replace the depleted inventory of first-generation radioisotope thermoelectric generators (RTG).

(3) Development of aerocapture as a means to reduce in-space propulsion requirements for orbiters and landers will significantly improve mission performance to all planets with atmospheres. Aerocapture is particularly important for three large missions:

Mission	Entry Mass (kg)	Mass Fraction (%)	Entry Speed (km/s)	Δv	Aeroshell L/D	Comments
Venus VSSR	1000	30	11-12	4-5	Low L/D	Permits orbiter and lander to be carried on a single launch vehicle. Alternative is SEP, extending mission by 1 year.
Titan Aerobot + Orbiter	860	27	6-9	3-6	Low L/D	Permits orbiter and aerobot to be carried on a single launch vehicle. Alternative is NEP.
Neptune/ NT Orbit	1800	40	27-33	5-8	High L/D	Enables launch of a Neptune/Triton orbiter on existing and planned launch vehicles. Alternative is NEP.

(4) Determination of whether a compact and efficient flight-qualified nuclear-fission reactor is feasible and affordable. If the answer is yes, develop this in parallel with the

second- and third-generation ion drives for the high-power nuclear electric propulsion (NEP) systems required to reach the outer Solar System. NEP appears to have significant advantages for an extended Neptune/Triton mission.

(5) Development of advanced chemical propulsion for missions (South Pole Aitken Basin Sample Return and Europa missions) that require chemical propulsion.

Outer planetary missions require low-mass compact batteries that have a long operational life of 10-15 years. In addition these batteries must have high radiation tolerance capability. Inner planetary missions, such as Venus In-Situ Surface Exploration and Venus Surface Sample Return, require primary and rechargeable batteries that can operate at temperatures as high as 735 K. Some of the planetary surface and subsurface missions, such as the Europa Lander, Titan In-Situ Explorer, Jupiter Deep Probe, and Comet Nuclear Sample Return require low-mass and compact primary and rechargeable batteries that can operate at temperatures as low as $\leq$ 175 K. Mars orbital missions require low-mass rechargeable batteries with long cycle- and calendar-life capabilities. Mars landers and rovers require batteries with low-mass and volume that operate at low temperatures ($\leq$ 235 K).

Rechargeable lithium ion battery technology with liquid organic electrolytes have been developed by the joint efforts of the Air Force Research Laboratory (AFRL) and NASA for low-temperature lithium Mars lander and rover applications. Flight hardware is presently under fabrication for the Mars Exploration Rover (MER) mission. There still remains the need to improve cycle life and calendar life, develop electrolytes that can enable the operation at temperatures of 215K and lower, and a need to improve the radiation tolerance of these batteries. Rechargeable lithium polymer battery technology is in an early stage of development (Technology Readiness Level (TRL) 2-3). This technology has the potential for higher specific energy and energy density than liquid electrolytes, but the main advantages are improved safety and flexible configuration. Lithium solid-state inorganic electrolyte battery technology is in a very early stage of technology development (TRL 1-2). This battery technology is projected to eventually have a very high specific energy and long cycle-life and calendar-life capability.

In the area of spacecraft communications it is assumed that current development of Ka-band capability and antenna arrays will mature in the early years of this decade. The next most important step is development of optical communications for a major leap forward in communications bandwidth, particularly for video-rate communications from Mars and for advanced exploration in the outer Solar System. Advanced optical and/or radio communications should be developed and flight-qualified towards the end of this decade for use by Mars Sample Return and the next generation of outer planets missions.

In the area of spacecraft systems, the key demand is for considerable autonomy and adaptability through advanced architectures. Lower-power, lower-mass spacecraft need to be developed commensurate with realistic cost and performance for the available expendable launch vehicles. Not unrelated is the need for more capable avionics in a more highly integrated package through advanced packaging and miniaturization of electronics and with a standardized software operating system.

New and increased science measurement capability in planetary science instruments and in environmental tolerance will be required for less mass and power. Miniaturization is the key to reduction of mass and power requirements. For the inner Solar System, electronics tolerant to extremes of temperature (both hot and cold) are required. High temperature, corrosion-resistant and pressure-tolerant systems are required for in situ exploration on Venus. For the outer planets, radiation-hard electronics, shielding, tolerance, and reliability are required.

As planetary exploration moves toward more in situ and sample-return missions, it will be necessary to develop planetary landing systems, in situ exploration systems, and Earth-return technologies. The key requirements for landing systems are autonomous entry, descent, hazard avoidance, and precision landing systems. Once on the surface, sample gathering and analysis become key technologies with attendant requirements for new surface science instruments, including biological measurements, and means for moving about a planet on, above, and below the surface. Systems for accessing difficult-to-reach areas will be required.

Rover technology should advance toward long-life and long-range capability with hazard-avoidance autonomy and the ability to operate on large slopes. Drilling techniques on both terrestrial and icy surfaces will be needed, advancing toward deep-ice penetration and submarine exploration in subsurface oceans. Aerial platforms for Mars and Venus will be required; they will be the forerunners of systems to be deployed on Titan and the outer planets. Advanced autonomy will need to be built into all these mobile mechanisms.

The means to return planetary samples needs to be developed beginning with small bodies and the Moon, advancing towards Mars, then Venus, and eventually more distant targets such as Mercury and the satellites of the outer planets. Some recommended missions will be sent to planets and satellites that are targets for biological exploration and will require meeting planetary protection requirements related to forward and back contamination. Technologies will be required to meet these requirements while reducing costs.

3.4.2 Mission-Specific Technologies

In addition to the multi-mission spacecraft technologies described in the previous section, there are mission-specific technologies required for the flight missions selected for this decade. These are briefly described below and summarized in Table 3-2.

Kuiper-Belt-Pluto Explorer

This mission is ready now, has no requirements for new technology, and can use one of the few remaining RTGs. Consideration should be given, however, to the use of an advanced solar-electric propulsion stage. SEP requires improved deployable, high specific power arrays.

Table 3-2. ESS Technology Developments Needed for Future Missions (Bold type indicates a priority item.)

Technology Area	Technology Need
Power	**Radioisotope power, high specific power deployable solar arrays,** in-space fission reactors
Propulsion	**NEP, advanced ion engines, aerocapture**
Communication	**Ka-band, optical comm**, large ground antenna arrays
Architecture	**Autonomy**, adaptability, lower mass, lower power
Avionics	**Advanced packaging and miniaturization**, standard operating system
Instrumentation	**Miniaturization**, environmental tolerance (T, P, radiation)
Entry to Landing	**Autonomous entry, precision landing**, hazard avoidance
In Situ Operations	Sample acquisition, handling and analysis; drilling; instrumentation
Mobility	**Autonomy**; surface, aerial, and subsurface mobility; hard-to-reach access
Contamination	Forward contamination avoidance
Earth Return	**Ascent vehicles**, In-space rendezvous, and Earth return systems

Europa Geophysical Explorer

Radiation-hard electronics is the key requirement in addition to the multi-mission spacecraft technologies for outer planet missions.

South-Pole Aitken Basin Sample Return

This could be the first test of sample return technologies to be used on Mars. The developments required are very nearly the same except for the system for braking from orbit. The common elements are automated descent, hazard avoidance and precision landing, advanced in situ sampling (perhaps even drilling), advanced in situ instrumentation (including radiometric age dating and chemical and mineralogical analysis), sample transfer, and ascent vehicle and Earth-return system. A means for communication with a lunar far-side station will be required. A successful lunar SPASR will provide early demonstration of planetary sample-return technology without the need for planetary protection and significantly reduce the risk for a Mars sample-return mission.

Jupiter Polar Orbiter with Probe

This mission will require advanced radioisotope power sources, radiation-hard avionics for the orbiter, and revival of the Jupiter entry-system technologies first developed in the 1970s. The probes should survive high-speed entry and be in communication to the depth where the pressure reaches 100 bars - whereas the signal from the Galileo probe was lost at 22 bars. Lightweight mass spectrometers for sampling at high pressures with internal gas processing for complex analysis are the key science instrument technologies. The deep probes developed for this mission will then be available for similar missions to the other giant planets—Saturn, Uranus, and Neptune. NEP is not required for this mission.

Venus In-Situ Explorer

The key technologies for this mission are system survivability, shallow drilling, sample acquisition, and sample transfer at extremely high temperature and pressure in a corrosive environment, high-temperature balloon materials, and long-lived compact power sources. In situ instruments will be required that can survive the Venus surface environment, and accomplish radiometric age-dating and chemical and mineralogical analysis of surface samples while at altitude. Use of advanced solar electric propulsion coupled with aerocapture would markedly increase the performance of this mission.

Comet Surface Sample Return.

The key technologies required are a sample-acquisition system without significant on-surface time, drilling, sample manipulation, and storage at cryogenic temperatures. Advances in automation, ion propulsion and solar- and/or radioisotope-power sources will improve the performance of this mission. SEP requires improved deployable, high specific power arrays. Depending on the activity level of the target comet, dust mitigation strategies for instruments, solar arrays, and other exposed surfaces of the spacecraft may be required.

Mars Missions

In addition to the multi-mission orbital, in situ, and sample-return mission technologies mentioned above, for which Mars is a prototypical benefactor, planetary protection issues (both forward and back) and attendant sample containment, Earth return, handling and examination facilities are key technologies. Of paramount importance is an improved entry, descent and landing capability.

A Mars-Earth return system, including ascent vehicle and in-space rendezvous and sample capture, are key technologies that can evolve from the vehicles developed for the Lunar South Pole-Aiken Sample-Return mission.

4. OSS TECHNOLOGY NEEDS AND PROGRAMS

This section integrates technology needs across the various Themes into unified technology needs for OSS, seeking to identify overlaps and commonalties between Themes wherever possible.

4.1. Observatory Technologies

4.1.1 GNC - Constellation Control/Metrology

The major emphasis for future space observatories will be on increased resolution. Increased resolution can be achieved alternately by utilizing multiple spacecraft, each supporting a moderate aperture device, to produce the resolution of an equivalent large aperture. Several of the envisioned future ASO and SEU missions incorporate interferometric systems on separate spacecraft that involve precision formation flying systems. Stringent requirements on relative positional accuracy and pointing are beyond the state of the art. Micro-Newton thruster technologies, currently under development for LISA, will demand further study to determine their applicability to other missions. Cryogenic technology is important, especially for the sub-mm and far infrared (IR) systems where a cooled primary mirror may be required. Tethers offer a potential means for reducing the fuel consumption requirements for formation flying interferometric systems.

In addition, future SEC missions will involve multiple spacecraft, although in these cases, constellation control and metrology technology is not considered to be as important as the technology of the multiple spacecraft deployed. Rather, the needs revolve about orbit insertion, telecommunications, and low-cost replicated spacecraft and instruments.

There are two substantial integrated programs working on the end-to-end challenges for formation flying. The first is at Goddard Space Flight Center (GSFC), focusing on the challenges from low-Earth-orbit out to the L2-Lagrange point, including the specialized sensors, relative navigation, and formation algorithms needed for the particular range of gravity and navigation signal availability (such as the Global Positioning System (GPS) or Deep Space Network (DSN)). The second formation flying activity is at the Jet Propulsion Laboratory (JPL) focusing on the challenges from deep space into L2, including efforts investigating nanometer-class spacecraft-to-spacecraft metrology. Both efforts include high-fidelity hardware-in-the-loop testbeds to support technology development, validate end-to-end system performance, and transition the technologies into missions.

Table 6-1 summarizes known needs for constellation technologies.

4.1.2 Cryocoolers

The principal need for cryocoolers is by the ASO, SEU, and SEC Themes for IR-observing instruments on future observatories. Cryocoolers that function in the 4–20 K temperature range are needed for various IR applications. These could also function as upper stages for sub-Kelvin coolers for detectors that operate as low as 0.05 K. In the longer run, cryocoolers are also needed for large aperture IR reflectors such as SAFIR. This would involve a large aperture (8-10 m dia.) at around 4-6 K. Detectors would be cooled to sub-Kelvin temperatures. SEU would also develop cryogenic x-ray micro-calorimeters using 6K heat sinks to drive their sub-Kelvin coolers. The ASO Theme's TPF may utilize several apertures at 30-40 K and cryogenically cooled detectors. The SEC Theme would use IR instruments to study Earth's water cycle. The ESS Theme needs cryocoolers to preserve samples from Mars, comets, and other sample-return missions, although the temperatures involved will probably be in the 140–200K range.

The NASA Technology Program has a rich variety of small technology tasks exploring various new concepts for cryogenic cooling of detectors. However, there is one technology development program that is overwhelmingly most relevant to upcoming mission needs: the Advanced Cryocooler Technology Development Program (ACTDP), originated in 2001. This cryocooler program is targeted at providing cryogenic cooling for a class of NASA missions including the TPF, ConX, and NGST. The requirements are representative of those for a flight-model cryocooler. However, in many cases, the engineering model and brassboard electronics hardware deliverables need only meet a subset of these requirements. In these applications the cryocooler load is a 6.5 K detector mounted remotely in a cryogenically cooled instrument that is thermally isolated from, and mounted onto, a room-temperature spacecraft. The cryocooler provides cooling at 6 K to cool the instrument detector, plus cooling at 18 K to cool the detector housing and thermal shields. The baseline operating point is defined as a load of 20 mW at 6 K on the 6K cold load interface in combination with 150 mW at 18 K on the 18K cold load interface with all heat rejection interfaces at their baseline temperatures. This program will not only develop prototype coolers for TPF, Con-X and NGST, but will also explore extensions of the technology to other temperatures and heat loads. It is expected that this program will be a source for most of the cryocoolers that will be used on future OSS missions in the near and intermediate terms and possibly beyond.

Table 6-1 summarizes known needs for cryocooler technologies.

4.1.3 Space Optics

Usually, the largest and most massive component of a telescope is its primary mirror. In order to launch larger and larger telescopes into space, we require new precision materials and structures that allow the areal density of large optical elements to be reduced. This challenge applies equally to normal and grazing incidence optical systems. Technology and processes must be developed to increase apertures, lower areal density, lower operating temperatures, and improve diffraction limited surface quality. But most importantly, this must all be accomplished rapidly and cost effectively. This requires continuous effort in materials, design, fabrication processes, performance characterization, and cryogenic mechanisms.

Early in 1999, the NGST Program embarked on a program called the Advanced Mirror System Development (AMSD) Program to develop the next generation primary reflector. The initial schedule planned for funding three contractors to develop alternate approaches in parallel over about 2 years, with a down-select to one contractor to develop flight mirrors starting in 2002. The parameters of importance to AMSD are: performance, scalability, cost, manufacturability, processes and teaming. Risk would be mitigated by testing a series of ever-increasing size and sophistication. The mirrors would utilize active wavefront control using cryogenic actuators. Later in 1999, NASA announced the award of four contracts, totaling nearly $14 million for the next phase in the development of large, extremely lightweight mirrors for space, under a collaboration between NASA, the United States Air Force, and the National Reconnaissance Office. Later, this Program seems to have been changed and five contractors were engaged to develop mirror systems:

- Raytheon Company of Danbury, Connecticut [silicon carbide - fused silica - beryllium]
- Eastman Kodak of Rochester, New York [lightweighted glass - SiC/glass hybrid]
- Ball Aerospace of Boulder, Colorado [beryllium]
- University of Arizona [glass meniscus]
- COI [silicon carbide].

It is noticeable that during the period from 1998 to 2002, the goals of the NGST reflector have gradually been relaxed in size from 8 m to 6.5 m, and density from 15 kg/m^2 to 20-25 kg/m^2.

Recently, NASA selected TRW to build the Next-Generation Space Telescope. The new space-based observatory will be known as the James Webb Space Telescope. Under the terms of the contract valued at $824.8 million, TRW will design and fabricate the observatory's primary mirror and spacecraft. TRW also will be responsible for integrating the science instrument module into the spacecraft as well as performing the pre-flight testing and on-orbit checkout of the observatory. The large, ultra-powerful infrared-optimized space telescope is designed to study the formation of the first stars and galaxies, the evolution of galaxies, the production of elements by stars, and the process of star and planet formation. When boosted into space, and after a 3-month coast, NGST's final stop is to be 940,000 miles (1.5 million kilometers) from Earth, at the L2 Lagrange Point. Also, NGST is to be outfitted with a large shield that blocks light from the Sun, Earth, and Moon, which otherwise would heat up the telescope and interfere with the observations.

A number of other smaller technology development activities continue to explore new approaches for lightweight reflectors for missions beyond NGST. Of particular interest is the hope that gossamer technologies could provide major breakthroughs in reducing the mass of large apertures for telescopes. NASA and the Air Force have briefly explored some approaches for gossamer reflectors, but this field is in its infancy.

One approach uses plastic membranes and creates two-dimensional curvature by inflating or by electrostatic control. This approach suffers from various difficulties, but might some day be appropriate for very long wavelength applications. The approach has suffered from attempts to push the technology toward visible wavelengths where it becomes very problematic. The attempt to emulate telescope configurations based on conventional architectures using gossamer materials may not be the best way to approach the problem. Some investigators have been examining new architectures that are more natural for thin film materials, such as use of diffractive optics, or use of cylindrical geometries. These may have promise, but they are still in early emergent phases.

A technology that has been explored in greater depth is the build-up of thin lightweight curved reflector sheets by laying them up on a very accurate glass mold. A considerable amount of development work has been done on creating carbon-fiber-reinforced plastic (CFRP) reflectors by this method. Most recently, the attempt was made to perfect this technique for the Herschel Space Telescope. Significant progress was made but these materials have innate non-uniformities that introduce distortions at cryogenic temperatures. In the end, the Herschel Telescope decided to utilize a silicon carbide reflector instead of the CFRP approach.

Another variant on building up thin lightweight curved reflector sheets by laying them up on a very accurate glass mold is known as nano-laminates. It lays down a sequence of thin layers of a metal alloy by sputtering onto a rotating mold. Surface densities in the range 2-5 kg/m^2 are envisaged, and the procedure appears to have the potential for fairly good surface accuracy. Its high thermal conductivity should help in reducing thermally induced distortions.

Thin reflectors created on a mold require a backing structure, and this presents significant technical challenges as well. Ultimately, deformable tertiary mirrors will likely be needed for these systems as well.

Experience shows that pursuit of gossamer mirror technologies has suffered from stop-and-start funding induced by overly exuberant expectations followed by great disappointment. These technologies should be pursued with sober acknowledgement of the challenges and risks based on realistic expectations, without demands for near-term gratification.

Technology development in lightweight, precision optics and coatings also offer the potential for exciting enhancements in future SEC 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.

Table 6-1 summarizes known needs for space optics technologies.

4.2. In Situ Technologies

4.2.1 Avionics in Extreme Environments

Survivability and operation in extreme environments are very challenging for some future ESS missions. Table 4-1 summarizes some mission environments. Table 6-2 summarizes some of the requirements for these environments.

In contrast to these conditions, the X2000 avionics systems are designed to operate between –55 °C and 70 °C. It is clear that any mission deploying only the X2000 or X2000-like hardware will not be able to survive in the environmental conditions described in Table 4-1.

Table 4-1. In Situ Mission Environments.

Mission	Low Temp.	High Temp.	High Radiation Levels	High Pressure	Other Environmental Conditions
Venus Surface Exploration and Sample Return		460°C		90 Bar	Sulfuric acid clouds at 50 km 97% CO_2 at the surface
Giant Planets Deep Probes	-180°C	380°C		100 Bar	
Comet Nucleus Sample Return	-140°C				Dust
Titan In-Situ	- 180°C			1.5 Bar	2-10% Methane Clouds Solid/liquid surface
Europa Surface and Subsurface	-160°C		5 MRad (5 mls Al)		

Hence such missions need to use additional measures (e.g., passive and active thermal control) to compensate for the mismatch between the hardware operating parameters and environmental conditions, or to develop hardware components that can reliably operate and survive in extreme temperature. A hybrid combination of these two approaches is an architecture where all temperature-sensitive components are maintained inside an insulated thermal enclosure and any hardware that is located outside has to be capable of survival in that environment.

A number of technologies are candidates for extreme high-temperature electronics. Conventional Si-based electronics has an upper limit of about 125°C. GaAs is claimed to be useful up to 450°C but this temperature is dangerously close to that at which some processing steps are performed. SiC technology shows great promise for high-temperature applications but it is still in an early stage of emergence. Other candidate semiconductors technologies may be based on GaP, AlN, GaN, cubic BN and diamond. The high-temperature electronics development is a system problem. As temperature increases, materials degrade. For example, polymers and solders melt or break down. Semiconductor die must be attached to packages and wire bonded to leads. These packages must be then attached to high-temperature-capable boards. And finally the system will require reliable passive devices (resistors, capacitors, and inductors).

In principle, Si-CMOS technology should be able to operate at the low temperatures required for CNSR, Titan, and Europa Lander missions. In practice, however, these devices need to be redesigned, and testing is required to verify their functionality at low temperatures.

The major driver for X2000 environmental requirements was the exploration of Europa. This has been a major driver in the selection and qualification of components, including: the choice of semiconductor (ASIC) technology; the requirements for tolerating single-event effects (SEE), which include single-event upsets (SEU) and single-event latch (SEL); the ability to survive a high total ionizing dose (TID); and the choice of shielding technologies to protect components that cannot tolerate large exposures to ionizing dose radiation. However, the X2000 Europa avionics system weighs 100 kg, uses 62 W per string, and occupies about 1/20 cubic meter (with radiation shielding). At this point, X2000 is two generations behind commercial technology, and this gap will grow over this coming decade, unless X2000 continues to scale its space PPC technology from 0.25 micron to lower features sizes. No such plans exist; however, a study is underway funded by JPL to explore those possibilities at 0.18 and 0.13 microns. In addition, the Department of Defense has recently put in place a long-term plan to fund 0.15 micron, radiation-hard foundry technology at Honeywell and BAE in the 2002-2005 time frame. It should also be noted that the current X2000 architecture and design for Europa Orbiter is not ideally suited for a small lander (< 10 kg package) on Europa.

4.2.2 Entry, Descent, and Landing/Aeroassist

Entry, descent, and landing (EDL) technology is needed for a number of future ESS missions in several planetary contexts. The most pressing and well-defined need for EDL is for missions that land on Mars. The object is to land safely within a short distance (5-10 km) of any targeted science site so that a rover can reach it for exploration. Present capabilities for EDL lead to a landing error ellipse of 30 × 100 km. A comprehensive EDL technology development program was devised by the Mars Exploration Program that had three major aspects:

1. Reduce the landing error ellipse to ~ 5 x 10 km.
2. After entry use short-range hazard detection and avoidance technology to maneuver the descending lander to a locally safe area.
3. Utilize a robust landing system to assure that a safe landing can be made on all but the most hazardous terrain, even if the precise landing and hazard avoidance systems fail.

The technology plan adopted by the Mars Exploration Program in 2001 had planned to reach NASA TRL 6 by the end of FY2003, but the program was cut in FY2002 because of lack of funds. This leaves the future outlook for EDL technology in doubt.

EDL is also required for other missions, notably CNSR, VSSR, Europa Lander (EL), and Titan Organic Explorer (TE). These EDL systems are quite different from the Mars case and have to be developed to a large degree separately. The EDL process will be fundamentally different for landing on small bodies such as comets, as compared to large bodies such as planets. Also, there is a significant difference between large bodies with and without an atmosphere, because aeroassist, parachutes and aerobots can only be used if there is an atmosphere. A key difficulty common to all these missions is that Earth-to-spacecraft communication delays are too long to perform EDL maneuvers via ground control. Hence, EDL must be accomplished autonomously with no human intervention.

Airbags are the most likely approach for bodies without an atmosphere, although the "stop-and-drop" propulsive approach may be possible. Contacting and anchoring to small bodies presents many challenges, particularly due to the complexity and variety of the in situ environments, including low-gravity operations, poorly characterized interior structures, insufficiently mapped surface features and unknown surface physical properties.

Aeroassist is a broad term chosen to represent a wide range of applications involving the use of atmospheric forces to execute a pre-planned aerodynamic maneuver. The four categories of aeroassist are direct entry, aerobraking, aerocapture, and aerogravity. Aeroassist technologies provide significant benefits to missions that involve entry, descent, and landing. The most pressing need is for aerocapture technology. Aerocapture has a high potential payoff in terms of mass savings for orbit insertion around distant planets, whether as part of an orbiter mission, or as a step in the process of launching a probe or lander for an in-situ mission. In general, the single subsystem with the greatest mass on such a spacecraft is the stored propellant. The savings generated by an aerocapture spacecraft versus an all-propulsive spacecraft could range from 45% (Mars) up to 82% (Neptune), depending on the mission.

Tables 6-3 and 6-4 summarize EDL technology needs.

4.2.3 Robotics and Planetary Access

Surface Access

Surface access is paramount to any in-situ science mission. Being able to accurately position science instruments at selected sites or on rocks is the most fundamental in-situ surface operation required for a rover or lander. Science instruments are strategically attached to a sample acquisition device such as a robot arm, so that each instrument can be placed in the correct orientation on contact (within the operational envelope of the arm). In some cases surface preparation is required. Various abrasion tools can be used to remove the weathering rind on a rock surface. Other devices are used to deliver samples to processing devices and science instruments.

Of particular importance is the need for component technologies that enable planetary surface sampling systems to be constructed and controlled. These include: advanced actuators (e.g., brushless, piezo), micro-sensors (e.g, rate, position/orientation, imaging, haptic, ranging), lightweight composite structures, sensor-based autonomous control algorithms (precision positioning, flexible structure control, path planning, hazard avoidance, position/torque-based impedance control, combined arm/mobility platform instability accommodation), and dual use of engineering sensors to augment science instruments.

Surface Mobility

Despite the highly successful rover on the Mars Pathfinder mission, and the much more capable rovers developed for the forthcoming Mars Exploration Rovers mission to be launched in 2003, planetary mobility is presently the key limiting factor on the scope, longevity, and extent of Mars surface missions. We can distinguish five generic approaches to surface mobility:

Technical Approach	Relative Maturity	Terrain Accessibility	Range/sol (m)
Articulated wheel rovers	Medium	Medium	~ 100
Inflatable wheel rovers	Low	High	~ 1000
Nanorovers	High	Low	~ 10
Legged rovers	Low	High	~ 10
Hoppers	Low	Very high	~ 10

Within the scope of articulated wheel rovers, improved rover autonomy is needed to enable safe navigation as well as autonomous science operations on Mars's surface to provide the onboard capability to negotiate relatively long distances (100–200 m/day) without supervision from the Earth. The use of the term *autonomy* here is slightly different than that used in Section 4.3.4.2. Autonomy in surface mobility involves providing a rover with sufficient sensors and decision-making power to negotiate a safe path through obstacle-strewn areas without continual oversight from Earth, with its implicit time delays. Technology is also needed to reduce the number of uplinks and downlinks required in making scientific observations. A system is needed for automated science operations and data retrieval and visualization. We also need to understand how the ability of rovers to negotiate terrain varies with scale. Large-size vehicles may be needed for carrying heavier payloads over long traverses on rough terrain.

New approaches based on inflatable wheel rovers and legged rovers have not been studied to any great depth. It is possible that such approaches could provide significant gains over capabilities of articulated wheel rovers for terrain accessibility or range.

Aerial Access

Aerial systems are enabling for missions to Titan and Venus. Titan and Venus have dense high molecular weight atmospheres. Aerial systems could augment other methods of exploration of Mars to cover large areas of rugged terrain where strata are exposed.

Owing to the high density of the atmosphere, successful launch of a Venus ascent vehicle to orbit is only possible at 62 km altitude and above. Hence, some form of air borne carrier is essential to lift samples from the surface to that launch altitude for sample return missions. The surface thermal environment (460°C) renders lengthy stays untenable so that the sampling vehicle must rapidly acquire the sample and then begin the ascent to the upper atmosphere in a period of hours. Aerial systems are also important on a Venus in situ mission without active cooling that would be used to recover a sample from the surface and transfer it to high altitude for analysis. Aerial systems could also be used for long duration near surface missions with active cooling.

For Titan missions, aerial vehicles are enabling in two key respects. First, an aerial vehicle can fly below the clouds that cover Titan and enable high-resolution surface imaging that cannot be done from orbit. Second, aerial vehicles with surface sampling capability can acquire data at multiple, widely separated sites independent of the terrain. Surface roving vehicles are very unlikely to provide this capability.

Aerial vehicles can be divided into heavier than air (HTA) and lighter than air (LTA) concepts. HTA vehicles consist of aircraft, gliders and helicopters. LTA vehicles consist of balloons and airships (balloons with propulsion). Anything but an unpropelled balloon or glider will require a source of power for propulsion. Gliders and balloons are attractive for Mars to explore regions of rugged terrain with exposed strata where rovers would be at a severe disadvantage. As a consequence of severe power restrictions, the LTA approach is the preferred solution to aerial mobility at Titan and Venus. These systems, which have come to be known as aerobots (a contraction of aerial robotic vehicle) include not only the balloon system that provides buoyancy and vertical and horizontal mobility but also guidance and control, communications and the ability to directly interact with the surface autonomously.

Although both Venus and Titan have dense, high-molecular weight atmospheres highly suited to the use of buoyant vehicles, the temperature conditions near the surface of these two bodies are very different. Nevertheless, there is a degree of technology commonality that can be exploiting in technology development in preparation for these missions.

Subsurface Access

One of the key goals of Mars exploration is to locate water on Mars. Subsurface access is vital to this quest. Deep basin, flow channel terminus, and polar cap sites offer possibilities for locating deep aquifers, interstitially bound ice, or ice sheets, respectively. Each site requires a different approach to subsurface access. Lightweight drills or robot arms on rovers and landers can access shallow surface ice. Heavy-duty deep drills or percussive penetration probes will be required to access deep aquifers. Polar caps, however, will require a different approach to subsurface access. Deep penetration will require cryobots (a contraction of cryogenic and robot) that melt their way through the ice sheet using a combination of surface contact heating and recycled hot water jetting to remove dust and debris released into the melt column away from the front of the vehicle. Instruments inside the cryobot allow imaging of the melt column, turbidity measurements, and melt water chemical/biological analyses as the probe descends. For Mars polar caps, penetration depths of ~100's of meters may be possible using surface solar/battery power down a tether with optical fiber communication to the lander. The initial goal is to achieve depths of 10-20 m; the intermediate goal is 100-400 m; and the long-term goal is to achieve depths of up to 2 km. In addition to depth, other requirements are mission-dependent and may involve the ability to bring up samples or cores in pristine condition, or sampling/operation of instruments down the hole. In the case of deep penetration drills, cryobots, or percussive moles, an array of state sensors, advanced materials, and autonomous control/fault management software technologies are needed, because these systems must be actively controlled and steered. Deep drilling cutting bit and debris management technologies will need to be expanded considerably.

Subsurface access will also be important for Lunar, Europa, Titan, and Venus missions. Emerging technologies such as ultra-sonic drillers and corers (USDC) are promising for Lunar rock sampling and Venus surface sampling. USDC technology is particularly suited to harsh environments. Europa and Titan represent extensions of the Mars polar cap environment with the added problem of colder temperatures (~90 K) and significantly different sampling regimes. For both of these environments, either a shallow (i.e., 10’s of cm depth) coring device or cryobot probe/sonde may offer viable options for in-situ subsurface science in either ice or ice/hydrocarbon liquid, respectively. The extreme temperature environments are exacerbated by high radiation on Europa. Both Europa and Titan in-situ science and sampling missions will also require major advances in power distribution and communication technologies. Depending on desired penetration depth, technologies such as radioisotope power systems (RPS) with high specific power, low resistance super-conductors for ultra-low mass tether power, cryogenic optical-fiber materials, and radioisotope heater unit (RHU)-powered micro-ice transceivers will be required.

Sample Processing/Handling

Once samples are obtained either at the surface or subsurface, they must be moved to either a suite of science instruments or a sample return canister. Several critical technologies will enable large and small samples to be processed and distributed in environments like Mars, Lunar, Venus, Europa, or Titan. These include controlled sample manipulation, sieving, filtration, splitting, retention, and disbursement.

Tables 6-3 and 6-4 summarize robotics and planetary access technology needs.

4.2.4 Planetary Protection and Returned Sample Handling

Forward planetary protection must avoid transporting terrestrial organisms to planetary bodies that could (1) contaminate the planet, or (2) appear in returned samples, or (3) interfere with in-situ instruments attempting to detect life. Technologies are needed to detect organisms at extremely low levels as well as for robust cleaning and sterilization methods which preserve spacecraft instrument integrity. One specific goal for this program is to reduce the probability of an Earth-sourced organism in the returned sample to less than 1% from a spacecraft platform cleaned to a 4A level and preferably from 4B, as well.

After samples are returned to Earth, they must be secured to prevent inadvertent release of possible foreign organisms, and the samples must be protected from contamination by terrestrial organisms. Returned sample handling technology includes cleaning and sterilization processes, cold sample storage and processing, and life-detection technology.

Tables 6-3 and 6-4 summarize planetary protection and sample return technology needs.

4.2.5 GNC—Rendezvous and Sample Capture/ Earth Return of Samples

For a Mars sample return, an autonomous sample rendezvous and capture system must be developed with the ability to autonomously locate, track and capture a small sample canister in Mars orbit or deep space for return to Earth. A lunar sample return mission designed to launch the sample into lunar or Earth orbit (as opposed to direct return to Earth) could be used to demonstrate this technology while providing the back-up of a manually controlled system in the event of problems.

For Mars, technology must be developed to provide secure containment of the sample, while preventing any possible Mars organisms from being inadvertently released into the Earth's environment. In order to accomplish this, the chain of contact from Mars to Earth must first be broken without breaking the seal on the container. Similar technology is needed for sample returns from other bodies that may harbor biologically active organisms.

Rendezvous and sample capture technology is also needed for other missions such as SPASR, VSSR and CNSR (see Table 6-4). Some of these requirements are quite different from those of the Mars Sample Return (MSR) mission, although the SPASR mission could be used to verify techniques to be used at a later date for the MSR mission.

4.3. Multi-Mission Spacecraft Technologies

4.3.1 Avionics

Avionics technology needs divide into the following categories:

- Processors
- Memory
- Sensor interfaces
- Data bus and architecture
- Packaging and interconnects.

The X2000 avionics will be optimized for NASA, and will satisfy the needs of many NASA missions. It should be the avionics of choice for many NASA missions. However, X2000 appears to fall short of some of the requirements listed in Table 5-2. As discussed in Section 4.2.1, X2000 is two generations behind commercial technology, and this gap will grow over this coming decade, unless X2000 continues to scale its space PPC technology from 0.25 micron to lower features sizes. The ESS SSETAG has recommended that NASA complete the ongoing 7-year (1998-2005) X2000 campaign, but with significant enhancements from 2003 through 2005. They also recommend development a next-generation avionics system from 2004 to 2009.

Table 6-5 summarizes technology needs in avionics.

4.3.2 Communications

Trunkline Communications to Earth

Technological limits on communications capabilities are a principal constraint on the science return of every science mission. Yet, almost all proposed space missions list communications technology only as "enhancing." The requirements listed in Table 6-6 indicate that the science community appears to feel that it has to live with whatever capabilities the engineers have currently created. The problem is that development of advanced communications systems is too expensive to be developed by individual missions, and only makes economic sense when amortized over the missions that utilize it.

For ESS missions, present limitations on data transmission are about 3×10^4 b/s from Mars and about 2×10^3 b/s from Saturn. This compares with required data rates for various kinds of data such as: SAR (10^5 to 10^8 b/s), multi-spectral imagers (10^5 to 10^9 b/s), video (10^6 to 10^8 b/s), and HDTV (10^7 to 10^9 b/s). By comparison with Earth-orbiting missions, the achievable quality of science data return is orders-of-magnitude less at planetary distances.

SEC missions face some clear technical challenges in the course of the next decade: managing high, uninterrupted data flows from geosynchronous solar-observing spacecraft; communications for multi-spacecraft missions and missions in deep space, relaying real-time data from near-solar encounters or from the far reaches of the heliosphere. Spacecraft exploring interstellar space will require communication links with Earth from distances of many hundreds or even thousands of AU. At the other end of the scale, communication with near-solar spacecraft is complicated by solar radio frequency (RF) emission and frequent conjunction with the Sun. Lastly, constellations in the geospace environment will require communications compatible with nanosats.

Several approaches can be taken to increase the data rates to the outer planets. These ideas can be grouped into the following categories:

- Increased RF frequencies (Ka, V, or W band)
- New apertures (distributed DSN or inflatable antennas for spacecraft)
- Exploiting optical communications
- Increased transmitter power.

The candidate frequencies above X-band (the currently used frequency, 8 GHz) are around 32 GHz (Ka-Band), 50 GHZ (V-Band) and 90 GHz (W-band). The theoretical gains above X-Band in the power density at the receiver are a factor of 16 for Ka-Band, and 1900 for W-band. However, as the frequency increases, atmospheric attenuation due to weather also increases. In practice, achievable performance improvements are noticeably less than theoretical (e.g., a factor of about 4-5 for Ka-band).

The advantage of changing to higher frequencies is well understood and the technical maturity of switching from X-Band to Ka-Band is quite high. A switch to V-Band or W-Band would be far more costly and higher risk, although the increased data rate could be substantial. The higher frequencies are strongly absorbed by the Earth's atmosphere. In-space relays will likely be required to convert the RF to lower frequencies for passing the data to Earth.

Adding antennas to the DSN will increase its capability in proportion to the added area. Since funding is always limited, lower-cost approaches to implementing such improvements in capability are being pursued.

One approach being studied is to use a large array of small receiving antennas on the ground. The satellite TV industry has developed low-cost fabrication methods for moderate size antennas. While inadequate when used alone, if a large number of these smaller antennas are phased up and used as an array, the effective collection aperture can be quite large, even exceeding DSN's 70-meter antennas.

Other ways to improve microwave communications performance is to increase the transmit-antenna aperture size on the spacecraft and/or increase the transmitted power. With limited faring sizes on launch vehicles, larger antennas may need to be deployable or inflatable. Higher radiated power may be available if spacecraft are able to utilize the nuclear reactors now under study. Transmission tubes would then have to be developed to take advantage of that extra power (1,000 W or more).

Another technology being considered for deep space communications is optical communications. The gains resulting from shorter wavelengths can be tens of dBs initially, with more improvements possible as the technology matures.

Initial work has been done on the development of an optical communication flight terminal for deep space. Known as the Optical Communications Demonstrator (OCD), this unit employs a NASA-patented, minimal complexity architecture and has been developed as a laboratory engineering model for a near-Earth transceiver at multiple Gbps, or for a deep space transceiver at kbps-Mbps. NASA/JPL has conducted several optical communications systems-level demonstrations to date.

Like higher RF frequencies, optical signals are also subject to atmospheric attenuation. Typical cloud cover attenuations are large enough to completely block the signal. Thus, an optical communications reception system must be designed with spatial diversity in mind from the beginning. Studies have shown that a network of seven stations, uniformly distributed around the Earth's circumference, can provide continuous availability in the high 90s .

Many of these technology advances, discussed above in the context of ESS missions, would have value for SEC missions as well. Because of the large link distances, spacecraft in deep-space face communications challenges. SEC has some unique needs in regard to large link distances such as systems that provide for high data rate communications from spinning spacecraft in deep space. Specific technology needs for Jupiter Polar Orbiter, Sentinels, and Telemachus include:

- Hi-EIRP telecomm
- Adaptive feed/uplink beacon
- Ka-band transmit network
- DSN 70-m equivalent with Ka-band downlink.

Tools that effectively compress data are vital to maximizing the science return from SEC missions. In wide use presently are lossless coding and compression that enable higher data rates (or reduced power). As mission needs evolve, there is increased interest in the adaptation of lossy compression (ubiquitous in imaging) to particle and even field data as a means of greatly increasing the science return. Experience suggests that there will be niche applications for such methods, especially given severe constraints on downlink.

In 2007, SEC intends to launch Solar Dynamics Observatory, a mission requiring Ka-band communications from geosynchronous Earth orbit (GEO) supporting a 150 Mb/s data rate to move its impressive data volume (high spatial, spectral, and temporal resolution data cubes). Perhaps as soon as a decade later, MTRAP could enter development, its 16K x 16K CCDs requiring Ka-band communications with a data rate ~750 Mb/s or five times that of SDO. Communications is clearly an area demanding both short-term solutions (some of which are underway for SDO) and long-term investments for SEC.

Communication Relays

There are needs for local communications infrastructures between multiple exploration vehicles on or near distant targets. In a situation where a lander is involved, there may be a corresponding orbiter that delivered the lander to the target and was then utilized to serve as a communications relay for data from the lander. For targets of intense investigation, such as Mars, there may even be a need for dedicated communications relay orbiters. Table 6-7 summarizes proximity communication technology needs.

Other Needs

Other communication technology needs include onboard data compression for images, communications data and other data, communications hardware such as onboard antennas, and improved radiometric navigation. Tables 6-8, 6-9, and 6-10 summarize these technology needs.

Return on Investment

The ESS Theme's SSETAG recently performed an informal study to estimate the return on investment in new communications technology for ESS missions. A study was done of the 24 ESS missions currently flying, based on the simplistic assumption that the science value of a mission is proportional to the number of bits of information returned by the mission. The costs of the 24 missions were summed up to provide a conglomerate total cost. The supporting communications infrastructure costs for the 24 missions were then added to the total mission costs to provide the total capital investment required for the entire mission set. Dividing by the number of missions gave the cost of the average mission. Additionally, the aggregate annual achievable science data volumes from each of these missions were also accumulated into a sum. Normalizing again by the number of missions gave the average annual data return per mission. By dividing the average per-mission data volume by the average per-mission cost, the number of bits/dollar generated by an average mission was computed. Then, this process was repeated for various investment strategies. Two new strategies were considered; one simply extended the life of the current DSN (with upgrades for Ka-band communications); the other augmented the DSN with a new Interplanetary Network.

For the current DSN case, the average mission cost was $503M and the average achievable annual return volume was 3 Gbytes. That indicated an average of 6 data Bytes/$. For the DSN extension case, the average mission cost rose to $523M but the per-mission data-return-per-dollar rose to 52 Bytes/$ (over 8 times improvement in the data return). For the new Interplanetary Network, the per-mission cost increased to $574M, but the average mission data return metric soared to 7315 Bytes/$. If an array of small antennas is used, the increase in data rate could be as much as a factor of 250 times. The costs are anticipated to be several billion dollars to enable – but with this increased data rate – the return on investment is potentially quite large.

It might well be that by investing an extra $70M per mission for 24 missions (total = $1.7B) in communications infrastructure, NASA can greatly increase the science return from future missions. The problem with this analysis is that investment of the $1.7B would eliminate three missions if the total NASA budget remains fixed. Is there political support to reduce the number of missions while we improve the communications infrastructure? Also, not all planetary data were created equal. If we have limited resources we will attempt to tap the most important data first. As more data handling capability is added, the value of the additional data per bit will gradually diminish.

Clearly, there is an immediate need for implementation of Ka-band communications capability. The development of optical communications technology will occur more slowly, and should include an appropriate set of early flight demonstrations. Detailed assessments of the ground station infrastructure requirements and corresponding technology developments need to be pursued. Relay networks also need further development.

4.3.3 Guidance and Control

The GNC system provides the space vehicle with the ability to determine its position and orientation with respect to a selected reference, to determine how to maneuver in order to get to a designated destination, and to maintain control and stability in response to external disturbances.

Needs for GNC technology (Table 6-11) include trajectory design, flight path estimation, metrology, and attitude control. Trajectory design is particularly needed for solar electric propulsion missions that involve low thrust over long time periods. Flight path estimation is needed for in situ missions involving aerobots or landers, particularly where a rendezvous is planned between an ascending vehicle and an orbiter. Metrology is an adjunct of constellation control.

Attitude control is a challenging technology on SEC nanosats, where mass and power are strictly limited.

4.3.4 Information Technology/Autonomy

4.3.4.1 Information Technology (IT)

There are many needs for information and autonomy technology on various missions. Ultimately, many of these involve shifting details of execution to the spacecraft, with uplink commands from Earth relegated to higher-level goals. For example, the command might tell the spacecraft to change its orbit, but the spacecraft computer determines how best to do this autonomously. There is also a need for more responsibility in housekeeping (monitoring, diagnosis, and response) to be relegated to the spacecraft. This is particularly true for in situ spacecraft and probes.

Because in situ missions may encounter difficulties or opportunities that were not predicted or imagined by mission planners, they need the capability to avoid problems and also to take advantage of science opportunities. Feature recognition is a critical element of hazard avoidance for landers.

The Office of Space Science has begun a three-phase program to assure that the IT pipeline will flow freely. Phase I was aimed primarily at assessing the relevance of ongoing current IT development programs to OSS mission needs, and promoting interaction and exchange of ideas between suppliers and users of IT. Phase II will be concerned with recommending changes in the Office of Aerospace Technology (OAT) IT Program to enhance relevance to OSS mission needs. Phase III will involve creation of collaborative OAT-OSS programs.

Infusion of IT technology into SSE missions has been slow. This is partly because in the past OAT technology programs have not generally covered infusion costs, and OSS project management structure has not usually included successful demonstration of IT as an important metric in project performance. However, OAT is planning a significant increase in allocations for infusion, and OSS is placing increasing emphasis on IT in its priorities.

A number of findings were reported in the OSS Phase I Report. These were divided into findings regarding OSS users of IT, and IT providers. A selection of a few important findings relevant to OSS users is summarized in Table 4-2. A selection of a few important findings relevant to IT providers are summarized in Table 4-3.

Table 4-2. Findings and Recommendation Regarding OSS Users of IT

Issue	Finding	Recommendation
Infusion paths: defined or vague	Only a small fraction of the IT products are directly relevant and seemingly ready for infusion. The majority of relevant IT R&D lack a defined infusion path into OSS missions and/or lacks the mechanism or funding necessary to implement the infusion even when a customer is identified.	Significantly greater emphasis on infusion plans must be developed in the future
Gaps between existing IT programs and mission needs	"There appear to be obvious and serious gaps between existing IT programs and mission needs in several areas, including processor technology, software reliability, and science data processing." This was seriously exacerbated by FY02 cutbacks in [OSS programs].	Despite significant existing investments in IT, several IT areas may still require augmentation.
Relevance to various OSS Themes	The bulk of NASA OSS-relevant IT is focused on planetary exploration. These call for some of the most exotic IT and thus attract the interest of those on the cutting edge of research. Non-planetary IT challenges are thought more mundane and less promising areas of research. Customers in other themes are viewed as more resistant to the benefits of IT infusion.	IT R&D should serve the needs of each division in OSS. This requires efforts by IT providers, as well as refinement by SEC, ASO, and SEU of IT requirements for their missions.
Mid-TRL development is neglected	The absence of a mid-TRL program addressing IT infusion across all Enterprise Themes contributes substantially to the low infusion of IT into missions.	Resources need to be committed to mid-TRL development and infusion for technology with broad potential payoff to OSS.

Table 4-3. Findings and Recommendation Regarding IT Providers

Issue	Finding	Recommendation
Relevance of IT technology to OSS needs	At high-level, good alignment between the OSS IT user requirements and the ongoing IT R&D activities. The study, however, did not review the ongoing investment in sufficient detail to make an in-depth assessment of this alignment. This study team did not have sufficient resources to permit detailed mapping and assessment of ongoing tasks.	Completing detailed mapping of IT needs to technologies and then prioritizing the technologies requires further analysis. (Phase II)
Level of communication between the two primary organizations (OSS and OAT)	The level of communication between the primary organizations (OSS and OAT) needs improvement. A fair amount of communication at technical level, but did not extend to high-level organizations. Communication depended heavily on existing relationships between individuals as opposed to more structured interaction. Level of communication at all levels improved significantly over course of assessment.	Additional interaction and communication is required to help ensure that current IT investment is leveraged across all OSS Themes and is focused to meet their requirements.
Effective technology transfer from research to application	• Principal investigators, mission managers, and program managers typically base their decisions upon local success criteria that are often sub-optimal when viewed from the Enterprise/Agency perspective. This is particularly true for technologies that are enhancing (as opposed to enabling), even though the total benefit of such technologies from a science-return perspective might be significant. • Information technologies often impact multiple aspects of the mission and hence must be considered early in the mission formulation and design process. Furthermore, it is a common practice for early mission formulation teams to base new mission designs (and success criteria) heavily on existing capabilities and technologies from prior mission designs without regard to emerging technologies.	• Technology providers/ mission developers need incentives. • Program managers must take higher-level view of entire program to help ensure that technologies are infused when most appropriate. • Technology must be appropriately focused on strategic enterprise needs and not just on researcher. • Missions must incorporate knowledge of advanced capabilities early in mission formulation process.

At this point, it is clear at a high level what is needed for NASA missions. However, there is no clear pathway defined yet to get from here to there, nor do there exist good metrics that reveal when we have arrived. Simply stating that we need robust, reliable systems is like the mice saying they "need a bell around the cat's neck." While the end result is of prime importance, there is no good way to assess whether we will arrive there without knowing the route. Without a systematic process for measuring performance within the five areas of information technology, we cannot find a path for achieving the high level goals. The three-phase program outlined previously is aimed at achieving this goal. Phase I is now complete and it has had a good effect already. However, much work remains before NASA achieves a productive unification of IT technology with OSS mission needs.

4.3.4.2 Autonomy

Autonomy is the capability created by a combination of sophisticated onboard (or ground) software and sensor readings, which enable some system-level decisions to be made without ground operators. Autonomy enables operations where uncertainty, light-time delays, or limited communication links to ground controllers make pre-ordained sequencing infeasible. Autonomy can reduce operations costs by migrating decision-making to onboard or ground systems, lessening the need for a large operations staff.

Autonomy implies that the ability to make decisions based on analysis of sensor data is imparted to an onboard or ground computer via software without human intervention. In its simplest form, this might imply that the programmer has thought of every possible eventuality that might ensue, and programmed in a response to each such occasion. However, at a higher level, the program might provide the computer with software that make an optimized decision based on a sophisticated state model incorporating sensor inputs. Autonomy can take several forms:

- Planning and execution
- Intelligent onboard science analysis
- Autonomous sample selection
- Automating operations
- Fault mode command and control.

<u>Autonomous planning and execution</u> might be applied to local management of a traverse of a rover on Mars, in which the rover chooses its own path based on sensor readings, rather than wait for commands from Earth. It could also be used for decision-making for making scientific observations of rocks. Autonomous onboard planning and execution might also be applied to navigation and control of course corrections for spacecraft or altitude adjustment of aerobots. Missions such as Magnetospheric Constellation with 50 to 100 spacecraft need very high autonomy and this must be accomplished with minimal mass, power and cost.

Intelligent onboard science analysis provides software that allows the onboard computer to scan and recognize features or events in science instrument data, and immediately take action such as observing unpredictable, short-lived events (flares, eruptions), or reacquire "bad" data, or down-link high-interest (possibly pre-processed) data.

Autonomous sample selection involves the capability to identify optimal sites for sample acquisition based on evaluation criteria in the program.

Automating operations involves transferring responsibility for functions to a spacecraft or ground system that are ordinarily assigned to ground staff. This might include planning and health monitoring. The cost of Earth-based operations is high. Autonomous spacecraft, systems, and ground stations ease the need for human interaction. Making access to the infrastructure available on demand of the spacecraft when its data buffer is nearing full capacity also relieves the need for rigorous human interactive scheduling for download. Another important point to be made is that high data rate download capability also enables greater use of infrastructure because data can be offloaded faster from the lower data volume spacecraft, thus enabling the infrastructure to service more missions in a fixed time-frame.

Normally, when a spacecraft computer detects a sensor reading that is out of allowable bounds, the spacecraft in put into a safe mode in which only minimal housekeeping functions are active. It then allows operators on the Earth to probe various sensors and subprograms, to locate the problem and remedy it. This can be an involved process, resulting in downtime. If it comes at a critical juncture, or if it recurs repeatedly, it could threaten mission success. Autonomous fault-mode command and control involves providing the onboard computer with enough intelligence to sift through the sensor data and take actions for remediation short of dropping into a full safe mode.

As in the case of IT, although the needs for autonomy can be defined at a high level, the lack of quantitative metrics makes it difficult to assess pathways of getting from where we are to where we want to be, or to even know when we have arrived. The ongoing three-phase process for assessing and revamping IT will also provide important insights in regard to autonomy, which is really a branch of IT. As the next phase evolves, important data and policy directions for autonomous systems technology should unfold.

Table 6-12 illustrates many needs for information and autonomy technology on various missions.

4.3.5 Power

Spacecraft power is typically provided by either a photovoltaic (PV) array or by radioisotope power systems (RPS). PV arrays are the power source of choice for most space missions within 2 AU of the Sun because of their high specific power (50-100 W/kg), efficiency (~26%), and reliability. Over the years, cell efficiency has continuously improved and will continue to improve. There is probably little need for

NASA to develop higher efficiency cells because this will occur as a natural outcome of the push toward higher efficiency for commercial Earth-orbiting satellites, although NASA should play a role in tailoring these cells to its needs, as it has in the past.

However, NASA is planning missions with unique environments for which the present and projected future state of solar power technology is inadequate. This includes missions that

- Require very high power levels and high voltages with light weight for SEP
- Carry sensitive instruments that require that solar arrays be electrostatically clean
- Approach the Sun and endure high temperatures.
- Go far from the Sun (low intensity/low temperature) (LILT)
- Endure strong radiation fields, such as at Jupiter or Europa
- Must operate in the dusty environment of Mars (or comets).

NASA can seek to provide power systems for such applications using either all-solar power or some combination of RPS and solar power. Solar electric propulsion spacecraft are manifestly solar-powered. Other missions could conceivably utilize solar power or RPS. RPS is a more appropriate choice for outer planet missions and would provide benefits for long-life Mars missions. If solar power is chosen for any of these scenarios, specialized solar cell and array technologies must be developed that go beyond the needs of conventional Earth-orbiting satellites. Some SEC missions must be electrostatically and magnetically clean. It is likely that many of these operating within 2 AU of the Sun will utilize solar energy and thus require electrostatically and magnetically clean solar arrays. There may be a few missions, such as the Inter-Stellar Probe, which utilize radioisotope thermoelectric generators (RTGs) and still must be electrostatically and magnetically clean.

In the past, missions that went well beyond 2 AU from the Sun utilized RPS that employed thermoelectric converters (RTGs). They are excellent for long duration missions. However they suffer from relatively low thermal-to-electrical conversion efficiency (~ 6%) that requires relatively large amounts of plutonium fuel, and they are rather heavy, with a specific power of about 4.5 W/kg. SiGe thermoelectrics must operate in a vacuum and are well suited for operation in space, whereas the PbTe-TAGS thermoelectrics require positive gas pressure to suppress sublimation of the PbTe, so this system is best suited for operation in planetary atmospheres, e.g., on Mars.

Several converter technologies are under development with the potential to increase the thermal-to-electrical conversion efficiency and the specific power of RPS. None of these are yet proven to be viable for space missions. Of these, the Stirling converter has the highest maturity. This system, with its 25% conversion efficiency, greatly reduces the amount of heat that must be rejected during cruise, entry, descent, and landing, and it greatly reduces the amount of radioisotopes needed at any power level, compared to RTGs. Such a device is ideal for Mars applications (which may have lifetimes of a few years) but it is not yet proven to have a sufficiently long life for long-duration outer planet missions. The Alkali Metal Thermal Electric Converter (AMTEC) is less mature, but appears on paper to have a potential conversion efficiency in the 16-20% range with a specific power of perhaps 8 W/kg. A longer-term possibility is the development of segmented thermoelectric technology to increase the conversion efficiency of RTGs from about 6% to up to perhaps as much as 12-15% while attaining 10 W/kg specific power.

It is unlikely that NASA can afford multiple RPS technologies for different types of missions because RPS systems are very expensive to develop and implement. Therefore, it is desirable to develop a converter with the best compromise system that can support the greatest number of missions effectively. Regardless of which RPS technology is used, it seems likely that future RPS systems should be packaged into modules supplying a moderate level of power (perhaps 100 watts, BOL) that can be multiplexed for missions that require more power. This gives NASA the greatest flexibility in matching modules to mission power needs.

As part of NASA's new Nuclear Systems Initiative, a NASA Research Announcement (NRA) was recently issued soliciting proposals for conversion technology development to begin in FY03. This is likely to provide significant support for Stirling, AMTEC, advanced thermoelectric, and possibly other conversion technologies. Eventually, a down-select to one of these must be made for implementation. This will reduce the priority of technology for solar arrays that can operate under LILT conditions, although electrostatically clean solar arrays for SEC missions and large arrays for SEP are still needed. However, the implementation cost and mass of such a RPS is likely to be much higher than for solar power. Therefore, solar power may be used on some missions (such as Mars Scout missions) where funding and mass is limited. At a second level, NASA indicates a strong interest in developing a nuclear reactor to power nuclear electric propulsion as a means of opening up the possibility of very ambitious space missions that could not be carried out with RPS or solar power. Previous attempts to develop space reactors were not necessarily encouraging, and many challenges remain, but the benefits of such a technology are likely to be significant for major missions.

The Nuclear Systems Initiative will also investigate feasibility and development of nuclear reactors in space, which could enable major missions involving multiple planetary targets.

Outer planetary missions require low-mass, compact batteries that have a long operational life of 10-15 years. In addition these batteries must have high radiation tolerance capability. Inner planetary missions, such as Venus surface exploration and Venus surface sample return require primary and rechargeable batteries that can operate at temperatures as high as 735 K. Some of the planetary surface and subsurface missions, such as the Europa Lander, Titan In-Situ Explorer, Jupiter Deep Probe, and Comet Nucleus Sample Return require low-mass and compact primary and rechargeable batteries that can operate at temperatures as low as $\leq$ 175 K. Mars orbital missions require low-mass rechargeable batteries with long cycle- and calendar-life capabilities. Mars landers and rovers require batteries with low-mass and volume that operate at low temperatures ($\leq$ 235 K).

Rechargeable lithium ion battery technology with liquid organic electrolytes have been developed by the joint efforts of AFRL and NASA for low-temperature lithium Mars lander and rover applications. Flight hardware is presently under fabrication for the Mars Exploration Rover mission. There still remains the need to improve cycle life and calendar life, develop electrolytes that can enable the operation at temperatures of 215 K and lower, and a need to improve the radiation tolerance of these batteries. Rechargeable lithium polymer battery technology is in an early stage of development (Technology Readiness Level (TRL) 2-3). This technology has the potential for higher specific energy and energy density than liquid electrolytes, but the main advantages are improved safety and flexible configuration. Lithium solid-state inorganic electrolyte battery technology is in a very early stage of technology development (TRL 1-2). This battery technology is projected to eventually have a very high specific energy and long cycle-life and calendar-life capability.

Energy storage needs for themes other than ESS are not clear at this time.

Table 6-13 summarizes power technology needs.

4.3.6 Propulsion

NASA's in-space propulsion technology efforts are aimed at advances in chemical propulsion, solar electric propulsion, aerocapture and solar sails. In this Blueprint, aerocapture is listed under "In Situ Technologies."

Needs for advanced chemical propulsion can be divided into several areas:

- Micro-thrusters for precision control of formation flying spacecraft
- Ascent propulsion for sample return from Mars or other planetary bodies
- Improved chemical propulsion for general space mission applications.

With the demonstration of solar electric power (SEP) by DS-1 to be a robust system in space, the door is now open for missions to exploit SEP. The requirements for SEP include requirements for thrusters and solar arrays to provide power. SEP is enhancing for many missions, and it is enabling for some. The following missions benefit significantly from SEP:

- CNSR (enabling)
- VSSR (enabling)
- All outer planet missions (enhancing)
- MSR (enhancing).

The requirements for SEP thrusters vary from mission to mission. In general, moderate increases in thrust, power, throughput, and specific impulse are needed compared to the thruster on DS-1. Although a number of different electric propulsion thrusters are under development, the shortest path from DS-1 to the required performance appears to be improved ion engines. These improvements appear to be eminently feasible.

In addition, the solar arrays that power the SEP system must be large, lightweight, deployable arrays that can thrust out to the required final SEP operational distance from the Sun (which, depending on the mission, can be as far as 5 AU). The requirements for solar arrays for SEP for outer planet missions were initially conceived assuming that thin film deployable arrays will be developed with very high specific power. This technology is still at an early emergent stage. At this point, the mass and cost of high power arrays appears to be a more serious constraint on SEP than the need for improved thrusters. Analysis is also needed to optimize the use of SEP in mission trajectories.

A solar sail is a propulsion concept that makes use of a flat surface of very thin reflective material that accelerates under the pressure from solar radiation (essentially a momentum transfer from reflected solar photons), thus requiring no propellant. Solar sails can substantially reduce overall trip time and Earth-launch mass for high-ΔV robotic missions in comparison to conventional chemical propulsion systems, and has a potential niche as a relatively low-cost means of propulsion in the inner Solar System (< 5 AU). In addition, the propellant-less nature of solar sails makes station keeping in so-called non-Keplerian orbits conceivable. Solar sails are deemed of great importance for some SEC missions. Mini-Magnetospheric Plasma Propulsion (M2P2), a type of magnetic sail, may be attractive for some ESS missions.

NASA recently announced a space Nuclear Systems Initiative, which will include development of nuclear electric propulsion (NEP). Clearly, it will take many years and considerable funding to develop such a system. In the interim, solar electric propulsion is a viable technology. NEP will have major advantages for major missions that have multiple planetary targets. However, SEP will likely remain as a viable technology for moderate missions.

Table 6-14 summarizes propulsion technology needs.

4.3.7 Structures and Materials

Structures and materials technology needs include:

- Multi-function (structural and thermal) structures to reduce mass
- Extraterrestrial materials simulation for mission planning
- Advanced manufacturing techniques for productions of large quantities of low cost nanosats
- Balloon materials for harsh environments of Venus and Titan and studies of the Earth's upper atmosphere
- Mechanisms for large deployable structures
- Metrology systems for measurement and control of large interferometric systems
- Very low power, deep cryogenic mirror alignment mechanisms

- Mechanical/thermal properties data at deep cryogenic temperatures for new composite materials.

Table 6-15 summarizes needs in structure and material technologies.

4.3.8 Thermal Control and Environmental Effects

Thermal control needs are divided into the following categories:

- Passive cooling of telescopes (sunshields)
- Preservation of cold samples for sample return missions
- Passive thermal control of probes that enter hot or cold environments (active thermal control is a possible alternative)
- Sunshields for missions that approach the Sun
- Multi-function (structural and thermal) structures to reduce mass
- Lightweight louvers and other thermal control hardware
- Capillary pumped loop, loop heat pipes, and deployable radiators
- Spray cooling for high flux applications
- Advanced sensor cooling techniques such as electrohydrodynamic pumping
- Variable emittance surfaces for radiators, solar sails, etc.
- Deep cryogenic thermal switches
- Flexible, deep cryogenic heat straps
- Analytical tools for modeling combined mechanical, thermal and optical design.

Environmental effects include maintenance of uniform spacecraft potential, dust mitigation for dusty environments, and environmental effects associated with use of solar sails together with contamination control techniques for space optics.

Table 6-16 summarizes needs in thermal control and environmental effects (other than cryocoolers).

4.3.9 Sensors/Instruments

Detectors and instruments are central critical technology needs of SEU observatories. These run the gamut from sub-mm, far-IR, near IR, optical, UV, X-ray and gamma-ray instruments; further detail is given in Section 3.1.2. ASO has a need for large format SWIR arrays. A vigorous sub-orbital and ground-based astrophysics instrumentation program is necessary to field and test new technologies and methodologies for space-borne instrumentation. These instrumentation programs are necessary to bridge the gap between low-TRL technology and flight implementation.

The development of large format detector arrays is critical for the sub-mm and far IR astronomy. Both direct detectors (such as bolometers and photoconductive devices) and heterodyne instruments are required.

In the near IR and optical bands, extremely large arrays of imaging detectors based on charge coupled devices (CCDs), and low band-gap array detectors (e.g., HgCdTe) are needed which provide new challenges in production yield, detector uniformity, detector packaging, high-speed readout, and onboard data storage.

Novel photo-cathode materials may achieve significant improvements in UV detector quantum efficiency. UV-sensitive CCDs with lower read noise would be very valuable. So-called "3-D" energy-resolving detectors offer tremendous promise, but the currently available array sizes are too small for the anticipated applications.

The development of cryogenic X-ray micro-calorimeter arrays has revolutionized the field in recent years. For future missions, much larger array sizes (e.g., 1000x1000) are required.

A factor of 25-100 improvement in sensitivity of gamma-ray detectors is required for an advanced Compton telescope.

Development of instrument technologies and instruments of mass and power commensurate with small, multiple-satellite class missions is an imperative.

Owing to the large number of multi-satellite missions in the SEC Roadmap, the development of instrument technologies and instruments of mass and power commensurate with small, multiple satellite class missions is an imperative. Some conventional instruments, such as magnetometers, are already close to the mass and power needed for a constellation mission. Basic versions of other required instruments are rapidly approaching the targets but need additional support (e.g., plasma instruments). A further, third class of instruments will require significant development if they are to be flown on future small-sat missions (e.g., electric field instruments).

In addition, SEC also requires detectors for its observatory-type missions. 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 micro-calorimeter 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.

The SSETAG summarized ESS instrument technology needs are shown in Table 4-4.

Table 4-4. Major Instrument Needs of ESS

Priority	Technology	Rationale for Priority	Current Gaps
1	Mini-GC/MS	Venus deep atmosphere probes; age dating systems Outer planet atmosphere/ surface Comet surface and dust	Several instruments previously funded by PIDDP. Need firm performance targets for missions. Trades of precision/integration time versus mass, power, volume. Sample delivery and concentration
2	Biotic/ prebiotic detection and analysis	Mars, Europa surface and subsurface Titan, comets	Performance targets: detection versus characterization. Comparison of viable instrument techniques: capillary electrophoresis, wet chemistry, GC, Raman, molecular-level imaging (e.g., AFM). Sample delivery and concentration
3	Sample collection and delivery mechanisms	Delivery of samples to GCMS, wet chemistry labs, microscopes, etc.	Each sampling system is tailored and expensive. Few concepts beyond breadboard stage. Laser ablation, drills, diggers, scrapers, etc.
4	Geophysical systems	Subsurface probing by radar, seismic methods. New technologies for NMR, deep EM sounding.	Miniaturization of radar systems and seismic sensors underway. Limited challenges to achieve target goals. Uncertain need for NMR and other new technologies.
5	Mineralogic character-ization	Raman, Mossbauer, X-ray diffraction/fluorescence	Numerous PIDDP-level efforts. Varying challenges with sample orientation and preparation.
6	Imaging systems	Required by most planetary missions	Few APS, CCD, and TIR detectors flight-ready. Microscopes demonstrated for MER mission.

Table 6-17 illustrates many needs for sensor and instrument technology on various missions.

5. TECHNOLOGIES: STATE OF THE ART VERSUS REQUIREMENTS; ONGOING EFFORTS; GAPS

There remains a great deal of work to assess how completely we understand the technology requirements for future missions, and also it is important to develop approximate time scales for when these requirements need to be met. At present, we have assembled all the requirements that are known, but it is likely that others have been missed. The required time scales are vague in most cases.

Rigorous gap analysis requires knowledge of requirements and state of the art. While requirements are known to a considerable extent, the state of the art remains uncertain in most instances, and therefore it is not possible to carry out a satisfactory gap analysis at this time.

This section of the Blueprint is not presented as an accomplished result. Instead it is a rather subjectively assembled set of educated guesses. Its main value is to serve as an indication of what a later edition of the Blueprint might look like after such a valid gap analysis is completed.

5.1 Assessment of Completeness

Mission technology requirements may be divided into three categories where:

(1) We know what the requirements are (blue in Table 5-1).

(2) We don't know the requirements but the need is so long-term that it is not imperative and urgent to develop a clear set of requirements at this time (yellow in Table 5-1).

(3) We don't know the requirements but the need is probably critical and the development is likely to be lengthy, so that we are taking a significant risk without a clear definition that leads us toward a development program (red in Table 5-1).

Table 5-1 provides a summary the technology areas in each of the above categories, color-coded as described above.

For those mission technologies with known requirements, there are three possibilities for the adequacy of the current development program where:

(1) The ongoing program is deemed adequate to provide the needed capabilities at an appropriate time scale (blue in Table 5-2).

(2) It is uncertain whether the ongoing program is adequate to provide the needed capabilities at an appropriate time scale (yellow in Table 5-2).

(3) The ongoing program is inadequate (or there is no ongoing program) to provide the needed capabilities at an appropriate time scale (red in Table 5-2).

Table 5-2 provides a summary of the adequacy of ongoing programs to meet those requirements that are well defined.

Table 5-1. Degree to which technology requirements are known. (See text for color code.)

Technology Element	Relevant Missions	Requirements known?	Comments
Observatory Technologies			
3.5 GNC - Constellation control/ metrology	BBO, GEC, LF, LISA, MagCon, MAXIM, MMS, MC, SPECS, TPF	Requirements are incomplete, vague and high-level in most cases.	Requirements for multiple spacecraft in formation are different than those used for light combining in interferometry.
8.1 Cryocoolers	CMBPol, Con-X, iARISE, ISP, ITMWaves, LF, MAXIM, NGST, SAFIR, SPECS, SPIRIT, SEU Probes,	Requirements for Con-X, NGST, and TPF are known. Others are known with less detail.	ACTDP Cooler for Con-X, NGST, and TPF is a "pathfinder" for all missions that follow.
10.0 Space Optics	Black Hole Finder, Con-X, iARISE, MAXIM, NGST, RAM, SAFIR, SPIRIT, SPECS, SDO, SPI, SUVO, TPF	Veracity of requirements varies from mission to mission. NGST, Con-X seem to be well-defined. Some remain vague.	NGST reflector is "pathfinder" for future near-IR apertures. Con-X is near-term x-ray optic.
In Situ Technologies			
1.2 Avionics in Extreme Environments	CNSR, EL, NO, EO, VSSR, ISP, CNSR, VSSR, TE	See Table A2-2B. Requirements are known to some degree.	Cold, heat and radiation are principal effects.
3.6 GNC - Rendezvous and sample capture/ Earth Return of Samples	SPASR, VSSR, CNSR, MSR	Requirements are very vague.	SPASR may be "pathfinder" for others.
11.0 Entry, Descent and Landing/ Aeroassist	CSSR, CNSR, EL, JPOP, MASR, MSL, MSR, NTP, SPASR, TE, VSSR	Requirements are very vague.	Requirements are different for atmosphere-less bodies and those with atmospheres. Aerocapture and aerobots are important.
12.0 Robotics and Planetary Access	CSSR, CNSR, MASR, TE, EL, MSL, MSR, SPASR, VISE, VSSR	Requirements known at high level. Few details.	Wide range of needs at hi-T, low-T; aerobots, rovers, drills; needs still vague
13.0 Planetary Protection and Sample Handling	CSSR, CNSR, MASR, EL, TE, VSSR, MSR, MSL	Requirements known at high level. Few details.	
Multi-Mission Spacecraft Technologies			
1.0 Avionics (other than 1.2)	CNSR, EL, EO, EXIST, ISP, MC, NO, PKE, SPECS, SRO, TE, VSSR	Requirements known to some degree.	Requirements divide into processors, memory, sensor interfaces, data bus and architecture, and packaging and interconnects.
2.0 Communic-ations	CNSR, EL, iARISE, ISP, JPOP, NO, MC, MMS, MRO, MSL, MSR, NGST, PKE, RAM, SDO, SRO, TE, TE, VSSR	Requirements known to some degree.	Requirements divide into spacecraft-Earth trunkline, proximity, data compression, hardware and radiometry

Table 5-1. Degree to which technology requirements are known (continued). (See text for color code.)

Technology Element	Relevant Missions	Requirements known?	Comments
Multi-Mission Spacecraft Technologies (continued)			
3.0 GNC (other than 3.5 and 3.6)	CNSR, TE, NO, SRO, VSSR, PKE, MSR, MC, EL, EO, Mars 2nd decade, SIM, TPF, LF, MAXIM, GEC	Requirements known at high level. Few details.	Requirements include trajectory design, flight path estimation, metrology, attitude control
4.0 Information Technology/ Autonomy	CNSR, EL, EO, HIGGS, ISP, ISTB, MC, NGST, NO, PKE, SDO, SRO, TE, VSSR	Requirements known at high level. Few details.	
5.0 Power	CNSR, CSSR, EGE, EL, EO, GEC, ISP, JPOP, MASR, MC, MMS , MSL, MSR , NO, NTP, PKB, PKE, SP, SRO, TE, VLL, VSSR	Requirements known to some degree.	Radiosisotope power, PV cells and arrays, batteries, PMAD are major sub-elements.
6.0 Propulsion	CNSR, EL, EO, EXIST, GEC, Geostorm, ISP, ITM Waves, LISA, MASR, MAXIM, MMS, MSL, MSR, NO, NTP, PASO, PKE, SPASR, SPI, SRO, TE, VSSR, Mars 2nd decade	Requirements known to some degree.	Chemical propulsion, electric propulsion, solar sails, ascent propulsion and micro-propulsion are major sub-elements.
7.0 Structures/Materials	CSSR, CNSR, MASR, EL, EO, MMS, MC, VSSR	Requirements known to some degree.	It is likely that there are missing requirements.
8.0 Thermal Control and Environmental Effects (other than 8.1)	CNSR, EL, EO, SAFIR, GSRI, ISP, JPOP, LF, MASR, MC, MMS, NGST, NO, NTP, PKE, SP, SPI, SRO, TE, TPF, VISE, VLL, VSSR	Requirements known to some degree.	Some “requirements” are probably spongy in the sense that the missions will take whatever capabilities can be supplied.
9.0 Sensors/Instruments	CNSR, CMBPol, Con-X, Dark Energy Probe, EL, JPOP, EXIST, iARISE, Inflation Probe, LISA, Mars 2nd decade, EO, EL, MAXIM, MSL, MSR, Scouts, NGST, NTP, TE, RAM, SAFIR, SDO, SNAP, SPIRIT/SPECS, SUVO, VLL, VISE, VSSR	Requirements known at high level. Few details.	Many different requirements for many missions. This is a broad area with as-yet little understanding of overlaps between mission needs

Table 5-2. Adequacy of Ongoing Programs to Meet Known Technology Requirements. (See text for color code.)

Technology Element	Adequacy of Ongoing Program	Comments
Observatory Technologies		
3.5 GNC - Constellation control/ metrology	Inadequate	Requirements not well known
8.1 Cryocoolers	Adequate for near-term missions	ACTDP should provide "springboard" for later missions
10.0 Space Optics	Uncertain	NGST telescope will provide "springboard" for later missions
In Situ Technologies		
1.2 Avionics in Extreme Environments	Varies from mission to mission	X2000 meets some requirements but is inadequate for others
3.6 GNC - Rendezvous and sample capture/ Earth Return of Samples	Inadequate	SPASR may provide technology to other missions if it is funded
11.0 Entry, Descent and Landing/ Aeroassist	Inadequate	MSL technology may be adequate, but aerocapture is lagging. Outer planets are lagging.
12.0 Robotics and Planetary Access	Varies with mission	Mixed bag. Mars may be on target but other bodies are lagging.
13.0 Planetary Protection and Sample Handling	Inadequate	
Multi-Mission Spacecraft Technologies		
1.0 Avionics (other than 1.2)	Uncertain	Difficult to distinguish between "desires" and rock-bottom needs
2.0 Communications	Inadequate	Tendency of missions to live with what is out there. They really need more.
3.0 GNC (other than 3.5 and 3.6)	Uncertain	Requirements not known.
4.0 Information Technology/ Autonomy	Inadequate	This whole field is under review.
5.0 Power	Uncertain	New technology programs are being planned. When they are in place, power will be in much better shape.
6.0 Propulsion	Inadequate	New programs, particularly in SEP, offer hope. Ascent, chem propulsion and solar sails are laggard.
7.0 Structures/Materials	Inadequate	There may also be missing requirements.
8.0 Thermal Control and Environmental Effects (other than 8.1)	Inadequate	Difficult to appraise this area.
9.0 Sensors and Instruments	Varies from mission to mission	This is an extremely broad field of endeavor and should be subdivided.

5.2 Technology Summaries: Tiling Diagrams

Ultimately, it is intended that future Blueprints will produce tiling diagrams that show for each technology the cost to develop, the effectiveness of ongoing programs, and the importance to future missions. Figure 5-1 shows a subjectively drawn tiling diagram for power technologies (nuclear reactor technology is not shown). The code used in this diagram is:

- **Size of Box** represents expected cost to develop technology to TRL 6
- **Color of Box** denotes adequacy of ongoing and planned technology programs to meet needs of missions: (**Red** = least adequate; **Yellow** = incomplete; **Blue** = Most adequate)
- **Mission number** denotes importance of technology to NASA missions:
  (5 = most important to missions; 1 = least important)

This tiling diagram has not been validated and is presented as an example of what a tiling diagram might look like. In later editions of the Blueprint, validated tiling diagrams for a wider range of technologies will be presented.

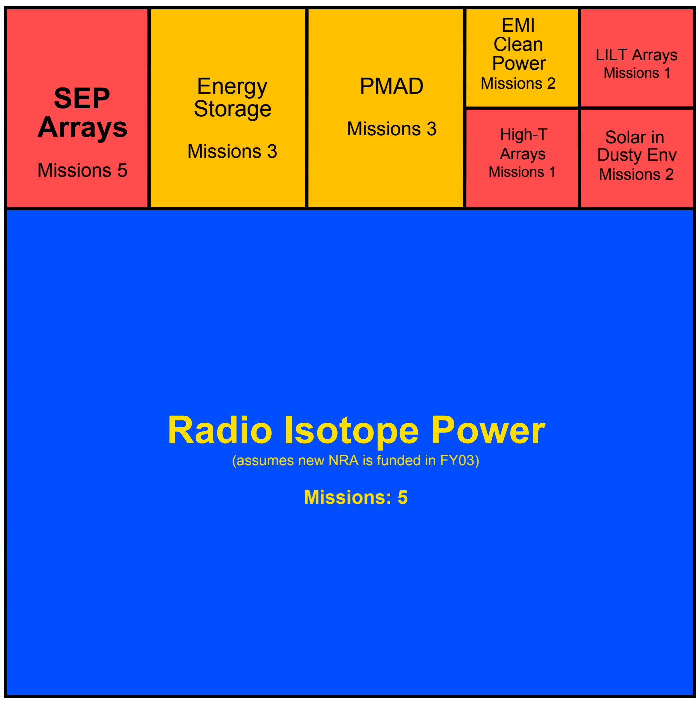


Figure 5-1. Rough Estimate of Tiling Diagram for Power Technology. (see text for interpretation code)

The Radioisotope Power block is colored blue based on the assumption that NASA will fund and carry through to completion, development of advanced conversion systems for radioisotope power based on the competitive NRA issued in late CY 2002. This block is the largest in size because radiosiotope power is relatively expensive to develop. The smaller SEP arrays block was colored red because the focus of development work on SEP up until now has been on thrusters, rather than arrays. However, it is likely that NASA will originate a new development program in SEP arrays in CY2003, which would convert this block from red to blue. NASA will then develop SEP and radioisotope power in parallel.

6. MASTER TABLES COMPARING NEEDS WITH STATE-OF-THE-ART

This Section summarizes the known detailed technology requirements for future OSS missions. Technologies are organized according to the taxonomy described earlier:

Observatory Technologies

3.5 GNC - Constellation control/ metrology
8.1 Cryocoolers
10.0 Space Optics

In Situ Technologies

1.2 Avionics in Extreme Environments
3.6 GNC - Rendezvous and sample capture/ Earth Return of Samples
11.0 Entry, Descent and Landing/Aeroassist
12.0 Robotics and Planetary Access
13.0 Planetary Protection and Sample Handling

Multi-Mission Spacecraft Technologies

1.0 Avionics (other than 1.2)
2.0 Communications
3.0 GNC (other than 3.5 and 3.6)
4.0 Information Technology/ Autonomy
5.0 Power
6.0 Propulsion
7.0 Structures/Materials
8.0 Thermal Control and Environmental Effects (other than 8.1)
9.0 Sensors/Instruments

Each requirement lists the missions driving the technology, the needs, the existing state of the art, a reference to current developments, and a brief assessment of whether current developments are adequate. While the population of the tables is far more complete than for the first edition of the Blueprint, there still remain a substantial number of entries in SOA and ongoing programs that require filling in.

Table 6-1. Space Observatories Technology

Space Observatories Technology	Driving Missions	Needs/ Capabilities	SOA	Current Development	Adequacy
3.5 GNC - Constellation control/ metrology	BBO	Measure graviton quanta with period 1 sec: goes beyond LISA		LISA	
	GEC	Autonomous control of spacecraft outside of 8/5 operations.	Autocon experiment on EO-1	GSFC formation flying work	Yes
	LF	Precision formation flying: autonomous formation flying control architecture and algorithms, baseline: 1000+ m, number of spacecraft: ~ 5, linear accuracy: 1mm, angular accuracy: 10 asec, "laser metrology and interferometric phase control in space at a level of ~ 5 nm"		GSFC and JPL formation flying work (Code R funded)	
	LISA	Optical interferometric measurement of the distance between proof masses separated by 5 million km with an accuracy of 20 picometers, requires laser stability (pointing and phase locking) over hours	LIGO, laser stability over millisec - separation of proof masses by a few km to an accuracy of 10^{-2} picometers	LIGO 2, LISA pre-project	Yes
	LISA	High precision formation flying with spacecraft relative positional accuracy to <10nm/ $Hz^{1/2}$ between 10^{-4} Hz and 1 Hz	Starlight spacecraft relative positional accuracy to 1cm, and pointing accuracy to 3 arc-min	Starlight, LISA preproject, LIGO 2	Yes
	LISA, MAXIM, TPF	Coarse position information for handling of in-space formation initiation and for large scale formation maneuvering	Inter-spacecraft microwave communication system		No
	MAXIM	Metrology to 1 micron	Chandra Optics, SIM Metrology, Chandra CCDs, Astro-E XRS (all single spacecraft)	MSTAR sensor developed at JPL under CETDP	Yes
	MAXIM	Very High Precision Formation Control (10 microns)		Formation control efforts at GSFC and JPL	
	MAXIM, PF	Very High Precision Formation Control (10 microns)		Formation Control efforts at GSFC and JPL	
	MC	Attitude Control System for nanosats Spin rate knowledge < $2X10^5$ rad/sec knowledge of spin axis position < 1 deg, knowledge of spin axis phase < 0.1 deg, spin axis drift rate <0.1 deg over 30 days; Ultra-low power			
	MC	Sun Sensor 0.5 kg, 5 V, 0.2 W, 1 degree			
	MC	Ground based; Automatic control and monitoring of a 50- to 100-spacecraft constellation			

Table 6-1. Space Observatories Technology

Space Observatories Technology	Driving Missions	Needs/ Capabilities	SOA	Current Development	Adequacy
3.5 GNC - Constellation control/ metrology	MC	Orbit placement & determination: Initial control of apogee ± 0.5 Re; knowledge ± 20 km, Δv = 1000 m/s, cost compatible with 20-kg, 20-w s/c costing several million dollars each			
	MMS	Constellation control: 4 or 5 s/c in loose tetrahedral configuration: position knowledge to 1% separation (as low as 100 m), tetrahedron orientation to 15 degrees	ESA mission: 4 s/c, ground tracking	Interspacecraft engrg, Formation flying testbed work at GSFC, APL crosslink transceiver, ITT Low-Power transceiver	Marginal
	SPECS	To mitigate the need for a great deal of propellant for imaging interferometry, tethers may be needed. A spin-stabilized, tethered formation is a possible configuration. Requirement: 10 cm positioning at the end of a tether that deploys to max length of 1 km.	Tether Physics and Survivablility Experiment. End bodies located to 15 cm (1-sigma) on 4-km tether via ground-based laser ranging	CETDP funded tether study (stable architecture, dynamic simulation capability)	No Dynamics, flight-system control
	TPF	Autonomous formation flying control: architecture, sensors, and algorithms, baseline: 75-1000 m, number of spacecraft: 5, linear accuracy: 1mm, angular accuracy: 10 asec, "laser metrology and interferometric phase control in space at a level of ~ 5 nm"		Formation flying sensor, estimator, and controller development work at JPL and GSFC.	
8.1 Cryocoolers	CMBPol	A robust cooling chain that can cool both the optics and the detectors, and maintain adequate temperature stability in all components			
	CMBPol	Cold optics and control of stray light so that the detector sensitivity is limited only by the photon noise of the CMB itself			
	CMBPol	• Detector cooling to 100mK @ 10uW • Optics cooling to 20K @ 10W	• ASTRO-E cyclic ADR • 20K @ 1W (Planck)	• Continuous operation ADR • Planck • ACTDP 18K stage	• ADR OK • Not OK for 20K capacity or temp. Stability (Planck)
	Con-X	Long-duration cooling technology to 50 mK	ASTRO-E cyclic ADR	ACTDP: 6K upper stage; Con-X: 60 mK stage	Yes

Table 6-1. Space Observatories Technology

Space Observatories Technology	Driving Missions	Needs/ Capabilities	SOA	Current Development	Adequacy
8.1 Cryocoolers	Con-X, SPIRIT, MAXIM	Sub-K cooler >4 μW at 50 mK, rejecting < 20 mW heat load to 4 to 8 K cryocooler	ASTRO-E cyclic ADR	Continuous operation ADR, ACTDP	OK
	iARISE	Cryocooler (20K, 5 year life)	None	Planck; ACTDP 18K stage	Yes
	Inflation & Dk En Probes	2-m cryocooled telescope	None	ACTDP	
	ISP	Cryocooler: low-mass, low-power, long life (>15 years) from s/c ambient 35-40 K to <5 K.	None	ACTDP	• Not okay for mass, power, lifetime
	ITM Waves	Cryocooler for IR instrument, consistent with a two-spacecraft mission within STP cost target.	TRL9 down to 50K	ACTDP	
	LF	Extreme cryogenic needs			
	NGST, TPF, Con-X	Power/Temperature:, 0.6 W @ 25°K, 0.1 W @ 12°K, 0.01 W @ 7°K, Lifetime: 10 year goal, L-2 orbit, Vibration: very low, "vibrationless", Mass: low, Efficiency: high		ACTDP, will yield 15 mW at 6K flight-ready by 2005.	Yes
	SAFIR	• Detector cooling to 50 mK @ 10 uW • Detector cooling to 1K @ 10mW	• ASTRO-E • Liquid Cryogen systems	• Continuous operation ADR	ADR OK
	SAFIR/ SPECS	Active cooling systems for filled aperture telescope, operating wavelength: < 0.5 mm (40-500 mm), telescope operating temperature: < 15 °K	None	ACTDP	ACTDP provides a start but needs to go well beyond current ACTDP
	SPIRIT, MAXIM	20 to >100 mW cooling at 4 – 8 K with 1 μN residual vibration	None	ACTDP	Vibration is secondary concern in ACTDP
10 Space Optics	Black Hole Finder	Wide-field hard X-ray optics			
	Con-X	Hard X-ray mirrors with high reflectivity from 6 to 40 keV with 1 arc minute resolution (8 arc minute FOV)	Astro-E		
	Con-X	Lightweight (180 kg per 1 of 4 spacecraft), high angular (15 arc-second) resolution soft X-ray mirrors. Multiple nested mirrors using replicated or segmented optics	ASCA, BBXRT, XMM, Chandra 3-4 nested mirrors	Con-X pre-project	No

Table 6-1. Space Observatories Technology

Space Observatories Technology	Driving Missions	Needs/ Capabilities	SOA	Current Development	Adequacy
10 Space Optics	iARISE	Antenna (25 m dia, 0.2 mm effective figure accuracy).	Unknown performance in space due to failure of IAE to inflate properly.	L'Garde 7 m protoype inflatable antenna has 1.3 mm rms surface error – not space demonstrated	Surface error – yes Size – no; need to go from 7 to 25 m; thermal issues remain
	MAXIM	Diffraction limited X-ray optics for 3 x 10^{-8} arcsec	Chandra Optics, SIM Metrology, Chandra CCDs, Astro-E XRS	Chandra optics technology does not exist and it would cost >>$10M to redo Chandra. MAXIM needs substantially larger area, lower weight, and higher precision; these conflict with each other.	No.
	MAXIM & MAXIM PF	3 cm by 100 cm λ-mirrors with smoothness of λ/100 for Pathfinder, λ/200 for full MAXIM	Chandra (quantitative capability in same units as requirement not available)		No
	NGST	6.5 m aperture with areal density 20-25 kg/m^2	HST: 2.5 m @ 200 kg.m^2	Recent contract to TRW to build telescope	Yes - if all well on TRW contract
	SAFIR, SPIRIT/ SPECS	<10 kg/m^2 areal density(1 kg/m^2 goal) deployable filled primary mirror 3-10 m diameter, diffraction limited at 30 μm, with good thermal conductivity at 4 K	• HST – 2.4 m diameter 180 kg/m^2, 270K, diffraction limited (post correction) at 0.3 μm • SIRTF – 0.85 m diameter 28 kg/m^2, 4 K, diffraction limited at 3 μm	AMSD for NGST and DoD – actuated 1.5 m diameter, 15 kg/m^2, 30 K, diffraction limited at 2 microns – delivery 2003	• real density – no • Operating T – yes • Actuators – no
	SCOPE, MTRAP, RAM	Precision UV Optics: 1-m f, 10-Å figure, 30-Å micro-roughness mirrors > 1-m diameter, < 10 kg/m^2, diffraction-limited at 120 nm. SOA: 0.5-m, ~ 18 kg/m^2	SOA: 15-cm f, 10-Å figure, 3-Å micro-roughness	Lightweight precision optics IRD task: >50 cm size, 30-60 Angstrom figure, 8 Angstrom microroughness	Need scale-up from to larger size from SOA
	SPECS	Cryogenic delay line with ~2 m of optical delay, low vibration	COBE FIRAS mirror transpor mechanism	TPF-funded cryo-delay line study working at LN2 temperature	No; Need lower operating temp (~4K), longer stroke length

Table 6-1. Space Observatories Technology

Space Observatories Technology	Driving Missions	Needs/ Capabilities	SOA	Current Development	Adequacy
10 Space Optics	SPECS	IR wide-field imaging interferometry: need Michelson stellar interferometer with several arcmin field of view; direct detectors	Mosaicing in ground-based radio and mm wavelength interferometry with coherent receivers.	Wide-field Imaging Interferometry Testbed at GSFC.	No. Further technique and algorithm development needed.
	SUVO	4 m x 8-12 m monolithic mirror. Field of view ~14' x 14'	HST - need to achieve increases of ~2.8 in aperture, ~5 in throughput (principally detector capability), and ~>2 in observing efficiency.	HST	No
	TPF	3 m-4 m dia. precision collectors (diffraction limited at 1-2 microns, temperature ~ 35K, areal density ~ 15 kg/m^2)	HST 2.4m (diffraction limited at 0.3 micron, areal density TBD kg/m^2)	NGST	NGST is starting point

Table 6-2. Non-Mars In Situ Technology Requirements: Avionics in Extreme Environments

Mission	Environment	Metric	Requirement
CNSR	Mission trajectory through galactic cosmic radiation	Total dose 20-50 Krad, SEU threshold LET: 20 MeV-cm^2/mg, SEU error rates are 10E-7 to 10E-8 errors/bit-day	Rad tolerant electronic systems, Rad tolerant mixed signal/ mixed voltage circuits
CNSR	Cold comet environment	System to reliably operate at 150 K in addition to 50K Rad TID	Rad tolerant low temp integrated electronics
EL	Intense radiation fields of Jupiter	2 M rad hard electronics systems and instruments.	
EO	Intense radiation fields of Jupiter		
ISP		Require radiation hardened microelectronics in the 100 KRad/100 mil range.	Radiation tolerant electronics
NO	Long transit mission	Radiation tolerance of 20 K rads in 12 years, Science data bit error rate better than 1 x 10-5 per bit per day	High density analog rad hard SEU immune electronics, 0.25 micron technology rad hard SEU immune next generation SOAC power electronics.
TE	Extreme (low) Temperatures: 90K		Cold electronics
VSSR	Vicinity to the Sun for radiation considerations.	Electronics tolerant to 23.7 Krads or better, SEU / SEL immunity up to the LET of 75 MeV/mg.cm^2	Radiation tolerant electronics
VSSR	Surface temperature of 700 K and a high pressure of 90 bars	High temperature tolerance of up to 420C and pressure tolerance of 100 atm pressure for > 1.5 hours	High temperature electronics thermally shielded in high pressure enclosures

Table 6-3. Mars In Situ Exploration Technology

Mars In Situ Technology	Driving Missions	Needs/ Capabilities	SOA	Current Development	Adequacy
3.6 GNC	MSR	• Rendezvous and sample capture • Sample containment & Earth return (Note 5)	Relatively little	MTP	No
11.0 Entry Descent and Landing	Mars 2nd decade missions	Aerocapture - reduce total spacecraft mass by 50% compared to propulsive capture	Not understood	MTP	No
	Mars 2nd decade missions	100 m < landing error, advanced hazard avoidance, robust landing system	30 x 100 km landing error, no hazard avoidance, PF landing system	MTP	No
	MSL, MSR, MLLN	5 x 10 km landing error, hazard avoidance: detect 30 cm hazards at 40-1000 m range with 200 m propulsive traverse, robust landing: tolerate 1 m hazards on 30° slope	30 x 100 km landing error, no hazard avoidance, PF landing system	MTP	Uncertain
	MSL, MSR	Landed mass of 1700 kg	300-700 kg	MTP	Uncertain
	MSR	Descent Autonomous Precision Navigation < 1 km	60 km	MTP	No
12.0 Robotics and Planetary Access	MSL	Long Range Surface Mobility (2 km)	Sojourner	MER, MTP base program	Yes
	MSL, MSR, Mars Scout missions	Surface and Aerial Mobility • Rover traverse 5-10 km in 100 sols • Long range systems (balloons, aircraft, inflatable rover)	• Rover traverse 0.5-1.0 km in 100 sols • No proven technology for aircraft, balloons, inflatables	MTP	No
		Subsurface access w/ mass and power limits • 2-20 m drill - short term • 200-400 m intermediate term • 2 km long term	0.5 m trench	MTP	No
	MSR	In Situ Sample Acquisition Sample Containerization	Some R&D on drills MTP – MSR tech	None	No
13.0 Planetary Protection and Sample Handling	MSL, MSR	Reduce probability of Earth-sourced organism in returned sample to < 1% without high temperatures	Heating to high temperatures	MTP Base Program	No
	MSR	Back Contamination Control Sample Containerization Terrestrial Sample Handling and Science Analysis	Lunar sample receiving facility	MTP Base Program	No
	MSR	Effective, affordable, autonomous sample return: • Sample containment & Earth return • Returned sample handling	Relatively little	MTP	No

Table 6-4. Non-Mars In Situ Technology Requirements

Non-Mars In Situ Technology	Driving Missions	Needs/ Capabilities	SOA	Current Development	Adequacy
3.6 GNC - Rendezvous and sample capture/ Earth return of samples	SPASR	Rendezvous and Sample Return (RSR) Technology	Shuttle-ISS	ST-6, MTP	no
	VSSR	Balloon launch to orbit Safe, accurate rendezvous and docking of two vehicles in orbit about Venus.	None Shuttle-ISS	None	No
	CNSR	Safe, accurate rendezvous and docking of two vehicles far from the Earth.			
11.0 Entry, Descent and Landing	Asteroid SR	Safe EDL for airless bodies 1200 kg @ 0.5 m/s descent autonomous precision navigation, anchoring			
	CNSR	**Landing system for small bodies:** • Touchdown relative v ≤ 2 cm/s • Deviation from desired orientation ≤ 5° • Landing accuracy ≤ 50 m • Solar array clearance > 1 m • Hazard avoidance (> 5 cm) **Return to Earth:** • Ballistic reentry capsule to survive 12.5 km/s velocity regime • Compatible with 150 K sample maintenance			
	CNSR,CSSR	Ballute/Aeroshell for aero entry for 13-16 km/s ΔV and mass fraction <TBD% in Earth return	Pathfinder: 10 km/sec ΔV, mass fraction 10%	None	No
	CSNR, CSSR	Safe EDL for airless bodies 640 kg @ 0.5 m/s descent autonomous precision navigation anchoring	Limited experiment with NEAR	None	No
	EL large lander	Safe EDL for airless bodies 490 kg @ 70 m/s Descent Autonomous Precision Navigation, accuracy and hazard avoidance relative to surface features (1 km accuracy).			
	EL small lander	Safe EDL for airless bodies 33 kg @ 70 m/s Descent Autonomous Precision Navigation, accuracy and hazard avoidance relative to surface features.			
	JPOP	Ballute/Aeroshell for AeroEntry for 60 km/s ΔV mass fraction <50%	Pathfinder: 10 km/sec ΔV, mass fraction 10%	None	No
	MASR	Ballute/Aeroshell for AeroEntry for 8-10 km/s ΔV and mass fraction <TBD%	Pathfinder: 10 km/sec ΔV, mass fraction 10%	None	No
	NTP	Ballute/Aeroshell for AeroEntry for 5-8 km/s ΔV and mass fraction <50%	Pathfinder: 10 km/sec ΔV, mass fraction 10%	None	No
	SPASR	Safe EDL for airless bodies 1560 kg @ < 1 m/s Descent Autonomous Precision Navigation	Surveyors, Russian SR missions	None	No

Table 6-4. Non-Mars In Situ Technology Requirements

Non-Mars In Situ Technology	Driving Missions	Needs/ Capabilities	SOA	Current Development	Adequacy
11.0 Entry, Descent and Landing	SPASR, CSSR, TE, CNSR, MASR	Hazard avoidance Autonomous detect and respond to science opportunities	MTP R&D	None	No
	SPASR, MASR	Earth Return Vehicle (8-10 km/s)	Stardust (8-10 km/s)	None	Yes
	TE	Safe landing on the surface - accuracy and hazard avoidance relative to surface features.			
	TE	Hazard avoidance			
	TE	Ballute/Aeroshell for AeroEntry for 6 km/s ΔV and mass fraction <27%	Pathfinder: 10 km/sec ΔV, mass fraction 10%	None	No
	VSSR	Safe landing on and hazard avoidance relative to the surface of Venus are needed.			
	VSSR	Ballute/Aeroshell for AeroEntry for 4-5 km/s ΔV and mass fraction <TBD%			
12.0 Robotics and Planetary Access	CNSR	Sample acquisition: • Return 200 to 500 cc of pristine cometary volatiles and dust • Obtain 3 to 6 samples from the surface and intermediate depths, up to 1-2 meters, with a substantial portion from the greatest depth • Segregate each sample at < 150 K • Integrate with sample handling chain			
	CSSR, CNSR, MASR	In Situ Sample Acquisition Sample Containerization	Some R&D on drills MTP – MSR tech	None	No
	CSSR, CNSR, TE, MASR	Autonomous anchoring			
	EL	In Situ Sample Acquisition; Sampling of ice from a depth of at least several centimeters below the surface; Prepare sample for instruments	Some R&D on drills	Mtp	No
	SPASR	In Situ Sample Acquisition Sample Containerization	Some R&D on drills MTP – MSR technology	None	No
	TE	Aerial Mobility: Materials for extremely cold environments (90 K)	None	None	No
	TE	In Situ Sample Acquisition Sample Containerization	Some R&D on drills MTP – MSR tech	None	No
	VISE	Aerial Mobility: Materials for extremely hot environments (730 K, sulfuric acid) payload = 30 kg = 20% mass fraction, 6 days operation @ 0-65 km altitude	None	None	No

Table 6-4. Non-Mars In Situ Technology Requirements

Non-Mars In Situ Technology	Driving Missions	Needs/ Capabilities	SOA	Current Development	Adequacy
12.0 Robotics and Planetary Access	VISE, VSSR, VLL	In Situ Sample Acquisition; Prepare Sample for Instruments; Coring device and sample handling system that can survive the surface environment and acquire a ~10 cm sample core ~1 cm dia. from hard basalt and manipulate into the sample capsule of VAV	Some R&D on drills Some R&D	Mtp None	No
	VSSR	Aerial Mobility: Materials for extremely hot environments (730 K, sulfuric acid) payload = 400 kg = 20% mass fraction, 1 day operation @ 0-62 km altitude			
	VSSR	• Balloon or blimp - material must provide adequate strength at 460 °C and tolerate sulfuric acid - requires thin material, low molecular weight buoyancy gas, and lightweight inflation hardware. Must lift 480 kg ascent vehicle to 60-70 km and provide stable platform for launch. • Sample acquisition of atmosphere and subsurface core to 20 cm • Sample preservation	Pioneer Venus None None	Some balloon deployment testing - only for Mars environment Mars Drill None	Inadequate Inadequate Inadequate
13.0 Planetary Protection and Sample Handling	CSSR, CNSR, MASR	Back Contamination Control Terrestrial Sample Handling and Science Analysis	Lunar sample receiving facility	None	No
	EL	Forward Contamination Control	Viking	MTP Base Program	Yes
	VSSR	Sample containerization; Terrestrial Sample Handling and Science Analysis			
	EL TE	Validation of terrestrial bio-contaminant sterilization is required for all spacecraft subsystems and subsystems			
	CNSR	Sample container remains sealed during Earth return as part of achieving 10^{-6} probability of release of >0.2 micron particle into Earth's biosphere.			

(Note: this table was prepared just prior to going to press on this Blueprint and there was not enough time to fill in many table entries. This will be upgraded in future editions.)

Table 6-5. Avionics Technology Requirements

Avionics Technology	Driving Missions	Needs/ Capabilities	SOA	Current Development	Adequacy
		See Table 6-2 for harsh environments			
Processors	CNSR	500 MIPS, <300g, rad tolerant			
	NO				
	EL	1000 MIPS, <1W, 2MRad			
	EO, PKE	High rate imaging: > 100 Mb/s			
	EO	>1000 MIPS, <5W, 4 MRad			
	MC	0.25 kg, 0.8 W, 100 kRad Si (total dose), instrument rate 10 kbit/s, 4 Gbit storage. Consistent with 100-spacecraft, 10-Kg, 10-W, $700K unit spacecraft cost			
	PKE	>1000 MIPS, <5W, 12-15 yrs			
	VSSR orbiter	>1000 MIPS			
	VSSR Lander	<1W			
	SRO	100-200 MIPS			
	ISP	>250 MIPS			
Memory	CNSR	Volatile, >2 Gb, >50 krad			
	CNSR	Telecomm, 2 Gb			
	EL	Volatile, 2000 krad			
	EL	Telecomm, 0.15 Gb			
	NO	Non-vol, 0.5 Gb			
	NO	Telecomm, 3.5 Gb			
	EO	Rad-hard mass memory: 1 Mrad, >1 Gb, speed > 50 Mb/s, power < 10 mW/Gb			
	EO	Telecomm, 2.2 Gb			
	PKE	0.5 Gb, Jupiter gravity assist > 50 Mb/s			
	PKE	Telecomm, 2.2-6.6 Gb			
	SPECS	Massive onboard storage; fast rad-hard processors			
	VSSR	0.5 Gb			
	VSSR Lander	Telecom, 1 Gbm			
	TE	0.5 Gb			
Sensor Interfaces	CNSR	10 Mbps			
	EL	>200 Mbps, >1 kHz			
	EO				

Table 6-5. Avionics Technology Requirements

Avionics Technology	Driving Missions	Needs/ Capabilities	SOA	Current Development	Adequacy
Sensor Interfaces	PKE	>100 Mbps, >1 kHz			
	VSSR	>400 Mbps			
	SRO	10-20 Mbps, 150-250 mW			
	TE	>1 kHz			
	ISP	50 mW			
	EXIST	0.1 mW/channel			
Data Bus and Architecture	EL	400 Mbps, fault-tolerant			
	EO	>100 Mbps, <10ms, dual, fault-tolerant			
	NO	>400 Mbps, <10ms, dual or triple, fault-tolerant			
	PKE	Fault-tolerant			
	VSSR	>1000 Mbps, fault-tolerant			
	SRO	>400 Mbps, <10ms, fault-tolerant			
	TE	Fault-tolerant			
	MC	Fault-tolerant			
	ISP	Fault-tolerant			
Packaging and Interconnects	EL	Radiation, cold, wet			
	EO	Radiation			
	PKE	15-20 yrs, low T			
	SRO	10-15 yrs, low M, Low P			
	TE				
	VSSR	High T, P			
	ISP	Compact packaging using integrated structure and electronic			
	NO	15+ yrs, low T			

Table 6-6. Spacecraft-Earth Communication Requirements.

Mission	Phase	Uplink/ Downlink	From	To	Requirement	State of the Art Spacecraft-Earth Comm	Desired	Would use if available
CNSR	High Rate	D	5 AU	Earth	324 Mbpd	10 kbps	100 kbps	1 Mbps
CNSR	Cruise	D	5 AU	Earth	108 Mbpd	10 kbps	100 kbps	
CNSR	Emergency	D	5 AU	Earth	50 bps	50 bps	500 bps	
CNSR	High Rate	U	Earth	5 AU	2 kbps	2 kbps		
CNSR	Cruise	U	Earth	5 AU	2 kbps	2 kbps		
CNSR	Emergency	U	Earth	5 AU	20 bps	20 bps		
CNSR	High rate		s/c	probe 50 km	72 kbps	72 kbps 400 MHz UHF 0.5W xmtr 2.3 kg 1 W	MCAS	
CNSR	High rate		probe 50 km	s/c	73 kbps	73 kbps 400 MHz UHF 0.5W xmtr 2.3 kg 1 W	MCAS	
EL	High Rate	D	Europa	Earth	265 Mb in 10.5 day encounter		2 kbps	
EL	Emergency	D	Europa	Earth			10 bps	
EL	High Rate	U	Earth	Europa	2 kbps		20 kbps	Higher rate
EL	Cruise	U	Earth	Europa				
EL	Emergency	U	Earth	Europa				
VSSR	High Rate	D	Venus	Earth	4 kbps	4 kbps	40 kbps	
VSSR	Emergency	D	Venus	Earth	10 bps		20 bps	
VSSR	High Rate	U	Earth	Venus	500 bps		5 kbps	Higher rate
VSSR	Cruise	U	Earth	Venus				
VSSR	Emergency	U	Earth	Venus	10 bps		100 bps	
SRO	High Rate	D	Saturn	Earth	55 Gb in 30 days	SOA cannot meet reqt	100 Gb in 30 days	
SRO	Emergency	D	Saturn	Earth	10 bps w/10° s/c antenna		10 bps w/ 50° s/c antenna	10 bps w/ 100° s/c antenna
SRO	High Rate	U	Earth	Saturn	2 kbps		4 kbps	
SRO	Emergency	U	Earth	Saturn				
NO	High Rate	D	Neptune	Earth	2 Gb in 30 days		Higher	
NO	Cruise	D	Neptune	Earth	100 bps from 30 AU			
NO	Emergency	U	Neptune	Earth	2 kbps to 30 AU			
NO	High Rate	D	Neptune	Earth	220 Gb in 2 yrs	70 m gnd, 20W Ka-band 3.3 m s/c antenna	6 m inflatable antenna, optical communication	
TE	High Rate	D	Titan	Earth	2 Gb in 30 days		Higher	Even higher
TE	Emergency	U	Earth	Titan	maintain comm all mission phases		Use wider beam antenna	Even wider beam antenna
EO	High Rate	D	Europa	Earth	18 Gb in 30 days		30 kbps	
EO	Emergency	D	Europa	Earth			10 bps full sky omni	
EO	Emergency	U	Earth	Europa	2 kbps		20 kbps	Higher rate
PKE	High Rate	D	Pluto	Earth	2.2-6.6 Gb (300 bps)		700 bps	2000 bps

Table 6-6. Spacecraft-Earth Communication Requirements.

Mission	Phase	Uplink/ Downlink	From	To	Requirement	State of the Art Spacecraft-Earth Comm	Desired	Would use if available
PKE	Emergency	D	Pluto	Earth	10 bps narrow beam		10 bps wider beam	10 bps full sky omni
PKE	Emergency	U	Earth	Pluto	10 bps narrow beam		10 bps wider beam	10 bps full sky omni
SDO	Continuous	D	GEO	Earth	40-60 Mbit/s			
MRO		D	Mars orbit	Earth	1 - 2 mbps			

The data in Table 6-6 are preliminary and have not been validated. One reviewer said: " *For EL, it is hard to believe that the mission cost can be justified on only 2 kbps for the high rate downlink, particularly when the desire for the uplink alone is 20 kbps. Is this a mistake? For NO and SRO, it seems that the missions might desire substantially more. Are they afraid to ask? For EO, it is hard to believe that 30 kbps high rate data is adequate to justify the cost of the mission. With all the scientific interest in Europa, it would seem that looking at it through a very small data rate window would not be desired. General uplink - It would seem that with software-intensive spacecraft emerging, there are increased needs for software program uploads. Uplink data rates of only 2 kbps are awfully low. Shouldn't the 'desire' be for much more in all of these missions?*"

Another said: "*The missions in Table 6-6 certainly appear to adhere to existing technology . It would seem worthwhile to determine how science could be improved with significantly higher data rates*."

Table 6-7. Proximity Communication Requirements

Mission	Requirement	Metric
MSL, MSR	Develop a multi-channel, reconfigurable, modular, programmable, compact radio - for landers, rovers, orbiters with communications protocols that are easily evolvable from mission to mission. Develop a network node for precise navigation location function	Increase the data rate for Mars proximity communications to 1-2 mbps
Mars Scout 1		50 Mb/day (12 minutes) to CNES 1 orbiter, Baseline: 450 Mbps, Desired Capability: 100 Mb/day, Would use if avail: 200 Mb/day
Mars 2nd decade		0.5 Gb/day (12 minutes) to CNES 2 orbiter, Baseline: 450 Mbps, Desired Capability: 1 Gb/day, Would use if avail: 2 Gb/day
EL	Proximity Communications in severe environments: high radiation	
NTP, TE, JPOP	Proximity Communications – VHF Communications in severe environments: high pressure/temp	

Table 6-8. Spacecraft Data Compression Requirements

Mission	Title	Compression Requirement	Desired
NGST	Lossless data compression, error correcting codes		
EO	Onboard image processing	10:1	
EO	Comm data compression		
NO	Onboard image processing	10:1	
NO	Comm data compression	8:1 lossy	20:1
CNSR	Comm data compression	8:1	Higher
CNSR	Comm data compression - probe	8:1	Higher
EL	Comm data compression	2:1	Higher
VSSR	Main s/c data compression	10:1	
VSSR	Probe data compression		
SRO	Comm data compression		
TE	Onboard image processing	10:1	
TE	Main s/c data compression		
TE	Probe data compression		
PKE	Comm data compression	Unknown	
MMS	Plasma distrib functions data compression	5000:1	
MMS	Broad band field data compression	100:1	

Table 6-9. Communication Hardware Requirements

Mission	Title	Requirement
ISP	Antenna	2.8 m rigid, < 2 kg/sq m; survive 16 suns perihelion
ISP	Ka band SSPA	50% DC to RF conversion
ISP	Pointing system	Point far-field antenna to 0.02°
ISP	Space Transponding Modem	SOAC based
MC	X-band transponder	ST5 transponder: resources consistent with 20 kg, 20 W, $1.4M s/c
ISP	Optical Comm	Flight-qualified, lightweight optical communications transceiver terminal. Integrated telescope and deep space optical communications ground receiver systems.
iARISE	Optical Comm	1-8 Gbps

Table 6-10. Radiometric Navigation Requirements

Missions	Requirements
TE (6 yrs) SRO (8-10 yrs) NO (12-13 yrs) PKE (8-9 yrs)	Radiometric navigation: Accurate navigation during cruise is desired, with minimal ground operations cost. The spacecraft's flight path must be estimated and controlled accurately at the time of atmospheric entry.

Table 6-11. Guidance and Control

GNC Technology	Driving Missions	Needs/ Capabilities	SOA	Current Development	Adequacy
		See Table 6-1 for constellation control			
		See Tables 6-3 and 6-4 for rendezvous & sample capture			
Trajectory design	EL, EO	Trajectory Design Algorithms/Delta-V Efficient Trajectory Design - multiple gravity assists			
	SRO	Trajectory Design Algorithms/Delta-V Efficient Trajectory Design			
	MC	Orbit placement & determination: Initial control of apogee ± 0.5 Re; knowledge ± 20 km, Δv = 1000 m/s, cost, mass production compatible with 20-kg, 20-w, $1.4M spacecraft,			
	MSL	The communications infrastructure (at Earth, Mars relays, and Mars surface) should be capable of supporting distance measurement and velocity for an incoming Mars spacecraft so that that spacecraft would be capable of autonomously entering the Mars atmosphere at a precise target point.			
	MSR	Develop tools for designing optimized low-thrust (SEP) trajectories for Mars applications, including planetary orbit insertion and orbital maneuvers.			
	CNSR, TE, NO, SRO, VSSR, PKE	Trajectory design algorithms should find trajectories that minimize propellant usage and thus maximize delivered mass. The algorithms should converge quickly and be simple for a user to operate. Accurate navigation during cruise is desired, with minimal ground operations cost.			
	Mars 2nd decade	Precision guidance into a corridor of 2x2 km, Reduction in mass of 45% vs all-chemical arrival mass at Mars			
	CNSR	Orbit determination: 50-100 km orbit determination accuracy during cruise, with minimal ground operations cost.			
	CNSR	Accurate flight path estimation and control to allow accurate instrument pointing at surface features, overflight of desired areas of the nucleus, and avoidance of collisions with the nucleus.			

Table 6-11. Guidance and Control

GNC Technology	Driving Missions	Needs/ Capabilities	SOA	Current Development	Adequacy
Flight Path Estimation	VSSR, TE, NO	Accurate, reliable estimation and control of a vehicle's flight path during hypersonic flight through an imprecisely modeled planetary atmosphere.			
	VSSR	Accurate flight path estimation and control over the course of the balloon ascent are needed.			
	EL, EO	Accurate navigation during cruise and while traveling through the Jovian satellite system is desired, with minimal ground operations cost.			
	SRO	Stationkeeping and formation flying relative to the ring plane to a vertical accuracy of 0.5 km.			
Metrology	SIM	Optical Metrology, Picometer, Linear and Angular: 1-D relative point-to-point measurement accuracy of 7 pm, over 10 m baseline, , 3-D relative baseline-to-baseline measurement accuracy of 50 pm for narrow angle astrometry, 450 pm for wide angle astrometry, 3-D absolute measurement of an entire metrolog			
	TPF	Precision Metrology: optical metrology:, linear: 1 nm accuracy, angular: 1 masec, operating temperature: < 40ºK, lifetime: 5 year minimum, 10 year goal, L-2 or Earth-trailing orbit			
	LF	Precision optical metrology: linear: 1 nm accuracy, angular: 1 masec, operating temperature: < 40 ºK, lifetime: 5 year minimum, 10 year goal, L-2 or Earth-trailing orbit			
	MAXIM	Detectors for Metrology to picometers			
Attitude Control	MAXIM Pathfinder	Very Fine Guidance Sensors: 30 micro arc second knowledge. Attitude control: 300 micro arc second pointing stability; 30 micro arc second control.			
	MC	Attitude control for nanosats: Spin rate knowledge < 2X10E5 rad/sec knowledge of spin axis position < 1 deg, knowledge of spin axis phase < 0.1 deg, spin axis drift rate <0.1 deg over 30 days. Sun sensor 0.25 kg, 3.3 V, 0.1 W, 1 degree resolution			
	GEC	Automatic maintenance of orbit; autonomous 24/7 control of spacecraft.			

(Note: Table 6-11 was prepared just prior to going to press on this Blueprint and there was not enough time to fill in many table entries. This will be upgraded in future editions.)

Table 6-12. Information Technology /Autonomy Requirements

Driving Missions	Needs/ Capabilities	SOA	Current Development	Adequacy
NGST, EO, TE, NO, SRO	Automated Planning & Execution, Adaptive Scheduling, Autonomous Operation; Command s/c with higher level goals than SOA			
TE, CNSR, EO, PKE, NO, SRO, ISP, VSSR	Spacecraft housekeeping: monitoring and diagnosis: Enables migration of additional monitoring & diagnosis functions to the spacecraft to lower operations cost. Enhances spacecraft fault protection algorithms to decrease mission risk.			
EL, TE, CNSR	Problem reporting: Landing in an uncertain environment with long light delays when communicating with the Earth. Performance of the onboard software to capture the most important sensor information when problem occurs.			
PKE, CNSR	Adaptive opportunistic science opportunities: High level commands to s/c allows it to take advantage of serendipity when it arrives at target			
TE	Intelligent software systems on Aerobot to enable more robust and opportunistic sample selection, controlling the timing of sample collection and local procedures.			
ISP, MC, ISTB, HIGGS, TE, SDO, VSSR	Autonomous health and safety monitoring: Fault detection, correction			
PKE, EO, TE, NO, SRO	Unified flight-ground architecture for low-cost software migration to s/c.Supports deferred software development throughout the long cruise period.			
MC	Automatic control and monitoring of a 50 to100-spacecraft constellation			
ISP	Autonomous flight path determination and correction/ adjustment.			
SDO	Autonomous Execution and Control			
SRO	Autonomously perform aerocapture cleanup and maintain the hover orbit			
SDO	Autonomous feature recognition/event detection.			
PKE	Image processing just prior to encounter to make final adjustments to the encounter sequence start-time. (enabling)			
CNSR	Image processing algorithms to compute small body relative velocities from scanning laser radar (SLR) images to within 1 cm/sec and to detect landing hazards in the range of 5 cm at 100 m altitude. (enabling capability), Achieve 10:1 data compression			
EL	Use of onboard instrument data processing during entry, descent, and landing operations to accomplish safe landing. Achieve 10:1 data compression (enhancing)			

(Note: Table 6-12 was prepared just prior to going to press on this Blueprint and there was not enough time to fill in many table entries. This will be upgraded in future editions.)

Table 6-13. Power Technology Requirements

Power Technology	Driving Missions	Needs/ Capabilities	SOA	Current Development	Adequacy
Electro-statically clean solar power	MC, MMS and other Solar-Terrestrial Probes	Electrically conductive lightweight plastic covers over panels; cost modestly higher than normal arrays	Electrically conductive heavy glass covers over individual cells; Hand-crafted shielding; interconnect array cost 5X normal cost	Small Task	Marginal at best
AO-resistant clean solar power	GEC	Electrically conductive lightweight plastic covers over panels; cost modestly higher than normal arrays. High AO flux during dipping into the upper atmosphere precludes use of silver for interconnects.			
Solar power for SEP	CNSR, CSSR MASR,TE, JPO, HIGO	High power deployable solar array • 23 kW (BOL) • Specific power ≥ 140-180 W/kg (BOL) • LILT resistant to 5 AU (TE and CNSR) • Compact, deployable			
	MSR	Lightweight deployable solar arrays (total power = ## kW, sp. pwr = ## W/kg, useful to ## AU)			
	NTP	Lightweight deployable solar arrays (total power = ## kW, sp. pwr = ## W/kg, useful to ## AU)			
	VSSR	Lightweight deployable solar arrays (total power = ## kW, sp. pwr = ## W/kg, useful to ## AU)			
	All SEP Missions	Thin film or concentrating arrays with specific power > 150 W/kg and acceptable stowage volume and cost. Resistant to arcing at high voltage. May be required to operate as far as ~ 5 AU under LILT conditions.	Arrays with unacceptably high mass, stowage volume, and cost. Arrays tend to arc at high voltages.		
Solar power in dusty environments	CSSR, MASR, CNSR	Dust Mitigation for S/C power systems specific power 100 W/kg	Some R&D Work on Extraterrestrial Material Simulation	None	No
	MSL, MSR	• Optimized cells for Mars spectrum • Dust mitigation • Advanced batteries for 500 cycles at -40°C	• Cells with reduced efficiency in Mars spectrum • No dust mitigation	MTP	Uncertain

Table 6-13. Power Technology Requirements

Power Technology	Driving Missions	Needs/ Capabilities	SOA	Current Development	Adequacy
High Temperature Solar Arrays	SP, other near-solar or Mercury missions	Cells with improved contact metallization, diffusion barriers, reflective coatings, high temperature adhesives that can operate at >300°C. Goal: 11% efficiency, 2-year lifetime at 425°C (also low-temperature PV for Mars)	Arrays heavily loaded with optical solar reflectors replacing many cells that must be off-pointed from Sun and operate at 130°C.	GaInP arrays, 15% RT effic, 400° survival	
LILT-resistant arrays	Solar-powered missions beyond Mars	Verified array performance under LILT conditions by test, with adaptive technology to overcome problems as they are found (may be required to also operate under high radiation conditions)	Conventional arrays with uncertain performance under LILT conditions due to lack of testing		
Radioisotope power	EGE	ARPS Power in high radiation field in vacuum 3.3 W/kg, 5 yr life			
	EL	ARPS Power in high radiation field in vacuum 10 W/kg, 5 yr life			
	JPOP, NTP	ARPS Power in vacuum 10 W/kg	RTG 5 w/kg		Yes
	MSL, MSR MLLLN	ARPS Power in atmosphere. High efficiency, modular RPS for Mars (25% efficiency, sp.pwr >6 W/kg)	RTGs (eff ~ 6%, sp.pwr.~ 5 W/kg)	Stirling converter at GRC	No
	NTP	ARPS Power in atmosphere 10 W/kg 15 year lifetime			
	PKB	ARPS Power in vacuum 3.3 W/kg	RTG 5 w/kg		Yes existing RTG
	TE	ARPS Power in atmosphere 10 W/kg 10 year lifetime			
	VLL	ARPS Power in high temperature atmosphere			
Nucl reactors	NTP	Nuclear Fission Power	Sp-100 R&D	None	No
Energy storage	EL, EGE	10 yr Life Low Temp Rechargeable Batteries (14 days active, 190 K, 115 W-hr/kg)	NiCd/Ni-H2	None	No
	MSL, MSR	High specific energy (>120 Wh/kg) and Energy Density (160 Wh/l) rechargeable battery; operation below -30°C; cycles =TBD		Code S, Code R, AFRL	
	NTP	Long Life Low Temp Rechargeable Batteries 47 Whr/kg	Li-SOCl2 250 W-h/kg @ 230-300 K, 5 yr life	None	No
	JPOP, TE	10 yr Shelf Life Low Temp Primary Batteries 400 Whr/kg @ 210-300 K	Li-SOCl2 250 W-h/kg @ 230-300 K, 5 yr life	None	No
	PKE, GEC, MC, EO	Rechargeable Batteries			
	NO	Primary battery			
	VSSR	Primary battery			

Table 6-13. Power Technology Requirements

Power Technology	Driving Missions	Needs/ Capabilities	SOA	Current Development	Adequacy
Energy storage	CNSR	Primary battery			
PMAD	EO, PKE, CNSR, EL, NO, VSSR, SRO, TE, ISP	Distributed DC-DC conversion, Conversion efficiency>90%, 200W/Kg power density			

Table 6-14. Propulsion Technology Requirements

Propulsion Technology	Driving Missions	Needs/ Capabilities	SOA	Current Development	Adequacy
Advanced chemical propulsion	GEC, ITM Waves, MMS	High Isp Chemical Propulsion			
	MSR, MSL, EL, CNSR, NO, SRO, VSSR, TE, EL, LISA, EXIST, MMS	Reduced mass for propulsion components such as tanks, valves, feeds			
	NO, TE, PKE	High efficiency chemical systems are needed for attitude maintenance and maneuvering.		Monopropellant green system	
	EL	Chemical propulsion needed for landing. Dual mode operations allows the same propulsion system to be used enroute for attitude control and small delta-V maneuvering.			
	EO	Bipropellant propulsion system needed to perform Jupiter Orbit injection and orbit maneuvering for gravity assist during orbital campaign. High thrust, low mass systems needed to provide high delta-V capability at the planet.			
	VSSR	Bipropellant propulsion system needed to perform orbit deflection maneuvers post aerocapture. High thrust, low mass systems needed to provide high delta-V capability at the planet.			
	SRO	Bipropellant propulsion system needed to maintain non-Keplerian orbit. High thrust, low mass systems needed to provide high delta-V capability at the planet.			
	SPASR, EL, EO	Lightweight chem. prop. components advanced chem. propulsion (High Isp ~ 330 sec) 460N thrust	Isp ~ 310 sec	ISTP	No
	PKE	Monoprop with Isp =260 s, freeze pt = -10 C			
Precision micro propulsion	LISA, MAXIM	Precision propulsion: micro-Newton thruster: 0.1 μN	1.0 μN	Electrical Micro-thruster Test in Space – STS Experiment	Yes

Table 6-14. Propulsion Technology Requirements

Propulsion Technology	Driving Missions	Needs/ Capabilities	SOA	Current Development	Adequacy
Ascent propulsion	SPASR	Ascent Vehicle		None	No
	VSSR	Multistage ascent vehicle for Venus Ascent, Solid Propellant, Four stage		None	No
	MSR	Ascent Vehicle	MTP	None	No
Solar Sails	Technology flt validation	Root Area (m^2) 1500, Areal Density (g/m^2)< 25			
	L1-Diamond	TBD' 0.98 AU/ 5yrs			
	Solar Polar Imager (SPI)	Root Area (m^2) 19,800, Areal Density (g/m^2)~ 13; Resistant to high temperatures; 0.5 AU/ 5 yrs			
	PASO	Root Area (m^2) 24,000, Areal Density (g/m^2)~ 9; 0.17 AU/ 5yrs			
	Inter-Stellar Probe (ISP)	Root Area (m^2) 122,900, Areal Density (g/m^2) ~ 1; 0.25 AU/ 2 yrs			
Solar electric propulsion	VSSR, MSR, CNSR, MASR, TE	SEP Thruster 3700 Isp, 3.4 Kw, 200 kg throughput	DS-1 3250 Isp 2.5 kw	ISTP	No
	NTP	SEP Thruster 5000 Isp, 5.4 Kw, 250 kg throughput	DS-1 3250 Isp 2.5 kw	ISTP	No
	Mars 2nd decade missions	• SEP Thruster (scale up) (throughput=200 kg, Isp=5000, pwr = 6 kW) • Low mass propulsion components (reduce tank mass by 50%, reduce transducer mass by 90%, reduce mN thruster mass by 70%, increase Isp for 5 lb-f biprop by 15 sec.	• Smaller scale SEP (throughput=100 kg, Isp=3000, pwr = 2 kW) • Conventional propulsion systems • No aerocapture	MTP	Uncertain
Nuclear electric propulsion					

Table 6-15. Structures and Materials

Structural Technology	Driving Missions	Needs/ Capabilities	SOA	Current Development	Adequacy
Materials and Structures (See Table 6-1 for Optics)	CSSR, CNSR, MASR, EL	Extraterrestrial Material Simulation	None	None	No
	EO	Multifunctional structures: To reduce the mass of the subsystems by as much as 30% for thermal/mechanical/cabling/packaging			
	MMS	Booms: axial 6 m long, 1 Hz, < 2.5 kg; radial 40 m long, 1st mode TBD, < 2 kg			
	MC	50 nanosats each with 3 scientific instruments. several million dollars per instrumented spacecraft; or 100 nanosats at $0.7M unit cost		ST-5: 3 s/c with 1 inst & 1 tech demo; unit cost ~ $5M	
	VSSR	Balloon materials: • Areal density < 60 g/m^2 (20 g/m^2 preferred) • Tensile strength = 5 to 8 ksi at 460°C • Storage at 100-200 kg/m^3 bulk density • Deployment from tight package at 460°C • Resistant to Venus environment • Must not interfere with RF communication • Must be fabricable into balloons	Several candidates using PBO and metallized PTFE Teflon	None	Inadequate

Table 6-16. Thermal Control and Environmental Effects

Therm Control Technology	Driving Missions	Needs/ Capabilities	SOA	Current Development	Adequacy
Thermal Control (See Table 6-1 for cryocoolers)	CNSR	Sample preservation at 150 K <			
	NGST	Passive thermal control for telescope < 70°K lifetime: > 5 years, 10 year goal, in L-2, solar rejection: 90%, size: 12 m x 30 m, mass: < 150 kg, reliable deployment mechanism, volume efficient packaging			
	TPF	Passive thermal control: telescope temperature: < 40 K via passive cooling, lifetime: 5 years minimum, 10 years goal, in L-2 or Earth-trailing orbit, Sun shield:, solar rejection: 90%			
	SAFIR, LF	Passive cooling of environment surrounding actively cooled (< 10 K) telescope, lifetime: 5 year minimum, 10 year goal, in > 1 A.U. solar rejection: > 90%, size: (large enough to shade 10-15 m aperture telescope)			
	JPOP	Passive thermal control for Probes entry	None	None	No
	NTP	Passive thermal control for Probe entry	None	None	No
	Solar Probe	Non-sublimating, thermal shield to operate at 1800°C	C-C material tested in relevant lab environment	Solar Probe (JPL/APL)	
	TE	Passive thermal control for 90 K	None	None	No
	VISE, VSSR	Passive thermal control to 730 K	None	None	No
	NO, PKE	Active thermal control.			
	VLL	Active thermal control for 730 K	None	Stirling	No
	ISP, SP	Thermal control near the Sun			
	SRO	Cooling electronics			
	VSSR	Insulated thermal capacity system to allow lander to operate on surface at 230-460°C, 90 atm, for 1-2 hours. This system does not require a pressure vessel and needs to maintain CO_2 envelope above the triple point.	Pioneer Venus	None	Inadequate
	CNSR, NO, EL, EO, PKE, TE, SRO, VSSR	Multi-function structures: Reduction in mass of passive thermal control by 20-40% by integrating thermal radiators with structural panels	Separate thermal and structural elements		
	CNSR, NO, EL, EO, PKE, SRO, TE	Lightweight thermal control hardware (30-50% lighter than SOA); reduce mechanical louver mass by 50-75%			
Environ-mental Effects	L1-Diamond, ISP	3-D models of solar sail interactions with solar wind/plasma environment.			
	MC, MMS	Active control of spacecraft potential			
	CSSR, CNSR, MASR	Dust Mitigation for S/C systems	None	None	No

Table 6-17. Sensors/Instruments Technology Requirements

Instrument Technology	Driving Missions	Needs/ Capabilities	SOA	Current Development	Adequacy
Remote sensors and instruments					
In situ sensors and instruments	CNSR	• Space instruments too numerous to list here • Laboratory for curation and in-situ testing of systems in simulated planetary environments			
	EL, JPOP	Miniature In Situ Instrumentation, high rad exposure			No
	Mars 2nd decade missions	• Definition of life • Instruments to detect life	None	MTP	Uncertain
	Mars, Europa surface and subsurface Titan, comets	Biotic/ prebiotic detection and analysis	Performance targets: detection vs. characterization. Comparison of viable inst techniques: capillary electrophoresis, wet chem, GC, Raman. Sample delivery and concentration	ASTID, ASTEP within Astrobiology Program	No
	Mars, Europa surface and subsurface Titan, comets	Delivery of samples to GCMS, wet chemistry labs, microscopes, etc.	Each sampling system is tailored and expensive. Few concepts beyond breadboard stage. Laser ablation, drills, diggers, scrapers, etc.		
	Mars, Europa surface and subsurface Titan, comets	Subsurface probing by radar, seismic methods; New technologies for NMR, deep EM sounding.	Miniaturization of radar systems and seismic sensors underway. Limited challenges to achieve target goals. Uncertain need for NMR and other new technologies.		
	Mars, Europa surface and subsurface Titan, comets	Raman, Mossbauer, X-ray diffraction/fluorescence	Numerous PIDDP-level efforts. Varying challenges with sample orientation and preparation.		

Table 6-17. Sensors/Instruments Technology Requirements

Instrument Technology	Driving Missions	Needs/ Capabilities	SOA	Current Development	Adequacy
In situ sensors and instruments	MSL, MSR, Scouts	A number of in situ instruments at TRL 6	A number of in situ instrument concepts at TRL 2-4	MTP	Uncertain
	NTP, TE	Miniature In Situ Instrumentation			No
	Venus deep atmosphere probes	Age dating systems Outer planet atmosphere/ surface Comet surface and dust	Several insts previously funded by PIDDP. Need firm performance targets for missions. Trades of precision/ integration time vs. mass, power, volume. Sample delivery and concentration		
	VLL, VISE	Miniature In Situ Instrumentation, high temperature (730 K), sulfuric acid			
Fields and particles sensors and instruments	Con-X	X-ray spectroscopy 25-100 times better resolution than Chandra	Chandra		
	Dark Energy Probe	Large-scale IR detector arrays: high quality data at redshifts z = 0.5 to 2			
Observatory instruments	CMBPol	Polarization sensitive multi-frequency direct detectors, NEP~10^{-17}, > 1000 pixels, (50GHz-500GHz operation)	Planck HFI	Antenna coupled TES or kinetic inductance detectors	No
	Con-X	High efficiency, multi-element x-ray calorimeter detector array with 2eV resolution from 0.25 to 10 keV, 6eV to 40keV with a >1000ct/sec pixel rate	10 eV resolution at 6 keV on Astro-E XRS	Con-X preproject	Yes
	EXIST	Large area (4-8m^2) , low-cost (~\$200/cm^2), high-uniformity CZT detectors	• INTEGRAL/ISGRI has 0.26 m^2 of CdTe detectors and Swift has 0.52 m^2 of CdZnTe detectors (both 2mm thick) vs. 2.7 m^2 (5mm thick) for each of 3 telescopes for EXIST • Low cost, high uniformity CsI-amorphous silicon detectors up to 42x42 cm exist for medical X-ray applications (25-125 keV)	• INTEGRAL/ ISGRI • CZT detector development currently funded under balloon program, flight expected 2005	Yes, anticipate TRL6 in 2004

Table 6-17. Sensors/Instruments Technology Requirements

Instrument Technology	Driving Missions	Needs/ Capabilities	SOA	Current Development	Adequacy
Observatory instruments	iARISE	Low Noise Amplifiers		Planck	Trade-off between receiver noise and antenna size
	LISA	Inertial Sensors accelerations ~3×10^{-15} $m/s^2/hz^{1/2}$ at a frequency of 10^{-3} hz	Ground testing accelerations ~10^{-10} $m/s^2/hz^{1/2}$ Gravity Probe-B accelerations ~2.6×10^{-10} $m/s^2/hz^{1/2}$ from 2-20hz (not used in GPB inertial sensor)	LISA Pre-project, ST7, DMS, SMART-2	Yes
	MAXIM	Detectors with sub-micron pixels.	Chandra Optics, SIM Metrology, Chandra CCDs, Astro-E XRS	Capability may already exist	Yes
	NGST	• Near IR detectors for 1-5 microns, @30 K, 4000x4000 array, 80% QE, low noise. • Mid IR detectors for 5-10 microns, @30 K, 1000x1000 array, 50% QE, low noise.	Rockwell HAWAII 2™ 2k x 2k, 2-micron array	Industry Program MIRI (selected)	Array size: Yes Operating temp TBD QE TBD Noise TBD
	RAM	Energy-resolving CCDs for simpler spectrograph design; 100 x 100 elements	SOA = 50 X 50	Unknown	
	SAFIR/SPIRIT/ SPECS	Wide Field Far IR FP arrays 10^4 pixels	MIPS, Herschel	1. TES bolometer array ~ 10^{-19} W/√Hz 2. Kinetic inductance detectors 3. Large Photocond arrays (e.g., BiB)	No
	SDO	Rapid readout imaging arrays 4k x 4k monolithic CCDs; EUV sensitivity; rapid readout (<2 sec).	Compound CCDs butt-bonded into 4k x 4k arrays; readout > 2 sec	Development and procurement coordinated by SDO Project and instrument teams	
	SNAP	Optical sensor technology: a) radiation hardness, b) long wavelength QE (700-1000 nm), c) small pixel size, d) production volume			
	SPIRIT/SPECS	High sensitivity direct detector array for spectroscopy with NEP < 10-20 W/rtHz and > 10^3 pixels in the 50 - 500 um range	IRS, Herschel	1. TES bolom array 2. Kinetic inductance detectors 3. BIBs 4. Hot Electron Bolometer Direct detectors 5. SQPC	No. Need a 1-2 magnitude improvement over current sensitivity

Table 6-17. Sensors/Instruments Technology Requirements

Instrument Technology	Driving Missions	Needs/ Capabilities	SOA	Current Development	Adequacy
Observatory instruments	SUVO	16K x 16K detector mosaic with four-fold improvement over SOA in UV	HST, QE's of current photon counters are low (10-50% FUV; 8-10% NUV)		No, need to achieve increases: ~2.8 in. aperture, ~5 in. throughput (principally detector caqpability), and ~>2 in. observing efficiency.

Appendix A. Technology Taxonomy to Level 3

1.0 Avionics
1.1 Electronics and Avionics Systems
1.1.1 CPU
1.1.2 Memory
1.1.3 Sensors/Effectors Interfaces (Analog/Digital)
1.1.4 Data Buses and Architectures
1.1.5 Diagnostic and Prognostic Systems
1.2 Electronics and Architectures for Extreme Environments
1.2.1 Rad Tolerant/Hard
1.2.2 Low Temperature
1.2.3 High Temperature
1.3 Packaging and Interconnects
1.3.1 Electronic Packaging
1.3.2 Data and Power Interconnections
1.3.3 Connectors
1.4 Tools and Testbeds

2.0 Communications
2.1 RF Systems and Components
2.2 Optical Communications Systems and Components
2.3 Data Compression
2.4 Tools and Testbeds

3.0 Guidance, Navigation, and Control
3.1 Cruise, Approach, and On-Orbit Navigation
3.1.1 Trajectory Design Algorithms
3.2 GN&C Architectures and Algorithms
3.3 Surface Navigation and Control
3.4 GN&C Measurement Systems
3.4.1 Radio Metric
3.4.2 Optical
3.4.3 Inertial
3.5 Precision Control and Distributed Spacecraft
3.5.1ACS/GN&C Sensors
3.5.2 ACS Actuators
3.5.3 Formation/Constellation Control
3.5.4 Metrology
3.5.5 ACS Systems
3.6 Rendezvous and Docking
3.7 Tools and Testbeds

4.0 Information Technology/Autonomy
4.1 Networks and Architectures
4.2 Distributed Data Handling
4.3 Modeling and Software Engineering
4.4 Planners and Schedulers
4.5 System Health Maintenance
4.6 Human Computer Interaction
4.7 Integrated Agents and Testbeds
4.8 Autonomous Execution and Control
4.9 Intelligent Assistants
4.10 Collaboration and Knowledge Management
4.11 Tools and Testbeds

5.0 Power
5.1 Photovoltaic Systems
5.1.1 Solar Array technology
5.1.2 Solar Cell Technology
5.2 Radioisotope Systems
5.3 Energy Storage Systems
5.3.1 Primary Batteries
5.3.2 Secondary Batteries
5.3.3 Fuel Cells
5.3.4 Other Storage Systems
5.4 Power Conversion
5.4.1 Chemical
5.4.2 Mechanical
5.4.3 Solid State
5.4.3 Other Conversion Technology
5.5 Power Management and Distribution
5.6 Alternative Power Systems and Advanced Concepts
5.7 Tools and Testbeds

6.0 Propulsion
6.1 Chemical Propulsion
6.1.1 Monopropellant Systems
6.1.2 Bipropellant Systems
6.1.3 Propulsion Tanks, Feeds, and Components
6.1.4 Ascent Systems
6.2 Electric Propulsion
6.3 Solar Sails
6.4 Precision/ACS Propulsion
6.5 Tools and Testbeds

7.0 Structures/Materials
7.1 Structures
7.1.1 Inflatable Structures
7.1.2 Deployable Structures
7.1.3 Erectable Structures
7.1.4 Structural Control
7.1.5 In-Situ Manufacturing
7.1.6 Multi-functional structures
7.2 Advanced Materials
7.2.1 Thin Film Materials
7.2.2 Thermal Mgmt. Materials
7.2.3 Thermally Stable Materials
7.2.4 High Performance Composites
7.2.5 Radiation Shielding Materials
7.2.6 Smart Materials
7.2.7 Space Environmental Effects
7.3 Tools and Testbeds

8.0 Thermal Control
8.1 Cryocoolers and Instrument Cooling
8.2 Passive Thermal Control Systems
8.3 Spacecraft Thermal Management
8.4 Tools and Testbeds

9.0 Sensors/Instruments
9.1 Direct Detectors
9.2 IR, Visible, and UV imagers/spectrometers
9.3 Radar and Submillimeter Technology
9.4 Instrument Optical & Opto-mechanical Components
9.5 Lasers and Laser Systems Components
9.6 Particles and Fields Detectors
9.7 In-situ Sensing Components
9.8 X-Ray/Gamma Ray Components
9.9 Tools and Testbeds

10.0 Space Optics
10.1 Adaptive Optics
10.2 Diffractive Optics
10.3 Refractive and Transmissive Optics
10.4 Reflective Optics
10.5 Optical Systems
10.6 Tools and Testbeds

11.0 Entry, Decent and Landing/Aeroassist
11.1 Aerocapture and Aeroentry
11.1.1 Planetary Atmosphere Predictions
11.1.2 Aerothermodynamic Analysis Tools
11.1.3 High Temperature Thermal Protection and Structural
11.1.4 Aeroshell and Inflatable Vehicles For Aerocapture
11.1.5 Earth Entry Vehicles For Sample Return
11.2 Descent and Landing
11.2.1 Maneuverable Entry Vehicles
11.2.2 Atmospheric Decelerators
11.2.3 Precision Landing and Hazard Avoidance Systems
11.3 Robust Landers
11.4 Aeroassist and aeromaneuvering
11.5 Tools and Testbeds

12.0 Robotics and Planetary Access
12.1 Surface Vehicles
12.2 Sub-Surface Vehicles/Drilling
12.3 Aerial Systems
12.4 In-Situ Resource Utilization
12.5 On-orbit robotics
12.5.1 Rendezvous & Docking
12.5.2 Assembly & Servicing
12.6 Tools and Testbeds

13.0 Planetary Protection and Sample Handling
13.1 Sterilization and Cleaning Technologies
13.1.1 Terrestrial contaminants
13.1.2 Non-terrestrial life
13.1.3 Verification & Validation
13.2 Isolation & Biobarriers
13.3 Molecular tagging
13.3.1 Tagging
13.3.2 Detection
13.4 Sample Acquisition & Handling
13.5 Sample Containerization & Encapsulation
13.6 Contamination Transport
13.7 Sample Transport
13.8 Archive and Curation

Appendix B. Acronyms and Abbreviations

ACT	Advanced Compton Telescope
ACTDP	Advanced Cooler Technology Development Program
AMSD	Advanced Mirror System Development
AMTEC	Alkali Metal Thermal Electric Converter
APS	Active Pixel Sensor
ARPS	Advanced Radioisotope Power Source
ASO	Astronomical Search For Origins
AU	Astronomical Unit
BBO	Big Bang Observatory
BOL	Beginning of Life
CGRO	Compton Gamma Ray Observatory
CMB	Cosmic Microwave Background
CMBPOL	Cosmic Microwave Background Polarization
CME	coronal mass ejection
CNSR	Comet Nucleus Sample Return
Con-X	Constellation-X
DBC	Dayside Boundary Layer Constellation
DSN	Deep Space Network
EDL	Entry, Descent, and Landing
EL	Europa Lander
EO	Europa Orbiter
EOL	End of Life
ESS	Exploration of The Solar System
EXIST	Energetic X-ray Imaging Survey Telescope
GEC	Geospace Electrodynamic Connections
GEN-X	Generation-X
GLAST	Gamma-ray Large Area Space Telescope
GNC	Guidance and Control
GP-B	Gravity Probe-B
GRC	Glenn Research Center
GREAT	Gravitational Echoes Across Time Mission
GSRI	Geospace System Response Imager
HIGO	Heliospheric Imager and Galactic Observer
HSI	High Resolution X-ray Spectroscopy Mission
iARISE	Advanced Radio Interferometry between Space and Earth
IHS	Inner Heliosphere Sentinels
IM	Ionospheric Mappers
IMC	Inner Magnetospheric Constellation
INTEGRAL	International Gamma Ray Astrophysics Laboratory
ISP	Interstellar Probe
IT	Information Technology

ITM Waves	Ionosphere-Thermosphere-Mesosphere Waves Probe
JPL	Jet Propulsion Laboratory
JPO	Jupiter Polar Orbiter
L/D	Length/Diameter
LF	Life Finder
LILT	Low Intensity/Low Temperature
LISA	Laser Interferometer Space Antenna
LWS	Living With A Star
LWS-GM	Living With a Star – Geospace Missions
MagCon	Magnetospheric Constellation
MAV	Mars Ascent Vehicle
MAXIM	MicroArcsecond X-ray Imaging Mission
MAXIM PF	MicroArcsecond X-ray Imaging Mission Pathfinder
MC	Magnetospheric Constellation
MCP	Micro Channel Plate
MEP	Mars Exploration Program
MER	Mars Exploration Rover Mission
MIO	Magnetosphere-Ionosphere Observatory
MMS	Magnetospheric Multi-Scale
MRO	Mars Reconnaissance Orbiter
MSL	Mars Science Laboratory
MSR	Mars Sample Return
MTRAP	Magnetic Transition Region Probe
NEP	Nuclear Electric Propulsion
NGST	Next Generation Space Telescope
NO	Neptune Orbiter
OAT	Office of Aerospace Technology
PASO	Particle Accelerator Solar Orbiter
PDR	Preliminary Design Review
PI	Planet Imager
PKE	Pluto-Kuiper Express
PV	Photovoltaic
RAM	Reconnection and Multiscale Probe
RBM	Radiation Belt Mappers
RPS	Radioisotope Power Source
RTG	Radioisotope Thermoelectric Generator
SAFIR	Single Aperture Far Infrared
SDO	Solar Dynamics Observatory
SEC	Sun-Earth Connection
SEE	Single Event Effect
SEEC	Sun Earth Energy Connector
SEP	Solar Electric Propulsion
SEU	Structure And Evolution of The Universe

S-F	Sentinels Farside
SI	Stellar Imager
SIM	Space Interferometer Mission
SIRTF	Space Infrared Telescope Facility
SOA	State of the Art
SP	Solar Probe
SPECS	Submillimeter Probe of the Evolution of Cosmic Structure
SPI	Solar Polar Imager
SPIRIT	Space InfraRed Interferometric Telscope
SRO	Saturn Ring Observer
SSE	Space Science Enterprise
STEREO	Solar-Terrestrial Relations Observatory
STP	Solar-Terrestrial Probe
SUVO	Space Ultraviolet Observatory
TE	Titan Organic Explorer
TIMED	Tropical ITM Coupler
TPF	Terrestrial Planet Finder
TSG	Technology Steering Group
VSSR	Venus Surface Sample Return