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In-Space Operations
Technology Capability Portfolio

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1 General Portfolio Overview

1.1 Technology Capability Overview

This in-space operations (ISO) technology capability portfolio summarizes key elements necessary to achieve priority national and agency goals in space over the next few decades. In particular, with a human return to the Moon and subsequent voyages to Mars, large and complex science facilities in space, and possible depots to supply extended space exploration, operating effectively in free space is one of the major enabling capabilities for scientific and human exploration beyond the immediate vicinity of the Earth.

The systems summarized here are intended to enable humans and their robotic partners and precursors to support lunar surface operations, prepare for the long human expedition to Mars, and assemble, service, rescue, and repair complex optical systems in space. Emphasis is on the period following conclusion of the International Space Station (ISS) program (~2015+), building upon the expensively hard-won operational and engineering experience from that program. A major strategic management challenge will be to preserve the capabilities necessary to achieve priority goals in space in addition to returning humans to the surface of the Moon.

In-space operations include use of space telerobotics, human extravehicular activity (EVA), bioastronautics and space medicine, advanced materials, robotic precursors that define environments on the Moon, Mars and in space, demonstration missions, and supporting operations on Earth, among other major elements in support of long-term NASA objectives.

The in-space capabilities discussed here refer to the ability of humans and machines, working together or separately, to:

- Support surface operations on the Moon from space
- Serve as precursors and demonstrations of capability and technology needed for human missions to Mars
- Develop temporary human habitat options for use during and between space operations
- Enable advanced in-space bioastronautics and general human health experiments in the post-ISS timeframe, including basic research necessary to support future long-duration human voyages
- Observe and assist, if needed, deployments intended to operate autonomously
- Assemble, service, upgrade, retrieve and repair complex human and science facilities in space
- Assemble very large systems for a class of missions and space activities that would not otherwise be possible due to the limits of launch vehicles, ground test facilities, or the influences of gravity
- Replace consumables and components, enabling servicing of systems to extend their lifetime
- Carry out major integration and test functions in space that are not possible on Earth
- Provide a temporary habitat for humans during and between operations in space

1.1.1 Background Context for the Development of This Portfolio

With the *Vision for Space Exploration (VSE)*, priorities from the National Academy of Science, and the support of Congress, NASA's goals in space are at the limit of human imagining — and beyond the limit of current and near-future capabilities: We seek answers to the questions: *Are we alone in the cosmos? How did life on Earth arise? What is humanity's destiny among the planets?*

Several months after the first presentation of the VSE, the Presidential Commission on Implementation of United States Space Exploration Policy ("Aldridge Commission") produced *A Journey to Inspire, Innovate, and Discover*. The report identified a number of very broad capability areas deemed necessary to achieve the priority civilian goals in space. In response, NASA created fifteen teams to develop options and investment strategies for these capabilities, as well as parallel strategic

roadmap teams. The strategic roadmaps were intended to define the missions and mission sets for science and human exploration. It was recognized at the start of the process that the capabilities identified by the Aldridge Commission did not cover all major capabilities necessary to the VSE. Notably absent, for example, were advanced materials, planetary protection, surface operations and support, space structures, and in-space operations. Originally, it was planned to produce roadmaps for these additional capabilities at the conclusion of the first round of roadmapping. However, NASA's Science Mission Directorate (SMD) already had underway a process to develop priorities and strategies for in-space operations, which was organized around a series of *Loya Jirga* workshops in Boulder, Colorado, and which included participation by other NASA Directorates.[1] The *Loya Jirga* process began well before the other roadmaps in this series and, as a result, followed a different process, although it paralleled the other roadmapping activities in many respects.

The goal of the series of *Loya Jirga* workshops was to bring together senior managers, technologists, and scientists to evaluate long-range priorities in scientific and human space exploration for NASA and its partners in academia and industry. The first *Loya Jirga*, in May 2003, developed technology priorities for future large optical systems in space. Some of the results of the first *Loya Jirga* contributed to the astronomy component of the VSE and identified and advocated major investment goals for the SMD.

The purpose of *Loya Jirga II* (*LJ II*), held in February 2005 was to identify and assess capabilities for operations in free space that would enable NASA and its academic, industrial, and international partners to achieve the human and scientific exploration goals that would not be possible otherwise. Early in the organization process of *LJ II*, it became clear that there was very broad interest in developing advanced in-space capabilities in the era after NASA no longer manages the ISS. Individuals working in robotics/telerobotics, bioastronautics, space astronomy, and extra-vehicular systems were solicited to participate in the roadmapping process. For example, long-term human-occupied facilities in space to follow the ISS – for example, human missions to Mars – could not be constructed, serviced, and repaired without capabilities far beyond those available today. Similarly, priority science goals in space (for example, extremely large optical systems) will require the capability to assemble, deploy, upgrade and repair very complex systems. These capabilities do not exist at present and are not planned for the near future; *LJ II* was originally intended to be a senior-level, community-wide effort to assess this shortcoming and develop recommendations.

1.2 Benefits and Traceability

The primary benefit of significant future capabilities for in-space operations is the ability to achieve major national goals in space in the period following the retirement of the Space Shuttle and ISS. Significant capability in space operations, techniques, technology, and human experience has been accumulated during the extended construction of ISS and such missions as Hubble Space Telescope servicing. These capabilities will need to be built upon and extended significantly in the decades to follow. A principal issue for NASA is continuity of the capabilities that currently exist, even while more advanced techniques are developed. The key issue is human capability in space, particularly beyond low Earth orbit (LEO), where future in-space operations will eventually be conducted. Such operations may require extended deployment of humans that might not be supportable solely with transit vehicles such as the currently planned Crew Exploration Vehicle (CEV). In this regard, considerable attention was given in *LJ* to the value of a permanent or semi-permanent in-space facility at the first Earth-Moon libration point (L1), although other locations

[1] *Loya Jirga* is a Pashto word that means "grand council" and represents a gathering of the elders to settle major issues that involve entire countries.

may eventually be determined to be more desirable. This "gateway," the most ambitious and broadly useful of the concepts considered in this roadmapping process, enables simultaneously goals for bioastronautics, lunar surface support, spacecraft servicing, maintenance, and repair, and human Mars precursors. The gateway is described in more detail below.

The relationship of the *Loya Jirga* workshops to the broader NASA goals of exploration is shown in Figure 1, which graphically illustrates the workshops' role in supporting NASA's broad goal of exploration of the cosmos.

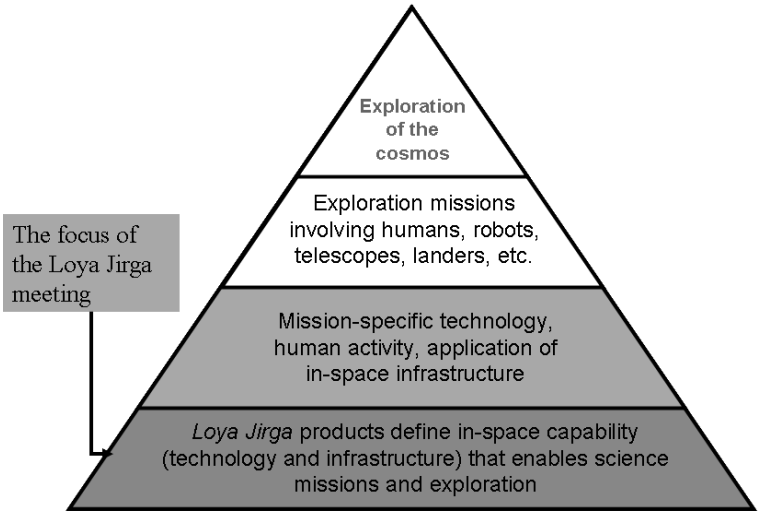

Figure 1. Role of *Loya Jirga* Activity in Supporting Future In-Space Capability

1.2.1 Missions/Science Goals Enabled by the Capability

Several classes of new missions depend on in-space operations for their implementation. Among these are the types of missions that, because their large size prevents them from effectively being launched by a single vehicle. Also, large space systems and spacecraft that operate in a zero-g environment can suffer a substantial penalty if one-g ground testing or launch conditions have to be included as critical design load cases. Moreover, commissioning of these large missions also demands a mechanism for testing them prior to operations. To undertake this type of testing in space may require a permanent or semi-permanent facility equipped for conducting such testing. Testing might be managed from the ground or by humans and/or robots working in proximity to the mission and test facility. In either case, in-space operations will be needed. Clearly, testing of certain types of systems (namely large telescopes or other systems with precision structures) will demand the most complex and detailed test facilities and may require the longest periods of testing. In addition, servicing of large missions was an important element of the deliberations of the members of *LJ II*. The value of such servicing is clear for observatories, where replacement of instruments and spacecraft components can keep the facility up-to-date, an operations strategy that has contributed to the success of the *Hubble Space Telescope*. In addition, servicing allows replacement of consumables such as cooling cryo fluids and propulsion fuels needed to maintain operations at a libration point such as Earth-Sun L2.

Perhaps most significantly, particularly with respect to the priority from the VSE to begin human voyages to Mars within only a few decades, in-space operations with a "gateway" facility may be necessary as a precursor or test demonstration site.

Other portfolios in this series of roadmaps adopted a notional mission sequence to identify the priority science and human exploration activities for the next 30 years for which advanced

capabilities must be developed. For this portfolio, the in-space operations group convened for the *Loya Jirga II* workshop and adopted three major future notional missions that were chosen to explore a wide range of plausible capability needs. In addition, each concept is intended to represent a significant element of the *Vision for Space Exploration*:

- Unmanned, large, complex nuclear-powered science missions to the outer planets that require in-space assembly and testing in advance of a long voyage that will not return.
- Very large optical systems with demanding tolerances for structural and optical performance, significant enough that precision deployment, assembly, and in-space testing are required.
- Human missions to Mars that require significant assembly in space and maintenance or repair during the voyage, and for which demonstration missions or precursors will be essential.

These mission concepts were not specified in detail, as the goal of the *LJ II* workshop and subsequent roadmapping activities were to identify broadly useful capabilities, rather than technologies that would be specific to particular missions.

1.2.2 Traceability to the Vision and Other Priority Agency Objectives

While the deliberations of *LJ II* concentrated on the three broad concepts (above), advanced in-space operations beyond that which is now possible are likely to be essential in achieving the *Vision for Space Exploration*. In addition to human missions to Mars, which seem unlikely without significant advances in bioastronautics and space assembly/support, for example, even smaller robotic missions may benefit. Space telerobotics may be a "breakthrough" capability and has been highlighted as an investment priority for some years by the Space Science Enterprise and Science Mission Directorate. On a much larger scale, human lunar operations may one day employ orbiting depot stations, which in turn may require in-space operations, either with humans or robots far more capable than currently available.

The foundation for these capability needs derives from earlier work by the NASA Decade Planning Team (DPT) and NASA Exploration Team (NEXT), plus the *Vision for Space Exploration*, all of which identify in-space assembly/servicing as necessary to achieve a significant number of goals for the exploration of space. Readers are referred to those documents and publications for background information (see our Bibliography).

1.3 Assumptions, Qualifications, Provisos, Legacy Activities

The following planning assumptions guided our approach to defining capability needs:

- Retirement of the Space Shuttle (~2010) and completion of applied bioastronautics research onboard the ISS (~2015) will occur on the schedule defined in the Vision for Space Exploration.
- Both basic and applied bioastronautics research in support of long human voyages (that is, to Mars) will be required in some manner after NASA ceases to manage the ISS (~2015 at least through the time of the first human missions to Mars).
- A major, sustained precursor, validation, and demonstration program will be required during the ~2020–2030 timeframe, well in advance of the first human mission to Mars to characterize environments, validate technology and choose the most effective locations for human visits.[2]

[2] Although the *Loya Jirga II* process did not consider in detail the technologies, human/robotic precursors and demonstration missions, it is likely that just the preparation for sending the first humans to Mars will dwarf that of the

- Major future capabilities in space (for example, a "gateway" facility) may be developed to support multiple agency goals (for example, lunar surface operations, large space facilities, and precursor development for extended human voyages).
- Increasingly challenging and extended human missions are likely to require scheduled maintenance and repair capabilities, as well as the ability to intervene in an emergency. Any of these operations will require the ability to work effectively and safely in free space outside a spacecraft.
- Very large and complex science facilities (for example, telescopes and complex spacecraft to the outer Solar System) are unlikely to be fully autonomously deployed or assembled (~2020 timeframe; for example, see also the Advanced Telescopes and Observatories capability portfolio).
- Although very large (that is, "heavy lift") launch vehicles may be available in the timeframe under consideration here (~2015+), mission goals and the complexity of future facilities in space are likely to require in-space support at least as capable as currently available (for example, ISS construction, HST servicing, etc.).

1.4 Summary of the "Gateway" Concept

A human-occupied "gateway" facility at a useful location in the Earth-Moon system and, simultaneously, as a precursor to the habitation system to take humans to Mars, has been evaluated for some years, beginning with the DPT and NEXT. A recent concept is shown in Figure 2, an assembly of complex in-space assets, and sustained preparations for long human voyages. Designs have been developed for single launches as a Space Shuttle-derived heavy-lift vehicle concept, for the current NASA architecture of Moon return. In a single launch, such a gateway will have approximately one third volume of the completed ISS and may be placed in different locations via a solar electric propulsion tug. Such a gateway could be outfitted to support lunar surface operations, a site for telerobotic assembly or servicing of expensive space assets, or bioastronautics and space wellness development. In other words, the gateway plays the role of an enabling "hub" in the architectures for exploration beyond the human return to the lunar surface.

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entire human lunar program. It is also likely to require a sustained effort at least two decades in duration before the first human footprints are on the martian surface.

Figure 2. Concept for a Gateway In-Space Operations Habitat

1.5 Key Architecture/Strategic Decisions

A major topic for discussion during the *Loya Jirga* workshops and the roadmapping follow-on was identifying architectural and strategic decisions that might significantly enable opportunities for future in-space operations. Table 1 summarizes some examples of the decision points and issues that will define the possible future use of human and robotic systems and presents the impact of these decisions.

Table 1. Architectural Factors That Will Influence the Role of In-Space Activity

Key Architecture / Strategic Decisions	*Date Decision is Needed*	*Impact of Decision on Capability (Capability Development Required)*
Derive architecture(s) for major space optical systems (surveillance, astronomy, Earth science) beyond JWST	2008	Large optical systems in space are major national assets for civilian and military uses. Successful deployment typically requires two decades of design, development, and coordination with other capabilities. Early definition of the schedule of these missions and their timing will define the pace at which technology and capability must be developed.
Develop roles for international partners in space operations	2008	Early definition can assist the international community in the planning of their contribution.
Define the types of space assets in the 2015+ timeframe to be serviced (rather than replaced or retired) and begin to develop the architecture to enable servicing.	2008	Defines the in-space operations that must be available and the capabilities to be invested in.
Initiate studies for long-duration (>6 months) space flight concepts to derive the investment strategies for post-ISS bioastronautics	2008	Bioastronautics and related in-space capabilities (e.g., closed-cycle life support) will require significant advances beyond that which can be developed and validated on the ISS or lunar surface. Experiments, demonstrations, and validations of an appropriate length are needed to fully characterize human reactions to Mars-like mission durations.

Key Architecture / Strategic Decisions	*Date Decision is Needed*	*Impact of Decision on Capability (Capability Development Required)*
Define the architecture for sustained lunar operations that may be supported by in-space capabilities	2008	Sustained lunar surface operations may require supporting cargo missions from low lunar orbit (LLO) or libration points as well as in-space operational locations that can support human operations on the lunar surface.
Define the architecture for human Mars voyages that require or are enhanced by in-space operations.	~2010	Defines the new capabilities needed to enable Mars missions. Human mission to Mars are likely to require assembly/servicing, the capability for in-space repair and recovery, advanced bioastronautics systems, as well as precursors and demonstration missions in space.
Identify in-space testing and integration options intended to overcome the limits of ground facility size and the effects of gravity	~2010	New modeling and test technologies are needed to replace strategies in use during the first 40 years of space flight.

Table 2 illustrates the trades that can be expected to emerge and influence the application and value of in-space capabilities.

Table 2. Trade Studies

Trade	*Trade Properties*
Launch vehicle mass and volume capacity versus in-space assembly	Trade properties include relative cost, both of development and operations, timeframe for the capability, and the range of priority goals in space that are enabled (for example, simultaneously lunar surface operations, in-space science goals, preparation for human voyages to Mars)
Optimal mix of autonomous precision in-space deployment and in-space assembly	Trade properties include complexity, the need for technology development (and the specific type of technology required), packaging of the system on the launch vehicles, etc. This latter item creates another trade: the complexity and reliability of the transition from the largest available launch volume to the required operations configuration.
Optimal mix of lunar surface capabilities and in-space capabilities in advance of humans to Mars	Human voyages to Mars will require capabilities that do not appear to be able to be developed solely from Earth and lunar surface or in-space operations: bioastronautics, repair/assembly, closed-cycle life support, etc.
Optimal locations for in-space operations and demonstrations	Locations for space operations should be assessed in the context of multiple NASA, military, and international goals: which are most enabled by what location?
Retrieval for servicing versus local servicing support	Factors involved include the fragility of observatory systems already in operating configuration, the reliability of robotic systems that might be used to conduct servicing and the limitations for human presence so far from a safe haven.
Common infrastructure versus dedicated facilities for human and robotic missions	Each option has its advantages; dedicated infrastructure can actually be built into the mission and provide persistent presence of necessary manipulators while common systems offer the potential for sharing technology between platforms by bringing them to a service center.
Optimal mix of advanced EVA systems and robotics	The allocation of roles to in-space human capabilities and robotic partners and functions supporting missions need to be examined with respect to identifying which task elements are most suitable for each agent and which capabilities need development investment.
Long-term versus occasional human presence at gateway	This trade is driven by the cost and complexity of new types of life support that can maintain the crew, as well as the launch capability needed to provide for their needs.
In-space versus Earthbound integration and test	The large size expected for exploration and observatory missions may have already reached the limit of the size of test facilities, the effects of gravity, and the scalability of this test approach. The in-space testing paradigm includes many cost and risk trades. The ability of modeling to accurately predict the effects of gravity, particularly in structural systems that have nonlinear dynamics (which all do at some scale) is not yet proved for the most demanding problems, such as planet detection. For the telescope community, it is widely assumed that the limits of testing on Earth will be reached with the JWST.

1.6 Major Technical Challenges

Table 3 summarizes some of the major technical and administrative challenges that will be faced in creating the new in-space capabilities.

Table 3. Major Technical and Administrative Challenges

Current – 2010
• Develop architectures and options for in-space capabilities that lead from current capabilities to the first human mission to Mars • Develop tools to model and predict the costs, risks, and benefits of having humans operate in free space (as opposed to restricting humans to an in-space habitat or to an Earth-based control station) • Develop systems-level tools to analyze in-space servicing (for example, what is the size, complexity, and total market value of space assets that justifies servicing capability development?) • Extend the productivity of bioastronautics into the time period after completion of NASA's management of ISS • Define appropriate roles for humans, robotics and telerobotics for in-space operations • Define the EVA requirements of the CEV and its upgrades • Define the development and construction path, component support and handling capacity, and concept of operations for future in-space gateways • Define the serviceability of future missions so that upgrades and repairs are possible
2010 – 2020
• Design, fabricate and deploy in-space assets consistent with the needs of missions that are assembled or serviced in space • Demonstrate a new generation of human spaceflight support systems, including the CEV, space suits, radiation protection, tools, contamination management, efficient life support systems and human-robotic collaboration technologies • Develop advanced in-space bioastronautics, space medical and surgical techniques in the post-ISS environment and in advance of application for long human voyages to Mars • Demonstrate a new generation of space system designs that support modular construction to aid servicing and designs that have a high level of technology commonality from one generation to another • Maturation of methods for precision navigation and proximity operations, docking, contamination control and situational awareness
Beyond 2020
• Development and use of robotic space and surface systems that are trusted to conduct operations on high-value assets without supervision • Deployment of a series of large optical systems in space for multiple civilian, military, and international needs • Complete bioastronautics systems and demonstration missions in advance of human voyages to Mars • Complete human-scale precursors and demonstration facilities in advance of human voyages to Mars: the "gateway" as a Block 1 version of the habitation system to Mars?

1.1. Key capabilities and status

The *Loya Jirga II* meeting and subsequent processes identified as the major capabilities are described below as breakout team topics and capability breakdown structure (CBS) categories. Table 4 summarizes the conclusions of the *LJ II* team with respect to the current state of maturity of these capabilities, measured in technology readiness level (TRL) and time required to bring the subcapabilities to a state of maturity for inclusion in the planning of support to major missions. The table also refers to the capability roadmaps (CRMs) and strategic roadmaps (SRMs) that were simultaneously being developed within NASA.

Table 4. Key Capabilities and Status

Capability/Sub-Capability	*CRM or SRM Enabled*	*Current State of TRL (estimate)*	*Development Time (years)*
Human Capabilities			
Space suits	CRMs HHSS, HESM	9 for current systems but new requirements mean an upgrade from 4 to 6 for major technologies	Up to 10 years, depending on the level of investment
Teleoperation	CRMs ATO, HESM, ASR	8	5
Reduced medical and mission	CRM HHSS	7-9 depending on mission	10

Capability/Sub-Capability	*CRM or SRM Enabled*	*Current State of TRL (estimate)*	*Development Time (years)*
risks associated with human health and performance		trajectory and duration	
Radiation protection	CRM HHSS	6	10
Robotics and Automation			
IVHM	CRMs HEPP, IST, ATO, HHSS, HESM, ASR, SI&S, AMSA SRMs RHLE, RHEM, SSE, ETS	4	15
Precision assembly	CRMs HEPP, IST, ATO, HESM, ASR SRMs RHLE, RHEM, SELP, UE, ESAS	6	15
Autonomous docking	CRMs HEPP, IST, ATO, HESM, ASR SRMs RHLE, RHEM, ETS, NS	6	5
Rendezvous and proximity operations	CRMs HEPP, IST, ATO, HESM, ASR SRMs RHLE, RHEM, ETS, NS	6	5
In-Space Transportation			
Human-rated launch vehicles	CRMs HEPP, IST, HHSS, HESM	High (9) for Shuttle, Soyuz but 4 for required new systems	10
Solar electric propulsion	CRMs HEPP, IST, ATO	5	5
Micropropulsion	CRM ATO	3-5 depending on technology	3
Nuclear electric propulsion systems	CRMs HEPP, IST, HHSS	3	5
Communication and Utilities			
1 Gbps communications	CRMs ATO, C&N, HESM, SI&S	4	5-25
Space environments monitoring	CRMs HPLS, HHSS	6	3
Precision timing and location technology in lunar and martian environments	CRMs IST, ATO, C&N, ASR, SI&S	9 in proximity to Earth, 6 in other locations	3-10
Large Optical Systems/Large Space Structures SRMs RHEM, SSE, SELP, ETS, UE, NS			
Advanced design and modeling tools	CRMs HEPP, IST, ATO, C&N, HPLS, ATO, ASR, SI&S, AMSA	5	5
Space assembly	CRMs HEPP, IST, ATO, HESM, ASR	3	10
Modularity	CRMs HEPP, IST, ATO, HESM, ASR	4	10
Advanced operations concepts and planning	CRMs HEPP, IST, ATO, HESM, ASR	3	10
Robotic assembly support systems	CRMs HEPP, IST, ATO, HESM, ASR	4	10
Ground simulation and test facilities	CRMs HEPP, IST, ATO, HHSS, HESM, ASR, SI&S, AMSA	3	5
Monitoring and remote repair	CRMs HEPP, IST, ATO, HESM, ASR, SI&S, AMSA	2	10
Culture and Process			
International participation	All CRMs and SRMs	NA	Can start immediately
Workforce	All CRMs and SRMs	NA	Can start immediately
Education and Public Outreach	All CRMs and SRMs	NA	Can start immediately
Commercial participation	All CRMs and SRMs	NA	Can start immediately

Abbreviations Used			
Capabilities Roadmap Focus Areas		**Strategic Roadmap Focus Areas**	
HEPP	High-Energy Power and Propulsion	RHLE	Robotic & Human Lunar Exploration
IST	In-Space Transportation	RHEM	Robotic & Human Exploration of Mars
ATO	Advanced Telescopes and Observatories	SSE	Solar System Exploration
C&N	Communication and Navigation	SELP	Search for Earth-Like Planets
RAPS	Robotic Access to Planetary Surfaces	ETS	Exploration Transportation System
HPLS	Human Planetary Landing Systems	ISS	International Space Station
HHSS	Human Health and Support Systems	SS	Space Shuttle
HESM	Human Exploration Systems and Mobility	UE	Universe Exploration
ASR	Autonomous Systems and Robotics	ESAS	Earth Science & Applications from Space
TSR	Transformational Spaceport/Range	SSSC	Sun-Solar System Connection
SI&S	Scientific Instruments and Sensors	AT	Aeronautical Technologies
ISRU	In Situ Resource Utilization	ED	Education**
AMSA	Advanced Modeling, Simulation, and Analysis	NS	Nuclear Systems
SECRA	Systems Engineering Cost/Risk Analysis		
NT	Nanotechnology		

2 Detailed Portfolio Discussion

2.1 Introduction

A comprehensive assessment of capability readiness is provided in the following six major topic areas of the Capability Breakdown Structure that the *Loya Jirga II* meetings concentrated on:

- Human Capabilities
- Robotics and Automation
- In-Space Transportation
- Communication and Utilities
- Large Optical Systems/Large Space Structures
- Culture and Process

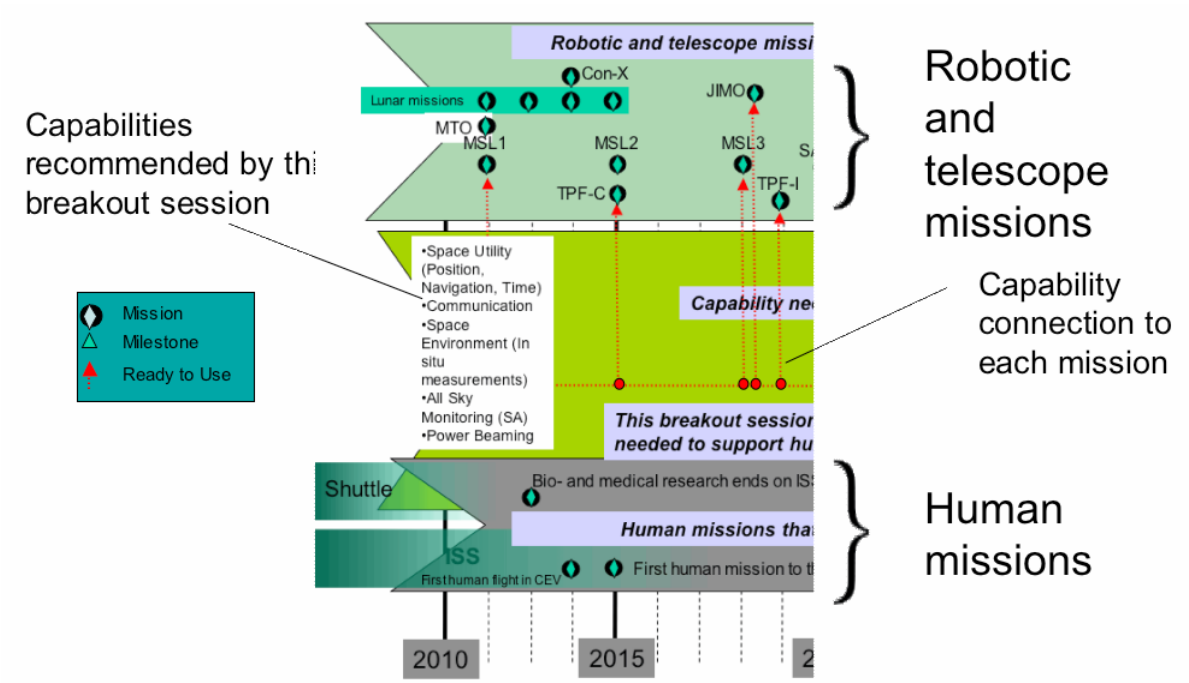
For each of these six topic areas, teams addressed, defined, and analyzed the relation of the capability topic development performance level and timing to the VSE objectives and missions, and the complementary interaction, support or dependency, of the several capabilities that enable particular missions or series of missions.

In most cases, participants assumed that the capability must be available at least five years prior to the initiation of the Phase A effort of the mission, so that integration with the mission is possible and, in the case of infrastructure, the properties of in-space operations resources could be clearly defined. Moreover, a need for maturity of TRL 6 is assumed for any capability associated with a flight mission.

2.2 The Portfolio

The essential content is presented in the following diagrams intended to show how technology developments support both human exploration and science missions. In many cases, the developments we propose are important to both types of missions.

Most figures use the following template (Figure 3). It includes, at the top of the drawing, robotic and telescope missions, showing their notional occurrence, adapted from NASA mission plans valid at the time of the *Loya Jirga II* meeting (winter 2004/2005). The bottom of each figure shows the equivalent information for human missions. The layer in the center defines the capability requirements defined by the particular topic teams. Red lines and dots illustrate which missions are served by each capability. Arrows from the capability in the center of each figure lead to the mission(s) that define both the performance required of the capability and the timing at which those capabilities are needed. Colors that fade out or in, as read going right to left, indicate the cessation of a program or the emergence of a program, respectively, as is illustrated in lines identified with Shuttle or ISS.



Abbreviations used:

BBO	Big bang observer	MSL	Mars Science Laboratory
BHI	Black hole imager	MTO	Mars Telecom Orbiter
Con	X Constellation X	SAFIR	Single Aperture Far infrared telescope
JIMO	Jupiter Icy Moons Orbiter	SPIRIT	Space IR Interferometric Telescope
LISA	Laser Interferometer Space Antenna	TPF-C	Terrestrial Planet Finder Coronagraph
LUVO	Large UV/Optical telescope	TPF-I	Terrestrial Planet Finder Interferometer

Figure 3. Key for Interpreting the Portfolio Diagrams

2.3 Summary Capability Needs

The summary results derived from the *Loya Jirga II* deliberations follow. Figure 4 shows the results for human in-space operational capability, indicating the timing requirements for the emergence of capabilities and their application to human and robotic missions. Figure 5 shows the results for robotics and automation. Figure 6 shows the results for in-space transportation. Figure 7

shows the communications and utilities capability needs. Figures 8 and 9 show the results for large space systems (including telescopes) for the periods 2010–2020 and 2020–2030, respectively. Figure 10 shows the elements of process and culture that are critical elements in the long-term sustainability of in-space capabilities.

In all cases, two general types of missions are considered: robotic/telescope missions and human missions, adapted from the notional mission sequence adopted by this roadmapping process. In all cases, the first mission to significantly benefit from the capability is the one that defines the timing. Also note that the needs are aligned with the mission date. Serious management planning is required far enough in advance of the development process so that the capability can reach an appropriate level of maturity in time for it to be integrated into the design. In most cases we assumed that the lead time for development was 5 years.

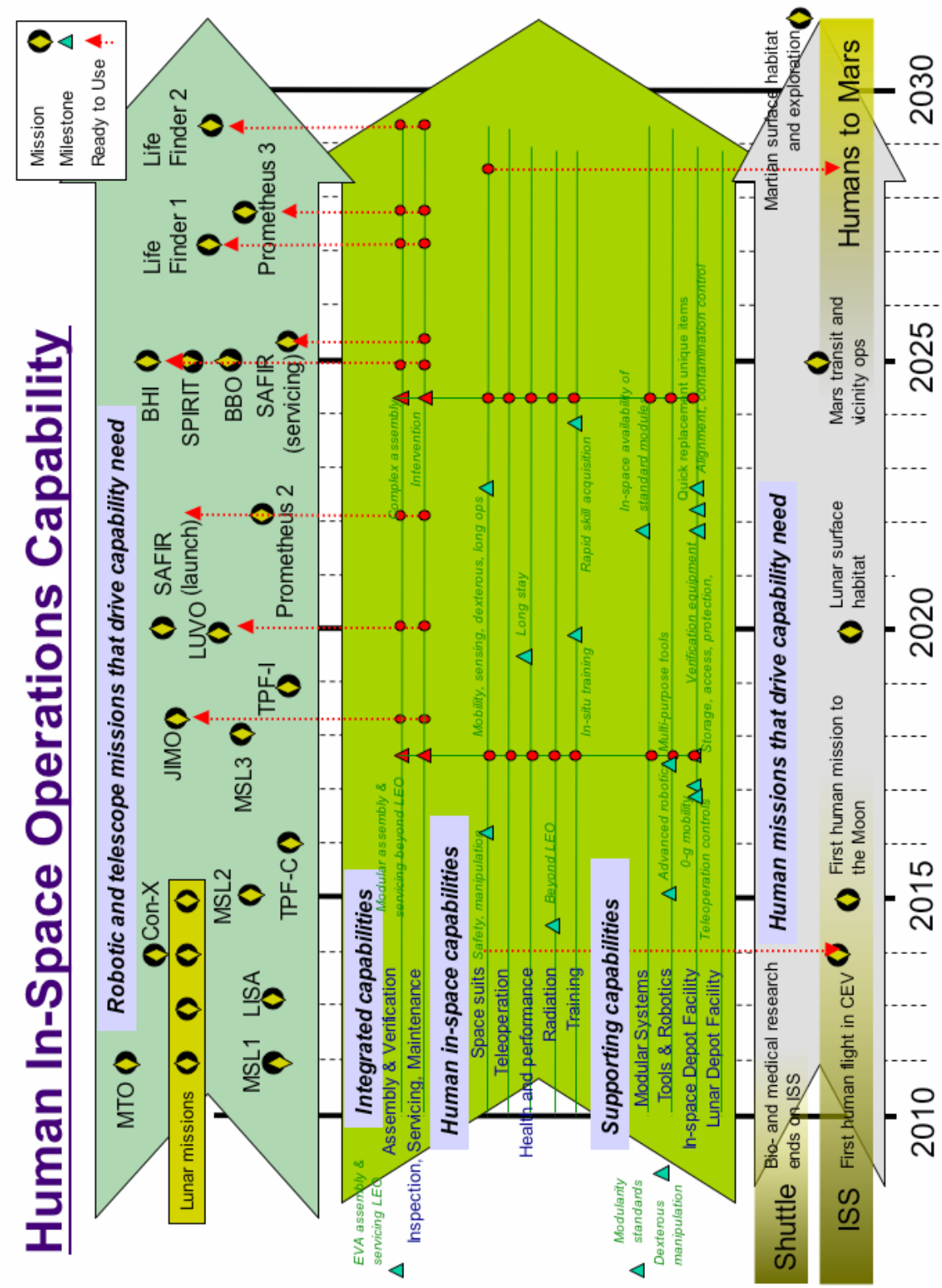


Figure 4. Human In-Space Operations Capability Needs

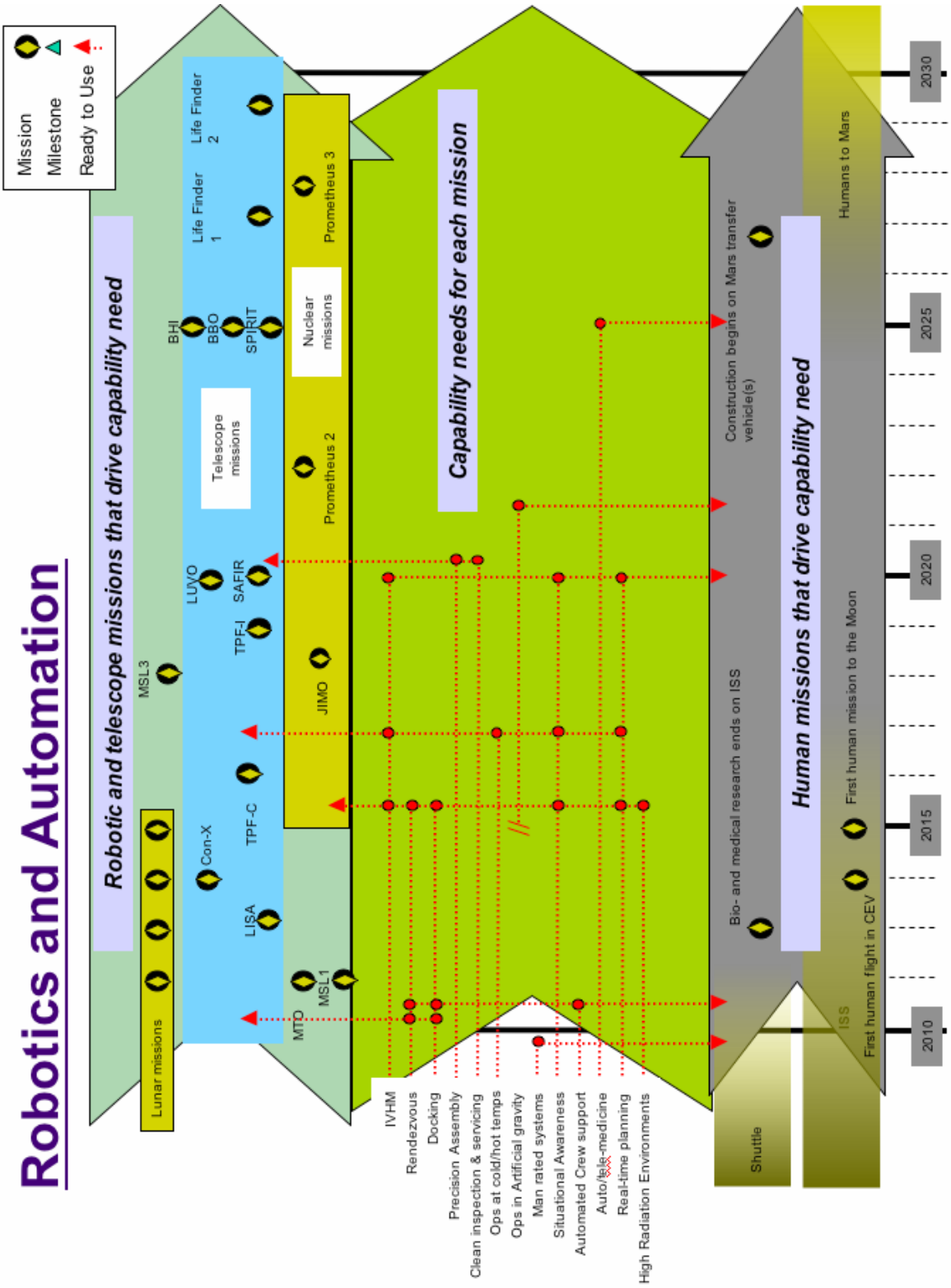


Figure 5. Robotics and Automation Capability Needs

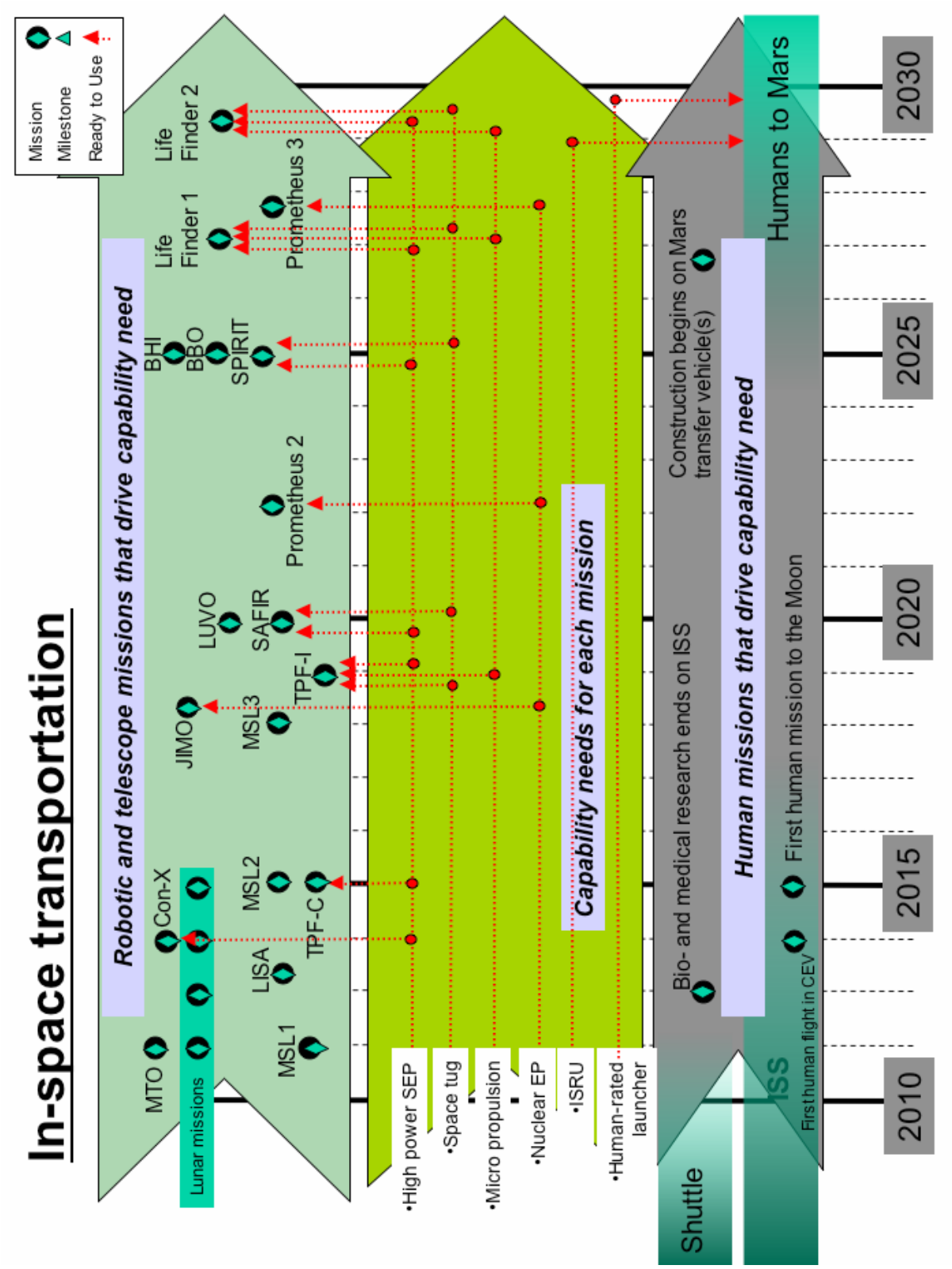


Figure 6. In-Space Transportation Capability Needs

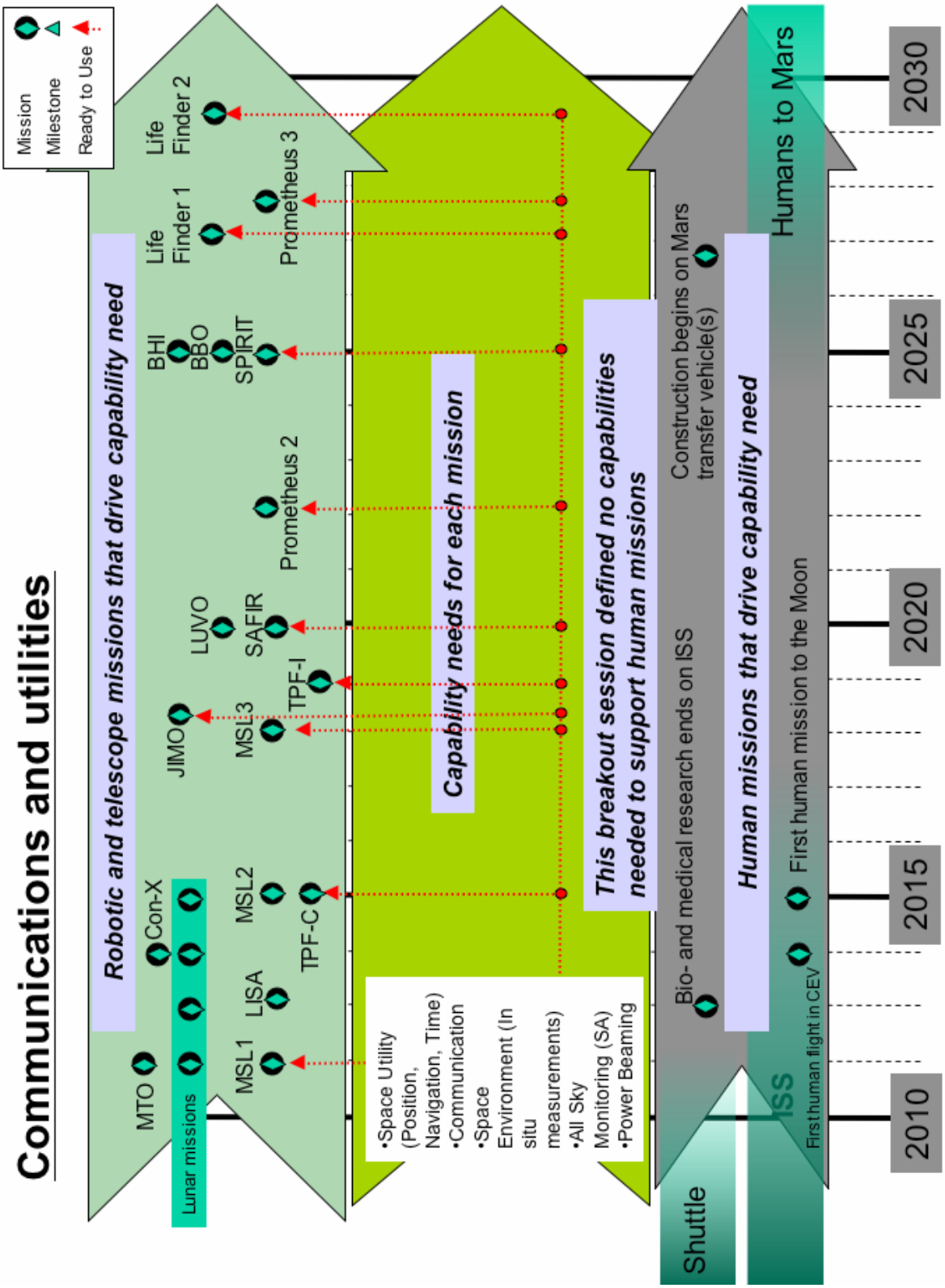


Figure 7. Communications and Utilities Capability Needs

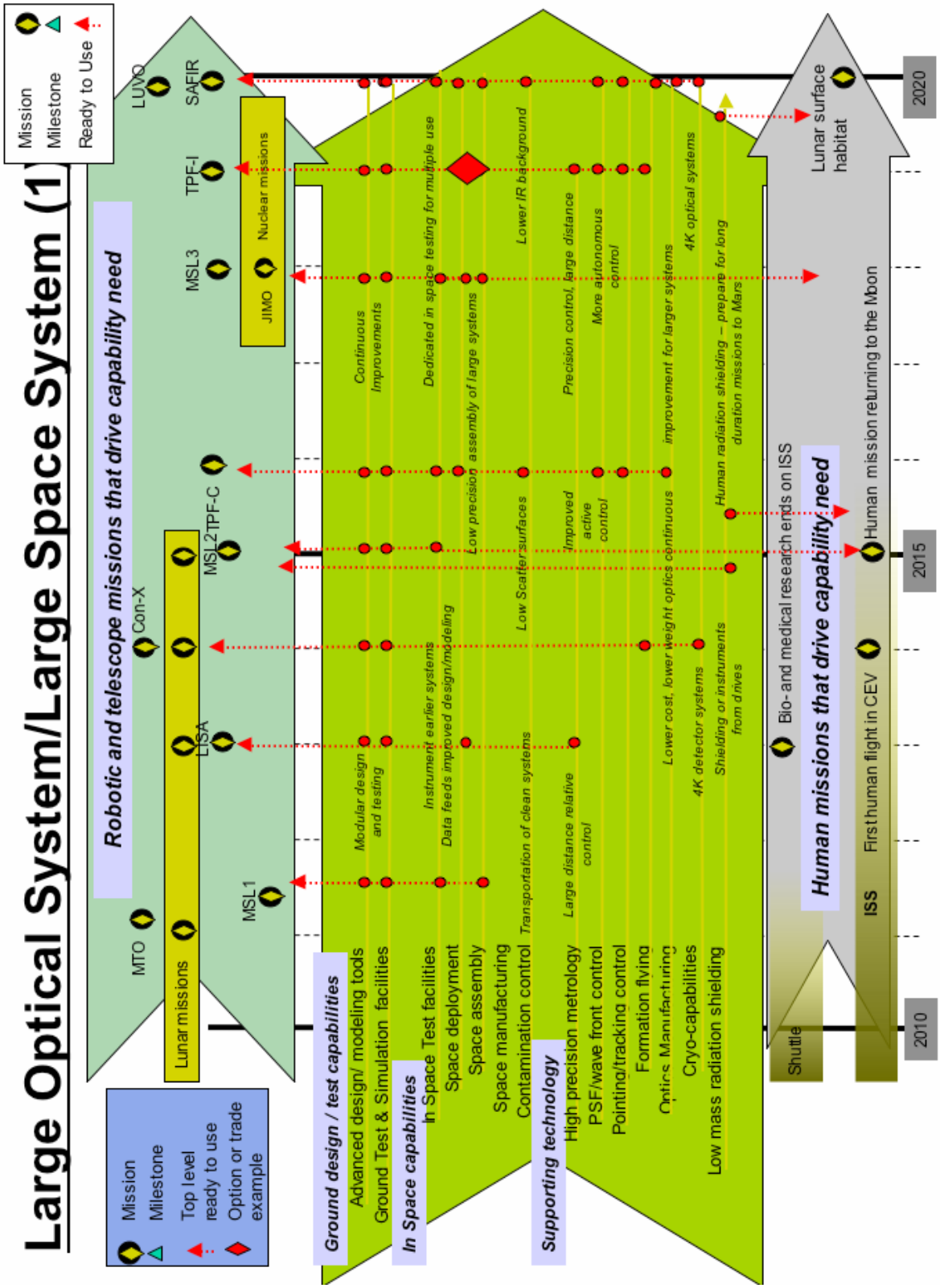


Figure 8. Large Optical System/Large Space System Capability Needs for Interval 2010 to 2020

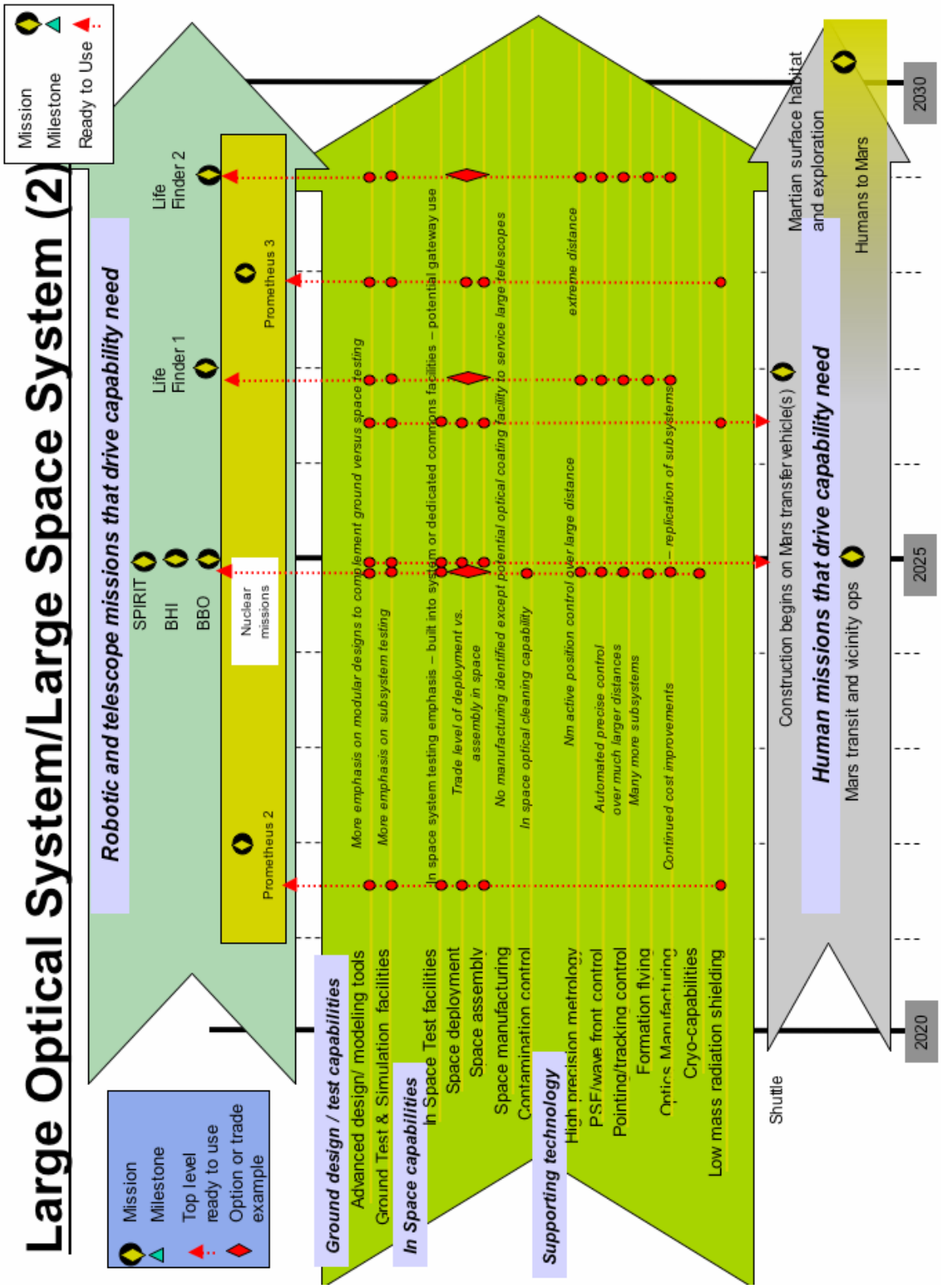


Figure 9. Large Optical System/Large Space System Capability Needs for Interval 2020 to 2030

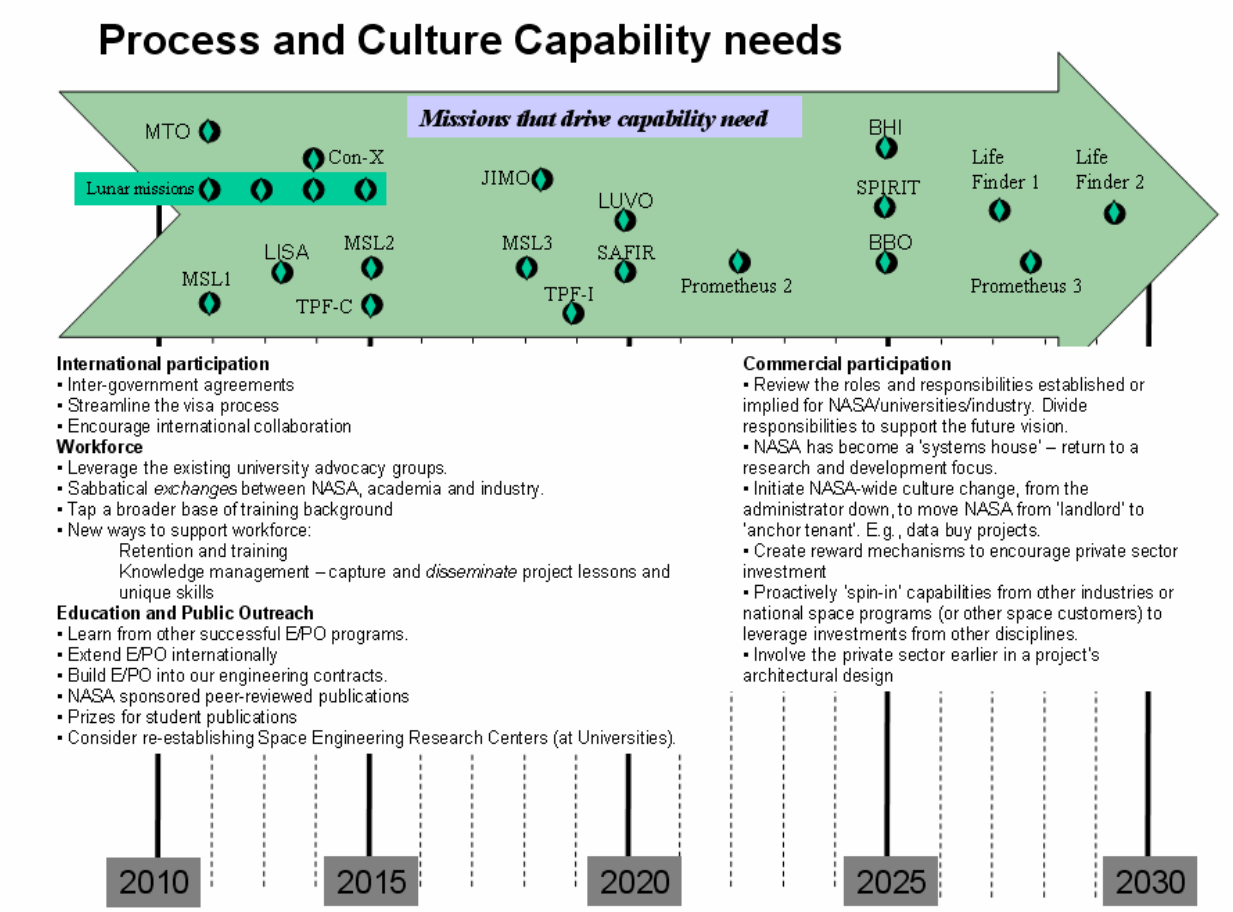


Figure 10. Process and Culture are Critical Elements in the Long-Term Sustainability of In-Space Capabilities

3 Process

A substantial part of this roadmapping effort was invested in documenting the results of the deliberations of both plenary sessions and topic teams formed during the *LJ II* meeting. Participants were encouraged to join in both types of sessions and a number of people 'floated' to encourage communication between the teams. Court reporters were present for the plenary sessions to create a full transcript of the discussion during presentation of reports from the breakout sessions. For each topic, the topic teams were directed to define a product that:

- Defines an array of in-space capabilities to enable NASA goals not otherwise possible, specifically the assembly and servicing of large, complex space systems and, perhaps, development of advanced bioastronautics/space medicine techniques in the era when ISS is no longer available.
- Enables a broad range of priority goals for multiple NASA themes: human and robotic exploration, bioastronautics, space operations, etc.
- Provides a robust approach consistent with scenarios that include new, large, launch systems in the 80- to 120-metric ton range, human presence at a libration point (Earth-Moon L1) gateway, the pace at which humans reach the Moon or Mars, and advanced robotics, among other capabilities.
- Ensures that the timing of the emergence of these capabilities is aligned with NASA's highest

priority goals, in particular multiple goals in the *Vision for Space Exploration.*

- Contributes to the success of various types of missions and to meeting their schedules through assembly by humans or robots (or both), intervention, if required, for deployed systems, servicing, upgrading, and other support activities.

3.1 Summary History

The foundation for these capability needs derives from earlier work by the NASA DPT, NEXT, the work of the NASA Space Architect, and the *Vision for Space Exploration*, all of which identify in-space assembly/servicing as necessary to achieve a significant number of goals for the civilian exploration of space. The *Loya Jirga II* meeting was a direct result of the success and influence of the first *LJ*, held in May of 2003. *LJ I* concentrated on capability needs for large space optics. Having completed that assessment, *LJ II* was organized to address broader needs associated with all in-space operations, human and robotic missions, and a variety of specific applications, such as the most current concept studies for military and civilian space optical systems.

3.2 Summary of Meetings

The *LJ II* deliberations occurred in a slightly different form than that was used for the more traditional NASA roadmapping efforts. That is, after meetings of the organizing committee that structured the work content and the subsequent meeting agenda, the main *LJ* activity took place over a small number of days during which both plenary and breakout sessions occurred. Recommendations from the breakout groups, for each of the topics shown in the portfolio CBS, were brought to the attention of the plenary session where they were debated and final revisions were made. Unlike the NASA roadmapping activities, which occurred over a period of months and might have included many meetings, the *LJ* activity was very compact. Followup meetings and teleconferences enabled leaders of each of the breakout sessions' topic teams to collaborate with colleagues to finalize their products. Subsequently, the organizing committee, augmented by additional contributors, compiled the topic team products into this portfolio.

3.3 Capability Breakdown Structure

A CBS is shown if Figure 11 from the team structure used by the *Loya Jirga* meetings to define the content for this roadmapping activity.

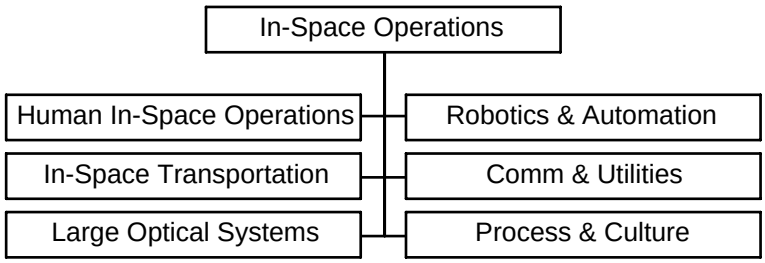


Figure 11. Detailed CBS Subcategories Produced by Each Topic Teams Displayed in the Individual Roadmap Charts

3.4 Connections to Other Capability Roadmaps

The *LJ* activity was intended to fill gaps between the topics covered by other capability to roadmapping efforts. As a result, there is a great deal of overlap with virtually all of the other NASA roadmapping activity. No formal relationships were developed with the roadmapping teams,

although a presentation was made to the capability roadmap on Human Exploration Systems and Mobility and Autonomous Systems and Robotics. Less formal relationships occurred because participants at *LJ* were also actively involved in the creation of NASA roadmaps and brought insight from those deliberations to the *LJ* meeting. At the same time, results from the *LJ* meeting influenced the capability roadmaps that were ultimately presented to the National Research Council, which acted as a reviewer on behalf of NASA.

4 Summary

The *Loya Jirga* deliberations showed that priority NASA goals require operations in space that are not achievable with existing systems, capabilities, and technologies. Indeed, it seems unlikely that the overarching priority for the President's *Vision for Space Exploration*—a human mission to Mars—will be possible without advances in space operations and robotics, bioastronautics and astronaut wellness, and extravehicular activity well beyond that which is currently available.

Sustained investment over decades toward well-managed requirements, beginning in the near future, will be necessary to enable in-space capabilities. As these capabilities become available, a large number of goals will be achievable: support for lunar surface operations, enabling complex space facilities, including depot systems, large science facilities, and the lengthy preparation required for humans to travel to Mars.

4.1 Bibliography

Space Construction

Dorsey, J. T., Sutter, T. R., and Wu, K. C. (1992). *Structurally Adaptive Space Crane Concept for Assembling Space Systems on Orbit*, NASA TP-3307.

Dorsey, J. *et alia,* (2004). *Technology Validation for On-Orbit Assembled, Large-Aperture Modular Space Telescopes*, presented at the Space Technology and Applications International Forum (STAIF-2004)

Lake, M. (2001), *Launching a 25-meter Space Telescope: Are Astronauts a Key to the Next Technically Logical Step after NTST?*, 2001 IEEE Aerospace Conference, Big Sky, Montana.

Rhodes, M. D., Will, R. W., and Coung, Q. (1994) *Baseline Tests of an Autonomous Telerobotic System for Assembly of Space Truss Structures*, NASA TP-3448.

Friedman, E. (2005). *The Technical Path to In-Space Testing of Large Optics*, Proc. SPIE, **5899**, 160.

Moe, R., and Doggett, W., Co-Chairs (2002). *Workshop on In-Space Construction and Maintenance of Complex Science Facilities.*

The In-Space "Gateway" and Site Selection

Moe, R., and Willenberg, H. (2003). *In-Space Servicing Accommodations: Architectural and Mission Implications*, IEEE AeroConference

Willenberg, H. J. *et alia*, (2002). *Site Selection and Deployment Scenarios for Servicing of Deep-Space Observatories*, IEEE Aerospace Conference Proceedings, **2**, 617.

Space Optical Systems

Friedman, E. J., and Espero, T. (2004). *The Role of Humans and Robots in the Assembly of Large Infrared Observatories*, Proc. SPIE, **5487**, 1030.

Friedman, E. J. *et alia* (2005). *Results of the NASA Loya Jirga: Large Space Telescopes and Infrastructure Support*, Proc. SPIE, **5899**, 50.

Lake, M. S. *et alia* (1999). *Structural Concepts and Mechanics Issues for Ultra-Large Optical Systems*, presented at the Ultra Lightweight Space Optics Workshop, Napa, California

Lester, D. F. (2005). *Strategies for Servicing the Single Aperture Far IR (SAFIR) Telescope (2005)*, Proc. SPIE, **5899**, 184.

Moe, R. T. *et alia,* (2005). *Application of In-Space Capabilities to a Large Infrared Telescope for Astronomy – SAFIR*, AIAA First Space Exploration Conference.

4.2 Acronyms and Abbreviations

CBS	Capability Breakdown Structure
CEV	Crew Exploration Vehicle
CRMs	Capability Roadmaps
DPT	Decade Planning Team
EVA	Extravehicular Activity
ISO	In-Space Operations
ISS	International Space Station
LEO	Low Earth Orbit
LJ	Loya Jirga (grand council)
LLO	Low Lunar Orbit
NEXT	NASA Exploration Team
TRL	Technology Readiness Level
VSE	Vision for Space Exploration
SMD	Science Mission Directorate
SRMs	Strategic Roadmaps

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