FINAL REPORT

STUDY IN SUPPORT OF SAFIR HUMAN/ROBOTIC DEVELOPMENT (SHRD)

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1. INTRODUCTION

This document is intended to summarize results of a study of the potential role of humans and robots in the servicing of the Single Aperture Far Infrared telescope (SAFIR). SAFIR is designed to be larger, colder and more capable than the James Webb Space Telescope (JWST), although some versions of SAFIR make the two systems appear architecturally quite similar. Endorsed in the most recent decadal survey of astronomy and astrophysics by the National Academy of Sciences (NAS)[1]. SAFIR will be an important component in the progression of infrared and submillimeter wave astronomy. A great deal of our understanding of the design and operation of SAFIR derived from the final report that was produced[2]. In summary, SAFIR has the following properties:

- 5 year mission with a goal of 10 years
- Operations at Sun Earth L2 (SEL2)
- 10 meter segmented primary aperture
- Operational over wavelengths from 30 to 800 microns
- A combination of active and passive thermal control that results in optics temperatures of near 4 K
- Approximate launch date ~2020
- Servicing will occur after the first 5 years of mission life and after each subsequent 5 year interval
- SAFIR will be designed for a fully automated deployment, much as is the case of JWST, with no human or robotic activity needed for its creation. Rather, the human and robotic roles will be confined to servicing operations.

The following art shows two views of SAFIR. Figure 1 illustrates a version of the observatory that uses a large structure to connect the telescope assembly to the spacecraft bus, which is hidden behind the sunshade. Also attached to the spacecraft are the typical subsystems, including solar panels, communication equipment and other hardware. The equipment in the vicinity of the spacecraft bus operate at ambient temperatures while the telescope assembly and other equipment in view in the image are cryogenic, protected from sunlight by the large sunshade. Other implementations of the observatory rely on different methods for attaching the telescope assembly to the rest of the observatory. Figure 2 illustrates the thermal design of the system, pointing out thermal radiators on the spacecraft bus and the inclusion of cold points (generated by cryocoolers on the warm side of the system) that reduce temperatures on various points of the

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[1] http://www.nap.edu/books/0309070317/html/

[2] "Science Promise and Conceptual Mission Design Study for SAFIR-the Single Aperture Far Infrared Observatory", available from Dan Lester of the University of Texas.

sunshade. Another implementation of SAFIR has been proposed that would allow for articulation of the telescope assembly to allow placing it in sunlight for the purpose of servicing at temperatures consistent with current spacecraft design. Versions of this approach are illustrated in Figure 3 and Figure 4. This approach has considerably influenced the choice of servicing options included in this report. While our analysis includes a wide range of possible implementations to enable servicing, the articulated boom approach has been included in the art work we have included to illustrate how components might be placed for easy access.

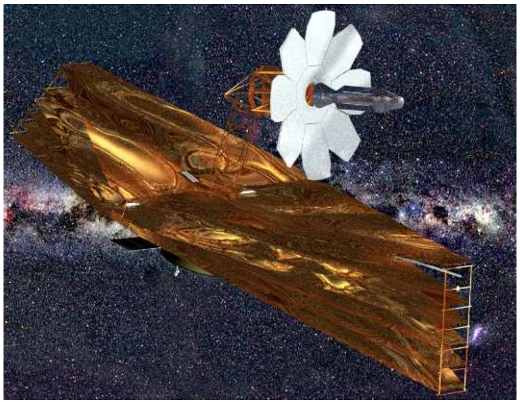

Figure 1 One concept for SAFIR, derived from the James Webb Space Telescope

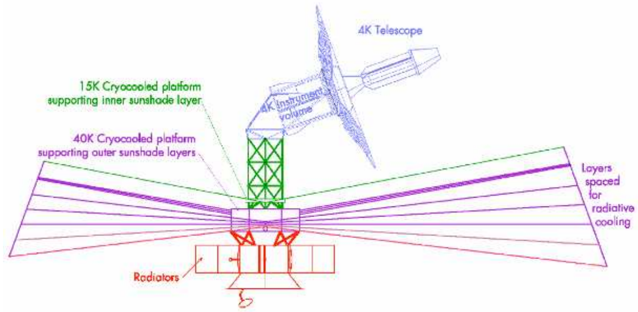

Figure 2 Thermal design of the SAFIR observatory

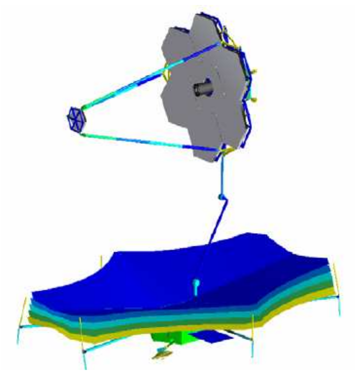

Figure 3 Implementation of SAFIR exploiting a articulated boom[3]

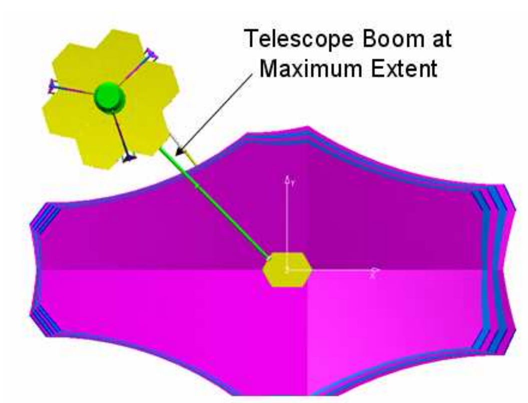

Figure 4 Exploitation of the articulation boom to place the telescope assembly in sunlight for warm servicing[4]

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[3] C. F. Lillie and D. R. Dailey, “A Mission Architecture for Future Space Observatories Optimized for SAFIR”, *SPIE Optics and Photonics 2005*, San Diego, July 31-August 4 [5899-27].

[4] Chuck Lillie (Northrop Grumman Space Technologies), “Servicing Concepts for the SAFIR Mission”, January 28, 2005.

SAFIR represents a complex and very ambitious mission, and has already been selected by the NAS as one of high potential. With a cryogenic aperture of 10 meters and a suite of sophisticated instrumentation, SAFIR will also represent a considerable expense. To compensate for this expense, any an all options for increasing the productivity and life of the mission should be explored. This study was initiated by NASA Science Mission Directorate (SMD) to consider the costs, risks and rewards of such mission life extension and other operations that might increase science productivity.

An essential element of any intent to engage in in-space activity around large telescopes must be that such an investment yields unique science capability not available from conventional methods. By 'conventional' we refer to launch of a telescope intact, such as in the case of the Hubble Space Telescope (HST), or a completely automated and unserviceable system such as JWST. One of the ground rules of the study was that in-space assembly of the observatory not be considered. This derived from the work already completed by the SAFIR design team, during which the benefits of developing a design that is derivative from JWST were revealed. To fully enjoy the JWST heritage and risk management approaches, the designers avoided reliance on in-space assembly.

Some specific examples of unique new capability that benefit the science productivity of SAFIR include the following:

- The potential for continuous maintenance of the observatory to extend its useful life from its design goal of 5 years to at least as long as HST, which, through the use of servicing, has functioned for 15 years. While this exceeds the stated 'goal' life of an unserviced version of SAFIR, it is a reasonable goal for a serviced version. Life extension is achieved by replacing failed components or those whose failure is imminent, replacement of fluids and gases needed for science or propulsion, and otherwise maintaining the system.
- Use of the combination of serviceability and life extension to add new sensors as technology for detectors, electronics and optics improves. Such replacement might allow simultaneous replacement of critical supporting hardware, such as cryocoolers.
- In order to extend the life so that new capability can be installed in the observatory, support system maintenance must be available. This includes replacement of propulsion fuel (since SAFIR will be deployed at Earth-Sun L2, where propulsion is required to maintain its position and desaturate momentum wheels), replacement of on-board machines subject to aging (such as momentum wheels, antenna gimbals, and cryocoolers) and possibly replacement of the sunshade, should its performance degrade over time.
- Augmentation of instrumentation by creating new optical paths to instruments not included in the launched version of the observatory.
- Other augmentations or modifications not now identified, thus providing future designers with the flexibility to invent new approaches for conducting science.

Boeing has initiated this study using its experience with in-space operations and the development of a number of different methods for identifying new strategies for maintaining space systems. Critical to our development of the results shown in this report was the contribution from Dan

Lester, Principal Investigator of the mission. The SAFIR team, under his direction, had already produced a very complete report[2] describing the properties of the mission, and included a discussion of possible servicing options. By reviewing those reports and through interviews with Dr. Lester, we were able to develop a complete list of the desired servicing capabilities, to which we added features derived from Boeing's experience with space operations.

It should be noted that considerable progress has been made on SHRD by the Johnson Space Center (JSC), principally by Brian Derkowski and his team. Early products from the JSC effort were used to initiate this work and assisted in assuring that a complete description of servicing options would be achieved.

In addition, language in the JSC statement of work provides an effective description of the goals of the Boeing study; "Although specifically assisting a particular mission concept, the overarching goal of these studies is to identify principles and operational scenarios that may be enabling for a wide variety of future complex systems in space (e.g., Earth observing, advanced nuclear missions, human-occupied facilities, or human missions to Mars)."

A number of parallel and relatively independent activities have also informed this study; they generally intended to define the role of all types of capability that enables large space systems, including telescopes. The activities include;

- The NASA Science Mission Directorate (SMD) portfolio document on in-space operations[5]
- The *Loya Jirga* meetings[6] sponsored by the SMD in 2003 and 2005
- The NASA Advanced Planning and Integration Office (APIO) roadmapping process which defined future telescope systems and their maintenance
- The National Research Council review of the APIO roadmaps[7]
- The NRC review of NASA's science roadmap[8]
- The NRC 'Decadal' Survey, "Astronomy and Astrophysics in the New Millennium"[9]

Finally, a number of recent papers have provided resources for evaluating the potential and risks of in-space servicing of large telescopes, including specific attention to SAFIR[10,11,12].

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[5] Ed Friedman (lead author) and Harley Thronson, "Future In-Space Operations: Technology Capability Portfolio", a report of NASA's Science Mission Directorate, October 2005.

[6] Ed Friedman, Rud Moe, Paul Graf, Jim Oschmann, "Results of the NASA Loya Jirga II: large space telescopes and infrastructure support", *SPIE Optics and Photonics 2005*, San Diego, July 31-August 4 [5899-06].

[7] Reviews were conducted but reports were not published. One of the reviews specifically dealt with in-space capabilities required to enable future telescopes.

[8] NRC, "Review of Goals and Plans for NASA's Space and Earth Sciences", http://books.nap.edu/catalog/11416.html, 2005.

[9] Christopher F. McKee* (co-chair) and Joseph H. Taylor Jr.* (co-chair), *Astronomy and Astrophysics in the New Millennium*, *http://www4.nationalacademies.org/news.nsf/isbn/0309070317?OpenDocument*

[10] E. J. Friedman, "Technical path to in-space testing of large optics", *SPIE Optics and Photonics 2005*, San Diego, July 31-August 4 [5899-19].

Other pertinent topics are being created elsewhere in the community:

- Exploration system architectures are being developed by a large number of contractors and final reports for the first contract phase have been released[13].
- Starting on September19, 2005, new details about the NASA Vision for Space Exploration (VSE) architecture (VSEA) were being released. Since the creation of this report is contemporaneous with those details, some elements of the VSE architectures may not be fully captured here. Future versions of this analysis can be made more relevant by including the appropriate details.
- The crew exploration vehicle (CEV) competition has begun; it will impact the technology and capability that will be available in space after the retirement of the shuttle and a dramatically reduced role for the US in the ISS.

2. RESPONSE TO THE ELEMENTS OF THE STATEMENT OF WORK

The following topics represent key results of the final report. They are organized according to the SOW elements. The reader may note differences between this report and recent findings of NASA documents, particularly in Section 1. This is a direct result of the dynamic state and completeness of current descriptions of the VSE architecture.

2.1 Completeness tests and analysis

The purpose of this task was to determine what VSEA assets might be available for exploitation by designers of SAFIR and other future telescope systems for which servicing is likely to be useful. Based on NASA goals for exploration and the approach of NASA to meeting these goals, as captured in their APIO roadmaps, the architecture of the VSE (as known on the publication date of this document) and other resources, one can detect the technical, operational and capability gaps that might prevent large observatories from being developed at a pace defined by science needs. Those science needs are defined in NASA's own roadmaps and in the guidance it gets from the Decadal Survey done by the National Academy of Sciences.

In conducting this task, we defined and characterized these gaps. For example, the planning documents of the Exploration Systems Mission Directorate (ESMD) that now exist reveal their current lack of attention to the properties, capabilities and location of in-space assembly and servicing centers (gateways). Rather, the attention is paid to the CEV, as well as the technical features of the ways humans will travel to the Moon. Working with this limited information, our team characterized the type, importance and timing of gaps that can be detected. The product of this task provides, once interpreted by SMD, input for guidance from SMD to ESMD and other elements of NASA that could influence the requirements for the planned gateways tom make such systems compatible with the needs of large observatories.

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[11] Dan Lester, Ed Friedman, Charles Lillie, "Strategies for Servicing the Single Aperture Far IR (SAFIR) Telescope", *SPIE Optics and Photonics 2005*, San Diego, July 31-August 4 [5899-21].
[12] D. F. Lester, R. V. Moe , B. J. Derkowski , E. J. Friedman, T. Espero, C. F. Lillie, "Enabling Opportunities for Large Space Telescopes in the Era of the Exploration Initiative" *AAS 206th Meeting*, 29 May - 2 June 2005.
[13] http://exploration.nasa.gov/documents/cer_reports.html

We find that the following results apply:

- The current VSE architecture[14] focuses on near-term assets and does not address in-space capabilities beyond those needed to enable human exploration of the Moon. Therefore, any reference in this report to the value of 'gateways' or other servicing platforms must be treated as desires rather than planned resources. At the same time, we find that the planned launch systems, continuity of workforce, frequency of launches and other elements of the VSE can be effective in supporting the needs of SAFIR servicing. Large launch systems can enable the SAFIR mission by allowing it to be implemented with fewer deployment complexities than would be required if smaller launch systems were used.
- The likelihood of SAFIR being an affordable mission will be enhanced as new launch systems and other architectural elements are developed, partly because the enhanced capability will be largely paid for by ESMD investments. SAFIR will also benefit from the larger dimensions of the launch fairings associated with new heavy lift cargo vehicle. Similarly, the VSE has shown preliminary plans for an Earth departure stage with the ability to move large cargo from low Earth orbit (LEO) to lunar trajectories. The timing of the SAFIR mission may still allow the effective use of in-space assets provided by the VSE that have not yet been defined. Since the first SAFIR servicing is likely to be no sooner than 2025 (based on a commissioning date of 2020), those new assets might have been developed and might be available for use. Some of them have been included in the planning associated with this study. At the same time, we have included among our options the possibility that in-space systems will not be in place and that robotic, telerobotic and automated systems might be put to use to accomplish the goals of servicing. The principal difference in these two futures is that in the case that no in-space assets are available beyond those associated with human visits to the Moon, those components required to enable servicing will either have to be embedded in the observatory or they will be launched specifically to support a servicing mission. The deficit of this approach is that assets cannot be aggregated and used for multiple missions. In view of this and other factors, our team has concluded that any in-space assets that might support servicing must be of a type that can support a large number of missions, including both observatories and manned systems, such as those that might be used for Martian exploration. In some cases, we have included capability within the observatory to act as its own servicing agent. Hopefully, and wide variety of options will be available to the designers of SAFIR so that the choice they make can benefit from investments made for other reasons.
- Lacking more detailed information, we anticipate that the VSEA is likely to expand in scope and capability, particularly in the interval when human exploration of Mars is beginning. Since the possible launch date of SAFIR is quite close to the initiation of Mars activities, we might expect that new in-space capabilities will be emerging that could allow humans to visit SEL2 for limited periods of time. Indeed, there is already interest in using such a location to prove the performance of both human and spacecraft systems

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[14] http://www.nasa.gov/pdf/133896main_ESAS_rollout_press.pdf

prior to committing them to the long duration trip to Mars. Access to SEL2 could allow more sophistication in the types of servicing that is considered. The pace of development of both human and robotic systems will determine which is most likely to play a key role in servicing. Capabilities might also include rendezvous and autonomous docking of large systems, advanced integrated vehicle health maintenance (IVHM), trusted robotic operations, new human capabilities.

- Vast improvements in the capabilities of human systems will be necessary as NASA prepares for Martian exploration. These advances may be consistent with interest in servicing SAFIR at SEL2. Indeed, there is already interest in using such a location to prove the performance of both human and spacecraft systems prior to committing them to the long duration trip to Mars. The pace of development of both human and robotic systems will determine which is most likely to play a key role in servicing.
- Based on the current description of human exploration of the Moon, it is evident that any evaluation of the servicing implementations must include systems that do not require in-space capabilities. That results in an emphasis on versions of the observatory that can include or use robots, tugs, arms and other manipulation methods that are launched specifically for a particular servicing mission. Such an approach, while feasible, disallows the possibility of accumulating assets and makes the cost of servicing higher. Moreover, such an approach provides little hardware or software (except through experience) that can be exploited by multiple missions that are to be serviced. It is too early to tell whether the lack of in-space assets is a death knell for servicing; in fact, studies of this type are required to determine if and how such servicing can be accomplished, whether or not in-space assets are available.
- Several other features of the VSEA might provide resources that will be useful in designing serviceable observatories:
  - CEV consists of a capsule and service module thereby allowing flexibility in the configuration of cargo and servicing components, both in the design of launch to orbit and in the configurations that are delivered to the servicing location.
  - CEV can accommodate 4 people for lunar missions, 6 for ISS CTV/CRV missions. This contingent of crew members can facilitate telerobotics supervision of servicing activities.
  - CEV can support 6 month space operations. This duration can allow a mix of lunar exploration and telescope servicing, thereby providing flexibility to the servicing designer.
  - CEV can carry autonomous operations, including docking. The ability to conduct some of its activities and autonomous mode should allow for efficient use of humans as supervisors of robotic activity.
  - CEV can carry several metric tons of cargo. This can allow inclusion of servicing tools and test equipment with the crew, thereby facilitating the delivery of necessary hardware to the servicing location.
  - Downmass capability would allow return of hardware to Earth's surface. Return of equipment can allow for repair and maintenance to control costs and can allow for detailed investigation of failure mechanisms to enhanced reliability.

It should be noted that a 'gateway' approach has been widely discussed as an enabling feature of any architecture in which servicing of large systems, including telescopes, could be imagined. During this contract, Boeing considered futures in which such in-space assets would be available and we considered the implications of a delay in availability of those systems. The consequences of those two possible futures are discussed in the following sections.

2.2 Impact on design of the observatory

This section of the final report is intended to document those design challenges that will face the observatory designers as they make SAFIR both an effective mission and one that can be serviced. While much of what is included here is independent of the properties of the VSEA, some changes are likely to be required as new details emerge. For example, should the VSEA include only limited in-space capabilities for cargo handling, the SAFIR platform may have to be amended with robotic arms or other manipulation systems.

2.2.1 Description of the observatory concept

Figure 5 and Figure 6 show a notional concept for SAFIR used for servicing analysis and potential servicing architecture graphics shown throughout this report. While not strictly consistent with any of the mission concepts that have been described in reference 2, the main features are included. The version shown here is derived from the concept in which the telescope and spacecraft are connected with an articulated boom. For simplicity, the primary mirror has been shown here with a small number of elements. This choice does not impact the concepts that follow. The spacecraft bus subsystems are shown as external elements to improve ease of access for replacement and servicing. Among the key replaceable items are the solar panels, the radiator panels, the communication antenna and other typical spacecraft components. As already noted, these components operate at conventional spacecraft temperatures as they are illuminated by the sun at all times. It should be pointed out that the cryocooler systems that maintain the temperature of the sunshade elements and the instruments are on the warm side of the observatory. As described below, the replacement of these components is complicated by the fact that they are plumbed to the cold points on the cold side of the observatory. Severing the connections between the cryocoolers and the locations whose temperatures they maintain is a complicating factor in component replacement.

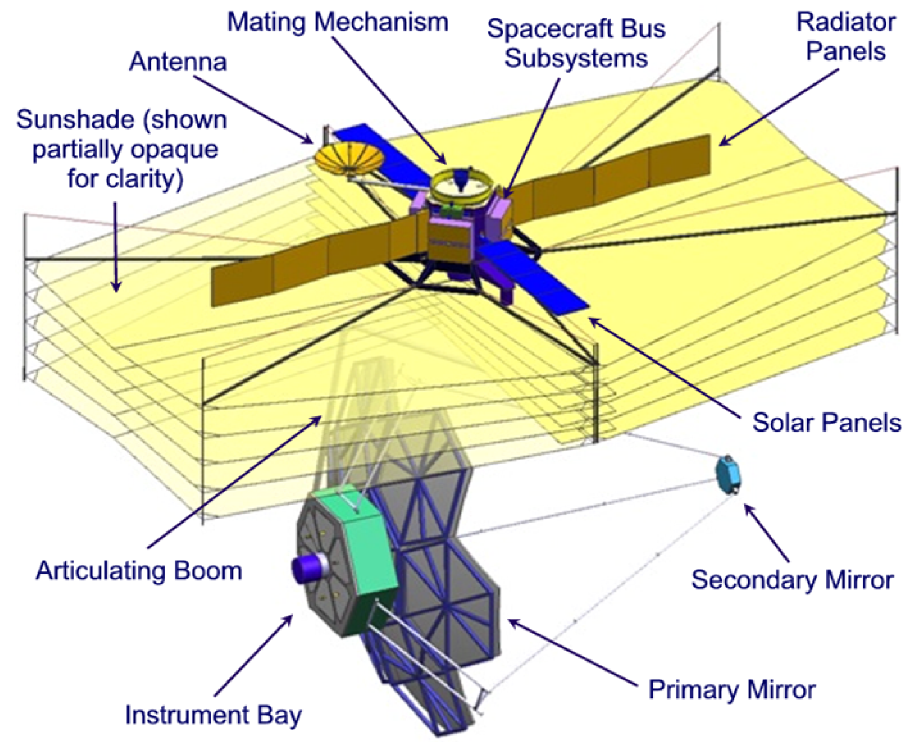

Figure 5 SAFIR layout. This view emphasizes detail of spacecraft bus. The sun is at the top of the picture in this view.

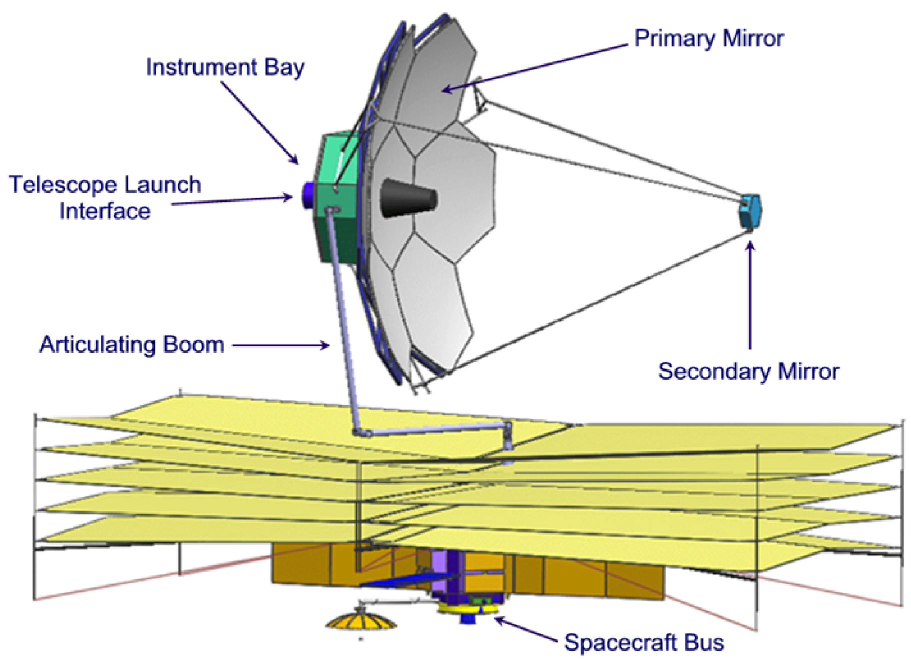

Figure 6 Side view of the SAFIR system. The sun is at the bottom of the picture in this view.

Since we intended the observatory to be serviceable after being in space for a number of years, the initial design must accommodate the servicing concept. Among the issues addressed were:

- Placement of components to facilitate replacement of key equipment
- Structural requirements of the observatory compared with the restrictions imposed by servicing of major elements, such as the sunshades or solar panels. Moreover, the structure must be designed to accommodate the small, but unavoidable, accelerations associated with returning it to the servicing location.
- Tolerance of the telescope to robotic or human operations in its vicinity, including the necessity for warming of the entire system prior to servicing. This includes defining the range of optical materials available to the designer, that can tolerate a servicing approach. At the same time, the observatory must be tolerant of thermal cycling from near absolute zero to temperatures consistent with the operation of robotic or human servicing agents. This will require a careful survey of all components in the spacecraft to assure that their performance and lifetime are not adversely affected by such a cycle.

Other factors are important in the accommodation of the observatory of a servicing approach. Those details are addressed in a database developed to capture the intersection of servicing requirements and servicing implementation. The database is described in subsequent sections.

2.2.2 Serviceability Considerations

In designing for serviceability, key areas to the process include deciding what systems/subsystems/components will be serviceable on the observatory, identifying available servicing methods, and the burden of serviceability to be placed on the servicing agent . While the majority of the burden might be placed on the servicer capabilities, some responsibility of the interface is carried by the observatory, referred to below as the 'client'. The components designated for removal and replacement are known as Orbital Replacement Units, or ORUs, and will be referred to as such for the remainder of this report. Figure 7 illustrates the possible decomposition of the observatory. Each of the elements shown separately are replaceable items. For example, in this approach, mirror segments can be replaced. The art work shown here does not include the details of doing so, however. That is, the interconnection mechanisms, electrical cabling and other interfaces associated with the mirror segments are not included here, but are considered in the discussions that follow. We also emphasize here a sunshade that is formed from two components. Either element of the sunshade can be replaced, should damage or aging require such replacement. Solar arrays and radiator panels are also replaceable. To a large degree, this approach arises from the size of the elements that are assembled during construction of the observatory. By concentrating on effective space and ground methods of connecting components mechanically, electrically, electronically, and thermally, ORUs are defined. Other factors enter into the choice of replaceable components; mainly the Mean Time Between Failure (MTBF) and the criticality of the component to mission success. The partitioning of the observatory into serviceable elements also depends on safety for the observatory itself, because of its enormous cost. This requires that any servicing plan include a risk assessment to assure that replacement or repair of components is a reversible process and that observatory operations can be recovered even if the servicing is not entirely successful.

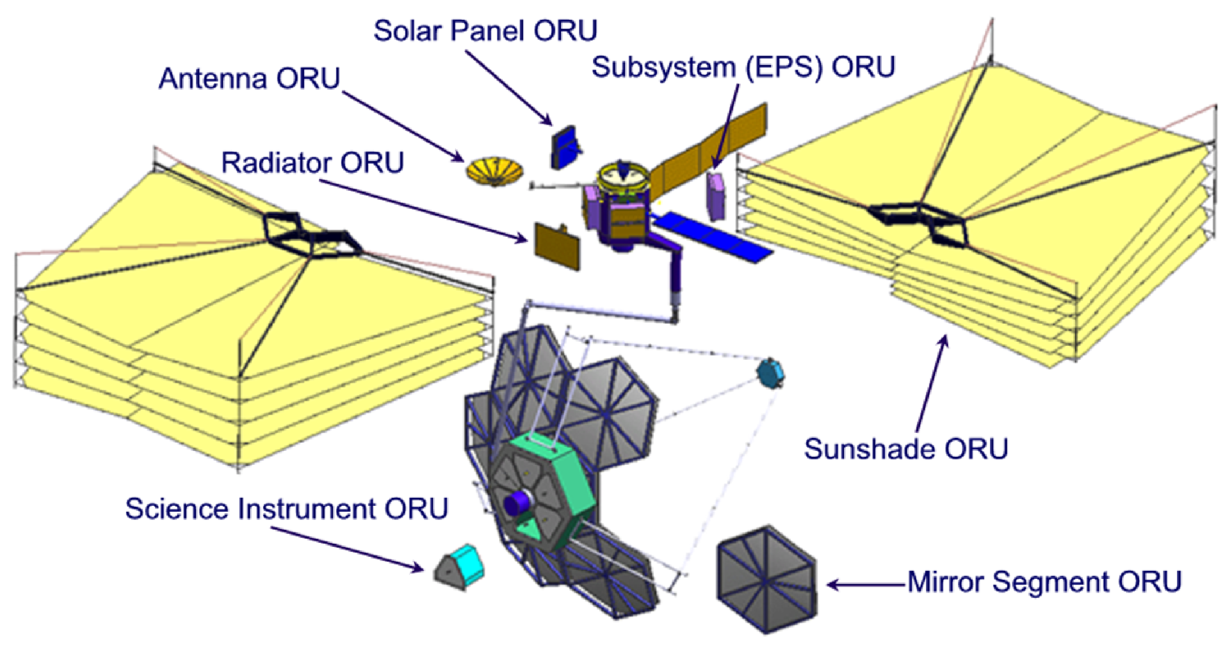

Figure 7 SAFIR serviceable components

Accessibility is a basic consideration in designing for servicing, and locations of the servicing worksites must be carefully thought out. Thermal shrouds or access doors should be robust for robotic manipulation, unlike the access doors on HST. Those doors can only be closed if two EVA astronauts are available. Thermal insulation cannot include soft blankets since they behave unpredictably in space. SAFIR could benefit from these lessons learned and incorporate thermal covers into the ORUs themselves. In Figure 7 , the thermal cover for the science instrument ORUs is integrated into the ORU providing one interface for the servicing agent.

Servicer access to these locations can significantly impact the layout of the client vehicle and need to be considered in the preliminary design. Similarly, any servicing plan that involves operating in the shadow of the sunshade will demand that the servicing agent and related components be able to tolerate that environment, which might imply operating temperatures far below those that are normally encountered in space operations. Clearly, these are only a few examples of the considerations that must be fully developed before a robust servicing plan and observatory design can be created.

Once worksites have been identified, analysis is performed to determine what physical and visual access to the site is required by the servicer. Translational corridors for the agent and the objects being moved from the cargo area to SAFIR and back must be determined during the initial configuration of the telescope. Physical access includes the work volume at the worksite required to allow the servicing agent to reach critical areas and perform the required tasks. This also includes any stability aids in the area required by the agent to minimize errors in placement due to structural flexing within the system. See Figure 8 and Figure 9 for representations of the current work volumes in practice for on-orbit servicing. While future systems might employ new concepts for servicing that expand these volumes, we have included the state-of-art dimensions to illustrate the nature of this problem. In addition, worksite locations must take into account the delicacy of the components, as illustrated in Figure 10. It shows that the worksite is in close proximity to delicate components like solar panels and radiators.

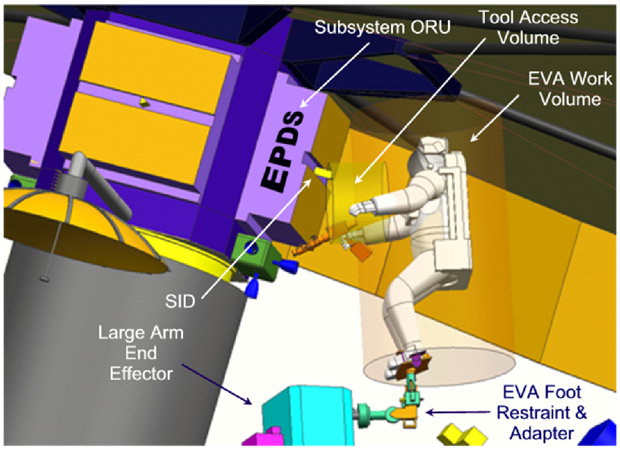

Figure 8 EVA agent performing subsystem ORU changeout. Note: Current ISS EVA work volume and tool access volume shown.

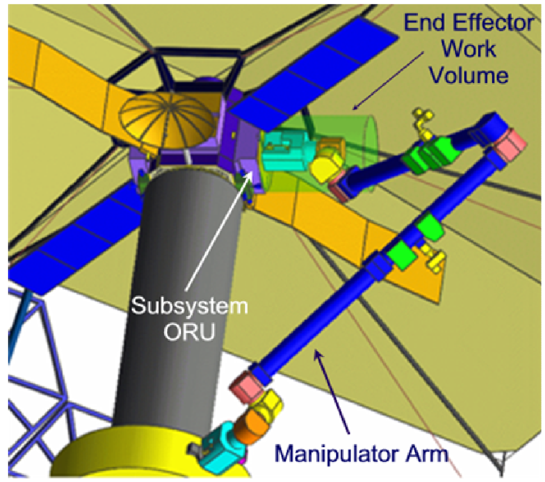

Figure 9 Robot performing subsystem ORU changeout. Note: Current ISS SSRMS end effector and assumed work volume shown.

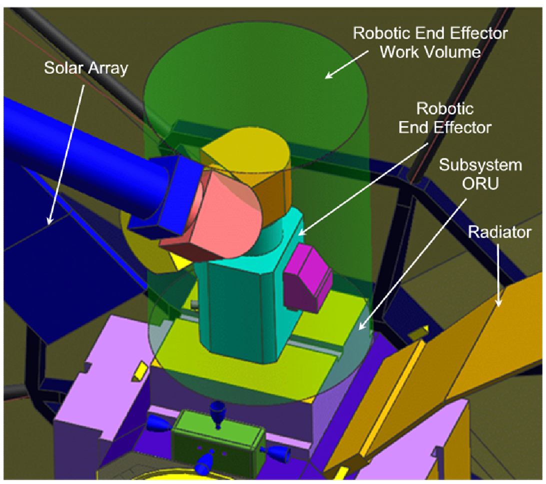

Figure 10 Robotic servicing of subsystem ORU. Note vicinity of delicate components such as solar arrays and radiator. Agent work volumes must be considered to ensure changeout of subsystem ORU without interference with other hardware.

Other access besides physical is to be considered, such as tools and visual access. Tool access must also be analyzed to ensure adequate space is provided for tool operations and removal of an ORU from the client vehicle. Visual access includes global identification cues at the worksite for the agent, including initial recognition of serviceable ORUs and discrete markings and indicators for alignment and proper engagement cues. Visual access encompasses lighting conditions to verify the servicing agent, whether human or robotic, can utilize visual cues effectively. Cameras and lights mounted on the agent, the visiting vehicle, robotic arm or on SAFIR will facilitate in the observation and recording of the servicing events. Lighting issues are particularly of concern if a decision is made to service the observatory while the sunshade is intact. This might require operations in the shadow of the sunshade, thereby demanding appropriate lighting or sensor systems as well as servicing agents that are tolerant of the temperature environment. Extended periods of operation in the shadow of the shade might result in the need for new technologies in space suits and robotic mechanisms and components. Limiting the operating time in the shadow of the sunshade is an alternative that could resolve this problem but at the expense of operational efficiency since the overhead associated with setting up a servicing activity can be quite high. Ideally, the servicing agent would be able to operate for whatever period of time is required to achieve the necessary component replacement or repair, rather than being limited by the temperature and lighting conditions. This is just one example of the types of compromises that might have to be made to enable servicing. A more detailed analysis, beyond the scope of this study, could resolve the nature of these compromises and their proper resolution.

Finally, the servicing solution must not result in inappropriate contamination of critical surfaces in the observatory. Clearly, the most sensitive surfaces are those that convey the astronomical signals into the instruments, but the instruments themselves are subject to contamination, as are other elements of the spacecraft, such as radiator panels. To fully address this issue, the observatory design and the temperature at which servicing might be conducted must be carefully chosen. A warmer servicing environment elevates the tolerance of the entire system to the presence of contaminants but doing so maybe a hazard to the life and performance of components that are sensitive to thermal cycling. Cold servicing avoids the thermal cycling issue but results in collection of volatile gases, water vapor and other contaminants on surfaces that might be intolerant of them. Cleaning technologies have been proposed, but their application to more than just the external components of the observatory is problematic. That is, keeping the optical surfaces in the instruments clean might require special protective doors, such as are described in the SAFIR final report. A collaboration between the observatory designers and the SAFIR science team will be required to assure that the proper selection of materials and operational concepts are exploited to control the contamination problem.

Minimizing the quantity and types of interfaces the servicer must be capable of accommodating reduces both servicer and SAFIR complexity in hardware and software areas. For the purposes of this study a Servicing Interface Device (SID) is assumed that would have the mechanical and structural properties required for an agent to capture, attach to, remove, and translate most of the identified ORUs on SAFIR. This philosophy allows for a simpler servicer to client interface and, when applied over multiple platforms, can reap the benefits of economies of scale. The decision to make wiring harnesses and fluid lines ORUs or maintainable has the biggest positive impact on the design of serviceable observatories. This will require a technology development program to assure that proper and reliable connectors and other hardware and software are available. Software will be required to automatically detect the presence of different types of components so that reprogramming of functions requires no human intervention.

When designing for serviceability there is a trade made on whether to change out large bundled subsystems or discrete individual components. By using a common architecture for the bundled ORU chassis, a common attachment and connector scheme can be used throughout the design of the spacecraft bus and the observatory. Within this chassis, the unique differences between the components can be accommodated and is especially useful when retrofitting or upgrading these systems at future servicing intervals. Given SAFIR's concept of operations for servicing, there is significant time invested in both the warm up of the telescope components to prepare for warm servicing and the transport to the servicing location (if applicable). Due to these considerations, it would be prudent to service the entire subsystem one time to eliminate failures at all levels within the subsystem. The ability to test the serviced observatory before returning it to SEL2 will be critical, as discussed in a later section of this report. Options might exist for re-acquiring the observatory for re-service if the failure existed at a higher level component than the discrete component replaced but such capability can only be achieved by including surpluses of propulsion fuel and other consumables. Such an approach may be intolerable because of cost, complexity or risk issues. Therefore, any servicing approach must emphasize highly reliable operations and should have a goal of, reducing the number and complexity of interfaces between the servicing agent and client. Common interfaces for a wide variety of subsystems can also enhance servicing reliability

Some other issues have to be addressed as well. For example, acceleration loads are frequently transferred by the servicing agent into the client and should be considered when selecting a service worksite on the client to maximize distance between agent and sensitive equipment or structure. When designing for servicing, the possibility of a failure of the detach system may require a contingency or backup method. Once again, this discussion does not address all of the design issues that must be considered as the observatory is designed for servicing. The examples provided here merely alert the reader to the range of issues that must be addressed. Similarly, we are able to provide some examples of design features that could be included to facilitate servicing:

- **Segmented Sunshade:** The sunshade could be designed such that it is removable in two halves. Manipulating one half of the sunshade is easier than working with the entire assembly and lends itself to simpler packaging onto the cargo carrier. If the sunshade were to have articulating capability, the servicing agent could essentially move the sunshade out of the way (wholly or partially) to gain access to the telescope components. In the event the sunshade is unable to restow for removal configuration, disposal of half the sunshade would also benefit from segmentation.
- **Articulating Boom is Robotic Servicing Arm:** If there will be an articulating boom to aid in access to telescope components for servicing, as well as minimize the size of the sunshade, (as shown in Figure 3and Figure 4) then it is conceivable the articulating boom could essentially be the robotic servicing system. It could stow the telescope assembly by attaching it to the structure of the spacecraft and proceed to service (given an arriving cargo vehicle with re-supply components and consumables) the spacecraft bus and/or the telescope assembly.

2.2.3 Unique technology needs for SAFIR telescope servicing:

During the analysis performed to satisfy Task 2 of the SOW, specific technologies presented themselves as development requirements to enable servicing of SAFIR. This short discussion is provided to document a few of these technologies and present the development need. Conclusions at the end of this report consider the benefit of further investigating all technologies needed to enable servicing of SAFIR as a follow-on task.

If the telescope is to be mounted on an articulating boom to provide servicing access to telescope components (science instruments and mirror segments), that boom or mechanical arm needs to carry cryogenic fluids (gas) through the boom and rotary joints. Robotic arms or articulating booms with fluid rotary couplers to transport the cryogenic gas through the rotary joints are a development need. The International Space Station developed a Flexible Hose Rotary Coupler to carry ammonia from the active cooling system to the articulating radiators with a capability of

+/- 105 degrees. Some of this technology may be extrapolated to develop rotary couplers for the articulating boom that can accommodate the gas pressures associated with the cryocooler technology. Moreover, the sensitivity of cryocooler mechanisms to contamination must be addressed in the design of these couplers and other equipment, such as disconnects. Currently the ISS large arm, the Space Station Remote Manipulator System (SSRMS), carries power and data (electrical) through its booms, not fluid.

With planned servicing of the telescope instruments that are cooled by the observatory active cryocooling system, self-aligning cryogenic in-space mate and demate connectors would have to be developed. These connectors will experience extreme temperature conditions, and must function to be demated and remated. This development should follow the standards for all servicing interfaces, but with the special need of carrying cryogenic gas through to the science instruments.

The technology and architecture must also consider disposal of the ORUs designated for replacement on SAFIR. Current ISS and HST servicing architecture carry the removed units back home to Earth. If servicing *in situ* at SEL2, the architecture should consider the disposal of the components. Jettisoning these large components in the vicinity of the observatory could cause potential collisions or degraded science. Of course, since SEL2 is a quasi-stable gravitational location, appropriate low levels of thrust can assure that disposed units will eventually leave the location of the observatory. Indeed, one of the attractions of libration points for telescope science is that natural debris cannot collect due to the competing gravity effects of Earth, the Sun and the Moon.

Other technologies already recommended by the work referenced in Task 1 of this report contribute to the practicality of SAFIR servicing, such as autonomous rendezvous and mating, increased mobility and non-contaminating EVA suits, and clean robotic maneuverability around the observatory. See Conclusions for further discussion of technologies.

2.3 Gateway and CEV properties

To provide an integrated assessment of the servicing operations, a Quality Functional Deployment (QFD) study was conducted. SAFIR servicing can be globally defined by a set of servicing requirements, which list the main servicing operations that are desired by the observatory managers. These services will need to be provided by a set of servicing functions, which are the methodology, hardware, and process options that could be employed by the servicing vehicle/observatory combination to fulfill the desired servicing operations. The overall space architecture will then need to provide the elements and architectural structure to support the defined servicing operations.

A two level database was developed to relate the servicing requirements to the servicing functions in one matrix (Matrix 1) and the servicing functions to the servicing architectures in a second matrix (Matrix 2). By assigning a ranking for each intersection in the matrices – based on viability, implementation options, applicability, risk, and benefit – a top level picture of the servicing interactions can be developed. Based on the relative weighting of these relationships, the end result of the analysis is a third matrix (Matrix 3), which shows how the various intersection combinations rank and provides an assessment of how well the potential and planned space architectures are equipped to satisfy the SAFIR servicing requirements.

Table 1 presents a list of servicing groups, which encompasses all servicing requirements into 5 levels and defines a priority rating for each group (10 is highest, 0 is lowest). These priorities provide a weighting function to the architecture assessment so that more desirable operations are given more importance, and architectures that support such operations are given a higher rating.

Table 1 SAFIR Servicing Priority Scale

Service Group	Comments	Priority
Mission Success	Scientific instruments and data gathering	10
Known Degradations	Consumable re-supply and vehicle survival	8
Scheduled Subsystem Servicing	Hardware maintenance	6
Mechanical Systems	Structural and mechanical actuators	4
Mirror Surface Activities	Mirror surface and segment maintenance	2

The highest servicing priority for SAFIR is instrument maintenance and replacement to upgrade and increase the science capability. Next in importance were items known to degrade or be depleted over the life of SAFIR, such as the sunshade, solar panels, and propellant. With the critical cryogenic operational temperature requirement on SAFIR, replacement of the cryocooler and associated fluids is also in this category.

The middle category includes normal subsystem maintenance hardware items such as attitude control, batteries, and electrical power distribution. Next priority are systems with moving parts such as the mirror segment actuators and any other structural replacements needed, which are highly dependant on the design, quantity, and reliability of such components.

Finally, all options for mirror segment replacement, repair, and/or coating, are lowest on the priority list, along with mirror segment expansion. While it would benefit SAFIR to eventually increase the diameter of the aperture, other systems such as the sunshade would need to be enlarged as well. It is expected that unless the mirrors are exposed to direct sunlight, they will not require recoating. The odds of damage to optics of sufficient magnitude to require mirror segment replacement is considered small. Thus, it ranks low in servicing requirements.

Table 2 is a more detailed breakdown of specific servicing requirements with brief comments. The table also shows the appropriate priority ratings that are assigned based on the servicing groups.

Table 2 SAFIR Servicing Requirements

Requirement	Comments	Priority
Cryo Gas Replacement	Replacing gas in cryocooler, more difficult than replacing cryocooler itself	8
Cryocooler Replacement	Replacing entire cryocooler	8
Solar Cell Replacement	Replacing Solar Arrays	8
Sunshade Repair / Repair Single Layer	Repair of sunshade, may encompass peeling back of sun-facing layer to expose a new one	8
Sunshade Replacement	Replacing entire sunshade	8
Propulsion Fuel Replenishment	Fuel supply for station keeping at L2	8
Facility Observations	Ability to inspect observatory to aid in servicing (close range observations) using cameras and lights	2
Instrument Replacement	Upgrade of instruments – highest priority for servicing mission	10
Thermal Control System Maintenance	ATCS – Active Thermal Control System. Includes servicing of entire subsystem minus the cryocooler	6

Table 2 SAFIR Servicing Requirements

Radiator Replacement	Replacing a Radiator ORU	2
Structural / Mechanism Replacement	Structural member replacement and servicing of electro-mechanical components	4
Mirror Maintenance or Mirror Recoating	Maintaining the surface of the mirror	2
Mirror Segment Replacement	Replacing a damaged mirror segment	2
Mirror Segment Actuator Replacement	Replacing the mechanical actuators behind the mirror segments	4
Mirror Segment Installation (Expansion)	Expanding the aperture by adding mirror segments	2
Unplanned Repair / Maintenance	Catch-all for unplanned servicing needs	10
Electrical Power and Distribution Module	Replacing entire EPDS Subsystem	6
Command and Data Module	Replacing entire C&DH Subsystem	6
Attitude Control Module (Gyros)	Replacing ACS Subsystem	6
Minimal Interruption to Science	Science friendly servicing	10

Table 3 is a list of various servicing functions that the servicing vehicle/observatory element combination can use to satisfy the servicing requirements. These functions encompass many different issues, from attachment methodology and observatory state (warm or cold, operating or dormant), to contamination management and fluid transfer process. They are meant to cover the many types of operations, hardware, conditional states, processes, and methodologies that will affect the various types of servicing requirements. Also shown are some possible options for each function and comments to cover some of the issues that were considered for the ratings.

Table 3 SAFIR Servicing Functions

Servicing Function	Options	Comments
Attachment Options	Formation Flying	No physical attachment.
	Tether	Non-rigid connection, but structures still separated.
	Hard Dock	Structural attachment of two vehicles or objects that can withstand high separation forces
	Soft Dock	Two objects are structurally attached thru a low loads device that can be readily detached with small forces. As used in this study, when large masses are connected only by robotic arm during servicing.
Observatory Status During Repairs	Fully Operational (Performing Science)	Cold servicing is assumed here.
	Safe Mode (No Science)	The telescope and bus systems involved with the specific servicing task being conducted are configured to allow safe servicing of the SAFIR system and for the servicing vehicle.
	Powered Down	All telescope and bus systems are powered down to minimum required to prevent damage while servicing is being conducted.
Attitude Control	Controlled by Service Vehicle	Responsibility to provide attitude control during servicing
	Controlled by Observatory	
	Controlled by Both	
Fluid Transfer	Via Tanks	Provide new containers on the observatory, requires multiple, complex servicing interfaces
	Via Hoses	Transfer the fluid from the servicing vehicle to the observatory, requires less complex servicing interfaces
Telescope Warm Up Options	Service vehicle heaters	Electrical heaters to warm up the telescope components
	Observatory heaters	
	Observatory rotates itself	Passive method to put the telescope in the sun to warm up
	Service vehicle rotates observatory	
Power Production	Controlled by Service Vehicle	Responsibility to provide power during servicing
	Controlled by Observatory	
	Controlled by Both	
Contamination Management	Contamination prevention	Develop methods to eliminate/prevent contamination
	Clean during servicing	Develop methods to clean contamination post servicing
Service Methodology	Autonomous	Tasks defined at goal level, high unplanned/recovery capability, artificial Intelligence capability.

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Table 3 SAFIR Servicing Functions		
	Automatic	Pre-scripted tasks uploaded and executed by the servicing vehicle, limited unplanned/recovery capability.
	Tele-robotic – Remote	Operator-in-the-loop, assumed on Earth, medium unplanned/recovery capability.
	Tele-robotic - Local	Operator-in-the-loop, assumed at same servicing location, high unplanned/recovery capability.
	EVA – Human Manipulation	Astronauts performing Extravehicular Activity to accomplish servicing tasks, may be augmented by robotics to increase accessibility (similar to ISS SSRMS), highest unplanned/recovery capability.
Service Frequency	Infrequent (10 years)	Longer than baseline servicing timeline.
	Frequent (5 years)	Baseline servicing timeline.
	Early (3 years)	Servicing before expected timeframe.
Access to Cold Side	Attach to Cold Side	Servicing vehicle would attach to the cold side of the telescope for access to instruments and other ORUs.
	Remove & Attach Telescope to Warm Side	Assumes robotic arm to detach telescope portion of observatory and temporarily stow on the spacecraft bus side.
	Telescope on Articulating Boom	Articulating boom moves telescope over edge of sunshade for servicing access.
Segmented Primary Mirror		Allows for mirror servicing.
Accessible ORUs		Servicing requirement on SAFIR.
Communications	Service Vehicle	Responsibility to provide communications during servicing.
	Observatory	
Command and Data Handling	Service Vehicle	Responsibility to provide C&DH capability during servicing.
	Observatory	
Propulsion	Service Vehicle	Responsibility to provide propulsion during servicing.
	Observatory	
Segmented Sunshade	Yes	Sunshade has been designed to facilitate servicing.
	No	Fixed sunshade.

Table 4 provides a set of servicing architecture operational options that incorporate both servicing vehicle elements and operational scenarios, and lists some comments that that describe each option. The possible servicing architectures were based on the following logic:

- Repair location – *in situ* (at the operational location) or offsite
- If *in situ* – trade repair platform
- If offsite – trade method of transport
- If offsite – trade transport destination
- If offsite – trade repair platform

For the initial assessment, all the combinations of offsite options listed were assumed to be viable, including space stations in cis-lunar orbits. This provides an overall comparison of the entire global trade space. A second assessment, with Earth Moon L1 (EML1) and cis-lunar stations removed from the trade space, was performed to determine the impact of architecture limitations.

The individual trades for method of transport, transport destination, and repair platform were assessed as single options. However, to arrive at a total architecture impact assessment rating, the offsite options needed to consider the combined impact of all three pieces (transport, location, and service platform) for direct comparison to *in situ* repair options, which only trade servicing platform options.

Table 4 Exploration Architecture Options				
Repair Location	Transport Method	Transport Destination	Repair Platform	Comments
In Situ @ Sun Earth L2				"Point" (actually region) aligned with Earth and sun; beyond Earth's orbit. No humans present (see Ground Rules). Need to regularly fire thrusters to stay in L2.
			Resident Remote Service Vehicle (RSV) based at L2 equipped with planned maintenance consumables (no consumable delivery from off-site)	Expected to be a larger robotic servicing vehicle (RSV) due to pre-configured servicing components and consumables. Sent to L2 when SAFIR is deployed. All levels of robotic capability except close range telerobotics.
			Resident Remote Service Vehicle based at L2 with consumable delivery as required	Generic smaller robotic servicing vehicle with custom cargo delivery. Able to service other clients in the L2 neighborhood. All levels of robotic capability except close range telerobotics.
			Servicing robotics on SAFIR with consumable delivery as required	Robotic capability resides on SAFIR with custom cargo delivery. All levels of robotic capability except close range telerobotics.
			Traveling Remote Service Vehicle from Gateway with consumables	Custom RSV with consumables/resupply cargo configured for SAFIR servicing. All levels of robotic capability except close range telerobotics.
Offsite				Non-L2 locations all have similar transit time to/from L2.
	Tug Transport			Space tug that propels SAFIR to servicing location and most likely servicing agent
	Self Transport			SAFIR provides own propulsion to transport to servicing location and servicer
		LLO Gateway		Dual or multi-use gateway enables human lunar exploration as well as servicing. May have frequent eclipses, depending on orbital inclination and time of month.
		L1 Gateway		Dual or multi-use gateway enables human lunar exploration as well as servicing. Location allows access to most of lunar surface.
		LEO Gateway		Frequent eclipses and thermal cycling.
		Cis-Lunar Orbit		In transit between earth and moon. Not a likely scenario (see Ground Rules).
			CEV + EVA Module + consumable supply	VSEA CEV with EVA capability. Needs cargo vehicle to carry supplies. Assumed no robotic capability. Human presence.
			CEV + Telerobotics + consumable supply	VSEA CEV with close range telerobotics. Needs cargo vehicle to carry supplies. Assumed no EVA capability. Human presence.
			Remote Service Vehicle (RSV)	Robotic Servicing Vehicle at a location other than L2. Needs cargo vehicle to carry supplies. No human presence. All levels of robotic capability except close range telerobotics.
			Unmanned Station with Telerobotics	Station is outfitted with high robotic capability, including autonomous systems. No human presence.
			Manned Station	Station has EVA capability and also high robotic capability, including autonomous systems. Human Presence.

The following ground rules and assumptions guided the assignment of rankings for each intersection in the matrices:

- Most of this evaluation is based on servicing the SAFIR in a warm state, a decision dictated by the Principal Investigator Dan Lester. Some elements of the SAFIR could benefit if the ability to service cold is developed.
- Whenever possible, to control contamination, the telescope is positioned as far away from the servicing worksites as feasible.
- No CEV (humans) at SEL2, although this option may be supported by 2025 by the VSEA - all servicing done at SEL2 is by robotic agents.
- Use of a cis-lunar orbit for servicing, in transit between Earth and the Moon, is not a likely scenario - however it is supported by VSEA and is included in this study.
- Resident robotic servicing vehicle at SEL2, with delivered cargo vehicle, is assumed as a viable alternative – this vehicle could service other observatories at SEL2.
- SAFIR self-service is a viable option.
- Spacecraft bus is based on common modular design suitable for other telescope missions. Spacecraft bus design allows for servicing and upgrades.
- SAFIR design must be able to disable a damaged or inoperable segment.
- The gaps between mirror segments should be as small as possible; segments would require precision alignment capability by servicing agent.
- Assume cryocooling system is serviced at every servicing interval.

The goal in developing the matrices is to span the trade space of likely and desired options for SAFIR servicing. These range from a minimal capability that is purely robotic, and is embedded or co-located with SAFIR, to enhanced versions of the VSEA, involving humans, mobile multi-use robots, and gateways.

In Matrix 1 (Table 5), SAFIR Servicing Functions (row headers) are scored as to how well they are suited to satisfy the desired SAFIR Maintenance Requirements (column headers). The servicing functions are grouped by categories of functions (attitude control, power production, etc.) that a servicing system may have to perform. Within these categories, options for fulfilling the function are listed. For example, within Power Production, options are: controlled by the servicing vehicle, controlled by observatory, or combined control. The trade space spanned was kept wide, but reasonable. For example, Telescope Warm Up Options contains four reasonable possibilities. It was decided that this category should encompass only warm-up options, not all thermal control options; i.e., servicing an observatory that remains cold was not considered a reasonable prospect, regardless of how extensive the VSEA infrastructure becomes.

The Servicing Functions within a given category were rated in terms of absolute, not relative, suitability for satisfying Maintenance Requirements. They were not ranked against each other, nor were they compared in a pair-wise manner. This is because the Servicing Functions are parameters that will not appear explicitly in the final Exploration Architecture Options versus SAFIR Maintenance Requirements output (Matrix 3). Rather, they are a bridge between the latter two quantities. Thus, it is possible that some, or even all, Servicing Functions within a category may receive equally high (or equally low) ratings. Relative preferences are not necessary at this step because they will emerge from the output of the process (or a straightforward modification of the output). The grouping by category does, however, provide context for the options.

Some categories that may be, in a wide sense of the term, considered Servicing Functions were not regarded as such if that category could be considered a core part of a different trade. For example, repair location (SE-L2, LLO, LEO, and EM-L1) was not regarded as a Servicing Function, but as an Architecture Option (Matrix 2), because these location options are a core part of what defines an architecture option. It is therefore necessary to retain repair location explicitly in the final output. The SAFIR Maintenance Requirements listed as column headers in Matrix 1 span the range of major subsystems, major structural elements, and consumables.

In Matrix 2 (Table 6), Exploration Architecture Options (row headers) are scored as to how well they are suited to meet the defined SAFIR Servicing Functions (now column headers). The process that was carried out was analogous to that of Matrix 1; i.e., ratings were absolute, rather than relative, but relative preferences are an expected output of the overall process.

The rating process for Matrix 2 differs from that used in Matrix 1 in at least one respect: in Matrix 2, there were four levels of groupings for the parameter whose suitability is being rated (architecture). The first level is Repair Location: In-Situ at SEL2 versus Offsite. Within Offsite, two Transport Methods (Tug Transport and Self Transport) can be used to access any of four Transport Destinations (LLO, L1, etc.). The final sub-category is Repair Platform, which consists of various combinations of service vehicles, CEV, etc.

If every combination of Architecture Option were rated in Matrix 2, then a total of 44 different architecture combinations would have to be assessed. However, in our initial attempt to rate every possible combination of Repair Location, Transport Method, etc, the dependence of the rating on Repair Platform was strong (i.e., ratings varied significantly from one platform to another), but these ratings tended to nearly repeat as the other architecture characteristics varied. Furthermore, in the Output Matrix (Matrix 3), all the combinations of architecture characteristics are listed, and the suitability of a completely defined architecture (with Repair Location, Transport Method, Transport Destination, and Repair Platform all specified) to satisfy the desired SAFIR Maintenance Requirements emerges by disaggregating the architecture characteristics.

Table 5 SAFIR Servicing Functions vs. SAFIR Maintenance Requirements (Matrix 1)

SAFIR Servicing Functions	INPUT MATRIX	SAFIR Maintenance Requirements and Priorities																			
	How well the various SAFIR Servicing Options are suited to satisfy the desired SAFIR Maintenance Requirements	Cryo Gas Replacement	Cryocooler Replacement	Solar Cell Replacement	Sunshade Repair / Replace Single Layer	Sunshade Replacement	Propulsion Fuel Replenishment	Facility Observations	Instrument Replacement	Thermal Control System Maintenance	Radiator Replacement	Structural / Mechanism Replacement	Mirror Maintenance or Mirror Recoating	Mirror Segment Replacement	Mirror Segment Actuator Replacement	Mirror Segment Installation (Expansion)	Unplanned Repair / Maintenance	Electrical Power and Distribution Module	Command and Data Module	Attitude Control Module (Gyros)	Minimal Interruption to Science
	Importance to SAFIR	8	8	8	8	8	8	2	10	6	2	4	2	2	4	2	10	6	6	6	10
Attachment Options	Formation flying	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	3
	Tethered	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Hard dock	3	3	3	3	3	3	2	3	3	3	3	3	3	3	3	3	3	3	3	1
	Soft dock	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Observatory status during repairs	Fully operational (performing science)	0	0	0	1	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	3
	Safe Mode (no science)	3	3	0	3	3	3	3	3	1	1	3	3	3	3	3	1	1	3	3	0
	Powered Down	2	2	3	2	1	2	3	2	3	3	1	1	1	1	1	3	3	1	1	0
Attitude Control	Controlled by service vehicle	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	3	0
	Controlled by observatory	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1
	Combined control	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1
Fluid Transfer	Via tanks	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Via hoses	3	1	1	1	1	3	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Telescope Warm Up Options	Service vehicle heaters	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Observatory heaters	3	3	1	1	3	1	1	3	3	3	1	3	3	3	3	3	1	1	1	2
	Observatory rotates itself	2	2	1	1	2	1	1	2	2	2	1	2	2	2	2	2	1	1	1	0
	Servicer rotates observatory	2	2	1	1	2	1	1	2	2	2	1	2	2	2	2	2	1	1	1	0
Power production	Controlled by service vehicle	1	1	3	1	1	1	1	1	1	1	1	1	1	1	1	3	3	3	3	0
	Controlled by observatory	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	1
	Combined control	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	1
Contamination management	Contamination prevention	1	1	2	2	2	1	2	3	1	2	1	3	3	3	3	1	1	1	1	3
	Clean during servicing	1	1	2	2	2	1	1	2	1	2	1	2	2	2	2	1	1	1	1	2
Service Methodology	Autonomous	3	3	3	1	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
	Automatic	2	2	2	1	2	2	3	2	2	2	2	2	2	2	2	2	2	2	2	3
	Telerobotic - Remote	2	2	1	1	2	2	1	2	2	1	1	1	1	1	1	1	2	2	2	2
	Telerobotic - Local	2	2	2	2	3	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	EVA - human manipulation	0	0	2	3	3	0	3	1	1	2	3	1	3	3	3	3	1	1	1	1
Service Frequency	Infrequent 10yrs	0	0	1	0	0	3	1	1	0	0	3	3	3	3	3	0	1	1	1	3
	Frequent 5yrs	3	3	3	3	3	1	1	3	3	3	1	1	1	1	1	2	3	3	3	1
	Early (~3yrs)	3	3	1	2	2	1	1	1	1	1	0	0	0	0	1	3	1	1	1	0
Access to cold side	Attach to cold side	1	1	1	3	1	1	1	2	1	1	2	2	2	2	2	2	1	1	1	1
	Remove & attach telescope to warm side	1	1	1	1	1	1	1	2	1	1	2	2	2	2	2	2	1	1	1	0
	Telescope on articulating boom	1	1	1	1	1	1	1	2	1	1	2	2	2	2	2	2	1	1	1	2
Segmented Primary Mirror		1	1	1	1	1	1	1	1	1	1	1	1	3	3	1	1	1	1	1	3
Accessible ORUs		3	3	3	3	3	3	2	3	3	3	3	3	3	3	3	3	3	3	3	3
Communications	Service vehicle	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	3	1	3	1	1
	Observatory	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	0	1	1
Command and data handling	Service vehicle	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	0	1	1
	Observatory	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	3	1	3	1	1
Propulsion	Service vehicle	1	1	1	1	1	3	1	1	1	1	1	1	1	1	1	3	1	1	1	0
	Observatory	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	0	1	1	1	2
Segmented sunshade	Yes	1	1	1	3	3	1	2	2	1	1	2	2	2	2	2	2	1	1	1	3
	No	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Legend		
(cyan)	critical	best
(green)	useful	better
(yellow)	helpful	good
(red)	marginal	bad

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Table 6 Exploration Architecture Options vs. SAFIR Servicing Functions (Matrix 2)

INPUT MATRIX

How well the various Exploration Architecture Options are suited to meet the defined SAFIR Servicing Options

SAFIR Servicing Functions (columns) vs. **Exploration Architecture Options** (rows)

Repair Location	Transport Method	Transport Destination	Repair Platform	Attachment Options				Observatory status during repairs			Attitude Control			Fluid Transfer		Telescope Warm Up Options				Power production			Contamination management		Service Methodology					Service Frequency			Access to cold side					Communi cations		Command and data handling		Propulsion		Segmented sunshade	
				Formation flying	Tethered	Hard dock	Soft dock	Fully operational (performing science)	Safe Mode (no science)	Powered Down	Controlled by service vehicle	Controlled by observatory	Combined control	Via tanks	Via hoses	Service vehicle heaters	Observatory heaters	Observatory rotates itself	Servicer rotates observatory	Controlled by service vehicle	Controlled by observatory	Combined control	Contamination prevention	Clean during servicing	Autonomous	Automatic	Telerobotic - Remote	Telerobotic - Local	EVA - human manipulation	Infrequent 10yrs	Frequent 5yrs	Early (~3yrs)	Attach to cold side	Remove & attach telescope to warm side	Telescope on articulating boom	Segmented Primary Mirror	Accessible ORUs	Service center	Observatory	Service center	Observatory	Service center	Observatory	Yes	No
In Situ @ L2																																													
			Resident Remote Service Vehicle based at L2 equipped with planned maintenance consumables (no consumable delivery from off-site)	0	0	3	1	3	1	1	1	1	0	0	1	1	2	1	0	1	1	0	1	1	3	2	1	0	0	3	3	3	1	1	1	1	1	1	1	1	1	1	1	2	1
			Resident Remote Service Vehicle based at L2 with consumable delivery	0	0	3	2	3	1	1	1	1	0	1	2	2	3	2	0	1	1	0	1	1	3	2	1	0	0	3	3	2	1	2	2	1	1	1	1	1	1	1	1	2	1
			Servicing robotics on SAFIR with consumable delivery	0	0	3	3	3	1	1	0	1	0	2	3	0	3	3	0	0	1	0	1	1	3	2	1	0	0	3	2	1	2	3	3	1	1	0	1	0	1	0	1	2	1
			Traveling Remote Service Vehicle from Gateway with consumables	0	0	3	2	3	1	1	2	1	0	2	3	2	3	1	0	2	1	0	1	1	3	2	1	0	0	2	1	0	1	2	2	1	1	2	1	2	1	2	1	2	1
Off Site																																													
	Tug Transport			0	0	3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	3	3	3	1	1	1	1	1	1	1	1	1	3	1	1	1
	Self Transport			1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	1	0	1	1	1	1	1	1	1	1	1	1	3	1	1
		LLO Gateway		0	0	3	2	0	1	1	2	2	2	1	1	0	0	0	0	2	0	2	1	1	3	2	1	2	2	3	2	1	1	1	1	1	1	1	1	1	1	2	2	3	0
		L1 Gateway		2	1	3	2	1	1	1	0	0	0	1	1	2	2	2	2	3	1	3	2	2	3	2	1	2	2	2	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1
		LEO Gateway		1	0	3	2	0	1	1	3	3	3	1	1	0	0	0	0	2	0	2	0	0	3	2	2	3	3	1	0	0	1	1	1	1	1	1	1	1	1	2	2	2	0
		Cis-Lunar Orbit		2	1	3	2	2	1	1	0	0	0	1	1	2	2	2	2	2	1	2	2	2	3	2	1	2	2	3	3	2	1	1	1	1	1	1	1	1	1	3	3	1	1
			CEV + EVA Module + consumable supply	1	1	3	2	0	1	2	1	3	0	1	2	0	2	1	0	1	3	0	0	2	0	0	0	0	3	2	1	0	0	0	1	0	2	1	1	1	1	1	0	3	1
			CEV + Telerobotics + consumable supply	1	1	3	2	0	1	2	1	3	0	1	3	0	2	1	0	1	3	0	1	2	0	0	1	3	0	2	1	0	0	2	1	1	1	1	1	1	1	1	0	3	1
			Remote Service Vehicle	1	0	3	2	0	1	2	1	2	0	1	3	1	1	1	1	1	2	0	2	1	3	3	2	0	0	2	1	0	2	2	1	1	1	1	1	1	1	1	0	3	1
			Unmanned Station with telerobotics	0	0	3	2	0	1	3	3	0	0	1	3	2	1	1	0	3	0	0	2	1	3	3	3	0	0	2	2	2	0	3	1	1	1	1	1	1	1	1	0	3	1
			Manned Station	0	1	3	2	0	1	3	3	0	0	1	2	2	1	1	0	3	0	0	0	2	3	3	3	3	3	2	2	2	0	3	1	1	2	1	1	1	1	1	0	3	1

Legend		
(cyan)	critical	best
(green)	useful	better
(yellow)	helpful	good
(red)	marginal	bad

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Once the decision about what categories to include in the trade space was finalized, numerical ratings from 0 to 3 were assigned, based on the suitability of one set of parameters to meet or satisfy the needs of another set; i.e., the suitability of Servicing Functions to satisfy Maintenance Requirements (Matrix 1), or the suitability of Exploration Architecture Options for Servicing Functions (Matrix 2).

A rating of 0 is considered negative; i.e., the option is an unsuitable choice for that particular requirement. For example, in Matrix 1, under Observatory Status During Repairs, the Fully Operational Option was rated 0 for repairs or replacement of any part or material pertaining to cryogenics, because it was assumed that Fully Operational meant servicing while cold.

A rating of 1 is neutral; i.e., the option is neither suitable nor unsuitable for the requirement. A rating of 2 signifies appropriateness, or usefulness. A rating of 3 signifies an option that is particularly appropriate to meet the requirement under consideration. While it may, in some cases, be critical to meet that particular requirement, often it is not crucial, but rather, a "best fit". In such cases, another option may also be appropriate, or at least, acceptable. For example, in Matrix 1, under Observatory Status During Repairs, the Safe Mode option received 3's for several Maintenance Requirements, because this option involves isolating the impacted subsystem, rather than powering down the entire telescope. However, Powered Down may still be an appropriate or acceptable option for some requirements, as seen by the ratings of 1 or 2 in such cases.

The essential issues considered in developing the rankings for the database included:

- Cost, risk and complexity of the addition of serviceability in SAFIR.
- Cost, risk and complexity impacts to the space architecture operations.
- Cost, risk and complexity impacts to the architecture elements and associated systems.
- Prior experience with in-space operations associated with servicing.
- Prior experience with human operations in space.
- Interaction of elements and integration and flow of operations.
- Technology Readiness Levels (TRLs) for proposed configurations and operations.
- Physical dimensions, mass, and kinematics for proposed configurations and operations.
- Orbital mechanics and dynamics, maneuvering requirements, and propulsion issues.
- Timelines and scheduling issues.

While these issues were not quantified, we considered them in assigning the ranking values.

Because not all options within a given category are equally likely, some options may emerge as particularly unsuitable to meet a variety of requirements, thus reflecting (without prior intent) the unlikelihood that it will be incorporated into the final VSEA. For example, Formation Flying and Tethered options were rated low across most or all Maintenance Requirements in Matrix 1, while Hard Dock was, for the most part, rated high in Matrix 1, because the repair or replacement of fluids and/or components is best facilitated by a firm attachment. When ratings for Exploration Architecture Options versus Servicing Functions were rated in Matrix 2, similar results are seen for the Attachment Options. Strictly speaking, this means that most Exploration Architecture

Options were highly suited to Hard Dock. However, this is an overly literal interpretation of the rating system. It is better to think of Hard Dock as highly suited to most Exploration Architecture Options. For example, for a resident RSV at L2 with no cargo resupply, soft dock is not particularly suitable, because of the size of the RSV. Thus, the workbook can serve as a decision-making tool that can aid in evaluating and selecting VSE Architecture options.

Exploration Architecture Options have been assessed for their suitability for Servicing Functions, though, as mentioned above, it sometimes pays to think of it as the other way around. The characteristics of the Exploration Architectures were only partially disaggregated; i.e., not every combination of Repair Location (*in situ* at SEL2 versus Offsite), Transport Method, Transport Destination, and Repair Platform was shown explicitly. Nevertheless, various dependencies emerge. For example, in Matrix 2, for Attitude Control System (ACS), Repair Platform options generally rank lower for *in situ* at SEL2 than for Offsite. This is due to the need to regularly fire thrusters to stay at L2. Thus, Offsite architectures are generally more suitable for most ACS options. The choice of Repair Platform could make a difference; e.g., for an unmanned or manned station, control by observatory is not desirable.

Some aspects of Exploration Architecture Options do not have varying dependencies with Servicing Function. While Transport Destination and Repair Platform do make a difference, Transport Method generally does not, except for those requirements that directly refer to propulsion, attachment, or frequency.

Once SAFIR is at its servicing location, a strong dependence on Repair Platform is seen, particularly for power and mass-dependent servicing tasks. For example, options involving CEV rate low for telescope warm-up, because the CEV is unlikely to have sufficient power to heat the telescope. However, assets such as unmanned or manned station are likely to be relatively massive compared to the telescope, giving them high ratings for such functions as Access to cold side/Remove and attach telescope to warm side.

In order to arrive at an integrated architecture assessment the two input matrices, Matrix 1 and Matrix 2 were hierarchically combined, following the QFD Process, into Matrix 3 (Table 7). This Matrix contains ratings of how well each of the defined architectures satisfies each SAFIR servicing requirement. The numbers in each cell represent a relative ranking score for each architecture capability with respect to each servicing requirement. The color labels were selected based on the ratings as shown in the legend, and provide visibility to quickly select the best options from the entire list. The column labeled “Architecture Ranking” is the relative aggregate score for each architecture option, again selected with respect to the ratings as shown.

Included in the ranking scoring is the proprietary ranking impact for each requirement, based on its relative importance to the SAFIR servicing operations (Matrices 1 and 2). This assigns a greater weight to an architecture based on its capability to satisfy more critical servicing requirements.

Also included are options to define individual architecture probability rating values, which could be used to input the likeliness for specific architectures to be developed – an architecture risk factor. For the data shown in Matrix 3 (Table 7), all architectures are shown with equal probability of 1 – even architectures that are not a likely probability are considered. This provides a “pure” analysis of the total trade space for reference. Matrix 3A (Table 8) has the probability value for four of the least likely architecture options set to zero – all cis-lunar space station options. These options ranked very high in the all architecture matrix, Matrix 3 (Table 7). As can be seen, in Matrix 3A (Table 8), this removal has the effect of shifting the ratings – other, more viable options, will now tend to have higher ratings.

Selection of more appropriate architectures should probably be made from the blue or higher green colored areas. Three of the highest ranking architectures from the more likely Matrix 3A options include:

- Servicing at ES L2 by a resident robotic servicing vehicle.
- Servicing at the L1 Gateway with a tug transport.
- CEV + telerobotics servicing in a cis-Lunar orbit with a tug transport.

Several conclusions can be formed based on the matrices:

- Things that tend to be not desirable
    - Resident robotic servicing vehicles with no scheduled delivery.
    - Any servicing with humans in the active, hands-on, loop.
    - Any servicing that involves SAFIR performing a self-powered transport.
    - Most options using a LEO servicing location.
    - Many options using a LLO servicing location.
- Things that tend to be desirable
    - Resident robotic servicing vehicles with consumables carried or delivered.
    - Robotic servicing in a cis-Lunar orbit.
    - Some station servicing options using a LLO or L1 servicing location.

To assess specific separate pieces of the architecture, separate summary rankings can be developed as shown in Table 9. This table shows a comparison of the aggregate relative rankings for comparison of:

- In-Situ versus Off Site Servicing.
- Tug Transport versus Self Transport to the servicing location (if Offsite).
- LLO versus L1 versus LEO versus Cis-Lunar Transport Destinations (if Offsite).

A can be seen, for both full architecture and partial architecture options, in situ repair ranks higher than off site repair. The cost in travel, both in time and materials, appears to negatively impact the transport options, and any benefits of having servicing performed closer to Earth, i.e. the use of humans for complex or unanticipated tasks, are not enough to offset the expense.

If off-site servicing is used, the use of a separate tug rates slightly higher than self transport. The impact of developing and carrying the extra capability for maneuvering, on-board the observatory, appears to outweigh the impact of requiring a separate maneuvering vehicle element and the extra outbound and return trips that are required.

If off-site servicing is used, the use of a cis-Lunar orbit appears to be better that other options because it provides the least disruption to the nominal operational design characteristics of the observatory. However, when the architecture options for station servicing in cis-Lunar orbit are removed from the trade space, the scores shift toward the selection of an L1 servicing location. Again, this appears to be because of minimal disruption to the design and science operations.

Table 7 Exploration Architecture Options vs. SAFIR Maintenance Requirements (Matrix 3) – Full Architecture Option List

Exploration Architecture Options

Repair Location	Transport Method	Transport Destination	Repair Platform	Possible Architecture	Architecture Ranking	Cryo gas replacement	Cryocooler replacement	Solar cell replacement	Sunshade repair/replace single layer	Sunshade replacement	Propulsion fuel replacement	Facility observations	Instrument replacement	ATCS Maintenance	Radiator Replacement	Structural/ Mechanism replacement	Mirror maintenance/ mirror recoating	Mirror segment replacement	Mirror segment actuator replacement	Mirror Segment Installation (expand)	Unplanned Repair/ Maintenance	Electrical Power and Distribution Module (BUS)	Command and Data Module (BUS)	Attitude Control System (Gyros) Module (BUS)	Minimal interruption to science
			OUTPUT MATRIX - Options Considered as Groups: How well the various Exploration Architecture Options are suited to satisfy the desired SAFIR Maintenance Requirements			SAFIR Maintenance Requirements and Importance Ratings																			
						8	8	8	8	8	8	2	10	6	2	4	2	2	4	2	10	6	6	6	10
In Situ @ L2																									
			Resident RSV based at L2 equipped with planned maintenance consumables (no consumable delivery)	1	85	28	27	25	28	28	26	27	30	25	26	26	28	30	30	29	29	25	26	25	28
			Resident RSV based at L2 with consumable delivery	1	94	31	30	27	30	31	29	29	33	28	29	29	31	34	34	33	33	27	28	27	30
			Servicing robotics on SAFIR with consumable delivery	1	91	31	28	26	30	29	29	29	33	26	27	29	31	34	34	32	32	26	26	26	29
			Traveling RSV from Gateway with consumables	1	95	32	29	27	31	31	31	30	33	28	29	29	32	34	34	33	33	27	29	27	31
Off Site																									
	Tug Transport	LLO Gateway	CEV + EVA Module + consumable supply	1	84	27	26	26	27	28	27	26	29	25	26	26	28	29	29	29	29	25	26	25	28
			CEV + Telerobotics + consumable supply	1	85	28	26	26	28	28	27	27	29	25	26	26	28	31	31	29	29	25	26	25	29
			RSV	1	87	28	27	26	28	29	28	27	30	25	27	27	29	32	32	30	30	25	26	25	29
			Unmanned Station with telerobotics	1	89	29	28	27	29	29	28	28	31	26	27	28	29	32	32	31	31	26	27	26	30
			Manned Station	1	93	30	29	28	30	31	30	29	32	28	29	29	31	33	33	32	32	28	29	28	31
		L1 Gateway	CEV + EVA Module + consumable supply	1	86	28	27	26	28	29	27	27	30	26	27	26	29	31	31	30	30	25	26	25	28
			CEV + Telerobotics + consumable supply	1	87	28	27	26	28	29	27	27	31	26	27	26	29	32	32	30	30	25	26	25	29
			RSV	1	89	29	27	27	29	30	27	28	31	26	28	27	30	33	33	31	31	26	27	26	30
			Unmanned Station with telerobotics	1	91	30	28	27	29	30	28	28	32	27	28	28	31	33	33	32	31	26	27	26	30
			Manned Station	1	96	31	30	29	30	32	29	30	33	28	30	29	32	35	35	33	33	28	29	28	32
		LEO Gateway	CEV + EVA Module + consumable supply	1	82	27	25	25	26	27	26	26	28	24	25	26	27	29	29	28	28	24	25	24	27
			CEV + Telerobotics + consumable supply	1	82	27	25	25	27	27	26	26	28	24	25	26	27	30	30	28	29	24	25	24	28
			RSV	1	85	27	26	25	27	28	27	27	29	25	26	27	28	31	31	29	30	25	26	25	28
			Unmanned Station with telerobotics	1	87	28	27	26	28	28	28	27	30	26	26	27	28	31	31	30	30	26	27	26	29
			Manned Station	1	91	29	28	27	29	30	29	29	31	27	28	29	29	32	32	31	32	27	28	27	30
		Cis-Lunar Orbit	CEV + EVA Module + consumable supply	1	91	30	29	27	29	30	29	28	32	27	28	27	30	32	32	31	31	27	28	27	30
			CEV + Telerobotics + consumable supply	1	92	30	29	28	30	30	29	29	32	27	29	28	31	33	33	32	32	27	28	27	31
			RSV	1	94	31	29	28	30	31	29	29	33	28	29	29	31	34	34	33	33	27	28	27	31
			Unmanned Station with telerobotics	1	96	31	30	29	31	32	30	30	33	28	30	29	32	35	35	33	33	28	29	28	32
			Manned Station	1	100	33	31	30	32	33	31	31	35	30	31	31	33	36	36	35	35	29	30	29	33
	Self Transport	LLO Gateway	CEV + EVA Module + consumable supply	1	81	26	25	25	26	27	26	25	28	24	25	25	27	29	29	28	28	24	25	24	27
			CEV + Telerobotics + consumable supply	1	82	26	25	25	27	27	26	26	28	24	25	25	27	30	30	28	28	24	25	24	28
			RSV	1	84	27	25	25	27	28	26	27	29	25	26	26	28	31	31	29	29	24	25	24	29
			Unmanned Station with telerobotics	1	86	28	26	26	28	28	27	27	30	25	26	27	28	31	31	30	30	25	26	25	29
			Manned Station	1	90	29	28	27	29	30	28	28	31	27	28	28	30	32	32	31	31	27	28	27	30
		L1 Gateway	CEV + EVA Module + consumable supply	1	83	27	26	25	27	28	26	26	29	25	26	25	28	30	30	29	28	24	25	24	27
			CEV + Telerobotics + consumable supply	1	84	27	26	25	27	28	26	27	29	25	26	26	29	31	31	29	29	24	25	24	28
			RSV	1	86	27	26	26	27	29	26	27	30	25	27	26	29	32	32	30	30	24	25	24	29
			Unmanned Station with telerobotics	1	88	28	27	26	28	29	27	28	31	26	27	27	30	32	32	31	30	25	26	25	29
			Manned Station	1	93	30	28	28	29	31	28	29	32	28	29	28	31	34	34	32	32	27	28	27	31
		LEO Gateway	CEV + EVA Module + consumable supply	1	79	25	24	24	25	26	25	25	27	24	24	25	26	28	28	27	27	23	24	23	26
			CEV + Telerobotics + consumable supply	1	79	25	24	24	25	26	25	26	27	24	24	25	26	29	29	27	28	23	24	23	27
			RSV	1	82	26	25	24	26	27	26	26	28	24	25	26	27	30	30	28	28	24	25	24	27
			Unmanned Station with telerobotics	1	83	27	25	25	27	27	26	27	28	25	26	26	27	30	30	28	29	24	25	24	28
			Manned Station	1	88	28	27	26	28	29	28	28	30	26	27	28	29	31	31	30	31	26	27	26	29
		Cis-Lunar Orbit	CEV + EVA Module + consumable supply	1	87	28	27	26	28	29	28	28	30	26	27	27	29	31	31	30	30	25	26	25	29
			CEV + Telerobotics + consumable supply	1	89	29	27	27	29	29	28	28	31	26	28	27	30	32	32	31	31	25	26	25	30
			RSV	1	91	29	28	27	29	30	28	29	32	27	28	28	31	33	33	32	31	26	27	26	30
			Unmanned Station with telerobotics	1	93	30	29	28	30	31	29	29	32	27	29	28	31	34	34	32	32	27	28	27	31
			Manned Station	1	97	31	30	29	31	32	30	30	34	29	30	30	32	35	35	34	34	28	29	28	32

Legend	
(cyan)	best
(green)	better
(yellow)	good
(red)	bad

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Table 8 Exploration Architecture Options vs. SAFIR Maintenance Requirements (Matrix 3) – Partial Architecture Option List – no Station at Cis-Lunar

OUTPUT MATRIX - Options Considered as Groups

How well the various Exploration Architecture Options are suited to satisfy the desired SAFIR Maintenance Requirements

SAFIR Maintenance Requirements and Importance Ratings

Exploration Architecture Options

Repair Location	Transport Method	Transport Destination	Repair Platform	Possible Architecture	Architecture Ranking	Cryo gas replacement	Cryocooler replacement	Solar cell replacement	Sunshade repair/replace single layer	Sunshade replacement	Propulsion fuel replacement	Facility observations	Instrument replacement	ATCS Maintenance	Radiator Replacement	Structural/ Mechanism replacement	Mirror maintenance/ mirror recoating	Mirror segment replacement	Mirror segment actuator replacement	Mirror Segment Installation (expand)	Unplanned Repair/ Maintenance	Electrical Power and Distribution Module (BUS)	Command and Data Module (BUS)	Attitude Control System (Gyros) Module (BUS)	Minimal interruption to science
						8	8	8	8	8	8	2	10	6	2	4	2	2	4	2	10	6	6	6	10
In Situ @ L2																									
			Resident RSV based at L2 equipped with planned maintenance consumables (no consumable delivery)	1	89	28	27	25	28	28	26	27	30	25	26	26	28	30	30	29	29	25	26	25	28
			Resident RSV based at L2 with consumable delivery	1	98	31	30	27	30	31	29	29	33	28	29	29	31	34	34	33	33	27	28	27	30
			Servicing robotics on SAFIR with consumable delivery	1	95	31	28	26	30	29	29	29	33	26	27	29	31	34	34	32	32	26	26	26	29
			Traveling RSV from Gateway with consumables	1	99	32	29	27	31	31	31	30	33	28	29	29	32	34	34	33	33	27	29	27	31
Off Site																									
	Tug Transport	LLO Gateway	CEV + EVA Module + consumable supply	1	88	27	26	26	27	28	27	26	29	25	26	26	28	29	29	29	29	25	26	25	28
			CEV + Telerobotics + consumable supply	1	89	28	26	26	28	28	27	27	29	25	26	26	28	31	31	29	29	25	26	25	29
			RSV	1	91	28	27	26	28	29	28	27	30	25	27	27	29	32	32	30	30	25	26	25	29
			Unmanned Station with telerobotics	1	93	29	28	27	29	29	28	28	31	26	27	28	29	32	32	31	31	26	27	26	30
			Manned Station	1	98	30	29	28	30	31	30	29	32	28	29	29	31	33	33	32	32	28	29	28	31
		L1 Gateway	CEV + EVA Module + consumable supply	1	90	28	27	26	28	29	27	27	30	26	27	26	29	31	31	30	30	25	26	25	28
			CEV + Telerobotics + consumable supply	1	91	28	27	26	28	29	27	27	31	26	27	26	29	32	32	30	30	25	26	25	29
			RSV	1	94	29	27	27	29	30	27	28	31	26	28	27	30	33	33	31	31	26	27	26	30
			Unmanned Station with telerobotics	1	95	30	28	27	29	30	28	28	32	27	28	28	31	33	33	32	31	26	27	26	30
			Manned Station	1	100	31	30	29	30	32	29	30	33	28	30	29	32	35	35	33	33	28	29	28	32
		LEO Gateway	CEV + EVA Module + consumable supply	1	85	27	25	25	26	27	26	26	28	24	25	26	27	29	29	28	28	24	25	24	27
			CEV + Telerobotics + consumable supply	1	86	27	25	25	27	27	26	26	28	24	25	26	27	30	30	28	29	24	25	24	28
			RSV	1	89	27	26	25	27	28	27	27	29	25	26	27	28	31	31	29	30	25	26	25	28
			Unmanned Station with telerobotics	1	91	28	27	26	28	28	28	27	30	26	26	27	28	31	31	30	30	26	27	26	29
			Manned Station	1	95	29	28	27	29	30	29	29	31	27	28	29	29	32	32	31	32	27	28	27	30
		Cis-Lunar Orbit	CEV + EVA Module + consumable supply	1	95	30	29	27	29	30	29	28	32	27	28	27	30	32	32	31	31	27	28	27	30
			CEV + Telerobotics + consumable supply	1	97	30	29	28	30	30	29	29	32	27	29	28	31	33	33	32	32	27	28	27	31
			RSV	1	98	31	29	28	30	31	29	29	33	28	29	29	31	34	34	33	33	27	28	27	31
			Unmanned Station with telerobotics	0	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
			Manned Station	0	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	Self Transport	LLO Gateway	CEV + EVA Module + consumable supply	1	85	26	25	25	26	27	26	25	28	24	25	25	27	29	29	28	28	24	25	24	27
			CEV + Telerobotics + consumable supply	1	86	26	25	25	27	27	26	26	28	24	25	25	27	30	30	28	28	24	25	24	28
			RSV	1	88	27	25	25	27	28	26	27	29	25	26	26	28	31	31	29	29	24	25	24	29
			Unmanned Station with telerobotics	1	90	28	26	26	28	28	27	27	30	25	26	27	28	31	31	30	30	25	26	25	29
			Manned Station	1	94	29	28	27	29	30	28	28	31	27	28	28	30	32	32	31	31	27	28	27	30
		L1 Gateway	CEV + EVA Module + consumable supply	1	87	27	26	25	27	28	26	26	29	25	26	25	28	30	30	29	28	24	25	24	27
			CEV + Telerobotics + consumable supply	1	88	27	26	25	27	28	26	27	29	25	26	26	29	31	31	29	29	24	25	24	28
			RSV	1	89	27	26	26	27	29	26	27	30	25	27	26	29	32	32	30	30	24	25	24	29
			Unmanned Station with telerobotics	1	92	28	27	26	28	29	27	28	31	26	27	27	30	32	32	31	30	25	26	25	29
			Manned Station	1	97	30	28	28	29	31	28	29	32	28	29	28	31	34	34	32	32	27	28	27	31
		LEO Gateway	CEV + EVA Module + consumable supply	1	82	25	24	24	25	26	25	25	27	24	24	25	26	28	28	27	27	23	24	23	26
			CEV + Telerobotics + consumable supply	1	83	25	24	24	25	26	25	26	27	24	24	25	26	29	29	27	28	23	24	23	27
			RSV	1	85	26	25	24	26	27	26	26	28	24	25	26	27	30	30	28	28	24	25	24	27
			Unmanned Station with telerobotics	1	87	27	25	25	27	27	26	27	28	25	26	26	27	30	30	28	29	24	25	24	28
			Manned Station	1	92	28	27	26	28	29	28	28	30	26	27	28	29	31	31	30	31	26	27	26	29
		Cis-Lunar Orbit	CEV + EVA Module + consumable supply	1	91	28	27	26	28	29	28	28	30	26	27	27	29	31	31	30	30	25	26	25	29
			CEV + Telerobotics + consumable supply	1	93	29	27	27	29	29	28	28	31	26	28	27	30	32	32	31	31	25	26	25	30
			RSV	1	95	29	28	27	29	30	28	29	32	27	28	28	31	33	33	32	31	26	27	26	30
			Unmanned Station with telerobotics	0	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
			Manned Station	0	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

Legend	
	best
	better
	good
	bad

Table 9 Architecture ratings for full architecture option list

	All Architecture Options are Possible	With no Cis-Lunar Space Station Options
In Situ	0.91	0.95
Off Site	0.88	0.82
Tug	0.89	0.83
Self	0.86	0.80
LLO	0.86	0.90
L1	0.88	0.92
LEO	0.84	0.87
Cis-Lunar	0.93	0.57

Two of the three architectures that ranked highest are shown in Figures 11, 12, 13 and 14. Figure 11 shows the SEL2 concept where a Robotic Servicing Vehicle with cargo resupply is attached to the observatory. The two panels in Figure 12 show details of that servicing approach, emphasizing replacement of science instruments. Similarly, Figure 13 shows a manned service station at EML1 and Figure 14 shows human EVA as a method for science instrument replacement.

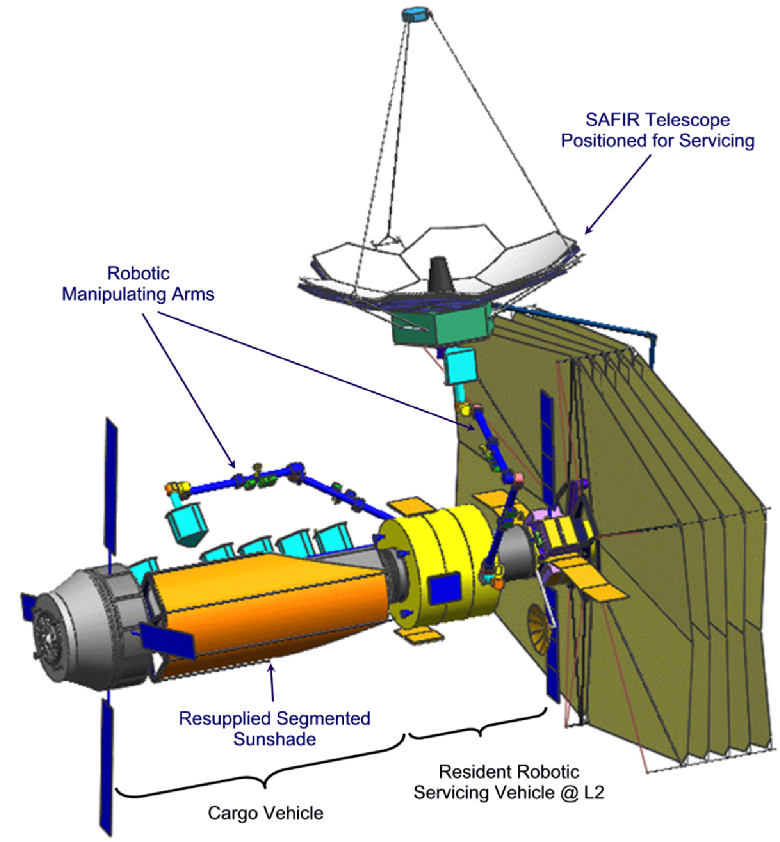


Figure 11 Possible in situ architecture for Robotic Servicing Vehicle with cargo resupply at SEL2

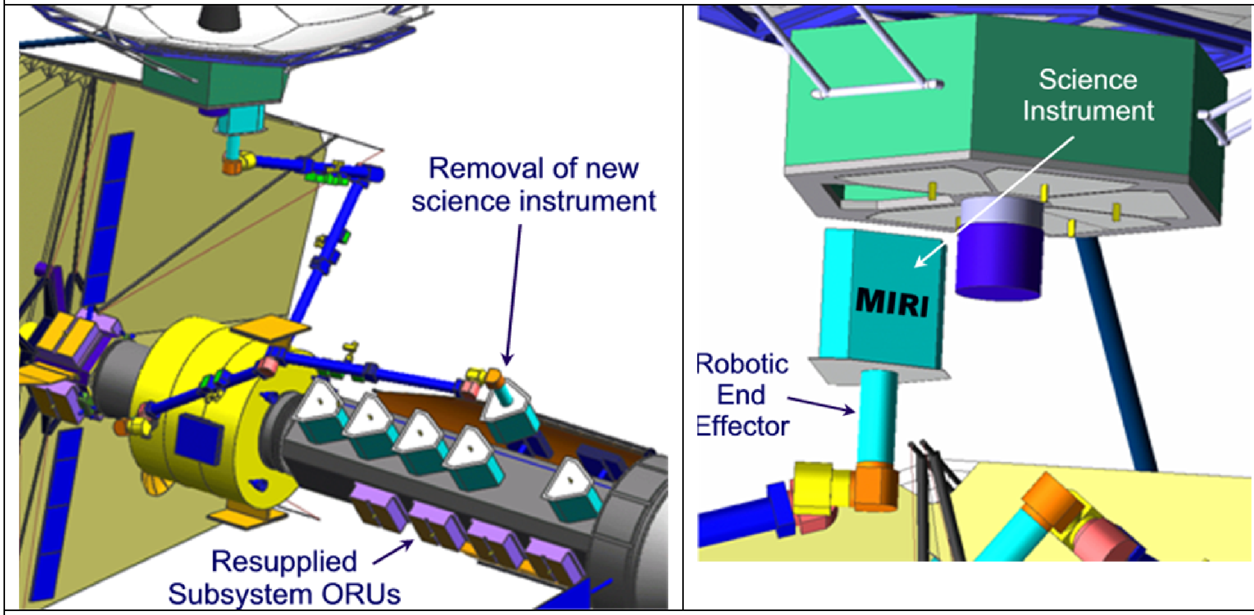


Figure 12 Two views o f the Resident Robotic Servicing Vehicle performing science instrument changeout at SEL2

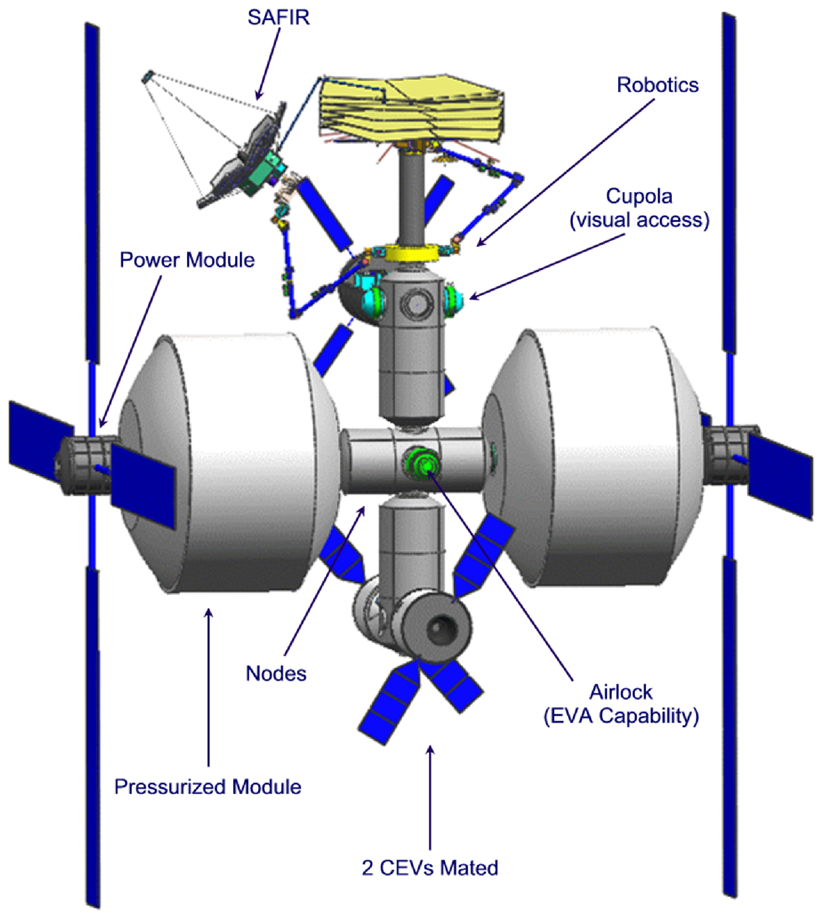
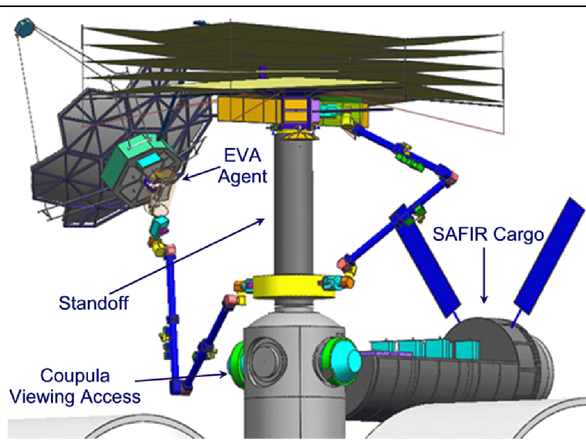


Figure 13 Possible architecture: manned station at EM L1 gateway



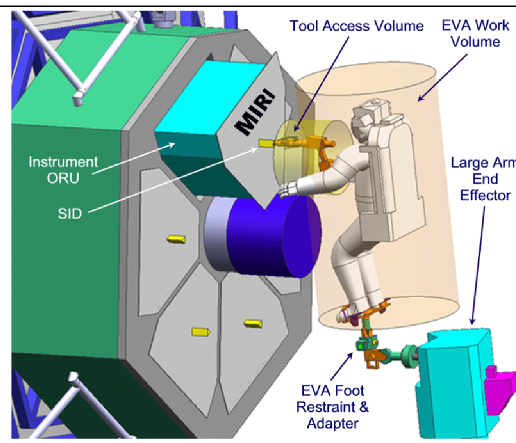


Figure 14 Manned station performing science instrument changeout at EML1

Finally, it is clear that NASA is thinking of future capability that could support servicing, as captured in this quote for the press conference at which Administrator Griffin fielded a question[15] about what can be accomplished by the CEV alone;

> *The crew exploration vehicle is designed with its launch system to go to low earth orbit. Once you're in low earth orbit, you can do any number of things. You must go through low earth orbit to go anywhere else. We can go to the moon. In later decades, we can go to Mars. We can service the space station. We can undertake the service of the Hubble space telescope or other space telescopes, as may exist.*

2.4 In-space integration and test

A critical factor in the successful servicing of SAFIR is the post-servicing confirmation that the observatory is working correctly. This is particularly critical for all servicing scenarios that include moving the observatory. This is true since problems that have emerged during the period of servicing are most economically dealt with while the observatory is a close proximity to the servicing hardware and facilities. Therefore, confirmation of both performance and functional capability of the observatory must be determined before the servicing cycle can be said to be successful. There are operational issues as well. For example, the sequence of events before during and after the servicing activity must be carefully orchestrated to assure that thrust loads on the observatory are within the structural design limits and that contamination limits will not be exceeded. Finally, there is a requirement to perform specific optical test to confirm that the telescope assembly and the spacecraft functions that support science are performing properly. Several recent papers have addressed the details associated with testing of an observatory after construction or servicing [10,16,17,18].

A series of tables follows that illustrate some details of the testing and validation activity that should be conducted after any servicing cycle. In all cases, we assume that appropriate action can be taken to remedy any difficulties that are found during this validation. Generally, this will mean that the servicing facility is nearby and that spare parts or repair kits are close at hand so that has little scientifically productive time is lost as possible.

Table 10 illustrates some examples of the tests that should be performed to achieve a high level of confirmation of the functionality and performance of the observatory. In some cases, dedicated test hardware will be required to conduct a thorough evaluation of the observatory performance. For example, the full determination of the encircled energy properties of the telescope may require a higher density focal plane array that is needed to conduct science. We also note that some initial petal phasing may need to be demonstrated since the servicing activity

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[15] http://www.nasa.gov/pdf/133896main_ESAS_rollout_press.pdf

[16] E. Friedman and T. Espero, "The role of humans and robots in the assembly of large infrared observatories", presented at *SPIE Astronomical Telescopes and Instrumentation 2004,* Glasgow, Scotland. Paper [5487-48].

[17] G. Matthews, "Future of large optical-system verification*", SPIE Optics and Photonics 2005,* San Diego, July 31-August 4, [5899-17].

[18] S. E. Kendrick, M. D. Lieber, "In-space observatory testing and ground-based integrated modeling and testbeds", Ball Aerospace & Technologies Corporation*", SPIE Optics and Photonics 2005,* San Diego, July 31-August 4, [5899-18].

is likely to have disrupted the mirror elemental positions. We also note that a validation of performance models will be required to sense virtually all servicing will result in replacement of components whose properties must accurately be assessed in the environment in which science is to be conducted. Finally, it must be noted that the overall performance of the telescope, as validated in Table 10, can only be achieved if the supporting and critical spacecraft components are operating properly. Therefore, it might be anticipated that some time will be required to diagnose any results that are inconsistent with expectations, in order to determine the source of the problem.

Table 10 Telescope testing

Test	What is measured	Action if system fails to meet specifications	Technology development required
Line of sight jitter	High bandwidth sensing of peak intensity location as a function of guide star magnitude and other operating conditions	Determine sources of on-board disturbance and consider their replacement. Evaluate performance of pointing sensors and controllers.	Provide means for conducting this experiment with observatory machinery running
Encircled energy and derived performance factors (Strehl ratio)	Properties of blur spot of single stellar components. Tests include PSF size, stability, shape (ellipticity).	All elements of the telescope and sensor systems are candidates for replacement to resolve inadequate encircled energy.	Method for enhanced FPA characterization (probably using a science instrument surrogate). Needs high bandwidth readout to fully characterize noise performance and effects of structural disturbances.
Focus control	Performance of secondary mirror actuator and focus elements in sensors, if any. Actuate the secondary mirror to drive the system through focus.	Isolate sources of the problem and consider replacement	Can be done with observatory instruments.
Characterization of individual segments of the primary mirror	Aberration properties of each segment, both before and after correction with active and adaptive optics controls. Assure corrections are in dynamic range of active controls.	Simple confirmation of ground tests, including visual inspection, prior to flight. Confirmation of performance of each petal in space will be derived from wavefront sensing functions.	Derives control concepts from JWST, but other options (larger numbers of actuators and a more flexible face sheet) could be incorporated
Demonstrate initial petal phasing	Use metrology to assure that each petal is within the dynamic range of the sensors and adjustments possible in the wavefront sensing and control system.	Re-perform this test upon addition of each new petal. This process has been described in a number of articles[19].	Minimal new capability is required; both ground and space systems are already using mature methods. JWST will demonstrate a mature system in space for the first time.
Settle time after slew	Pointing quality using reference star(s). Slew and stop, measuring PSF while stabilizing pointing with FSM and measure pointing noise with FSM disabled	Refine observatory model. Torque profiles adjusted to minimize settling time. Confirm performance of all relevant subsystems.	Slew from star to star and explore the structural dynamics induced as a function of the torque shaping that is used. Determine how structural dynamics influences the optical performance of the system.

[19] D. S. Acton et al, "James Webb Space Telescope wavefront sensing and control algorithms", *SPIE Astronomical Telescopes and Instrumentation 2004*, Glasgow, Scotland, 21–25 June 2004, Paper 5487-35.

Table 10 Telescope testing			
Test	**What is measured**	**Action if system fails to meet specifications**	**Technology development required**
Model validation	Campaign of experiments using de-center and tilt secondary mirror. Explore performance of adaptive optics. Explore impacts of tip, tilt, piston and radius of curvature variation of individual segments to compare results with model predictions. Perform experiments under different thermal conditions.	Adjust model parameters that define thermal and structural performance. Confirm by conducting experiments at the highest and lowest temperatures for which the observatory is designed.	Continued advances in model performance are expected, but must be validated through space testing. A full featured integrated model provides the foundation for an observatory management tool.

Table 11 illustrates some of the testing that is required to assure functionality in spacecraft subsystems and other components critical to observatory operations.

Table 11 Spacecraft component testing			
Test	**What is measured**	**Action if system fails to meet specifications**	**Technology development required**
Contamination rate monitoring	Deposition rates for key contaminants over a period of time	Chemical analysis to determine source of contamination and replace.	None; existing International Space Station and other monitoring equipment is already adequate.
Power consumption of all systems	Consumption as a function of operational condition	Consider component replacement	None
Optimization of pointing control algorithms	Determine pointing error under a variety of operating conditions (on-board disturbances off or on, different operational states, steering mirror on or off). Note that this is particular a critical when components are replaced since the Mass properties of the observatory will change.	Confirm functionality of key components, adjust algorithmic parameters	None
Attitude control noise performance	Pointing noise as a function of operational condition, using artificial pointing signals to CMGs[20]	Consider component replacement	None
Determine pointing noise not associated with service platform	Use the designed track methodology but monitor with a Koester prism interferometer (or equivalent) as used in the Hubble fine guidance sensor.	Diagnose and consider component replacement	Requires new technology for proximity operations without contact to assure full isolation of the two platforms
Visual inspection	Position and orientation of observatory components prior to, and just after, installation. Success of deployment	Physical intervention by astronauts or robotics, including telerobots	Requires small robotic camera systems or astronaut visual inspection
FPA cooler performance	Temperature performance as a function of thermal loads	Replacement of cryocooler or the sensor it services	Reliable connection mechanisms

Table 12 illustrates some properties of the structure that must be characterized part of completing the servicing activity.

Table 12 Structures testing and characterization			
Test	**What is measured**	**Action if system fails to meet specifications**	**Technology development required**

[20] Tobin Anthony and Greg Andersen, "On-Orbit Modal Identification of the Hubble Space Telescope", Paper WA15-9:35 of the *Proceedings of the American Control Conference*, Seattle, Washington, June 1995.

Table 12 Structures testing and characterization			
'As built' structures modal properties	Disturb the structure using methods described above using on board attitude control equipment. Use science sensors to detect the resulting impacts on pointing and higher order aberrations. See also[21].	Tune the control system to suppress resonances.	None for pointing errors, but the technology currently in hand must be extended to allow characterization of higher order aberrations
'As built' masses and moments	Mass properties, center of mass, moments of inertia	Control algorithm tuning	None
Active and passive damping tests	Residual modes during disturbance testing with controls on and off	Determine that all components are working within specification; consider replacements.	None

Table 13 illustrates some of the sensor and detector testing that might be undertaken to assure proper performance after servicing.

Table 13 Sensor and detector testing

Test	What is measured	Action if system fails to meet specifications	Technology development required
Wavefront sensor detector performance and functionality	Dark current, linearity, noise properties for wavefront sensing (WFS) based on Shack-Hartmann (SH) approach. Confirmation of focus control for systems using focus diversity methods. The latter requires the presence of a science camera or surrogate test element.	Replacement of WFS system or its components, including focus controller	None, except that reflectivity of optics to the sensor must be high enough to use shorter wavelength so that light sources can be used that are sufficiently abundant to provide a reference with high probability.
Wavefront sensing and control subsystem	Demonstrate that RMS wavefront performance is retained after re-pointing between two stars. Compare results using focus diversity with SH sensor (if present).	Refine algorithms	None, both diversity and SH sensing are mature technologies
Active optics demonstration	Exercise all actuators and sensors to determine functionality as petals are added.	Confirm that dynamic range specifications are met	None
Flat field science detector array	Variation in output of science detectors over entire focal plane	Develop calibration table	None
Science detector noise properties and sensitivity	Dark current, linearity, noise properties over entire focal plane	Replacement of FPA or entire sensor	None
Fine steering mirror (FSM) performance	Residual LOS noise with on-board disturbances and no other LOS control	Replacement	Requires method for external replacement of FSM, if needed.

Table 14 shows a short list of measurements that should be made after servicing to assure that cryogenic system performance is as it should be.

Table 14 Cryogenic system testing

Test	What is measured	Action if system fails to meet specifications	Technology development required
Measure mechanical noise properties of	Base motion disturbance using magnetohydrodynamic or other high bandwidth, sensitive ACS sensors. Detect stimulation of structural modes of optics or	Replacement of cryocooler	None

[21] Russell D. Glenn et al, "Controller Redesigns for the Hubble Space Telescope", *Proceedings of the 26th Southeastern Symposium on System Theory*, Paper 0-8186-5320-5/94, 20-22 March 1994.

Table 14 Cryogenic system testing			
cryocooler	structures. This testing occurs over a period of time to detect trends.		
Cryo fluid consumption rate	Boil-off rates and fluid pressure variations as a function of thermal conditions	Determine cause of excessive consumption. Consider replacement of components causing this problem. Consider changing servicing schedule.	None
Model validation	Validate predictions of consumption rates	Once consumption rates are confirmed, determine what model assumptions or adjusted parameters need refinement	None

3. CONCLUSIONS

SAFIR and missions of its type will likely be too expensive to be used for their design lifetime and replaced. Indeed, HST has demonstrated the value of building in serviceability from the beginning of the design and the exploitation of that capability to add new features, overcome failures and assure that key science systems are using the latest technologies. Moreover, new emphasis on the exploration of the Moon and Mars is likely to add capabilities not possible in prior eras. Exploiting these new capabilities should allow new observatories to enjoy life extension and enhanced science productivity. At the same time, we have quantified and ranked the importance of particular advances that are critical to enabling servicing. The database included with this document should allow NASA decision-makers to draw their own conclusions about the relative importance of particular investments based on a set of assumptions about what servicing functionality is necessary. Moreover, the weighting functions provided by Boeing can be debated and changed, leading to new results for those new selections. The change in weighting functions might be needed to differentiate the current results from those that would apply to other telescope systems. For example, a number of key results of this study derive from the fact that SAFIR is intended to be a cryogenic system operating at the extremes of current technology. A telescope of similar size but not required to be at cryogenic temperature would result in a different set of investment goals.

Remaining incomplete at this time (due to budget and schedule limitations) are the inclusion of the technologies that enable the capabilities, the costs and schedule of inventing those technologies (or adapting them from other applications), the current and required TRL for each technology and other details that would allow complete description of an investment portfolio. With such details, NASA could derive an automated roadmap of program development necessary for achieving particular servicing needs. Properly structured, such a fully populated system could act as a management tool for NASA. Tools of this type of have already been shown by Weisbin[22] and others.

The database that has been developed was designed with two levels of hierarchical inputs, the service requirements and the servicing functions. While this data provides a top level guideline for design and operational decisions, this is only the bridging piece of a more integrated system development approach. Additional matrices can provide visibility to the technology infusion that is necessary for the development of: the required servicing capabilities from the SAFIR side, and

[22] C.R. Weisbin, G. Rodriguez, and A. Elfes, "Technology Resource Allocation for NASA and Its Enterprises," submitted for publication to the Journal of Systems Engineering, December 2003.

the servicing functions from the servicing architecture side. These would include TRL impacts in terms of schedule and cost for development to required levels.

Concurrently, each servicing function can be decomposed from the subjective level to more objective functions. This would allow for direct input of variables on a numerical engineering basis and provide for higher fidelity results.

To provide programmatic, affordability, and utility limits, additional matrices would be developed from an architectural viewpoint. By considering the cost of each required servicing element and linking each element to its development, deployment, and operational costs, an integrated benefit versus cost analysis can be developed.

At each layer of detail, additional information is captured to allow a quantified ranking of the importance of the options that can be used to provide servicing. It is anticipated that future application of the database can provide NASA with a tool for determining the most effective investment approach by determining which capabilities have the largest possible impact on enabling servicing.

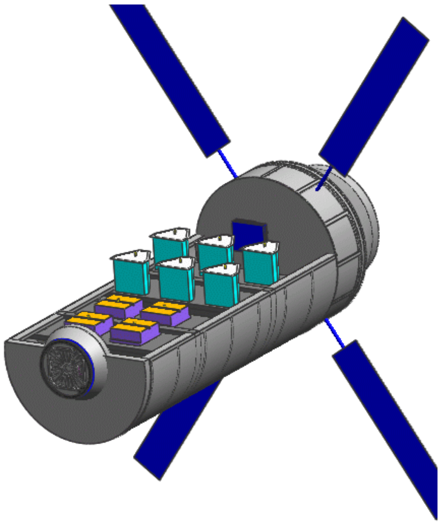
Additional work would be required to keep the database current as new versions of the VSEA emerge and investment commitments are made by the ESMD. In so doing, NASA SMD should be able to inform ESMD about the essential construction, storage and servicing elements that must be included in the VSEA to enable servicing.

ACKNOWLEDGEMENTS

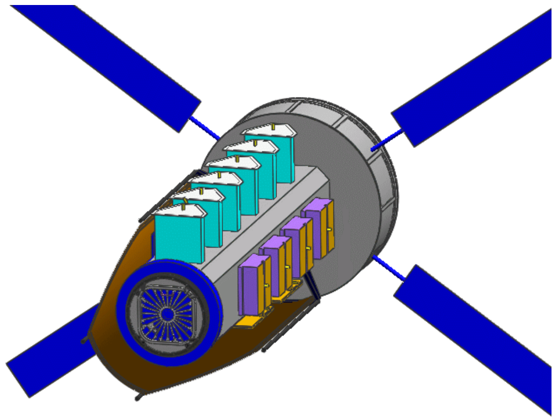
The program management (Ed Friedman) would like to acknowledge the contribution of Boeing employees Gary Bingaman, Seth Potter, and Mike Fruhwirth. Tracey Espero, who led the Huntington Beach California contingent of the staff is to be commended for her organizational and technical skills. Without her leadership this report would have suffered. We also acknowledge the contributions of Dan Lester of the University of Texas and Chuck Lillie of Northrop Grumman Space Technologies for their insightful guidance in the area of servicing requirements, SAFIR mission science and other factors that led directly to the ranking of the servicing needs.

APPENDIX

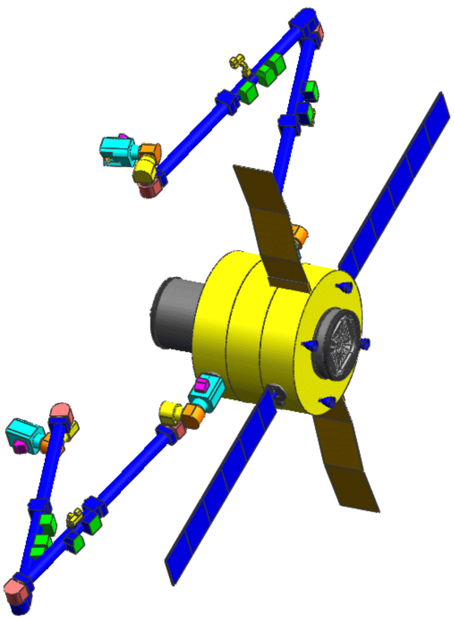
The following art work illustrates some possible implementation of in-space systems that can facilitate servicing.



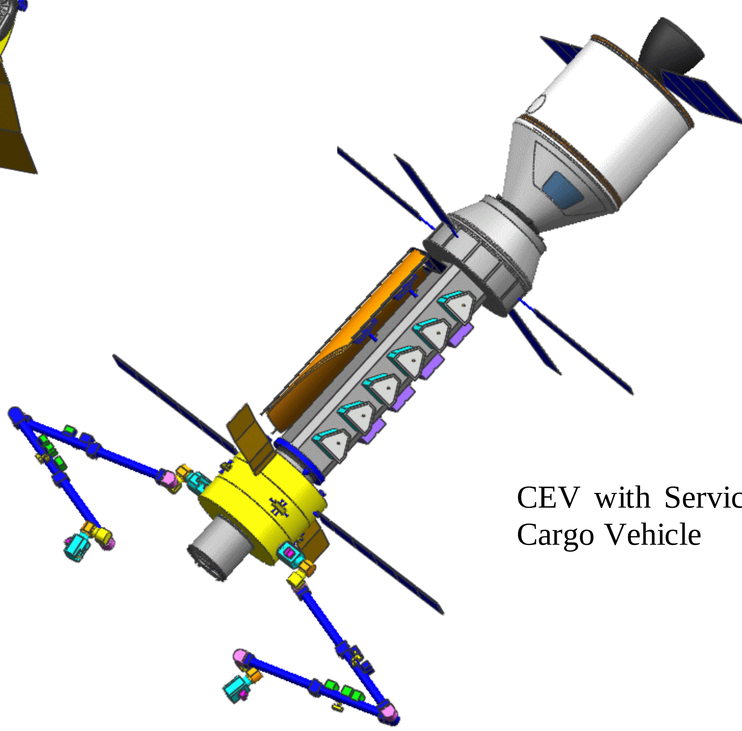
Manned Station Cargo Vehicle



Resident Servicer Cargo Vehicle



Resident Servicer



CEV with Servicer and Cargo Vehicle