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Stellar Imager (SI): Enhancements to the Mission Enabled by the Constellation Architecture (Ares I/Ares V)

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ABSTRACT

Stellar Imager (SI) is a space-based, UV/Optical Interferometer (UVOI) with over 200x the resolution of HST. It will enable 0.1 milli-arcsec spectral imaging of stellar surfaces and the Universe in general and open an enormous new "discovery space" for astrophysics with its combination of high angular resolution, dynamic imaging, and spectral energy resolution. SI's goal is to study the role of magnetism in the Universe and revolutionize our understanding of: 1) Solar/Stellar Magnetic Activity and their impact on Space Weather, Planetary Climates, and Life, 2) Magnetic and Accretion Processes and their roles in the Origin & Evolution of Structure and in the Transport of Matter throughout the Universe, 3) the close-in structure of Active Galactic Nuclei and their winds, and 4) Exo-Solar Planet Transits and Disks. SI is a "Landmark/Discovery Mission" in 2005 Heliophysics Roadmap and a candidate UVOI in the 2006 Astrophysics Strategic Plan and is targeted for launch in the mid-2020's. It is a NASA Vision Mission and has been recommended for further study in a 2008 NRC report on missions potentially enabled/enhanced by an Ares V launch. In this paper, we discuss the science goals and required capabilities of SI, the baseline architecture of the mission assuming launch on one or more Delta rockets, and then the potential significant enhancements to the SI science and mission architecture that would be made possible by a launch in the larger volume Ares V payload fairing, and by servicing options under consideration in the Constellation program.

Keywords: Space Missions, Interferometers, Constellation Program, High Angular Resolution, Magnetic Activity

1. INTRODUCTION

The Stellar Imager will enable "high definition" 0.1 milliarc-sec (mas) spectral imaging of the Universe from 1200 – 6600 A and open an enormous new "discovery space" for Astrophysics in the UV/Optical by combining that high, sub-mas angular resolution, with dynamic imaging and concurrent spectral energy resolution. The science goals of SI are to understand:

- ***Solar and Stellar Magnetic Activity* and their impact on *Space Weather, Planetary Climates, and Life***
    - Understand the dynamo process responsible for magnetic activity
    - Enable improved forecasting of solar/stellar magnetic activity on time scales of days to centuries
    - Understand the impact of stellar magnetic activity on planetary climates and on the origin and continued existence of life
    - Techniques:
        - spatially resolve stars to map the evolving atmospheric activity and trace dynamo patterns
        - high temporal resolution, disk-resolved asteroseismic probing of internal stellar structure and flows (at least to degrees of order 60)
- ***Magnetic Accretion Processes* and their roles in the *Origin & Evolution of Structure* and in the *Transport of Matter* throughout the Universe**.
    - Understand accretion mechanisms in sources ranging from planet-forming systems to black holes
    - Understand the dynamical flow of material and the role of accretion in evolution, structure, and transport of matter in complex interacting systems

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- **Active Galactic Nuclei (AGN) Structure**
  - Understand the close-in structure of AGN including jet forming regions, winds, and transition regions between Broad and Narrow Line Emitting Regions
- **Dynamic Imaging of the Universe at Ultra-High Angular Resolution**
  - Understand the dynamical structure and physical processes in many currently unresolved sources, such as: AGN, supernovae, planetary nebulae, interacting binaries, stellar winds and pulsations, forming stars and disks, and evolved stars
- **The study of exo-solar planets by imaging:**
  - transits across stellar disks
  - debris and shells surrounding infant star-disk systems
  - dynamic accretion, magnetic field structure, and star/disk interactions in these systems.

Stellar Imager is a cross-theme mission addressing science goals of both the NASA Heliophysics and Astronomy and Physics Divisions. In the Long-Term NASA Strategic Plan, SI is a "Flagship and Landmark Discovery Mission" in the 2005 Heliophysics Roadmap (see Fig. 1), a potential implementation of the UVOI in the 2006 Science Program for the Astronomy and Physics Division, and a candidate Large Class Strategic Mission for the mid-2020's. The science mission concept, technology development plans, and a "baseline" mission architecture were developed in a 2005 NASA "Vision Mission" (VM) study (see "NASA Space Science Vision Missions" (2008), ed. M. Allen[1]) and it has been recommended for further study in an 2008 NRC report[2], and Ames Workshop report[3], on missions potentially enabled/enhanced by an Ares V launch. The science goals of SI are discussed in further detail in three Astrophysics Decadal Study Science Whitepapers[4],[5],[6] and the mission architecture in a response to the Decadal Survey RFI for mission concepts[7] (Ref. 4-7 can be downloaded from http://hires.gsfc.nasa.gov/si/.) This paper is a summary of presentations made to the NRC panel and Ames workshop as well as that made to the August 2009 SPIE meeting.

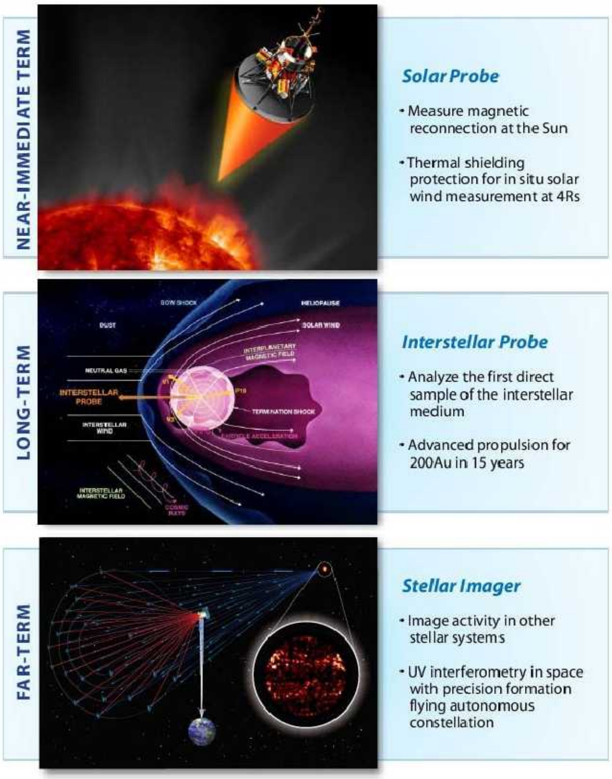


Fig. 1. Heliophysics Division Landmark Discovery Missions, from the 2005 Roadmap.

2. CAPABILITIES OF STELLAR IMAGER

The various science goals discussed above drive a variety of performance requirements placed on the SI observatory. These requirements are summarized below in Table 1.

Table 1. SI Capabilities Required by the Science Goals

- **wavelength coverage: 1200 – 6600 Å**
- **access to UV emission lines** from Lya 1216 Å to Mg II 2800 Å
  - Important diagnostics of most abundant elements
  - much higher contrast between magnetic structures and background
  - smaller baselines (UV save 2-4x vs. optical, active regions 5x larger)
  - ~10-Å UV pass bands, e.g. C IV (100,000 K); Mg II h&k (10,000 K)
- **broadband, near-UV or optical** (3,000-10,000 K) for high temporal resolution spatially-resolved asteroseismology to resolve internal stellar structure
- angular resolution of 50 mas at 1200 Å (120 mas @2800 Å) to provide ~1000 pixels of resolution over the surface of nearby (4pc) dwarf stars,
  and more distant giant and supergiant stars.
- **angular resolution of 100 mas in far-UV** for observations of sizes & geometries of AGN engines, accretion processes in forming exo-solar systems, interacting binaries and black hole environs, and for dynamic imaging of evolving structures in supernova, planetary nebulae, AGN, etc.
- **energy resolution/spectroscopy** of R>100 (min) up to R=10000 (goal)
- Selectable "interferometric" and "light bucket/spectroscopic" modes
- a **long-term (~ 10 year) mission**, to enable study of stellar activity cycles:
  - individual telescopes/hub(s) can be refurbished or replaced

SI is designed to obtain images and spectral information simultaneously. Simulations of these spectral imaging capabilities on a variety of targets are shown in Figure 2.

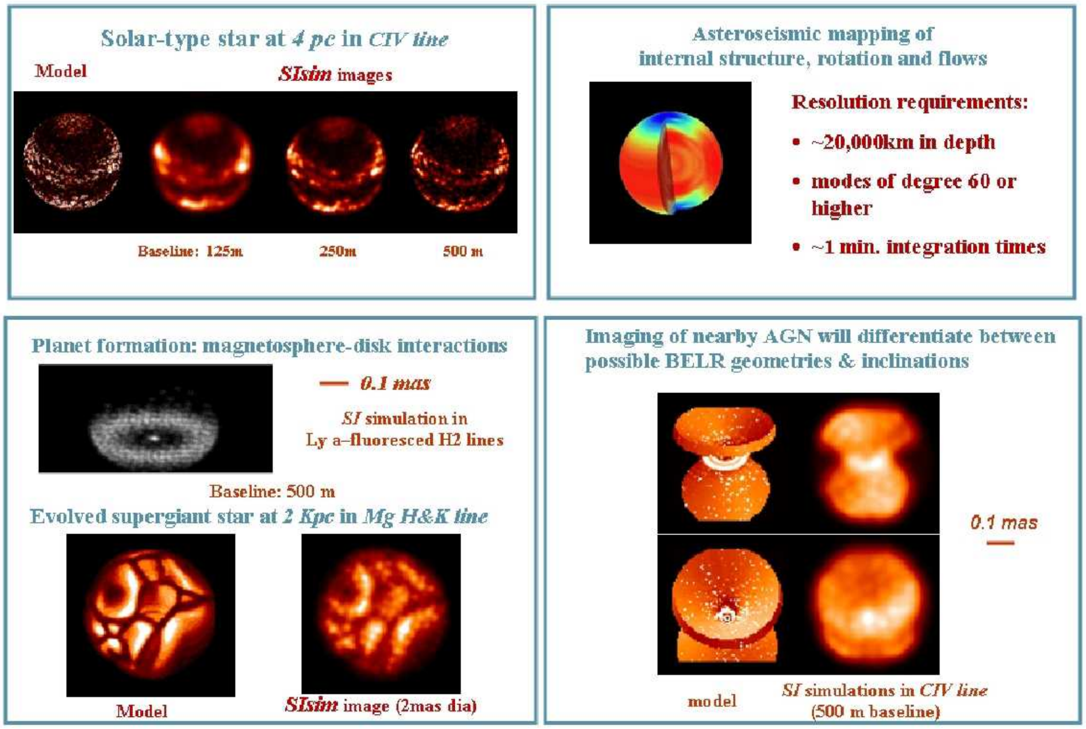


Figure 2. Spectral Imaging capabilities of SI.

The extremely high angular resolution of SI means that successive images taken with separations of hours to weeks will detect dramatic changes in many objects – for example:

- mass transfer in binaries
- pulsation-driven surface brightness variation and convective cell structure in giants and supergiants
- jet formation and propagation in young planetary systems
- reverberating AGN
- and many other variable and evolving sources

Figure 3 illustrates the velocity resolution of SI as a function of the distance of the target and the number of days between successive exposures.

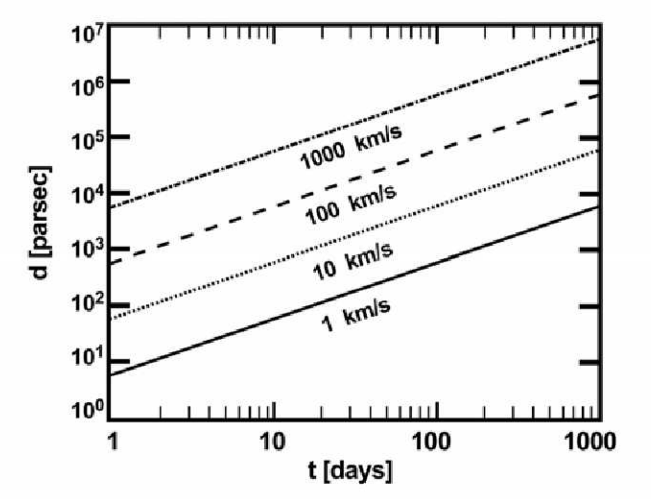


Figure 3. SI will resolve the dynamical evolution of many astrophysical objects for the first time.

3. “BASELINE” ARCHITECTURE FROM VISION MISSION STUDY

The baseline design (see Figures 4 and 5) derived during the NASA Vision Mission Study (the full report can be downloaded from http://hires.gsfc.nasa.gov/si/) is a space-based UV-optical Fizeau Interferometer with an outer diameter that can be adjusted from 100-1000m (with a typical observing configuration of 0.5 km). It would be located in a Lissajous orbit around the Sun-earth L2 point to enable precision formation flying. This design incorporates 30 primary mirror elements (in a sparse array whose outer diameter varies as noted above) focusing on common beam-combining hub. The study identified large advantages to flying more than 1 hub (beam-combiner) spacecraft: it would provide a critical-path redundancy and major observing efficiency improvements, by allowing the 2nd hub to be pre-positioned while the first is being using in an observation.

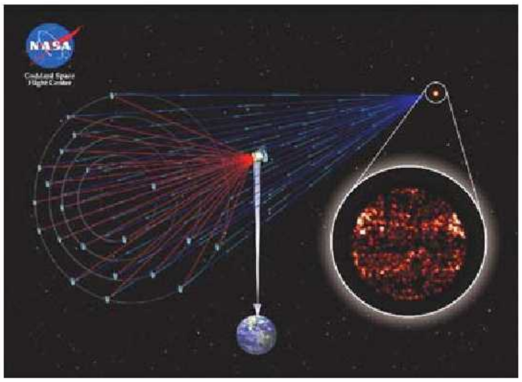


Figure 4. SI mission architecture from Vision Mission Study.

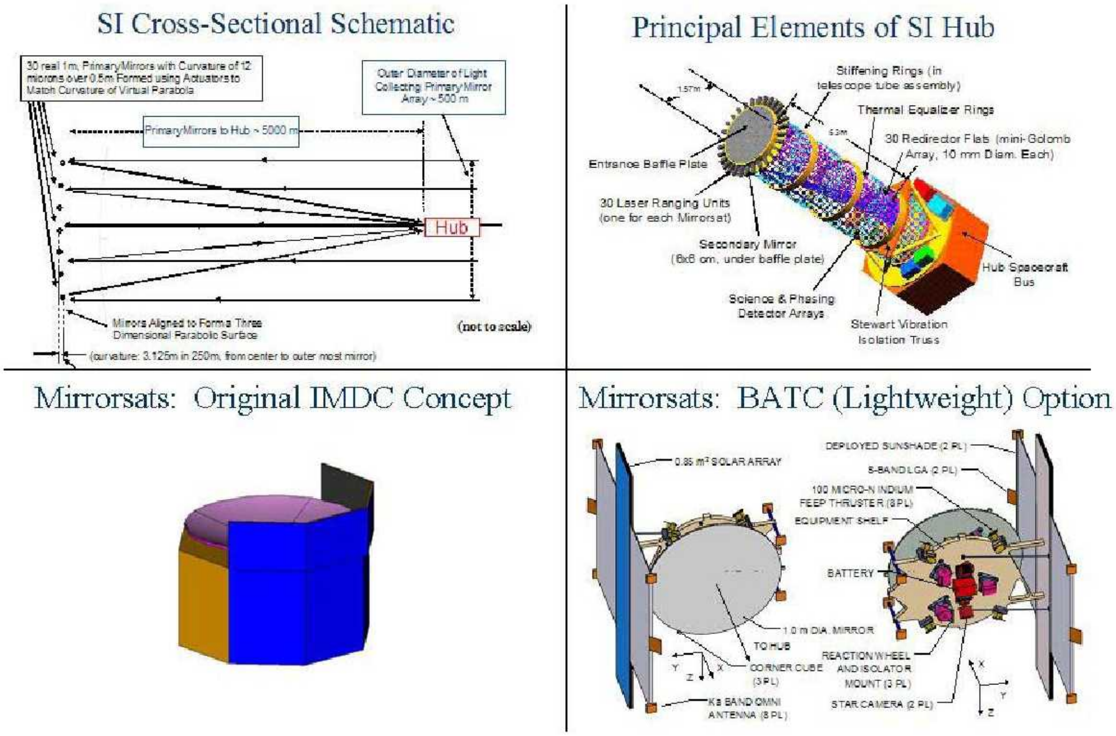


Figure 5. Overview of the Vision Mission Study SI Design Concept

SI designs with 1 meter primary array elements (e.g., the basic "minimal" VM design) and one beam-combiner hub can be launched on a single Delta IV Heavy using the 19+ meter long fairing, as shown in Figure 6.

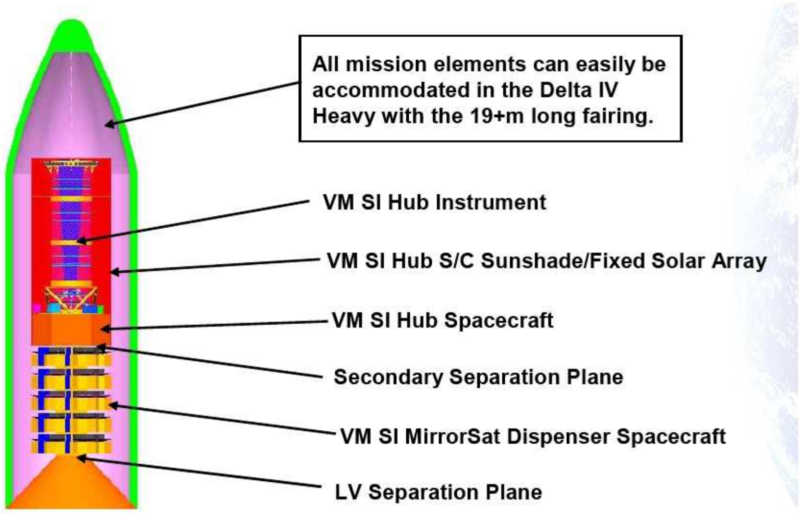


Figure 6. There are several launch options for the basic VM Design (1-m primary mirrors) using Delta IV vehicles. One hub spacecraft plus 30 mirrorsats can be sent to L2 in a single launch using a 5mx19.1m fairing as shown. If two hubs are to be deployed and/or a metrology reference craft is needed, then two or more launches are needed.

4. BENEFITS TO SI OF CONSTELLATION PROGRAM

4.1 Benefits of launch on an Ares V

The VM design includes 30 primary mirrors, each 1m in diameter. Larger diameters are desirable, if costs permit, for improved sensitivity, but will not readily fit into 1-2 Delta IV launches. With the Ares V and its much larger fairing volume, or other similar large fairing vehicle such as an Atlas V HLV, it is quite feasible to utilize mirrors 2m or more in diameter, without requiring multiple launches. These larger mirrors dramatically increase the sensitivity and science productivity of the observatory, especially for the fainter extra-galactic sources such as AGN, Quasars, black hole environments, etc. In SI's "light bucket" mode, in which all mirrors dump all of their photons down into a single aperture for maximum sensitivity spectroscopic observations (no imaging), 30 two-meter mirrors provide the equivalent of an 11m diameter monolith, 4x more light than 1m mirrors and nearly 20x the light gathering capability of HST.

In addition, designs with an additional metrology reference craft (which may be needed to control the positioning and precision pointing of the overall system of 30+ spacecraft) and/or 2 beam-combining hubs could be launched on a single vehicle using an Ares V, rather than the multiple launches needed if currently available vehicles such as the Delta IV are utilized. Figure 7 illustrates the large gain in fairing volume attained with the Ares V.

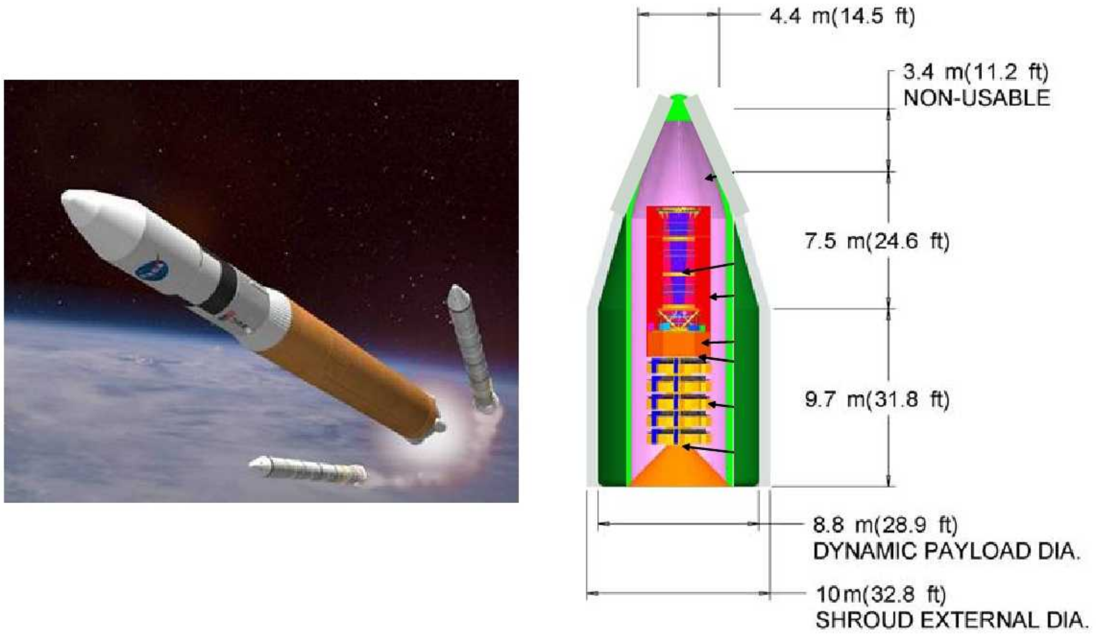
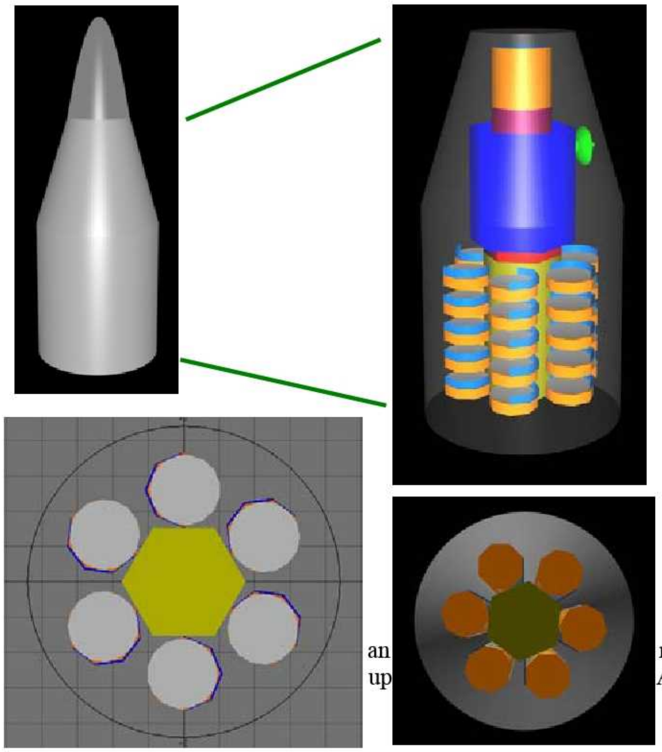


Figure 7: Left: an artist's concept of an Ares V launch. Right: The entire Delta IV SI 1m launch configuration, including the Delta IV fairing, fits well inside the Ares V shroud with plenty of margin, illustrating the tremendous gain in fairing volume enabled by the Ares V!

4.2 Packaging SI in an Ares V shroud

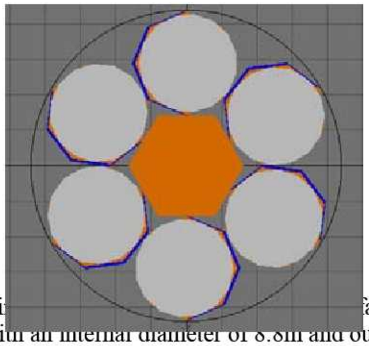
We have performed a study for the NRC Panel of packaging concepts for SI designs using 2m and larger diameter primary mirrors. The results are shown in Figure 8. We have utilized an Ares V shroud with a 8.8m inner diameter and a 10.0m outer diameter. With a hexagonally shaped "mirrorsat" dispenser 1.75 m on a side, 6 mirrorsats with 2m diameter mirrors can be included at each level of the hexagon and five levels can be filled while still leaving plenty of vertical space for the hub spacecraft and plenty of radial margin around the outside of the dispenser spacecraft (Fig. 8, left). We then investigated the maximum size mirrors that could safely fit into the same Ares V shroud if mirror size were not limited by cost considerations. Using a slightly smaller dispenser hexagon, 1.63m on a side, 30 mirrors 2.75m in diameter will fit inside the shroud, as shown in Figure 8 (right).



Mirrors 2m in diameter
Dispenser Hexagon 1.75m on a side

Ares V shroud assumed to have 8.8m inner diameter, 10.0m outer diameter

Largest Mirror Size accommodated by this shroud is 2.75m in diameter (with Hexagon 1.63m on a side)



an mirror elements i fact,
up Ares V shroud with an internal diameter of 8.8m and outer

4.3 Benefits of in-situ servicing with Ares I/Orion CEV or robots launched via Ares

Although the SI baseline design does not require that humans and/or robots be able to access and work on SI at the Sun-Earth L2 site, the mission could benefit greatly from such a capability. In particular, the long lifetime requirement for SI (5-10 years or more) is most easily met if the design can be made modular so that humans in the Orion vehicle and/or robots can readily service and replace key components of the mirrorsats and hub. An obvious and simple capability that would help enable SI would be the ability to refuel the spacecraft to ensure it will be able to perform station-keeping/orbit maintenance and target-to-target maneuvering over the desired long lifetime. Servicing of the critical hub spacecraft would also be of great utility, since it, unlike the mirrorsats, is a single-point failure, unless more than one hub is launched initially or a second is available for later launch-on-need.

In the timeframe of interest (2024+) for SI, NASA systems developments for Moon, Mars, and in-space sites may be expected to produce major advances in robotic capabilities. These developments and mission deployments will make a variety of robots increasingly available with increasing performance and versatility for assembly, servicing, and related operations in space. The Sun-Earth L2 site is relatively unfavorable for human visits, due to radiation hazards and the vehicle provisions and flight durations required for return. Robotic servicing at L2 will be relatively advantaged early in this timeframe, although the operations will require extensive autonomy, with limited supervision by ground-based controllers, due to command-response latencies of several seconds at that distance. Modular systems with simple interfaces are particularly well suited for such operations. As the capabilities for human activities are extended to Mars and other destinations later in the timeframe, visits to L2 by humans may become a more readily supported approach. Although the uniquely human capabilities for handling unstructured situations could conceivably relieve the need for simplifying operations through modular design, modularity will continue to support increased efficiency and risk reduction. Figure 9 (left) shows an Orion capsule mated to a crew module for possible using in human servicing, while Figure 9 (right) shows the Orbital Express mission which has demonstrated the basics of robotic servicing in space.

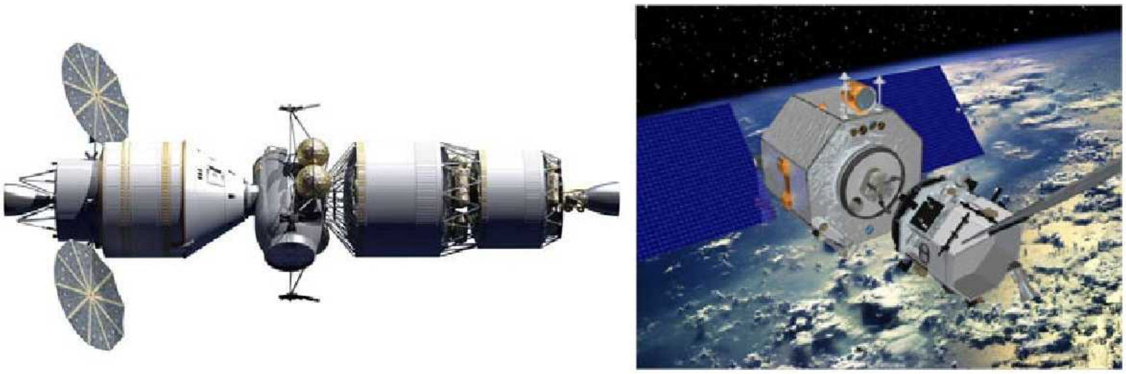


Figure 9: Left: LSAM L1 Stack – Orion mated to a crew module (http://www.futureinspaceoperations.com/). Right: Orbital Express has demonstrated feasibility of autonomous (robotic) on-orbit refueling and reconfiguration (http://www.darpa.mil/orbitalexpress/).

4.4 Summary of Major Benefits to SI from use of Constellation Architecture

The Ares V and its larger fairing volume (or similar proposed HLV versions of the Delta or Atlas vehicles) enables inclusion of larger primary mirror array elements in the SI design (e.g., 2.0 – 2.75 m diameters vs. the 1m diameter mirrors) without requiring the additional launches needed using a Delta IV vehicle. These larger mirrors would greatly increase the sensitivity of the observatory and dramatically increase its science productivity, especially for fainter, extra-galactic sources, such as AGN. The Ares V may also enable launch on a single vehicle of designs which include more than 1 hub (strongly desired for operational efficiency and redundancy) and/or a reference metrology/pointing control spacecraft. SI can also benefit significantly if elements can be serviced during its long operational life (elements re-fueled, fixed, replaced) – a possible role for the manned Orion/CEV or robots deployed by an Ares launch

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