# Assessment of In-Space Operations with Large Space Telescopes within a Lunar Architecture - Status

## Harley Thronson Briefing

**SHRD Team**

**March 2005**

# Work Performed to Date

- **Past work using FAIR/DART, and other concepts**

- **Early Scoping activities at JSC**

- **Preliminary Analysis by SHRD Team**
  - **Concept of Operations using SAFIR**
  - **Assessment of modifying SAFIR for human/robotic operations**
  - **Identification of functions???**
  - **List of trade studies to be performed**

- **CTS Requirements Analysis**
  - **Point of Departure architecture description**
  - **Gap Analysis of current CTS (rev. D) requirements vs. in-space telescope capability need**

- **Future work**
  - **Paper**
  - **Follow on activities here with SHRD team?**

# SHRD Team

- **Study Customer: Harley Thronson, Assistant Associate Administrator/Technology, SMD, NASA HQ**

- **Major Stakeholders:**
  - **Exploration Systems Mission Directorate: Bret Drake**
  - **Science Mission Directorate: Marc Allen**

- **Study Team**
  - **Coordination:**
    - **Brenda Ward, NASA - JSC**
    - **Brian Derkowski, NASA - JSC**
  - **SAFIR/Large Telescope Advisors:**
    - **Dan Lester, Univ. of Texas**
    - **Tracey Espero, Boeing Team**
    - **Rud Moe, NASA - Goddard**
    - **Chuck Lillie, NGST**
  - **Robotics Expertise:**
    - **Rob Ambrose, NASA - JSC**
  - **Human EVA Expertise:**
    - **Robert Trevino, NASA - JSC**
  - **Crew Office Rep:**
    - **Joe Tanner, NASA - JSC**
  - **Other Expertise: Jim Geffre (JSC), Judith Watson (LaRC), John Charles (JSC)**

# Summation of Task
# (Per subsequent discussion with Harley)

**Derived Task Statement**

- The task is to study areas that previously have not been addressed by anyone, esp. SAFIR team. In particular, studying the feasibility of human/robotic intervention (either servicing, deployment, other) with a SAFIR-like (10m class) telescope via a CEV at L1 (or other likely places).

- Three concepts are to be developed (per the original task language): (in Priority Number)
  1. Direct astronaut assisted deployment/upgrade/repair from within the CEV via EVA; assess how this capability can augment/enable telescope science goals. (Most importance)
  2. Telerobotic deployment/upgrade/repair from within the Crew Exploration Vehicle; assess how this capability can augment/enable telescope science goals.
  3. Introduce the small pressurized platform called "Gateway" or outpost to the Studies 1 and 2, and assess how this additional hardware can augment/enable telescope science goals.

**Schedule/Depth of Study**

- By the Loya Jirga II conference (early February) the study team should show at a high level:

1. Whether Items #1 or #2 above (telerobotic or human EVA telescope intervention) were feasible and,
2. What high level capability/functionality is enabled (from a telescope/science capability) by having those resources available at the L1 point.

- With approximately two months to work, the product can be at a preliminary level. However, the delivery at that time should give the audience (scientists, contractors performing design studies, policy makers?, others?) enough ideas so that they could promote further thinking on this topic and raise subsequent discussions.

# HQ Task Language (from Harley)

**Task Language (continued)**

- **Studies must produce sufficient information to:**
  - **Permit costing [How much information is sufficient? -- Half order of magnitude; That is, what is the range of cost?]**
  - **Permit identification of necessary technology investments, and the value of the capabilities to priority ESMD and SMD goals.**

- **Primary Figure of Merit**
  - ***Increased capability* to support large, complex facilities in free space as opposed to purely autonomous deployment or Earth-bound telerobotic options.**
  - **How do we quantitatively measure this? By the priority (science and exploration) goals that are enabled -- or significantly enhanced -- by these capabilities. For example, does it appear that telerobotic capabilities alone are both necessary and sufficient to build, erect, maintain, repair, etc future plausible large in space facilities? Or, is human EVA likely to be required, say, to build plausible Mars-bound human missions?**

# Summarize past work

- Assess past work throughout NASA and within EX so that work is not repeated.
- Finding of survey include:
  - Much work has been done and is ongoing of characterizing human versus robotic interaction, best practices, and optimization
  - Much work has been performed to characterize assembling large structures on-orbit and in-space
  - Given a rough baseline design (FAIR DART), work has been performed previously by JSC-EX and others on assembly, test, and deployment of large aperture telescope.
  - Many programmatic and technical lessons can be learned from the Hubble Servicing Experience

# Past Work Summary

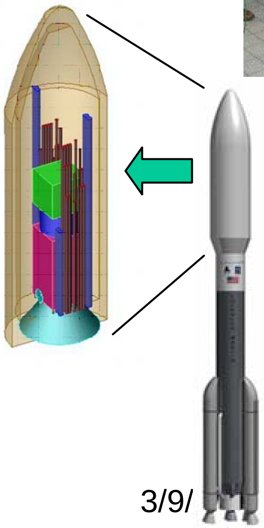
- **Some examples of past studies applicable to assembling and servicing large structures on-orbit are shown below:**
- **Team Next – FAIR/DART Study**
  - Selected a large (10 m), lightweight IR/SubMM gossamer telescope, DART, as the baseline design for conducting initial set of studies. This design tests the limits of conventional deployment/assembly technologies
  - Investigated three scenarios for assembly and/or deployment
    - **Scenario 1. LEO assembly + E-M L1 deployment--w/astronaut assistance** (Excepts were shown earlier)
      **(see Filled Aperture Infrared (FAIR) Telescope Assembly 57 pg presentation from JSC, Dec 01)**
    - **Scenario 2. E-M L1 assembly & deployment--w/astronaut assistance**
      **(see Human & Robot Cooperative Teams 18 pg presentation from JPL, Jul 02)**
    - **Scenario 3. E-M L1 or E-S L2 fully autonomous deployment**
      **(see Summary Report on the NExT Telescope Team Design Workshop from JPL, Sept 02)**
  - For **astronaut** assembly concepts, Scenario 1 assumes Space Shuttle-EVA infrastructure and Scenario 2 assumes a Gateway Infrastructure are operational & staffed appropriately for assembly of large structures.
- **Site Selection and Deployment Scenarios for Servicing of Deep-Space Observatories, Willenberg, et. Al. Boeing Phantom Works and Leete and Moe, NASA GSFC**
- **Hubble Servicing Lessons Learned**
- **Evaluation of Hardware and Procedures for Astronaut Assembly and Repair of Large Precision Reflectors, NASA/TP-2000-210317, LaRC (Watson, et. Al)**
  - **Presented a detailed look at using EVA to assemble large, truss-supported segmented reflectors for telescopes 10m in diameter and larger**
- **Metrics for In-Space Telescope Assembly Techniques: How to best use human and robotic resources for in-space tasks**

# Past Work: Human/Robot Collaboration for Telescope Assembly

- Advanced telescope assembly and servicing will represent tasks of variable difficulty, risk, frequency, and criticality
- Relative strengths of humans and robots in performing a wide variety of tasks are well-established conceptually
  - Humans are unequaled in unstructured, unpredictable, innovative scenarios
    - Better suited for single-point, low-repeatability, non-linear tasks – tasks that require critical thinking skills and specialized forces
    - Rapid response – can quickly assess a situation and provide an appropriate course of action without passing through multiple layers of intervention
    - Examples: “Rescue” of HST and GRO, satellite servicing missions (Westar/Palapa, Intelsat, Spartan), multiple examples on ISS, Apollo landings
  - Robots are best at high-risk access, repetitive tasks
    - Can be rapidly deployed
    - Can tolerate harsh environment for longer periods
    - Examples: Robots have gone to harsh environments (Venus, Jupiter) not currently accessible to humans
- There is much experience to validate these general notions
- Large science facilities in space will be assembled and serviced by squads of humans *and* robots

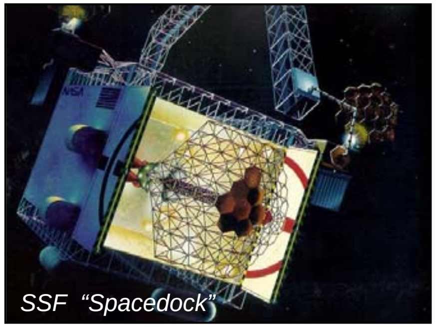
# Past Work: Current Capabilities for Telescope Assembly & Servicing

- All human-assisted servicing of astronomical telescopes is limited to existing LEO platforms
  - Shuttle and ISS-based servicing (*e.g.* Hubble servicing missions)
  - Payload manipulation limited to Shuttle and ISS robotic arms
  - Shuttle EMU Suit for EVA (high contamination, limited mobility and sensory feedback)
- Expendable Launch Vehicles with < 4 m diameter fairings available to launch telescopes
  - Will launch a 6-m-diameter segmented mirror telescope (JWST)
  - Studies have shown that telescopes significantly greater than ~10 m apertures cannot be launched and deployed intact, *i.e.* assembly required
- No robots with the capabilities envisioned to aid assembly & servicing have been built or flown
- Payload lift capabilities limited to ~20 tonnes and no crew transfer available beyond LEO

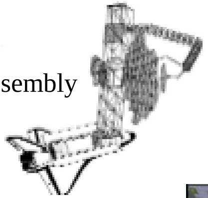


# Past Work: Assembly & Servicing Gap Analysis

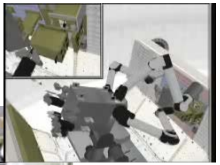
- Need Assembly and Servicing Platforms beyond LEO, including:
  - Supporting infrastructure w/ payload manipulation capabilities and habitation equipment
  - Radiation protection and thermal control of work area
  - Human transportation between worksites
- Need Mobile, Intelligent Robot Assistants
  - Remote control (teleoperation) enhancement
  - Improved autonomy and capability
    - Inspection (*e.g.* Aercam, PSS)
    - Assembly/Servicing Assistants (*e.g.* Skywalker, Robonaut, Ranger)
- Need EVA improvements
  - Low contamination suits
  - Radiation protection when operating beyond LEO
  - Information system upgrades (HUD, sensory enhancements)
  - Mechanical force augmentation/tactile feedback
- Need heavy-lift launch vehicles and crew transportation beyond low-Earth orbit



*SSF "Spacedock"*

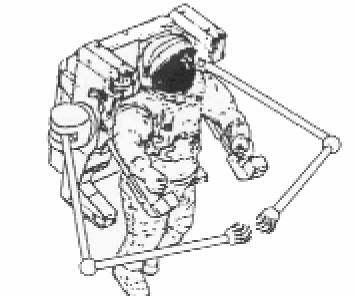


STS Assembly



*Ranger*

*Robonaut*



*MMU w/ Manipulators*

*Mini-Aercam*

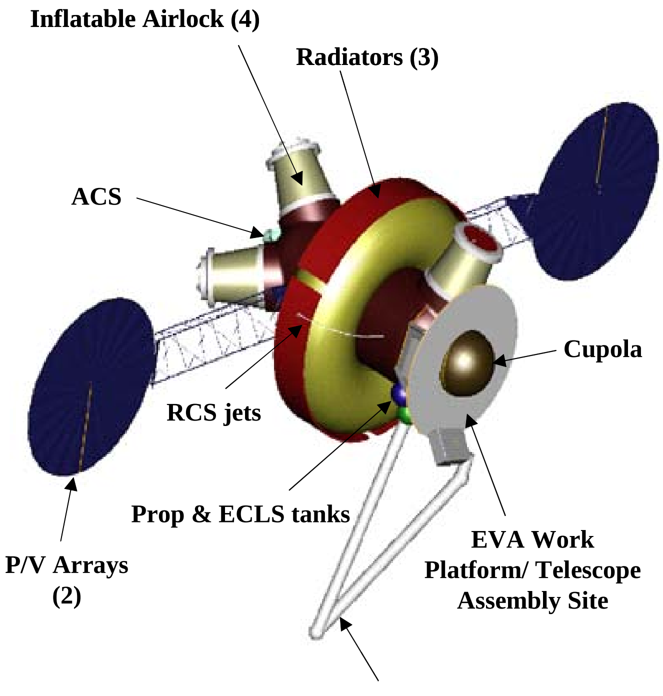
# Past Work: Telescope Construction and Servicing using a L1 Gateway “Outpost”

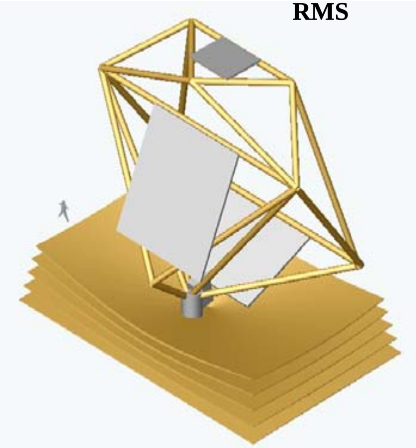
<u>Hardware Support</u>

- **Docking for crew transfer vehicle and telescope component delivery module**
- **SSRMS-class large manipulator**
- **Small, dexterous robot to aid inspections and assembly/maintenance tasks**
- **EVA Airlock and teleoperator control station**
- **Unpressurized partially enclosed work area**
- **Structure/platform to restrain the telescope during work**
- **EVA and robotic-compatible storage areas for tools and telescope components**

<u>Mission Support</u>

- **Complete assembly at Lunar L1:** 2 weeks **for** 2 teams **of EVA crew;** 6-8 EVA sorties
- **For telescope maintenance missions, assume** 1 team **of EVA crew for** 2 weeks
- Total Mission Time at Gateway: 25 days





Not Shown to Scale

# Recent SHRD Work Analysis Products

# CTS Requirements Analysis

- NASA Level 0 Exploration Requirements do mention telescope science.
  - “1.7 NASA shall conduct advanced telescope searches for Earth-like planets and habitable environments around other stars”

- Current work in ESMD to date has focused on lunar architectures, telescopes/in-space assembly/servicing are not explicitly mentioned in the Exploration Systems of Systems Technical Requirements Document (ESMD-RQ-0010, Rev. D) or lower-tiered documents (i.e. CTS Spiral 1,2,3).

- It is ***unclear*** whether requirements that are being considered (like the Systems of Systems Technical Requirements or the lower level Crew Transportation System Requirements) are sufficient to meet the needs (servicing, deployment, test, etc) of future space science platforms such as large space-research structures and telescopes.

- It is immediately ***clear***, through a quick look at the features of developing concepts of the Crew Exploration Vehicle that capabilities one would need to perform a servicing or assembly mission directly from the CEV, as is currently done from the Shuttle orbiter for example, are not included.

- This “missing” functionality needed to perform certain assembly/servicing missions could be allocated to the CEV (though a significant change to requirements) or other elements within the lunar architecture (additional infrastructure).

# Defining Functionality Needed to Carry Out “Intervention Missions”

- **Before augmenting a CEV design or proposing “Gateway Outposts”, some work must be done to identify what functionality is needed to assembly, service, test, etc. large space structures like telescopes.**

- **In addition to identifying functionality, consideration must also go to assess what benefits and/or capability is enabled by having specific functionalities. These benefits or enabled capabilities will serve as the justification for adding functions to the lunar architecture.**

- **To begin our study process, the SHRD team selected servicing as the first type of intervention mission to study. Others “mission categories” identified that should be consideration are listed on the next page.**

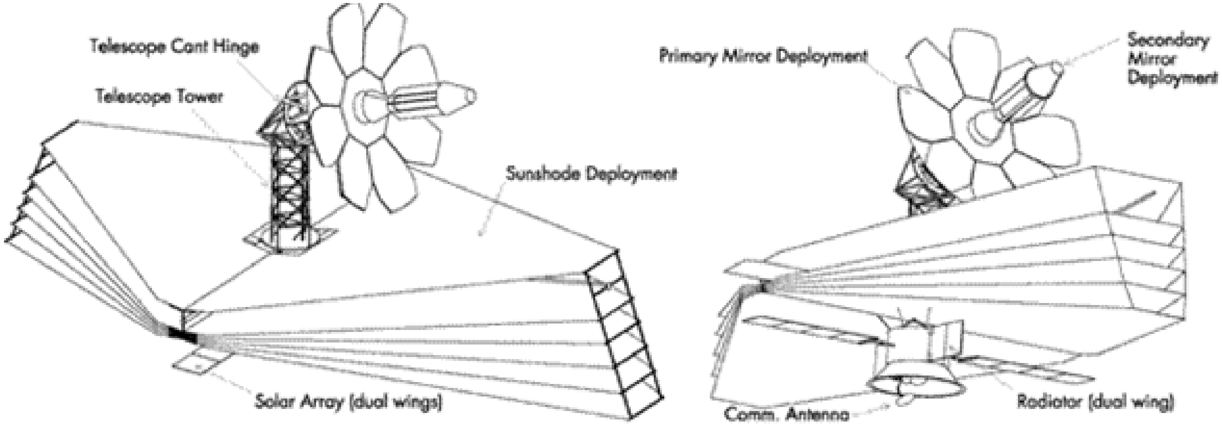
- **A similar process could be applied to the remainder of in-space operations to drive out benefits and what technologies enable that particular mission.**

# “Intervention” In-Space Operations

| | *Mission Categories* | *Definition* |
|---|---|---|
| 1.0 | Assembly/Deploy/Outfit | Assemble structure from prepackage components. Small unexpected events may occur, but mission is largely predesigned and throroughly planned |
| 2.0 | Calibrate/Test | A battery of tests are performed to characterize instruments following launch and assembly/deployment. Small unexpected events may occur, but mission is largely predesigned and throroughly planned |
| 3.0 | Verify/Test | A battery of tests and steps are taken to validate models of spacecraft in space. Small unexpected events may occur, but mission is largely predesigned and throroughly planned. |
| 4.0 | Inspect | Inspect structure and instruments prior to and/or following deployment. Data is sent to mission control for planning. |
| 5.0 | Monitor/Intervene | Monitor automatic processes and deployment activities; intervene if necessary. Any number of unexpected events may occur and corrective action steps may not be predefined |
| 6.0 | Service/Upgrade | Maintain or enhance initial design performance through replacement of pre-considered units, fluid replenishment, etc. Small unexpected events may occur, but typically mission goes by plan. |
| 7.0 | Diagnose/Repair | Maintain or enhance initial design performance through replacement of previously anticipated or non-anticipated units, fluid replenishment, etc. Many unexpected events may occur. Part of mission may be planned in detail, but lots of intervention required. |
| 8.0 | Decommission | Safe spacecraft; recover key instrumentation, boost spacecraft into final parking orbit. May or may not be preplanned event. |

# Single Aperture Far Infrared (SAFIR) Observatory Overview*

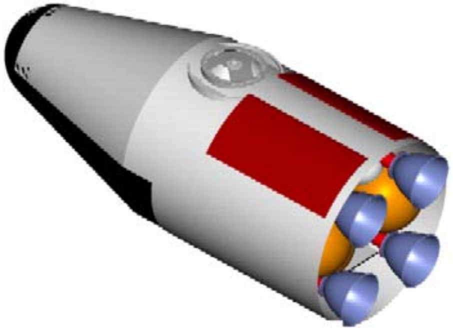
- A conceptual design for SAFIR exists which is based largely on the current design work for the James Webb Space Telescope (JWST). SAFIR is a Vision Mission within the Science Mission Directorate (SMD) [2015-2020 beginning operational time frame]
- The 10m diameter primary mirror is deployed piecewise, along with the secondary mirror and sunshield. Mirror and sensors operate at 10 K
- Deployed to Earth-Sun L2, the observatory can keep both Sun and Earth on the spacecraft side of the observatory, with the telescope on the far side. The thermal radiator for active coolers, solar array, and communications antenna are on the Earth-facing side of the observatory
- Baseline concept is fully autonomous with no servicing/assembly needed.
- Concept work is ongoing that will study how to add-in features to the current design for human/robotic servicing. (led by Chuck Lillie, NGST)
- A detailed SAFIR autonomous mission, has recently been complete by Team X/JPL. Refer to SAFIR TeamX 2004.ppt



* Information from “Application of In-space Capabilities to a Large Infrared Telescope for Astronomy—SAFIR”, AIAA 1st Space Conference, Feb. 2005

# Introduction to Concept: CEV

**Overview: A notional design for a Crew Exploration Vehicle (CEV) could be (analogous to the Apollo missions) comprised of the Command Module (CM) and Service Module (SM). The CM and SM can be scaled to accommodate a designated mission (including delta-V, crew size, duration, power levels, life support consumables, etc.)**



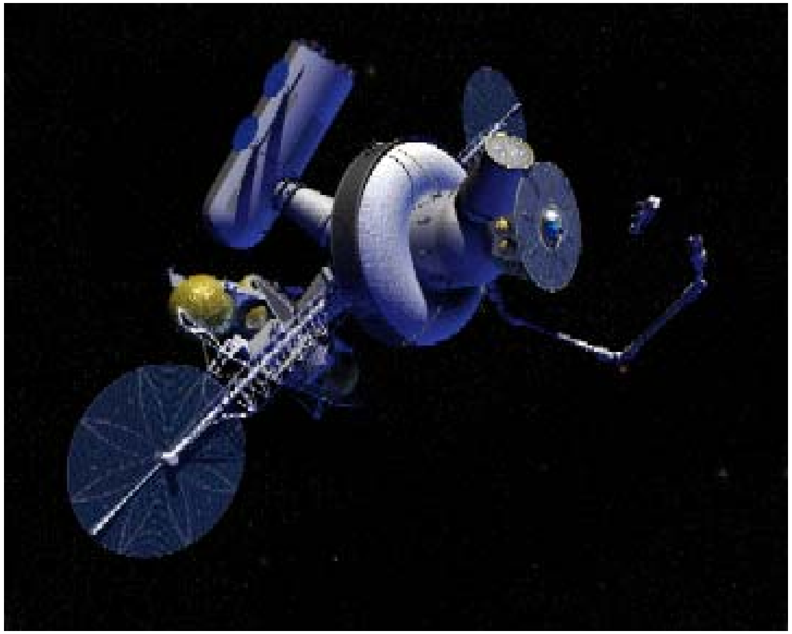
*Note: Conceptual Representation of past LTV, predecessor to current CEV*

- **Destination:** **LEO, Lunar surface, Lunar L1**
- **Crew Size:** **Assume 4 persons**
- **Mission Duration:** **up to 10's days (0-3 days (estimated) at L1)**
- **Other features (TBD):**
  - **No Airlock:** Assume no capability for planned EVA. Gemini-style suits with umbilical, emergency tools
  - **Radiation Protection:** Planned into the design of the crew module to provide a core level of biological protection
  - **Payload:** XX kg of internal payload assumed
  - **Robotic Agents:** No external robotic arm or manipulators in concept
- **Architecture Features:**
  - **Options exist in architecture to preposition hardware (robotic agents, tools, etc.) at L1**
  - **Nominal 2 weeks between launches**
  - **Other??**

# Introduction to Concept: Lunar $L_1$ Gateway

**Mission:** The Lunar $L_1$ Gateway is a mission staging and crew habitation platform stationed at the Lunar $L_1$ libration point for assembling and maintaining large astronomical observatories and conducting expeditions to the lunar surface.

- **Destination:** **Lunar $L_1$**
- **Element Design Lifetime:** **15 yrs**
- **Crew Size:** **4 persons**
- **Mission Duration:** **10-30 days**
- **Element Mass:**
  - **Launch:** **22,800 kg**
  - **Outfitting:** **600 kg**
  - **Post-outfitting:** **23,400 kg (52,000 lb)**
- **Element Volume:**
  - **Launch:** **145 $m^3$**
  - **Inflated:** **275 $m^3$**
- **Power & Propulsion System:**
  - **Average/Peak:** **12 kWe/15 kWe**
  - **Power Generation:** **Photovoltaic Arrays**
  - **Energy Storage:** **Li-ion Batteries**
  - **Propellant:** **$O_2/CH_4$**
- **Support Missions:**
  - **Outfitting at LEO:** **One mission/architecture**
  - **Human Consumables:** **Two missions/year**
  - **Life Support resupply:** **One mission/two years**



Existence of such a facility is tied to architecture path chosen for lunar missions

# 2005 AIAA Paper

- Several SHRD team members (led by Rud Moe and Dan Lester) contributed to a paper entitled “Application of In-space Capabilities to a Large Infrared Telescope for Astronomy—SAFIR” for the AIAA 1st Space Exploration Conference held in Orlando this past February.
- This paper was intended to serve as a map to trades and analysis necessary to characterize in-space operations (with a SAFIR telescope mission as the model) and their potential benefit to science.

- The paper summarized the case for in space operations through
  - General Benefits of In-Space Capabilities to Large Telescopes
  - In-Space Operational Impacts to SAFIR Mission Designs
  - Venues for Astronaut-Assisted Deployment/Upgrade/Repair
  - Application of CEV and “Gateway” Concept with Human-Robotic Supported Assembly Capability at Earth-Moon L1
  - A Scenario for SAFIR Servicing at an Earth-Moon L1 Gateway

- The discussion references many past papers and studies including:
  - Mark S. Lake, “Launching a 25-Meter Space Telescope, Are Astronauts a Key to the Next Technically Logical Step After NGST?”, Presented at the 2001 IEEE Aerospace Conference IEEE Paper No. 460 Big Sky, Montana March 10-17, 2001.
  - Mark Lake, Lee Peterson and Marie Levine, “Rationale for Defining Structural Requirements for Large Space Telescopes”, Journal of Spacecraft and Rockets, Vol. 39, No.5, September-October 2002
  - “On-Orbit Vibration Technology Assessment”, prepared by A. M. Kabe and E. M. Hall II, ATR 2001 (8001)-1, The Aerospace Corporation, August 22, 2001
  - 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.
    NASA Exploration Team, FY02 Annual Report, October 2002
  - M. Lo, “The TPF Mission at L2” COSPAR02-A-03279 in COSPAR Symposium on Space Based Astronomy, October 2002, Houston TX.

  - Additionally, the paper had significant contribution by The Boeing Company, in particular (Ed Friedman, Mike Kaplan and Tracey Espero)

# General Benefits of In-Space Capabilities to Large Telescopes**

**Larger aperture**

- Large collecting apertures in space represent the future of at least UV, optical, and infrared astronomy.
- Assembly in space enables the deployment for use of structures that cannot be launched in a single vehicle.
- Reduction in accommodations for actuation, linkages, and constraints for serially operated deployments

**Higher performance structure**

- Launch efficiency is improved. Denser packing results in lift capability, volume, diameter being maximized.
- Superior dynamical performance during operation can be realized. Deeper truss segments can favorably increase structure performance by reducing impact of the frequency of the first bending mode of the
- Smaller optical surface deformations may relax requirements on dynamic range performance of active optics.

**Fewer dollars spent on testing infrastructure**

- It is important to note that no detailed cost comparison has been performed; however, a few advantages are:
  - No large, very clean, extreme low temperature vacuum chamber is required to conduct tests.
  - Final performance validation of both the structure and optics would be done in space (versus in distributed testing)
  - Eliminates costly need for simulating starlight with enough accuracy that performance of the observatory can be confirmed.
  - Increasingly harder to test large structures in existing test chambers due to size and to a 1-G environment.

**Better reliability of deployment**

- Assembly step-wise verification, enabling workarounds as needed before committing the entire system.
- Alternatively, a traditional mechanical deployment process may also benefit from the availability of a mobile agent with sensing and some possibility of access for viewing and physical interaction.
- In-situ dynamical tests to check on linkages and locks, and sensitive mapping of structural characteristics

**Extended mission life**

- Ability to change out subsystems accommodates system failures and lifetime management (e.g. HST).
- Opportunity for retanking of consumables (propellants and instrument cryogens) is another facet of the lifetime management capabilities that would be enabled by in-space operations.

**Enhanced productivity**

- Mission productivity can be enhanced by installing upgrades in technology as they become available. This applies to science detectors and instruments particularly, but also to supporting components such as data systems, power systems, control systems, etc. (e.g. HST)

***[From "Application of In-space Capabilities to a Large Infrared Telescope for Astronomy—SAFIR"]***

# In-Space Operational Impacts to SAFIR Mission Designs**

**Modular design with in-space operations interfaces**

- **For SAFIR, which is baselined as a near-term Vision Mission, it would seem that design for simple robotic module exchange or add-on would be most prudent, since the advanced human EVA capabilities in space would still be in development for human operations on the Moon.**
- **Likewise, advanced dexterous and precise robotic operations may also be in early stages of implementation, although the decade of robotic testbed and precursor missions should provide some robust and reliable operating systems capable of more than the Shuttle and ISS systems of today.**
- **Modularity design for simple robotic-only module exchange or add-on would require interfaces that fit together with minimal requirements for preprocessing and no requirement for dexterous handling or complicated interactions.**

**Approaches for assembly and servicing of components which operate at cold temperatures**

- **SAFIR achieves its huge infrared sensitivity by being very cold. As such, the thermal characteristics of the observatory require special attention to contamination control.**
- **Outgassing of newly installed components, thruster plumes, and waste (gas and water) dumps from human facilities can all condense out on observatory components that are cold. Such condensation can seriously reduce observatory performance, both optical (because of coating opacity) and mechanical (because of interference on contacting surfaces in bearings.)**
- **While robotic servicing at the ~4 to 10K operating temperature could be considered, such efforts are likely to be very costly, and considerations for SAFIR should include strategies for safe thermal cycling of the observatory, as well as zone isolation.**

**Approaches for safe operations in the vicinity of a large, delicate structure**

- **The precision optical alignment of the SAFIR telescope and the fragility of the stretched mylar sunshields call for special attention to safe operations with an external agent.**
- **If left deployed, the mylar sunshield can be torn or otherwise penetrated by collisions with the in-service agents, or with debris released in the vicinity.**
- **In the baseline configuration, the sunshield is between the cold telescope and the warm spacecraft bus, so service opportunities on the observatory have to contend with a large shield that separates disparate regions that are the targets for such servicing.**

***[From “Application of In-space Capabilities to a Large Infrared Telescope for Astronomy—SAFIR”]***

# In-Space Operational Impacts to SAFIR Mission Designs** (continued)

**Docking ports on the observatory, spacecraft control connections.**

- **Fly-around agents that grab the observatory near where the servicing is to be done, remotely controlled and/or monitored by a CEV, the scale size of subsystems to be exchanged and the range of grab-on points that need to be accommodated may argue for a more fixed base of operations.**
- **Alternatively, the team envisions a CEV or the servicing facility hard-docked to the observatory at a fixed location, ideally on the spacecraft bus end.**
- **Some method of assessing the cold side of the sunshield (perhaps an arm on the servicing equipment or telescope) to access the telescope is required. While this strategy poses complications, the sunshield could protect the telescope from CEV contamination.**
- **Docking at the spacecraft bus allows for simple control connections between the CEV or servicing facility and the observatory.**

**Dependence on service providers' schedule, motivation, interaction compatibility, etc**

- **Use of shared multi-purpose, multi-mission designs, interfaces, supporting systems, and processes usually entails some compromise from optimum single-point solutions to establish the commonality that is the basis for reuse and cost avoidance.**
- **A design to accommodate a service provider's interfaces, capabilities, and limitations should be well worth the burden of imposed requirements if the cost avoidance is substantial; otherwise there is no basis for departure from the traditional stand-alone approach.**
- **The higher the capitalization of a reusable facility, the greater the efficiency gained through its reuse, particularly if the greater part of the investment has a slow technology rate of development which obviates obsolescence. This applies to sharing of the operational availability as well, leading to manifesting issues for supporting flights, competition for mission slots, and dependence on continued operation and availability.**
- **A fleet stand-down of launch vehicles is familiar history, affecting an entire queue of clients very substantially. Until alternative service providers are available, commitment to a capability provided by a unique external organization does involve some risk.**

**Specific equipment for telescope in-space assembly and servicing**

- **The SAFIR program would be responsible for providing unique equipment for SAFIR assembly and servicing that would not be provided by the Exploration mission systems for their assembly and servicing of vehicles, habitats, depots, communications terminals, logistics supply, etc.**
- **This may entail specific handling and test equipment such as super-clean process controls, sunshield system for thermal stabilization, precision structure metrology, astronomy instruments verification equipment, etc.**
- **Some portion of this investment that is not built into SAFIR itself may be left behind at the supporting facility and made available for reuse by subsequent telescope assembly and servicing missions.**

***[From "Application of In-space Capabilities to a Large Infrared Telescope for Astronomy—SAFIR"]***

# Venues for Astronaut-Assisted Deployment/Upgrade/Repair**

**While SAFIR is baselined for operations at Earth-Sun L2, the relevance of in-space opportunities for SAFIR in LEO and Sun-Earth L2 should be addressed,**

## LEO Servicing/Operations Considerations

- LEO appears to be an unfavorable locale for many reasons.
- The day-night cycle in LEO is highly disadvantageous for power management, as substantial batteries or at least fuel cells need to be used to allow continuous operation. These day-night cycles are of particular concern for an observatory like SAFIR, which relies on critically optimized thermal properties.
- The most significant problem is the thermal one; the structure will never get mechanically quiet unless special accommodations are made. These accommodations are likely to degrade performance at L2 and will add mass and cost if the telescope is going to be aligned and tested in LEO.
- Another issue in LEO is gravity gradient effects that will complicate testing of pointing performance, as will torques produced by atmospheric drag on the large sunshield.
- The LEO environment is potentially very risky for large mylar sunshields, in that debris can be expected that will produce penetrations (at a rate much higher than from micrometeorites at L2) and compromise the shielding efficiency.
- Finally, the delta-V required for transfer to L2 from LEO is large (3-5 km/s), and the accelerations and mechanical loadings entailed could require costly structural modifications to the observatory. The propulsion demands for both deployment from and return to LEO are substantial, and would require a propulsion module for the observatory of substantial size.
- Transfer from LEO to L2 and return for servicing also involves repeated transit through the radiation belts around Earth, entailing risk to sensitive components and requiring provisions for mitigating damage.

## Sun-Earth L2 Servicing/Operations Considerations

- Human-attended opportunities at L2 are unlikely in the short term, at least because an early-phase CEV will not support such lengthy journeys which can be of order months (which in itself is a risk factor). Routine access of humans to L2 will have to contend with particle radiation risks from solar flares, and the lack of opportunities for quick emergency return as a result of such storms, equipment failure, or medical emergency.

***[From “Application of In-space Capabilities to a Large Infrared Telescope for Astronomy—SAFIR”]*

# Venues for Astronaut-Assisted Deployment/Upgrade/Repair** (continued)

## Sun-Earth L2 Servicing/Operations Considerations (continued)

- **Opportunities for robotic agents at L2 are more feasible, and both replacement of entire subsystems and retanking of consumables appear increasingly feasible. But human control from Earth of robots at L2 involves several second delays that would reduce effectiveness of operation. As a result of this unavoidable control latency, there would be strong incentive to making such agents largely autonomous, which, while intrinsically feasible, will add cost and technical risk.**
- **Alternatively, simple and well-designed servicing tasks could be performed reliably, for example module replacement or add-on, by limiting the complexity of the servicing systems but consequently reducing the possibilities for rescue or upgrade to an unproductive extent.**

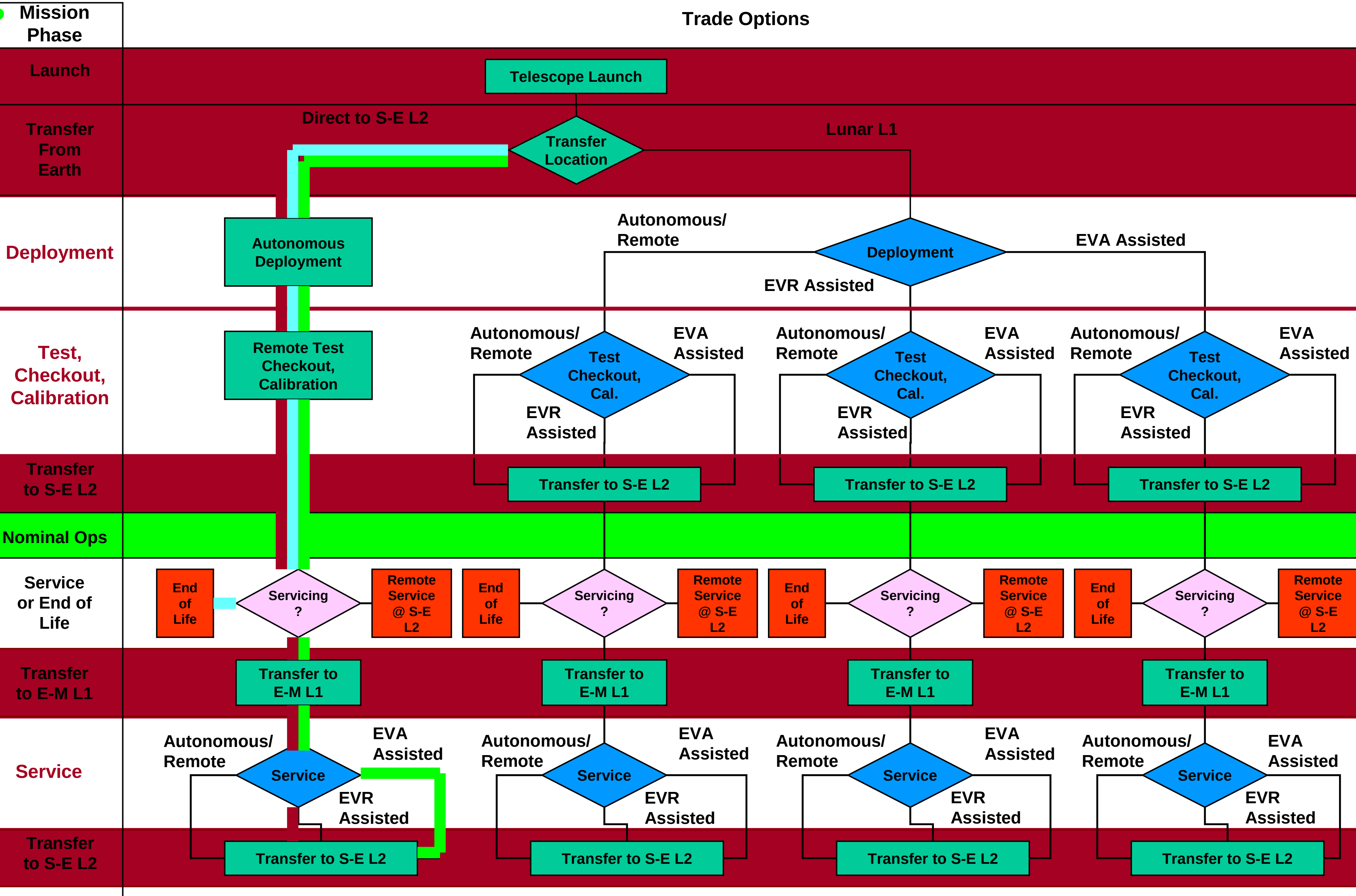
## Earth-Moon L1 Servicing/Operations Considerations

- **Operations at E-M L1 have been proposed by a number of authors, and were the basis for the NASA Exploration Team space architecture studies. L1 may have significant relevance to the Exploration agenda; access to the lunar surface at all latitudes is energetically equivalent, such that an “outpost” there would offer considerable flexibility.**
- **The orbital dynamics at Earth-Moon L1 are similar to Earth-Sun L2, in that the location is semi-stable, and requires little station-keeping propulsion.**
- **Science operations at L1 are significantly less enabling than at Earth-Sun L2, because radiation from Earth and Moon cannot be reliably blocked along with the Sun, making for issues in scattered light and thermal management.**
- **Of special importance is the fact that Earth-Moon L1 is connected to other solar system Lagrange points by pathways that are highly economical energetically. While it requires several months to travel between Earth-Moon L1 and Earth-Sun L2 on such a low-energy pathway, the departure and orbital insertion propulsion burden is remarkably modest – of order 100 m/s, a major advantage for a massive observatory.**
- **The programmatic convenience of the L1 site, “gateway” access to L2, and the fact that it is thermally much more stable than LEO, makes it an important venue, at least for integration, test, and servicing of science instruments. Consideration of gateway deployment and servicing for the Terrestrial Planetary Finder (TPF) has already been given.**

*****[From “Application of In-space Capabilities to a Large Infrared Telescope for Astronomy—SAFIR”]***

# Operational Concept Development

# *Proposed* L1 Telescope Mission Trade Space Examined



**Mission Phase** | **Trade Options**

**Launch**

Telescope Launch

**Transfer From Earth**

Transfer Location

Direct to S-E L2

Lunar L1

**Deployment**

Autonomous Deployment

Deployment

Autonomous/ Remote

EVR Assisted

EVA Assisted

**Test, Checkout, Calibration**

Remote Test Checkout, Calibration

Test Checkout, Cal.

Autonomous/ Remote

EVR Assisted

EVA Assisted

**Transfer to S-E L2**

Transfer to S-E L2

**Nominal Ops**

**Service or End of Life**

End of Life

Servicing ?

Remote Service @ S-E L2

**Transfer to E-M L1**

Transfer to E-M L1

**Service**

Service

Autonomous/ Remote

EVR Assisted

EVA Assisted

**Transfer to S-E L2**

Transfer to S-E L2

# Bracketing the Trade Space

**To bracket the trade space and the multitude of options for telescope deployment/ repair/ upgrade the following four missions are proposed for study:**

- ✓ Concept 1: Baseline Reference Mission; (Conceptual Study completed by JPL) [blue]
  - SAFIR sent to Sun-Earth L2; Autonomous Deployment; Nominal Mission;
  - Disposed of at end of nominal mission/critical failure

- Concept 2: CEV-based Human EVA Servicing at E-M L1 (Product, Priority 1 ) [green]
  - SAFIR sent to Sun-Earth L2; Nominal Mission;
  - sent back to E-M L1;
  - human (EVA) with some robotic support servicing,
  - sent back to S-E L2 for extended mission

- Concept 2a: CEV-based Robotic Servicing (w/human IVA) at E-M L1 (Product, Priority 2 ) [maroon]
  - SAFIR sent to Sun-Earth L2; Nominal Mission;
  - sent back to E-M L1;
  - pure robotic servicing (could have human IVA in nearby asset)
  - sent back to S-E L2 for extended mission

- Concept 3: L1 Gateway-based Servicing at E-M L1 (Product, Priority 3 ) (update of past work)
  - SAFIR sent to Sun-Earth L2; Nominal Mission;
  - sent back to E-M L1;
  - Human (EVA) or Robotic Servicing of telescope based out of L1 Gateway Outpost,
  - sent back to S-E L2 for extended mission

# Summary of JPL Work – SAFIR Autonomous Mission

- **To characterize a fully autonomous telescope mission, using SAFIR, a JPL Team X study was commissioned independent of the SHRD team. This work bracketed the mission design, system and subsystem layout and specification and began to characterize mass, cost and risk.**

- **A modified version of the James Webb Space Telescope currently in development was used to represent a SAFIR telescope.**

- **In this case, SAFIR is packaged with a Delta 4 Heavy and launched directly into an operational halo orbit at Sun-Earth L2**

- **The work of Team X found:**
  - **The extreme thermal operational requirements (near 4K) and spacecraft size drove thermal shield size/mass**
  - **The primary cost drivers relate to the thermal control requirements and the size and complexity of the telescope and associated instruments.**

- **Cost and risk number were developed during this quick 3-day study. These could potentially serve as a baseline for comparing mission options (such as servicing, assembly, etc.) with a variety of agents (robotic, human EVA, etc.)**

# CEV Servicing Mission to Telescope

# Application of CEV and “Gateway” Concept with Human-Robotic Supported Assembly Capability at Earth-Moon L1

- Spiral 1 CEV will consist of LEO demonstrations. Spiral 2 and later concepts for the CEV and other architecture elements are capable of lunar missions with short surface duration stays with longer mission for each spiral. In later spirals, uncrewed cargo vehicles would also have access to the lunar vicinity, surface, and libration point orbits.

- As shown earlier, the notional preliminary concepts for a Spiral 2 CEV are optimized for transportation functions only:
  - No airlock, no extensive accommodations for astronaut EVA other than emergency response
  - No positioning crane/robotic manipulator
  - Minimal internal cargo
  - No external accommodation volume.
  - Minimal return capability of internal cargo to Earth; No external cargo return to Earth

- Conceptually, the CEV could be augmented by provision of an additional workstation module which could carry, for example, a teleoperated servicing robot, a suite of tools, some spare parts, replacement modules for servicing, etc. [and serve as the structural attachment for telescope docking].

- Allocation of this additional functionality/mass to CEV could be constrained by CEV crew escape system capability, CEV launch vehicle mass and by Earth Departure Transfer Stage capability.

- Alternatively, if available for use, an Earth Moon L1 Gateway “Outpost” could also provide the functions needed to augment the CEV for telescope servicing.

# Implications for In-Space Operations given recent Lunar Architecture Work

- **It is widely known that lunar architectures in consideration not all use the E-M L1 point to stage missions to the moon's surface.**

- **Alternatives to staging and rendezvous through L1 include, lunar orbit rendezvous (various iterations), lunar surface rendezvous and Earth orbit rendezvous. Each is advantageous given a set of operational objectives and constraints.**

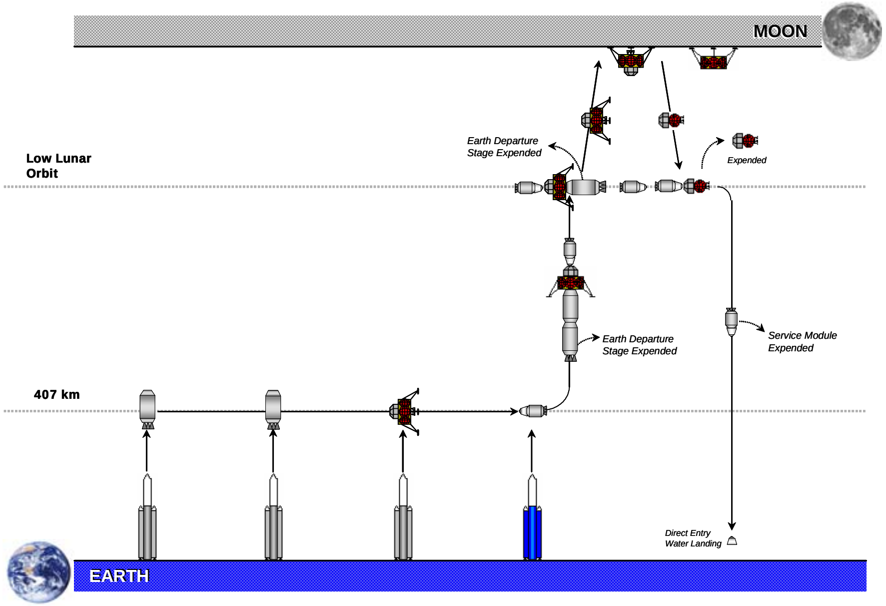
- **Additionally, not all missions staging through the E-M L1 point utilize a "Outpost" habitat/structure. Given the ESMD requirements recently released, there seems to be no real requirement for a structure/habitat at the L1 point. Although that the need for a propellant depot or other maintenance/warehouse structure may be discovered as architecture studies mature.**

- **Therefore the question is raised:**
  - **Given a lunar architecture that is not initially planned to stage through EM L1, with its elements (CEV, Earth Departure Stage, Landers, etc.) optimized for lunar orbit and surface operations, could an L1 mission be carried out?**
  - **If so, what really could be done on such a mission?**

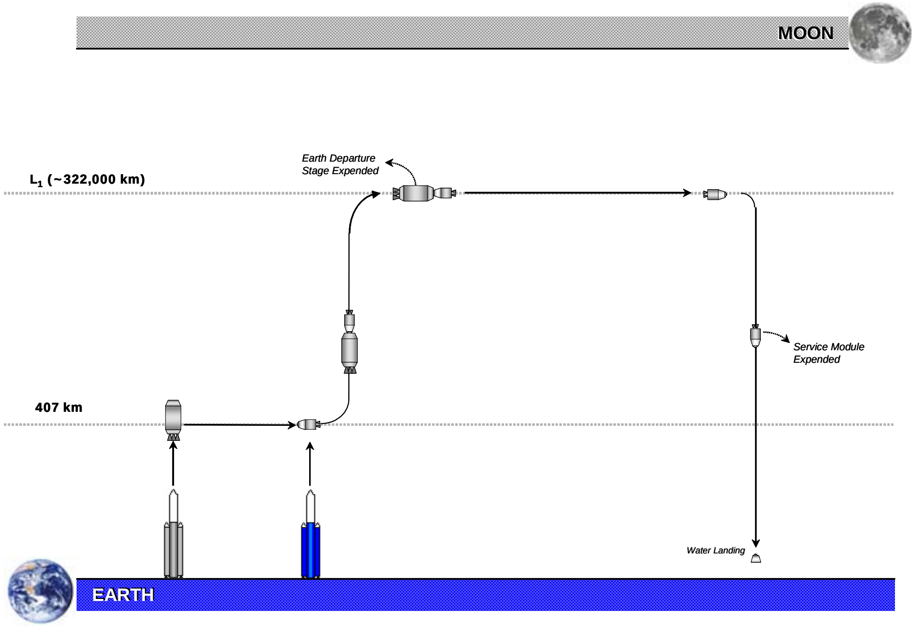
# Implications for In-Space Operations given recent Lunar Architecture Work (continued)

- Recent work did consider several lunar architecture variations, optimized for lunar orbit or surface missions. The purpose was to assess the feasibility of using elements sized for a lunar mission for the infrequent L1 servicing mission.
- An example of one of these possible architecture variations is shown below:

**Notional Lunar Orbit Staged Mission**



**L1 Variation**



- As shown is this example, a mission variation to EM L1 is possible using elements like CEV.
- General observations included:
  - Given a notional CEV mission duration of about 16 days; less than 3 days were available for actual operations at L1; assuming a few days of transit time and LEO loiter.
  - Additional days may be possible, but were limited in consumables and volume requirements for the extended mission duration.
  - Limited mission ops based on CEV description in earlier charts

# Scenario for SAFIR Servicing at an Earth-Moon L1**

- **A highly simplified strawman scenario for SAFIR servicing at the Earth-Moon L1 gateway has been developed. Our study will use a picture like this as a starting point for more detailed in-space servicing plan for the observatory.**

### SAFIR is retrieved from L2

- **SAFIR cryocoolers are shut down, the instruments set to a safe configuration (apertures closed, etc) and the observatory is allowed to warm.**
- **The observatory is removed from L2, and sent on a trajectory to L1, using on-board thrusters and fuel. Another option is for retrieval by a separate L2 tug that docks with the observatory. This would be needed if the on-board propulsion system were inoperable.**
- **After months of transit with precise navigation and slight trajectory corrections, SAFIR arrives in the vicinity of EM L1. Upon L1 insertion, SAFIR is put into a slow rotisserie mode to finish bakeout of contaminant accumulated during the operations lifetime.**

### Pre-service inspection

- **While SAFIR is still at a stand-off position relative to the servicing facility at L1, fly-around robotic agents based from the facility provide a clear overall survey of the observatory to assess its structural condition and abnormalities. Rotisserie mode provides illumination for all parts of the observatory.**
- **Inspection is used to finalize the servicing plan and determine if any updates to the servicing mission objectives are necessary. A servicing logistics module carrying all the servicing components and agents will have been launched to couple with the CEV or servicing facility before SAFIR arrives.**

### CEV or agent connection

- **The CEV, or a mobile or extensible operating agent of the servicing facility, is deployed to rendezvous with and capture SAFIR, bringing the spacecraft bus interface to dock with the CEV or servicing facility where direct power and control connections are established and all the servicing tools and replacement parts are accessible.**
- **Functionality and safety checks are established.**

*****[From "Application of In-space Capabilities to a Large Infrared Telescope for Astronomy—SAFIR"]***

# Scenario for SAFIR Servicing at an Earth-Moon L1** (continued)

## Subsystem replacement

- An extensible agent, perhaps a reconfigurable crane, uses tools to sequentially remove and replace individual subsystems as required. Sunshield patching or wholesale replacement is the last item.

## Retanking

- The station-keeping propulsion system is serviced either with replacement modular components or retanked.

## Intervention-enabled redeployment

- While SAFIR is attached to the CEV or servicing facility, major deployments (e.g. new sunshield) are commanded. Active mobile agents are available for mechanical intervention if something jams or sticks.

## Early system checkout

- SAFIR is released from the servicing facility to the stand-off position to allow system functional test. The observatory is put into sun-oriented attitude, allowing the inner shield and telescope to cool.
- All SAFIR systems are powered up and functionally tested.
- Basic pointing and stabilization tests are conducted on the telescope while it is still warm. Cooldown profiles are compared to expectations and the experience base. When the basic tests are completed satisfactorily, the CEV or mobile extensible agents are withdrawn agent from SAFIR.

## Detailed system checkout

- SAFIR is allowed to cool while in the vicinity of L1, reaching temperatures below 50K.
- The built-in active cryocoolers put the cooled sensors into their operating range.
- The scientific instruments are exercised, and performance is matched to expectations for performance at the temperature achieved.

## Return to L2

- Upon full and satisfactory completion of all performance tests, the SAFIR observatory departs from L1 and travels to, and is injected back into L2. SAFIR Science operations restart.

***[From "Application of In-space Capabilities to a Large Infrared Telescope for Astronomy—SAFIR"]***

# SAFIR Servicing Concept Development[†]

- **During January 2005, part of the SHRD team, led by Chuck Lillie, considered a strategy to retrofit the current SAFIR telescope concept that would enable servicing. Recall the baseline JPL mission was fully autonomous and did not include servicing or other human/robotic involvement.**

- **The purpose of this was to generate a model so that more detailed servicing analysis using a CEV and other agents could be performed.**

- **The team found the following:**
  - **On-orbit servicing for SAFIR is technically feasible**
  - **Required design modifications to SAFIR are well within the state-of-the-art**
    - **No show-stoppers identified**
  - **Benefits of servicing to SAFIR science clearly demonstrated by HST's experience**
    - **Orders of magnitude greater sensitivity and productivity**

- **SAFIR Servicing Considerations and Concerns**
  - **Contamination from:**
    - **Servicing vehicle propulsion system**
    - **EVA suit effluents**
    - **Fluid transfer**
  - **EVA compatibility**
    - **Provision of handholds and foot restraints**
    - **Cold surface touch constraints**
  - **Thermal control**
    - **Thermal interfaces**
    - **Thermal cycling**
  - **Added costs for servicing**
    - **Cost benefit trade with political overtones**

[†] **Courtesy of Chuck Lillie, NGST**

# SAFIR Servicing Concept - Approach†

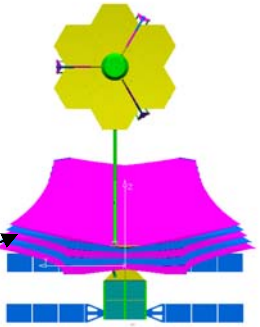
- Robotic Servicing with Telerobotic Presence
  - Follows the HST Robotic Servicing Approach
    - Spacecraft bus plus servicing module with RMS and dexterous manipulator
    - ORU's for avionics plus new instruments
  - Also compatible with Astronaut servicing
- Launch with ELV and rendezvous with SAFIR at L2 or Earth-Moon L1 "Gateway"
  - Trade off 10 sec command latency vs. 3-mo. transit time from L2 halo orbit to EM L1 point
- Dock with SAFIR at launch vehicle interface
  - Use servicing arm to grapple SAFIR RMS fixture and position servicing vehicle for latch engagement.
- Avionics in spacecraft bus and telescope located in Orbital Replaceable Units (ORUs)
  - Modularized at unit or subsystem level
    - Trade off modularization costs vs. ORU production costs
  - Mounted internally or externally
    - Trade ease of access vs. thermal control system complexity, etc.
- Trade space includes:
  - Hinged panels with boxes on inner side,
  - Externally mounted boxes,
  - Pie-shaped subsystem modules inserted radially into hexagonal bus structure, and
  - Customized modules w/replacement hardware attached externally and connected via power and data buses
- ORU's packaged for easy replacement
  - Positioning guides
  - Kinematic mounts
  - Blind Mating connectors
  - Single rotary device to lock into position
- Science instruments located in axial instrument compartment in replaceable modules ala HST
  - Shared focal plane
  - Cold plate or other thermal interface for detector cooling
- Solar arrays and Secondary Mirror Assembly could be packaged for on-orbit replacement
  - Sunshield not easily replaced

†Courtesy of Chuck Lillie, NGST

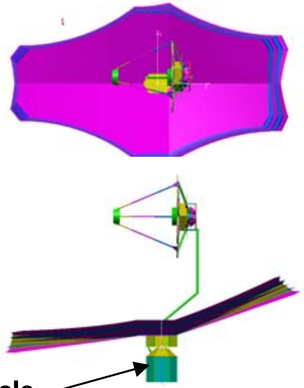
# SAFIR Servicing Concepts[†]

## SAFIR with Servicing Vehicle

- Servicing Vehicle docked with SAFIR at launch vehicle interface
  - Initial contact occurs when servicing arm grapples RMS adaptor on the SAFIR spacecraft bus
  - Servicing arm used to move Servicing Vehicle into docking position
- Servicing vehicle consists of spacecraft bus and service module



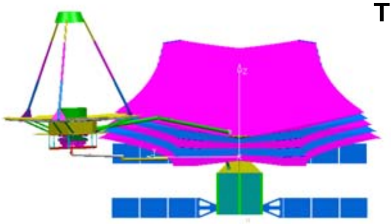
SAFIR in Nominal Operational Attitude



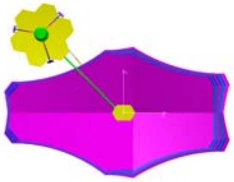
Servicing Vehicle

## Payload Compartment Servicing

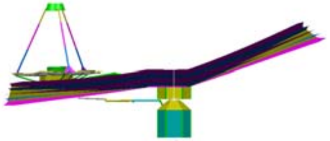
- Telescope Boom positions payload at edge of sunshield within reach of servicing arm
  - Payload (gradually) pre-heated to avoid thermal shock
- Instruments removed/installed axially with servicing arm
- Instrument compartment side panels hinged up for access to telescope electronics



Payload Positioned for Instrument Replacement



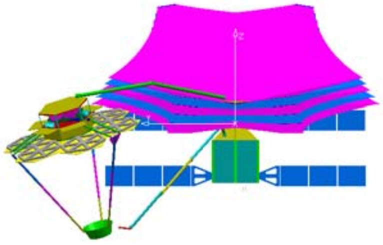
Telescope Boom at Maximum Extent

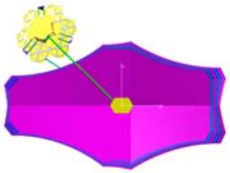


Servicing Arm Removing an Instrument

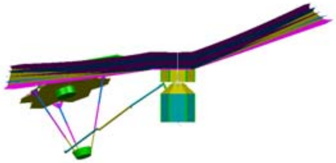
## Secondary Mirror Accessibility

- If necessary, payload could be rotated to position secondary mirror assembly with reach of servicing arm
  - SMA not likely to need replacement, but could be packaged as an ORU if desired.
- Graphics illustrates flexibility of design approach
- Quick look suggests primary mirror segments might be replaceable if desired.





Telescope Boom at Maximum Extent



[†]Courtesy of Chuck Lillie, NGST

# Application of CEV with Augmentation Module at L1**

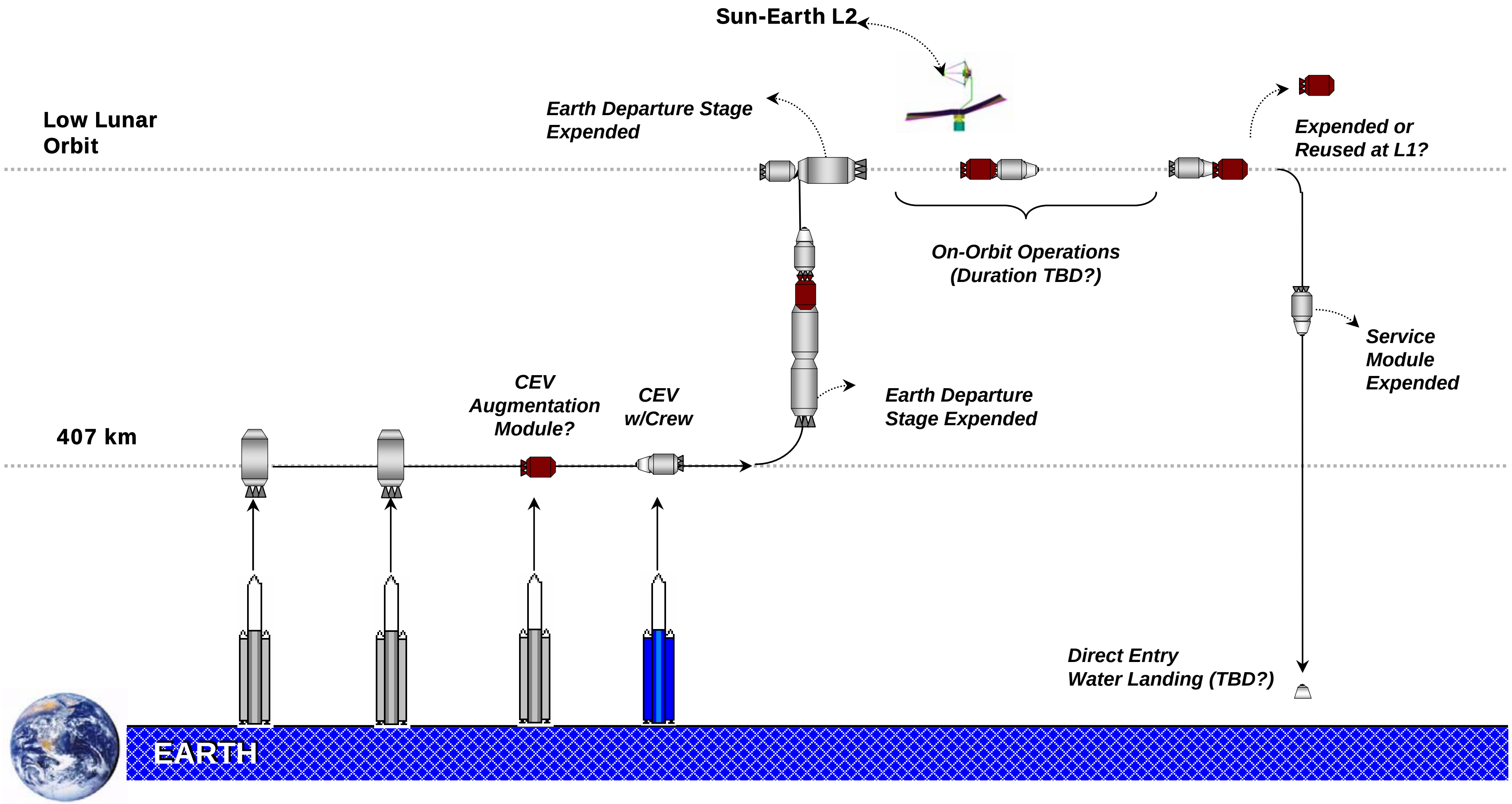
CEV (w/augmentation module) Mission Sequence

- SAFIR would have to be launched (for assembly assistance) or moved (for robotic servicing) to the rendezvous point in advance of CEV.
- The CEV augmentation workstation module would have to be outfitted with whatever SAFIR operation-specific equipment is needed; this would be completed by an earlier launch of a SAFIR-specific kit to rendezvous with and be captured by the workstation module.
- The CEV would then rendezvous with the workstation [module]; the crew would operate the workstation equipment to load the workstation with the specific outfitting kit.
- Subsequently, the CEV and workstation [module] with the kit installed would rendezvous with SAFIR and the crew would perform the needed assembly assistance or servicing operation using the workstation equipment and the SAFIR-specific outfitting contents.
- SAFIR would have to accommodate a transfer stage for delivery to (and for servicing, a round trip to and from) its operational site in a Sun-Earth L2 libration orbit. For transfers from a L1 servicing site, this transfer stage may be quite modest in capability, and may be the same propulsion system that is used for station-keeping there.
- When servicing complete; CEV returns home, possibly leaves consumable/service module at L1 or module sent into disposal orbit via low transfer features of Lagrange points.
- SAFIR transferred back to SE L2.

***[From "Application of In-space Capabilities to a Large Infrared Telescope for Astronomy—SAFIR"]***

# Application of CEV with Consumable/Service Module at L1

- **Notional Mission Ops Flow of a SAFIR Servicing Mission. This sketch assumes:**
  - **Separate Launch of a Crew Augmentation Module or Consumable/Service Module**
  - **No Gateway Available (live out of CEV w/attached module)**



**Sun-Earth L2**

**Low Lunar Orbit**

*Earth Departure Stage Expended*

*Expended or Reused at L1?*

*On-Orbit Operations (Duration TBD?)*

*Service Module Expended*

*CEV Augmentation Module?*

*CEV w/Crew*

*Earth Departure Stage Expended*

**407 km**

*Direct Entry Water Landing (TBD?)*

EARTH

# Application of CEV and “Gateway” Concept at L1**

## Use of a Earth-Moon L1 Gateway “Outpost” Facility

- **If the gateway facility has established the core capability for assembly and servicing in the timeframe of SAFIR initial deployment (now intended to be 2015-2020), it may be prudent for the SAFIR program to make use of this facility rather than rely on autonomous deployment.**

- **The advanced EVA capabilities for direct and intense interactions are not likely to be established in the timeframe. However, even the use of the more limited robotic-only early capabilities for deployment assistance and module exchange servicing may be productive enough to make a difference in overall mission success and risk mitigation approaches.**

- **To the extent that the gateway facility will play a major role in an ambitious lunar program, special planning will have to be done to accommodate “shipyard” issues, such as flotilla formation maintenance, hazard avoidance, contamination mitigation, etc. While such a busy gateway facility would offer SAFIR a lot of flexibility in in-space tasks, the price for that convenience is the resulting congestion.**

- **Of some interest for a gateway facility and astronomical telescopes is the potential for in situ checkout before they are sent to L2. L1 is, itself, a potentially cold facility, in that the solid angles subtended by the Earth and Moon are still quite small, and passive cooling there will not be highly inferior to that available at L2. It seems clear that all warm spacecraft systems (communications, stabilization, etc.) can be fully checked for SAFIR at L1, and ideally much of the science payload can be functionally tested as well.**

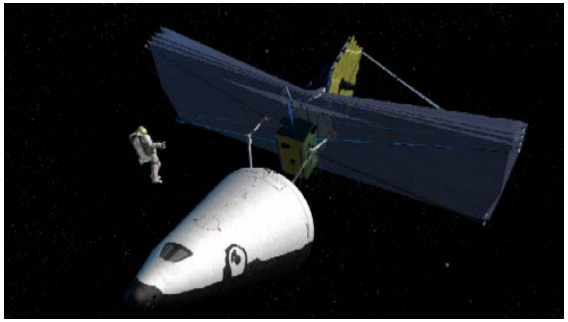
- **Using on-board cryocoolers to put the infrared sensors into their operating range, a warmer-than-spec telescope will allow pointing, tracking, imaging, and spectroscopic functions to be verified, though with higher background noise, and scattered light. The optical alignment of the telescope could, in principle, be verified, and diffraction-limited performance assured.**

***[From “Application of In-space Capabilities to a Large Infrared Telescope for Astronomy—SAFIR”]***

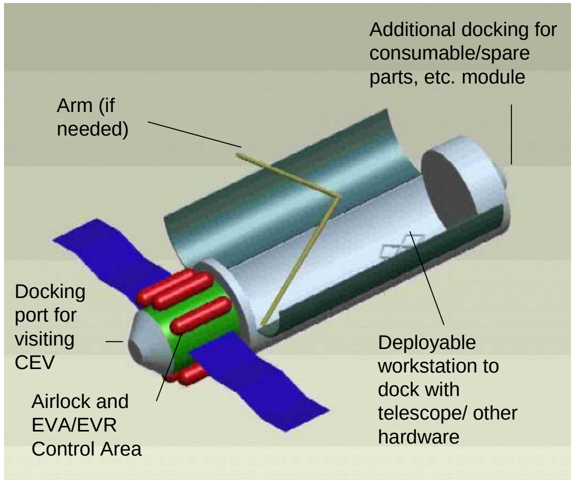
# Implementation: Artist Concepts

- **Possible Implementations of SAFIR intervention (servicing, repair, etc).**

Augmented CEV concept



Range of implementation methods (not inclusive)



EX Concept of Consumable and Servicing Module – (Baseline CEV would dock to this module)

Artist image of L1 Gateway Infrastructure

# Summary of work to date

- **Identified general benefits associated with in-space operations/capabilities with respect to telescopes and telescope science.**

- **First-Order “model” has been developed for a SAFIR telescope servicing mission:**
  - **Defined SAFIR telescope servicing concept and potential impacts to the telescope design**
  - **Defined what elements (CEV, docking structure, etc.) are needed to carry out the servicing, given that human/robotic operations in space (in particular servicing) are desired**
  - **Defined a baseline mission sequence to assess operations strategies**
  - **Discussed current notional concepts of CEV and lunar architectures to understand implications of adding a telescope servicing mission to an existing lunar architecture**

- **Through first pass analysis and consideration, the team is able to map enabling capabilities and how exactly they benefit a particular mission (like servicing, etc.) with more resolution.**

- **Major Servicing Issues**
  - **Sun Shield is a major impediment to performing service (out of line of sight comm., extremely cold?) (may be easier to use robotics only on cold side)**
  - **Interchangeability of major components can enable human EVA or robotic servicing ops**
  - **Others?**

# Future Work

# Summary *Strawman* Enabling Capabilities

| *Specific Capability* | *What is Enabled?* | *Mission Type Enabled* | *General Benefit to Science* |
|---|---|---|---|
| **Component Modularity** | • On-orbit replacement of instruments, actuators, etc.<br>• Assembly of Large Structures | Servicing, Assembly | • Larger Apertures<br>• Higher Perf. Structure<br>• Longer service life |
| **Fluid Transfer** | • Replenishment of s/c fuel and cooling | Servicing | • Longer service life |
| **Automated Rendezvous and Docking** | • Less intensive operations at worksite | Servicing, Assembly | |
| **Low Thrust/High Efficiency Propulsion** | • Alt. Method of Transfer between SEL2 to EML1 | | |
| **Autonomous Robotic Operations** | • On-orbit replacement of instruments, actuators, etc.<br>• Assembly of Large Structures<br>• Mitigates communication latency | | |
| **Advanced EVA Operations** | • On-orbit replacement of instruments, actuators, etc.<br>• Assembly of Large Structures<br>• Less structural req. on telescope (handholds, etc.) | | • Longer service life<br>• Larger Apertures<br>• Enhanced Science Productivity (upgrades) |
| **Low Contamination EVA Suit** | • EVA personnel could get in close proximity to sensitive optics/sensors | | |
| **Payload Delivery to Servicing Site** | • EVA tools/spare parts at worksite<br>• Robotics to worksite | | |
| **Airlock at Servicing Site** | • Multiple Human EVA possibilities | | |
| **Hard Dock (for telescope) at Servicing Site** | • Less structural attach points on telescope<br>• Perhaps less complicated operations | | |
| **Long Duration (2 weeks?) Habitat** | • More time for assembly and servicing activities; could get more accomplished | | |
| | | | |

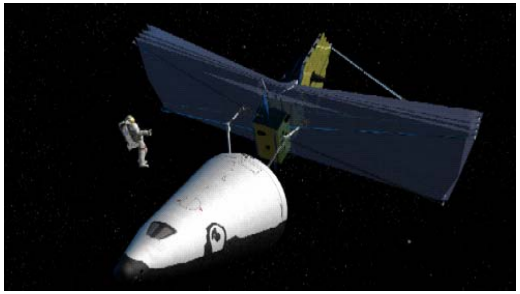
# Summary *Strawman* In-Space Operation vs. Benefit

| In Space Operation | Specific Tasks | What Benefit / Science Enabled? | Resources/Investment Required? |
|---|---|---|---|
| **Assembly/Deploy /Outfit** | • **Add thermal shielding to enhance performance** | | |
| | • **Assemble large pre-fab parts from smaller, cheaper launchers** | | |
| | • **Add/remove actuators, sensors** | | |
| **Calibrate/Verify /Inspect/Test** | • **On-orbit structural dynamics tests** | | |
| | • **On-orbit contamination inspection** | | |
| | • **On-orbit optical alignment, adjustments to get within actuator range** | | |
| | • **Check out subsystems, especially on warm s/c** | | |
| **Inspect** | • **On-orbit temperature surveillance (fly-around monitoring)** | | |
| | • **Inspect telescope for safe deployment/no damage** | | |
| **Monitor/Intervene** | • **Allow basic intervention in autonomous deployment** | | |
| **Service/Upgrade** | • **Clean (recoat?) optics** | | |
| | • **Refuel thrusters (orbital insertion, stationkeeping, momentum dumping)** | | |
| | • **Replace with new capability astronomical sensors** | | |
| | • **Configure with different operational setpoints** | | |
| | • **Changeout instrument expendables (e.g. cryogen)** | | |
| **Diagnose/Repair** | • **Patch/replace solar shield** | | |
| | • **Replace aging/broken subsystems** | | |
| **Decommission** | • **Safe spacecraft; boost into final parking orbit** | | |
| | • **Recover key instrumentation for engineering evaluation (long duration, deep space exposure; for Mars?)** | | |

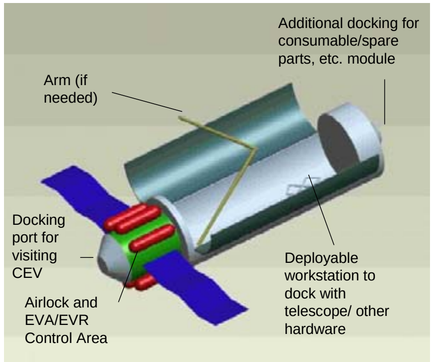
# CEV Augmentation to Perform In-Space Operations

- **Another trade to be performed is to explore adding capability to the CEV to carry out a notional servicing mission**
- **As mentioned earlier, this can be envisioned in three general categories which attempt to bracket the trade space (but not limit the possibilities):**

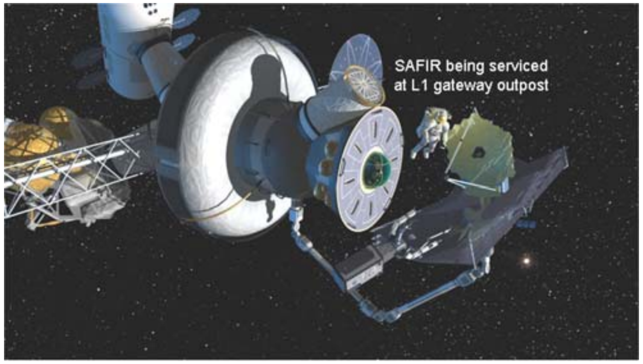
Augmented CEV concept



EX Concept of Consumable and Servicing Module – (Baseline CEV would dock to this module)



EM L1 Gateway Infrastructure



- **Much detailed work has been done to characterize assembly operations at the Earth-Moon L1 Gateway “Outpost”; although the baseline telescope at the time was the FAIR-DART concept (maybe more intricate than SAFIR?)**
- **What has not been explored in any detail is an augmented CEV.  This could take many forms as shown above.**

# Fully Human EVA vs Robotic EVR - *DRAFT*

- **Human EVA or Robotic EVR (Common Needs)**
  - **Positioning agent (Robotic Arm, Crane, etc.)**
  - **Tools or End Effectors**
  - **Transport of Human or Robots from LEO to EM L1 (or SE L2)**
  - **Transport of Spare Parts, Propellant, etc from LEO to EM L1 (or SE L2)**
  - **High Bandwidth Communication**
  - **Require a docking station on the telescope (either to spacecraft structure or free flying workstation)**
  - **Operations support on Earth (monitoring and control)**

- **Human EVA (Servicing)**
  - **Uniquely Requires:**
    - **Airlock (multiple uses)**
    - **Foot Restraints, Handholds, etc.**
    - **Habitat with consumables for longer stay at L1**
  - **Considerations**
    - **Function of cost; available infrastructure?**
    - **Mission risk; is reducing programmatic risk of telescope worth increased risk of human EVA mission**
    - **Frequency; can servicing missions be cost effective (vs. sending up new telescopes)**

- **Robotic EVR (Servicing)**
  - **Uniquely Requires:**
    - **Autonomous Operations to get past latency (~4 seconds at L1, ~10? seconds at L2)**
    - **High Dexterity (depends on interface design)**
  - **Considerations**
    - **Function of cost; available infrastructure? (almost same as that of human EVA, except airlock, special tools/handholds, etc.)**
    - **Mission cost; is reducing programmatic risk or enhancing capability of telescope worth increased cost of robotic mission**
    - **Frequency; can servicing missions be cost effective (vs. sending up new telescopes)**

# Future Work: Critical Trades

- Within each in-space capability, there is a continuum of approaches one may take. One possible further analysis is to explore this continuum.
- "Level of implementation" versus benefit/requirements. An example is shown below:

| Incrementally challenging approaches | What this accomplishes | What this requires |
|---|---|---|
| Simple ORU replacement or add-on in-situ | Designed-in servicing & upgrade | Robotic access to L2<br>Functional robot<br>Modular design for servicing |
| Complex repair or upgrade | Assembly assistance or intervention<br>Extended capability or upgrade | Advanced robotics or modest human-robotic capability |
| Hubble paradigm intervention | Rescue, complex intervention for repair, retrofit expansion, or upgrade | Full-up Gateway at L1<br>Logistics support for human-robotic operations |

# Future Work: Critical Trades

- Eventually the team will have to characterize the issues posed below for a much more detailed analysis:
  - Contamination by CEV/robot outgassing near cold telescope?
  - Contamination by stationkeeping thrusters during rendezvous
  - Docking architecture/ports, data/power connections; impacts on SAFIR
  - Risks from thermal cycling of the observatory?
  - Sun-synchronous or rotisserie mode servicing?
  - Earth downlink for SAFIR? Implications on available communications architecture
  - Separate L2-L1 tugs?
  - Human qualification of observatory systems?
  - Modularity/compatibility of facility subsystems?
  - Stationkeeping at L1 with large solar sail? Illumination behind shield?

- Verify Assumptions Concerning future in space infrastructure
  - Robotic capabilities will increase with time power/grip/fault tolerance
  - Robotic intelligence will increase with time nav/situation awareness/etc.
  - Telepresence awareness will increase with time
  - Downlink bandwidth will increase with time
  - Latency will stay pretty much the same; Humans are favored for high bandwidth decision-making

- Big Questions
  - Human Operations at Sun Earth L2?; Any commonality to a Mars Mission?
  - How do you build a space telescope so it benefits from "presence“? [Partially answered]
  - What kinds of things are really "fixable" and what aren't? [Partially answered]
  - What economies can you have on a telescope that offers intervention?
  - Is there anything that prevents full-up cryotesting at L1?
  - Required stay duration for astronauts servicing SAFIR at gateway?
  - What "high bandwidth decisions" go with SAFIR deployment or service?

# Future Tasks: What is Needed?

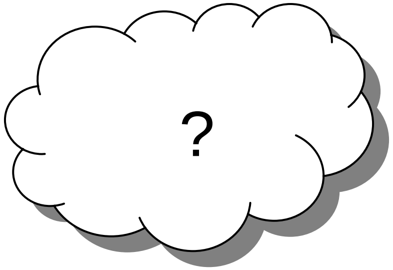
- **At first glance, it seems that a study designed to assess the feasibility of a "Servicing and Consumable Module" is needed.**

**Possible Use Cases (and subsequent requirements):**

- L1 Telescope Service, Assembly and Repair
- LEO customers? Potential satellite servicing, LEO telescopes, TBD NASA (and other government entities)
- L1 Lunar/Mars Servicing, Assembly and Repair

**Potential Lunar Architecture (CEV) Capability Gaps:**

- Current concept capable of only <3 day stay at L1
- No nominal EVA capability
- No external payload
- Small internal payload
- No hard docking capability (to satellite/telescope



**Enabling Technology Development:**

- Human EVA Improvements
- Advanced Robotic Technology
- Automated Rendezvous and Docking
- In-space fluid transfer

**Possible Desire for less In-space Infrastructure:**

- Gateway "Outpost" Design Studied to Satisfy Some Telescope Assembly Requirements
- Alternatives to Gateway which are smaller and have more uses could potentially reduce program cost

# Other Potential Products

- Identify Users and Identify Their Requirements
  - NASA and other Telescope Assembly, Servicing, Repair Needs
  - Potential other customers needs

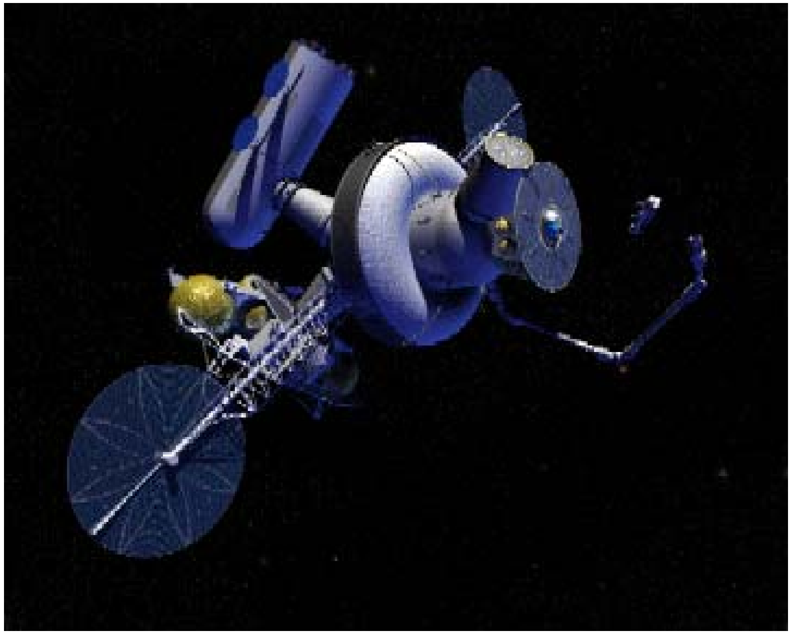
- Understand how current Lunar and Mars Architectures are addressing these needs and identify the gaps

- For the requirements that the current architectures are not satisfying:
  - Collect Requirements
  - Determine how best to allocate those requirements on current architecture elements
  - If needed, propose and define new elements (servicing module, etc.)

# Future Task: Update Lunar $L_1$ Gateway Concept for SAFIR-type Missions

**Mission:** The Lunar $L_1$ Gateway is a mission staging and crew habitation platform stationed at the Lunar $L_1$ libration point for assembling and maintaining large astronomical observatories and conducting expeditions to the lunar surface.

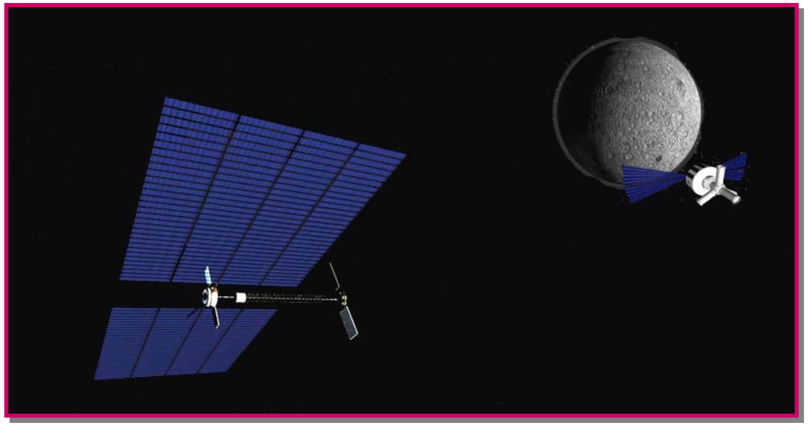
| | |
|---|---|
| **Destination:** | **Lunar $L_1$** |
| **Element Design Lifetime:** | **15 yrs** |
| **Crew Size:** | **4 persons** |
| **Mission Duration:** | **10-30 days** |
| **Element Mass:** | |
| ▪ **Launch:** | **22,800 kg** |
| ▪ **Outfitting:** | **600 kg** |
| ▪ **Post-outfitting:** | **23,400 kg (52,000 lb)** |
| **Element Volume:** | |
| ▪ **Launch:** | **145 $m^3$** |
| ▪ **Inflated:** | **275 $m^3$** |
| **Power & Propulsion System:** | |
| ▪ **Average/Peak:** | **12 kWe/15 kWe** |
| ▪ **Power Generation:** | **Photovoltaic Arrays** |
| ▪ **Energy Storage:** | **Li-ion Batteries** |
| ▪ **Propellant:** | **$O_2/CH_4$** |
| **Support Missions:** | |
| ▪ **Outfitting at LEO:** | **One mission/architecture** |
| ▪ **Human Consumables:** | **Two missions/year** |
| ▪ **Life Support resupply:** | **One mission/two years** |

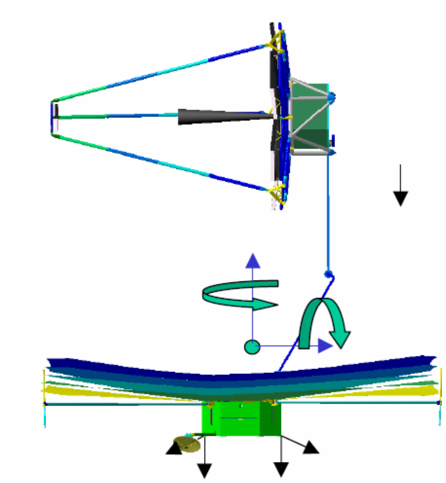


- Update structural attach point
- Visiting Vehicles based on latest study data
- SAFIR-unique requirements
- New technology?
- Updated Traffic Flow Model?

# Transport Options between E-M L1 and S-E L2

- There is a potential requirement to transport the SAFIR telescope from the operational orbit at the Sun-Earth L2 point to assembly/servicing/test point at the Earth-Moon L1.
- Potentially, high-efficient, low-thrust options could be available during the required operational period.
- More study should be performed to:
  - Explore if the thrusters already on board the telescope/spacecraft should be used or if another piece of infrastructure should be used instead.
  - Assess the availability [if deemed needed] of low thrust options given the desired operational period
  - Identify other users of a low thrust technology in a lunar architecture.
  - Assess implications for yet another element which needs maintenance and resupply





# Upcoming SPIE Paper

- **The SHRD team will submit a paper to the upcoming SPIE Optics and Photonics meeting in San Diego, July 31 through August 4, 2005. Manuscript due date is 5 July 2005. A title an abstract have already been submitted to the organizing committee.**

- **This presentation and subsequent trade studies and concept exploration will form basis for the paper.**

- **Title: "Strategies for Servicing the Single Aperture Far IR (SAFIR) Telescope“**

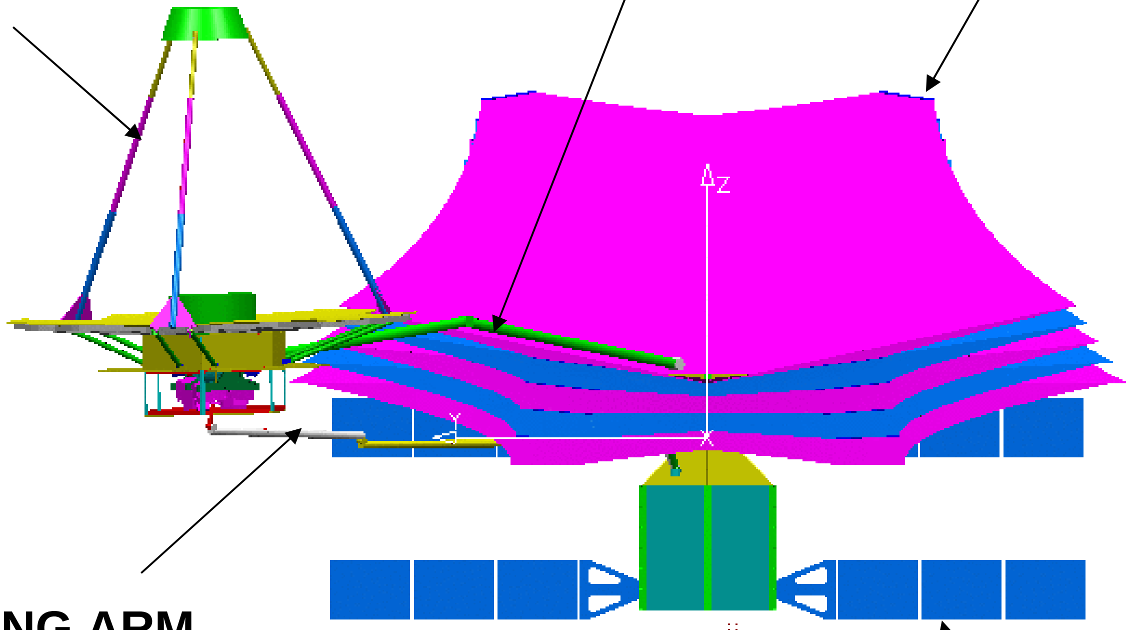
- **Tentative Authors**
  - **Dan Lester (University of Texas)**
  - **Brian Derkowski (NASA JSC)**
  - **Mark Dragovan (NASA JPL)**
  - **Tracey Espero (Boeing)**
  - **Ed Friedman (Boeing)**
  - **Chuck Lillie (Northrop-Grumman)**
  - **Rud Moe (NASA GSFC)**

- **Abstract:**

**The Single Aperture Far Infrared (SAFIR) observatory is a high priority mission for NASA and the space astronomy community. This ten-meter diameter telescope at <10K temperatures will chart the formation of galaxies and elements in the early universe, map debris disks around stars to track hidden planets, and explore the chemistry of life in the universe. While baselined as a autonomously deployable telescope, we consider enabling factors that in-space operations would bring to this telescope, in particular servicing opportunities that would dramatically increase the scientific lifetime and productivity of the observatory. Use of humans and robots, at both the operational site of Earth-Sun L2, and an Earth-Moon L1, are considered, and required capabilities are reviewed. SAFIR shares many characteristics of future large telescopes in space, and strategies developed for this strawman case are applicable for broader planning efforts.**

# Backup

# Payload Compartment Servicing†



TELESCOPE BOOM

SUNSHADE

TELSCOPE

SREVICING ARM

SERVICE MODULE

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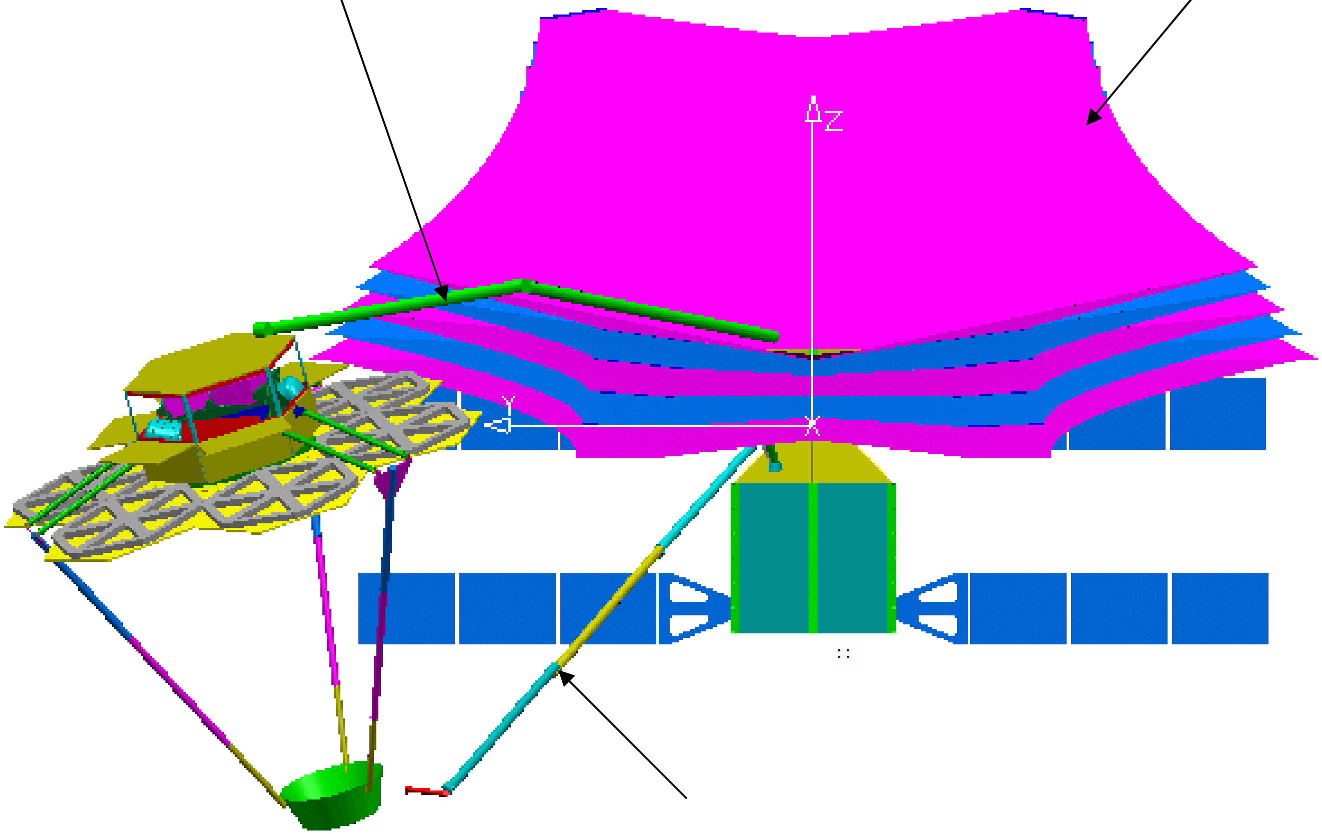
†Courtesy of Chuck Lillie, NGST

# Secondary Mirror Accessibility[†]



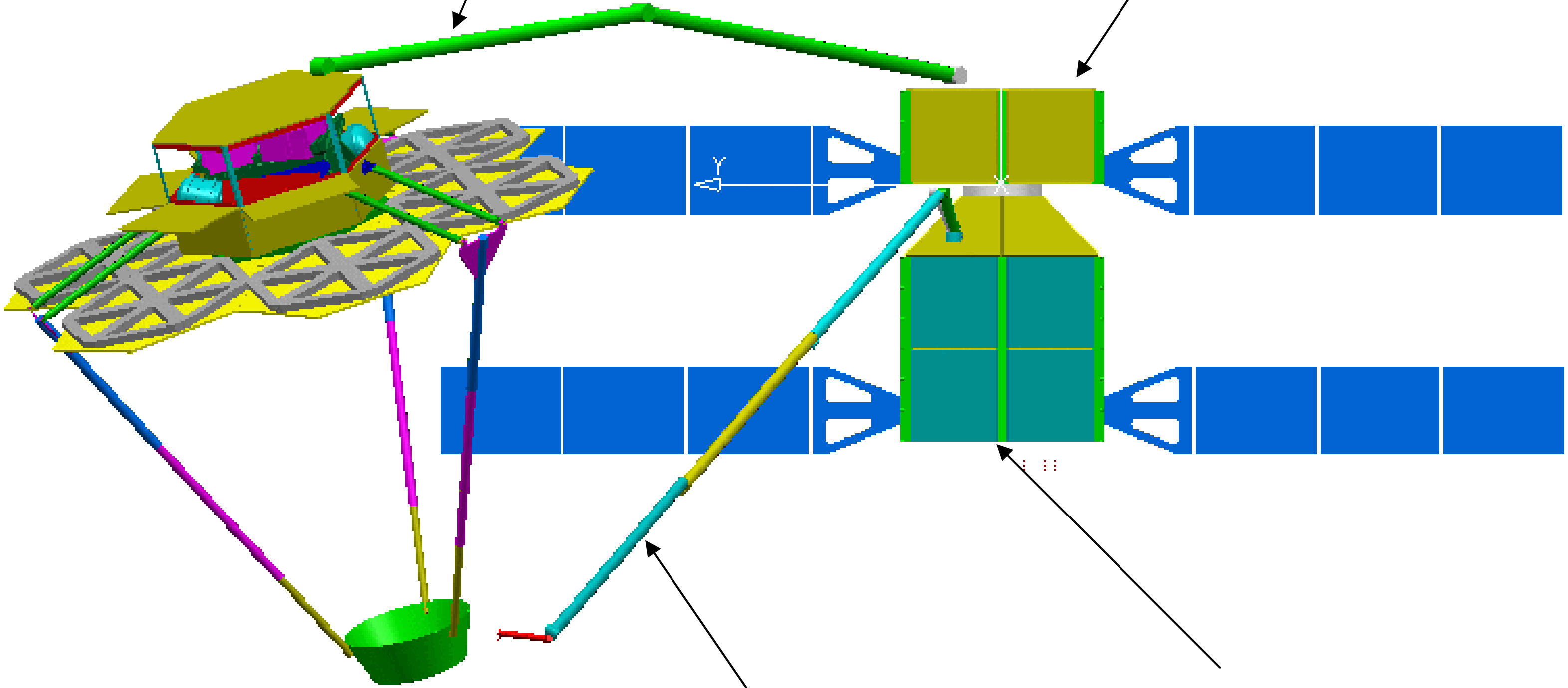
TELESCOPE BOOM

SUNSHADE

SERVICE ARM

[†] Courtesy of Chuck Lillie, NGST

# Telescope Servicing[†]



SPACRAFT BUS

TELSCOPE BOOM

SERVICE MODULE

TELESCOPE

SERVICE ARM

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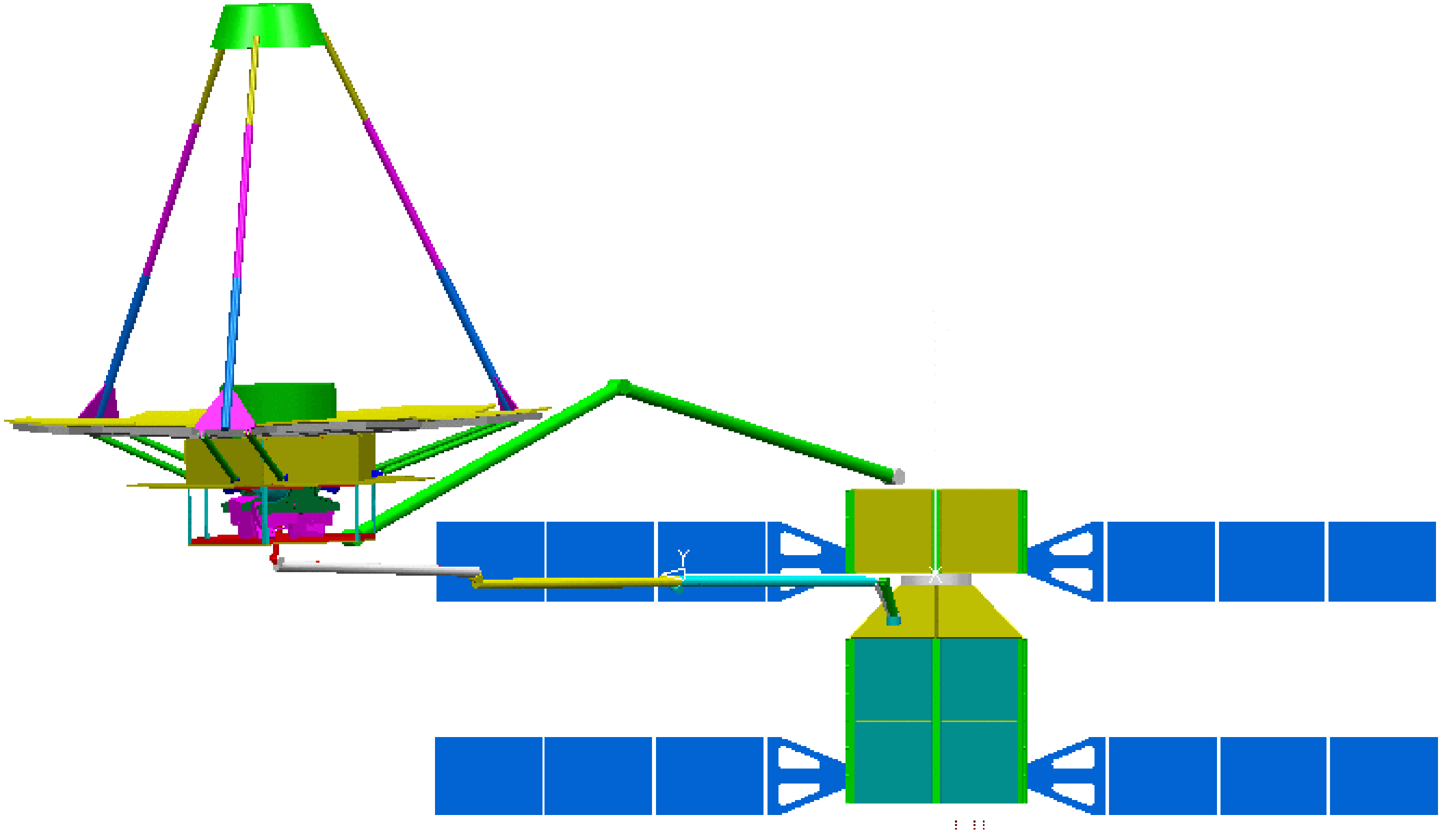
[†] Courtesy of Chuck Lillie, NGST

# Telescope Avionics Servicing[†]



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[†] Courtesy of Chuck Lillie, NGST

# Define Methods of Implementing Tasks

- **Additionally, identified methods of implementing various missions with notional definition to bin the how to accomplish the type of things that will be required from telescope/other customers. It is possible to use a combination of the methods during a particular mission.**

| ***Method*** | ***Definition*** |
|---|---|
| As Built | Features are built into the system and do not require intervention, assembly, etc. |
| Automatic | Mechanisms built into telecope/large structure. Preplanned events are performed per a programmed timeline. |
| Remote Control | Mechanisms built into telescope/large structure. Preplanned events are carried out via a signal from remote spacecraft (CEV, Gateway) or Earth |
| Robotic | External agents (as opposed to built into the telescope/structure) that could be free flyers or positioned by external means that could inspect, grapple, articulate, etc. Could be commanded from nearby spacecraft or from Earth depending on communication requirements |
| Human EVA | Suited Crew members that are positioned by external means or translate under their own effort that could inspect, grapple, articulate, touch, etc. |

# Map Current CEV Capabilities to Needed Telescope Tasks

EXPLORATION ANALYSIS

Range of Key Properties of proposed Lunar Architectures (CEV only)

ty of Lunar Architecture (CEV only)

| CEV Properties | Does current Spiral 2 CEV Concept Incorporate these properties? | Possible Tasks for a SAFIR Telescope Mission | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 1.0 **Assemble/ Deploy Outfit** | 1.1 Assemble Primary Reflector | 1.2 Assemble/ Deploy Sunshield | 1.3 Deploy Communication Antenna | 1.4 Deploy Solar Panels? | 1.5 Assemble/ Deploy Thermal Shielding | 2.0 **Calibrate/ Test** | 2.1 Calibrate optics | 2.<br>C<br>de |
| **Mission Duration at L1** | | | | | | | | | | |
| <3 days | **Yes** | | | | | | | | | |
| 3-10 days | | | | | | | | | | |
| 10-14 days | | | | | | | | | | |
| 10-21 days | | | | | | | | | | |
| 21< days | | | | | | | | | | |
| **Payload (Mass) to L1 (Equipment, Spares, Fixtures, Etc.** | | | | | | | | | | |
| <200 kg internal only | | | | | | | | | | |
| 200-1000 kg | | | | | | | | | | |
| 1000-5000 kg | | | | | | | | | | |
| 5000 kg< | | | | | | | | | | |
| **Types of External Manipulation/Inspection Agents Deployed From CEV** | | | | | | | | | | |
| No EVA or robotic | | | | | | | | | | |
| Robotic free flyer | | | | | | | | | | |
| Robotic manipulator | | | | | | | | | | |
| Robonaut-like | | | | | | | | | | |
| Human EVA w/robotic assistant | | | | | | | | | | |
| Human EVA only | | | | | | | | | | |
| **Structural Docking Port for Telescope for CEV?** | | | | | | | | | | |
| Yes | | | | | | | | | | |
| No | | | | | | | | | | |

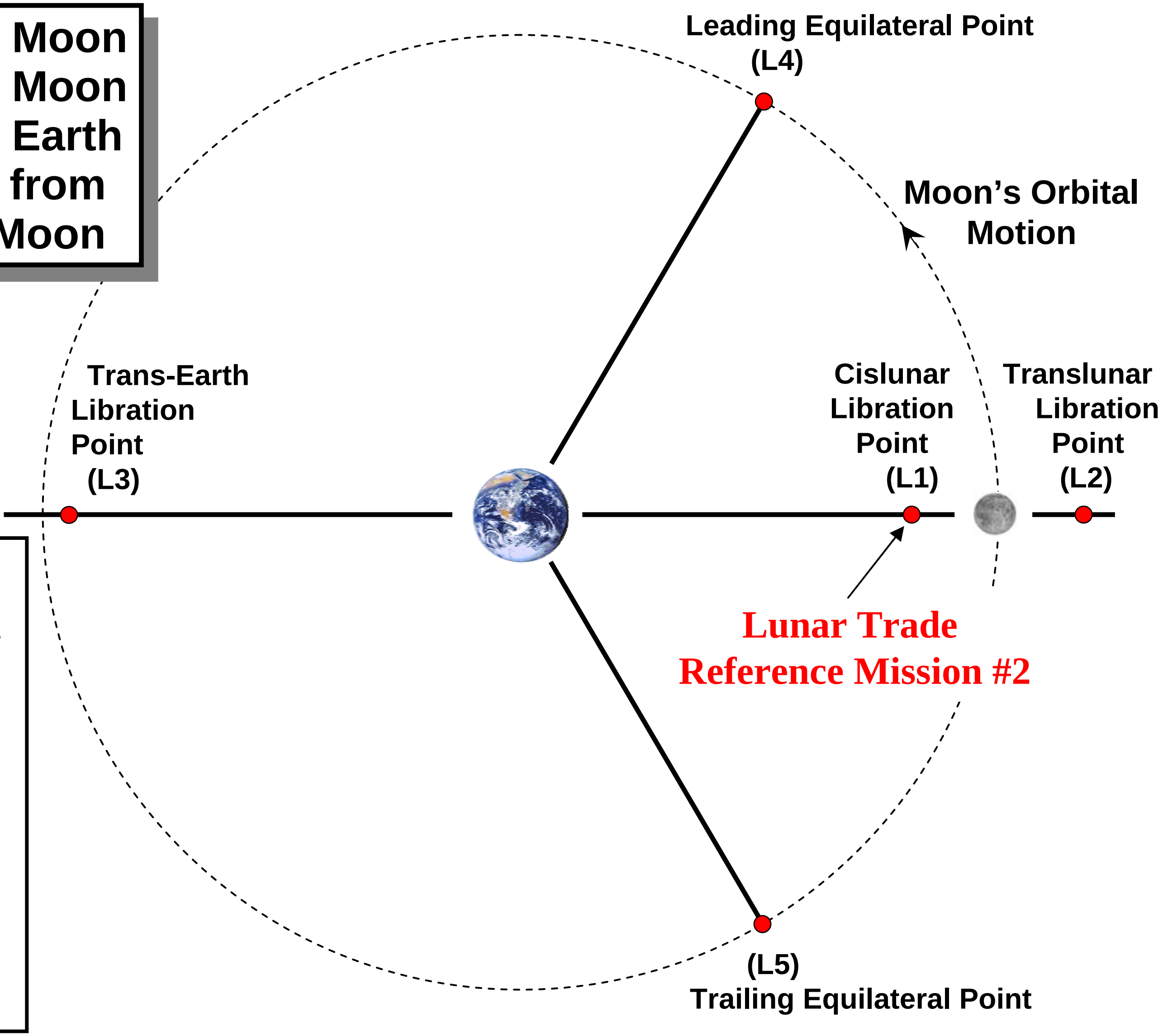
# Identify Methods of Implementation and Understand Possible Benefits or Mission Enhancements

***Mission Categories***

| | | Possible Tasks for a SAFIR Telescope Mission | Possible Implementation Methods (see Definitions) | Benefit (Why would you want to perform this task in space?) | Disadvantages (Why not?) |
|---|---|---|---|---|---|
| 1.0 | | Assemble/Deploy/Outfit | | | |
| | 1.1 | Assemble Primary Reflector | as-built, robotic, EVA | Assembling primary reflector in space allows for a reflector that could be much larger than the 10 meter diameter currently designed | Possibly complex operation requires robotic and/or EVA support. |
| | 1.2 | Assemble/Deploy Sunshield | | | |
| | 1.3 | Deploy Communication Antenna | | | |
| | 1.4 | Deploy Solar Panels? | | | |
| | 1.5 | Assemble/Deploy Thermal Shielding | | | |
| 2.0 | | Calibrate/Test | | | |
| | 2.1 | Calibrate optics | | | |
| | 2.2 | Calibrate detectors? | | | |
| | 2.3 | Obtain sample data for analysis? | | | |
| 3.0 | | Verify/Test | | | |
| | 3.1 | Verify Structural Dynamics | | | |
| | 3.2 | Verify Thermal Performance | | | |
| | 3.3 | Verify Contamination Control | | | |
| | 3.4 | Verify Optical Alignment | | | |
| 4.0 | | Inspect | | | |
| | 4.1 | Visually inspect telescope post-launch, pre-deployment | | | |
| | 4.2 | Visually inspect telescope/structure post deployment | | | |

# L1: Cislunar Earth-Moon Libration Point

**L1 – 57,731 km from Moon**
**L2 – 64,166 km from Moon**
**L3 – 381,327 km from Earth**
**L4 & L5 – 384,400 km from Earth and Moon**



**Leading Equilateral Point (L4)**

**Moon's Orbital Motion**

**Trans-Earth Libration Point (L3)**

**Cislunar Libration Point (L1)**

**Translunar Libration Point (L2)**

**Lunar Trade Reference Mission #2**

**(L5) Trailing Equilateral Point**

- Equilibrium points in a 2-body system
  - Earth-Moon, Sun-Earth, Sun-Mars, etc.
- Collinear points (L1, L2, L3), "unstable"
- Equilateral points (L4, L5), "stable"
- Station-keeping achievable for very small ΔV (<10 m/s/yr)

Jerry Condon / EG5 / gerald.l.condon@nasa.gov / 281-483-8173