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The Future of Space Astronomy will be Built: Results from the In-Space Astronomical Telescope (iSAT) Assembly Design Study

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Abstract

The current paradigm for space observatories is to launch them within a single fairing, either as a monolith or as a folded and stowed system that is autonomously deployed in space. Over the last several years, robotic in-space assembly (ISA) has emerged as an attractive alternative that has the potential to address many of the challenges that have been encountered with the current paradigm. However, there is currently very limited systematic understanding of how ISA compares with the current paradigm. Therefore, a large team was established and funded by the NASA Astrophysics Division over the past two years to assess a feasible approach for a large-aperture observatory assembled in space. ISA assessment led to a handful of formal findings, which was communicated to the NASA Astrophysics Division and the Astro2020 Decadal Survey. In summary, they are (1) With key capabilities demonstrated in space over the last decade, ISA has emerged as a viable approach for observatory assembly; (2) ISA removes the constraint of fitting the entire observatory into a single, specific launch vehicle by taking advantage of multiple launches; (3) The ISA approach can enable observatory sizes that cannot be achieved by conventional, single-launch approaches; (4) ISA offers an in-situ approach to servicing the observatory and replacing instruments by re-using the on-board robotics needed to originally assemble the observatory in space; (5) ISA changes the risk posture of observatory development and provides opportunities to better manage the risks; and (6) ISA offers opportunities for reducing the costs of observatories with 5 to 15 meter-class aperture diameters in comparison with the conventional, single-launch approach, particularly when including the servicing infrastructure in the mission. For observatories with aperture diameters larger than 15 meters, ISA appears as the only feasible approach. This paper describes the Study, the trade space analysis for observatory in-space assembly concept of operations and related technological elements, the process of the study, the key findings and representative rationale supporting the findings. The accomplishments reported on here were possible only because of the commitment of the many participants, whose names may be found here.

Keywords: In Space Assembly, Space Observatories, Robotics

1. Background

Space astronomy is on the eve of a generation of new large-aperture space observatories. James Webb Space Telescope (JWST) [1] is nearing its launch date and the Wide Field Infrared Survey Telescope (WFIRST) [2] observatory is entering its major development phases. The formulation of concepts for subsequent large space observatories is actively being pursued by the scientific and engineering communities: four large study teams [3-6] submitted their concepts to the National Academies' Astro2020 Decadal Survey in the summer of 2019. The lessons learned from JWST and the Hubble Space Telescope (HST) [7] can serve as invaluable experience for charting the future course of space observatories.

In-space assembly (ISA) of large observatories has been postulated and studied for a few decades. Even the JWST observatory had an early concept for robotic assembly. Developments over the last two decades point to perhaps the arrival of ISA as a feasible approach for implementing space missions. Moreover, it is not a new paradigm: the International Space Station (ISS) was assembled in space. The Hubble servicing missions involved significant assembly: instruments, solar arrays, and numerous other sub-systems. More recent developments of ISS-based robotic attachment of instruments [8] and the planned robotic servicing missions [9-10] all underscore the significant developments in relevant capabilities that enable ISA.

Against the backdrop of the recent developments in ISA and with the opportunity to inform the Astro2020 Decadal Survey, a study was chartered by the Astrophysics Division of NASA's Science Mission Directorate to answer a pertinent question: "When is it worth assembling observatories in space rather than launching them in a single fairing and deploying them in space?" The study was called the in-Space Assembled Telescope (iSAT) study [11]. It was conducted between May 2018 and July 2019 and had contributions from more than 70 subject matter experts from different NASA centers, other government laboratories and agencies, industry, and academia. This paper presents a summary of the iSAT study and its findings.

2. The ISA Paradigm

The overall architecture developed by the iSAT study consisted of the following sequence. First, the observatory is designed as an assemblage of different modules. These modules have interfaces for assembly and manipulations. The modules are designed to enable efficient packing in the launch fairing. The granularity of the modules is also related to the complexity of the robotic assembly steps. Hence working with a few, larger modules that are self-contained (e.g., built-in avionics) is preferred over working with many small modules. This also reduces the number of interfaces and assembly steps.

The first major departure from the conventional single-launch based deployment approach is the availability to use multiple launch vehicles. The cost of launch vehicles has reduced over the last decade with many commercial providers. Using multiple launch vehicles increases the total net mass and volume available to the observatory, which has multiple benefits, as discussed in later sections.

The first launch delivers the observatory spacecraft, the robotic system(s), and the first set of modules to the assembly location. Note that the assembly location can be different from the operational location. The robotic system(s) assemble the modules to the spacecraft and await the delivery of the next set of modules.

A subsequent launch brings up the next set of modules. The modules are delivered to the assemblage using a Cargo Delivery System (CDV). The robotic system(s) on the assemblage berths the CDV to the observatory spacecraft. The robotic system(s) unload and assemble the modules incrementally. Each step of assembly is followed by a set of in-space verification and validation (IV&V) steps. This is to ensure "correct-by-construction" at every step of the assembly.

This process is repeated. That is, subsequent launches and CDVs bring new sets of modules to the assemblage, the on-board robotic system(s) assemble the modules to the assemblage, followed by an IV&V step of the incremental assembly. Once the observatory is completely assembled, a full-system level verification and validation step is carried out before commissioning the observatory.

3. Component Capabilities and Technologies

From the above considerations on the architecture for in-space assembly of an observatory, the iSAT study identified the following as key enabling capabilities and technologies for ISA of an observatory.

- Modular components of the observatory
- Multiple launch vehicles
- In-Space transportation or Cargo Delivery Vehicles (CDVs)
- Rendezvous and Proximity Operations (RPO)
- Supervised autonomy robotics
- In-space verification and validation (IV&V)

Eventual adopted observatory point designs are likely to differ in the types of modules, the number of launches, the specific in-space verification and validation steps, the kinds of behaviours needed from the robotic systems, the location of assembly, and other relevant parameters. However, it is likely that all large observatories (i.e., aperture size greater than fairing diameter) that are assembled in space are likely to need these fundamental capabilities and technologies.

4. State of Art of Underlying Capabilities and Technologies

No observatory has yet been assembled from its modules in space. However, the International Space Station was assembled in space from its modules and used many of the fundamental capabilities and technologies from section 3. While lessons learned from the ISS assembly can feed forward to an observatory, the scope of effort needed for assembling the ISS is unlikely to be available for space telescopes. The James Webb Space Telescope used some level of modularity in its design. For example, the mirror modules were independently developed as modular elements. However, they were assembled on the ground with significant human involvement. There are similar examples from various other endeavours in space which point to prior experiences and existing capabilities that can be leveraged and adapted for in-space assembly of an observatory. A few representative examples of the key capabilities are briefly discussed here.

<u>Launch Vehicles</u>: The last two decades has seen significant developments from the commercial sector in cost-effective launch vehicles. The achievements of United Launch Alliance [12] and SpaceX [13] are representative of the large launch vehicles while EELV Secondary Payload Adapter (ESPA) rings [14] and RocketLabs [15] are examples of smaller launch capabilities that have emerged as lower-cost alternatives to existing capabilities.

At the same time, the cost of observatories has grown with aperture size to a point where the costs of launch systems are not a major fraction of the overall cost. When JWST was first formulated at approximately a billion dollars, the launch cost of about $300 million was a significant fraction of the overall costs. However, at a final cost of more than $8 billion, the launch cost is effectively a small fraction of overall costs.

These two factors - (i) net reduction in the cost of a launch and that (ii) other aspects of the observatory cost far outweigh the cost of launch - offer the opportunity to explore mission concepts that take advantage of more than a single launch. In space assembly of observatories can thus take advantage of this feature and use multiple launches to overcome some of the challenges with the current approach of deployment from a single launch.

Cargo Delivery Vehicles (CDVs): SpaceX Dragon [16], Northrop Grumman's Mission Extension Vehicle (MEV) [17] and the Cygnus vehicle [18] are representative capabilities of commercial in-space transportation systems that have emerged within the past decade. In the future, there may even be "intelligent" upper stages of launch vehicles that can serve as CDVs. NASA's Power and Propulsion Element [19] for the Lunar Gateway, development of solar electric propulsion or hybrid propulsion SmallSat systems, and robotic servicers such as the DARPA Robotic Servicing of Geosynchronous Satellites (RSGS) mission [9] or NASA Restore-L [10] are other examples of early-stage capabilities being developed to eventually enable in-space transportation and cargo delivery.

Rendezvous and Proximity Operations (RPO): This represents the capability to find an object in space, travel to it, maintain precise, relative pose in proximity, and/or interact with it or be docked/berthed to it. This includes sensors, such as LIDARs and cameras, as well as spacecraft control and navigation capabilities (e.g., algorithms and propulsion systems). Over the last two decades, significant progress has been made on RPO capabilities for different sizes of spacecraft. The Dragon resupply vehicle to the ISS [20], the servicing missions such as NASA Restore-L, DARPA RSGS or the MEV, the OSIRIS-Rex mission [21], the DARPA Orbital Express mission [22], Mars Sample Return and Orbital Sample Capture mission concept studies [23], the C-PODS mission [24] with CubeSats, and many others exemplify the achievements and continued work in this area. With the combination of hybrid propulsion systems (chemical or Solar Electric Propulsion combined with cold gas), advances in sensors, and spacecraft control algorithms, RPO has emerged as a robust capability that can easily be straightforwardly adapted and leveraged for observatory ISA.

Supervised Autonomy Robotics: While the ISS was assembled with significant astronaut involvement and high-bandwidth telerobotics, future ISA of an observatory is most likely to be conducted using supervised autonomy robotics. Robotic hardware and supervised autonomy capabilities have matured significantly over the last two decades. The Mars rover and lander missions (MER, MSL, Phoenix, Insight [25-28]) have all used supervised autonomy for operations on the surface of Mars, which included interactions with the Martian surface for sample acquisition and handling. The Mars 2020 rover [29] will further these capabilities with the ability to assemble the surface samples into sample tubes and sealing them for possible later retrieval. The robotic arms on the ISS have similarly been used for years to conduct berthing of spacecraft, assembly, and servicing activities. The planned NASA Restore-L and DARPA RSGS missions both include supervised autonomy behaviours for interactions between spacecraft. The NASA Tipping Point In-Space Robotic Manufacturing and Assembly program (IRMA) missions [30] also plan to feature robotic hardware and supervised autonomy capabilities for pathfinder in-space assembly demonstration. Robotic actuators, sensors, avionics, software, and other related technologies are at a high maturity level. The needed future developments are primarily in adapting and leveraging these capabilities appropriately for specific behaviours and requirements needed for in-space assembly of an observatory.

Modular Components and In-space Verification and Validation: Architecturally, these are not new capabilities or technologies. Orbital Replacement Units (ORU) have been used and continue to be used on the ISS. Instruments are designed as modules that are assembled to the ISS using standard interfaces on the Japanese Experiment Module (JEM) [31] using the on-board robotic arms. The DARPA Orbital Express mission demonstrated ORU exchange and robotic berthing between two spacecraft. Connectors and interfaces for in-space modular assembly and servicing are also being developed commercially. In the same manner, each of these examples also involve in-space verification and validation of the associated assembly or servicing steps. However, an observatory is going to have unique modules that have not yet been developed to sufficient detail. Concepts, designs, and prototypes for modular trusses, reflector rafts, laser metrology, modular soft good elements, and other components have been in continual development. However, the net maturity level for modular components of a detailed observatory design is still at a fairly low level.

Similarly, the assembly of an observatory is likely to involve a large and diverse set of in-space operations unlike any undertaken thus far. The verification and validation of these steps needed for the assembly towards meeting stringent optical performance requirements are yet to be fully conceptualized and developed. This also includes the development of specific robotic autonomy behaviours. Much work remains to be done in modularization of an observatory, developing the robotic behaviours, and developing the verification and validation (both on ground and in space) steps needed to meet the observatory performance metrics.

5. iSAT Study Methodology

The Study benefitted from contributions from a large group of subject matter experts (SMEs) from six different NASA centers and other government laboratories, fourteen commercial companies, and several academic institutions. The experience base included relevant missions such as HST, ISS, JWST, WFIRST, NASA's Restore-L and DARPA's RSGS missions, and the Mars robotic missions. The Study was conducted in the following five phases. Each phase was conducted through weekly teleconferences and an in-person several day meeting.

Step 1: Reference Observatory Selection: For its reference telescope architecture, the Study chose an off-axis, non-cryogenic, segmented-filled aperture operating in the UV/V/NIR portion of the electromagnetic spectrum. Concept designs of the constituent modules of the observatory were then designed. To understand the scalability aspect, the Study chose four different aperture sizes (5, 10, 15, and 20 meters). For uniformity, it used the same modularization architecture for all aperture sizes.

Step 2: Concept of Operations Selection: The Study developed a notional concept of operations by evaluating a large trade space of launch vehicles, assembly orbits (LEO, GEO, HEO, cis-lunar, SE-L2), robotics architectures (arms, free flyers, multi-limbed robots) and operational approaches (low versus high bandwidth telerobotics), role of astronauts, and assembly platforms (ISS, Gateway).

Step 3, Qualitative Analysis: Drawing upon the diverse experience base of SMEs from notable missions, the Study conducted a qualitative analysis on how ISA may impact the science, cost, and risk posture of future observatory missions.

Step 4, Quantitative Analysis: The iSAT study conducted a quantitative mission planning and resource estimation activity. About 40 Study SMEs were set up in seven sub-teams composed of the key elements of the observatory (a) structures, (b) optics and instruments, (c) robotics, (d) thermal engineering and sunshade, (e) spacecraft, (f) launch systems, and rendezvous and berthing, and (g) systems engineering. Working closely together over six months, each group developed a first-order, project life-cycle implementation plan spanning phases A-E, a list of activities and development plans for each phase, a high-level Master Equipment List (MEL) and Power Element List (PEL), integration, test, and validation plans, overall schedule, launch manifest, and resources needed including workforce and facilities.

Step 5, Relative Cost Estimation: The iSAT study used the MEL from step 4 to develop an architectural, relative, cost comparison between the ISA approach and the conventional, single-launch based deployment approach for three observatories (5, 10, and 15 meters). The 20-meter size was found to be beyond the capability of conventional approach even with future planned launch vehicles.

6. Reference Telescope Architecture

The iSAT study engaged a large group of SMEs to select a reference observatory architecture for the iSAT study. The group considered many different architectures including sparse apertures, monolithic apertures, on-axis and off-axis configurations, different types of reflectors, and other pertinent parameters. The Study wanted to choose an architecture that could be scalable from an aperture 5 meters up to 20 meters in diameter while maintaining engineering feasibility. The Study recognized the diversity in choices of observatory architecture, and that the final findings could vary for a specific aperture size and its specific architecture.

Based on lengthy discussions and navigating the large option space, the iSAT study chose an off-axis, non-cryogenic, segmented aperture observatory operating at UV/V/NIR range with the structural stability to accommodate a coronagraph. The operating environment was chosen to be the Sun-Earth 2nd Lagrange Point (SE-L2). The team felt that this architecture was a good reference architecture for the iSAT study as it captured various representative challenges associated with space observatories. This was not a down-select, but instead primarily a notional architecture to be used as a reference in the iSAT study.

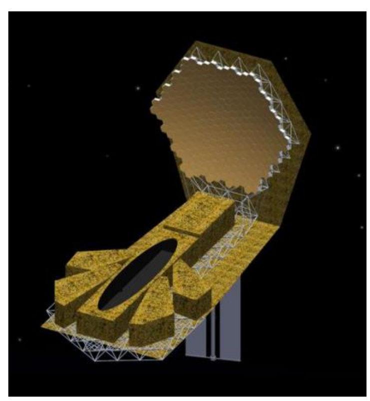

Figure 1: Adopted reference architecture chosen

The iSAT study then used this architecture to develop a modularization approach to design the observatory from modules that could be assembled in space. The modularization approach also considered the limitations of launch vehicles, capabilities of robotic systems, engineering feasibility of developing the modules, among other considerations. The final modularization scheme comprised of the following elements:

- Modular truss elements that can be deployed and assembled to form the backplane truss as well as the metering truss between the primary and secondary mirrors
- Optical "rafts", with each raft consisting of a structural plate onto which seven, 1 meter-class reflector segments are assembled along with their actuators and avionics.
- Instruments were treated as separate modules
- Modules that are robotically deployed and assembled to form a notional sunshade
- Robotic elements were treated as separate modules
- The observatory spacecraft was chosen as a separate module.

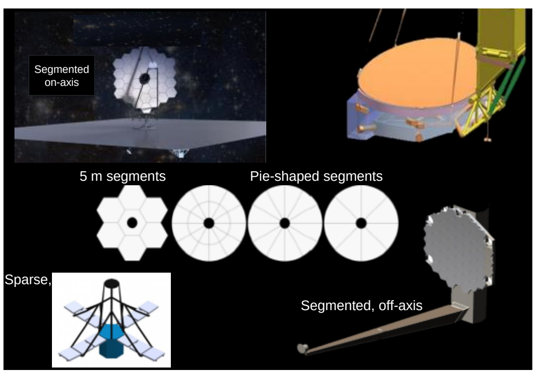

Figure 2: Representative trade space of different observatory architectures considered by the iSAT study

7. Trade Space Options for Concepts of Operations

Within the iSAT study, the following trade space considerations were discussed and consensus-based selections were made by the study members. Note that in some cases, it was recognized that depending on the point design of the observatory and circumstances of prevalent other capabilities, the selections could very likely vary. However, the selections represent a complete and feasible set of choices that enable an end-to-end observatory assembly mission scenario concept.

7.1 Launch Vehicles:

The future of launch vehicles is fairly exciting with new prospects of larger and more capable systems than current rockets from both the government and the commercial sector. Fairing sizes of 8-10 meter diameters are anticipated to be available for launch to the Cis-Lunar environment and beyond. These are expected to complement the existing 5 meter-class fairing based launch systems. The size of the fairing and launch capacity can dramatically alter the logistics of an ISA mission. The observatory module designs are customized to maximally use the fairing capabilities in order to reduce the complexity of in-space operations. The iSAT study group chose to work with the existing 5 meter-class launch vehicles. The rationale being: (a) capabilities, availabilities, costs and other logistics of future launch vehicles are not yet well understood, (b) larger fairings would only enhance what can be achieved even with the existing launch capabilities, (c) ISA of an observatory should be decoupled from the availability of a specific future capability, (d) ISA of the observatory should be achievable with capabilities available today or their subsequent adaptations, and (e) the capabilities, costs, loads, and other specifications of current launch systems are very well understood and have high reliability.

7.2 In-Space Transportation:

The study group discussed the trade between using a cargo delivery vehicle (CDV) and a space tug. A CDV can be reusable and represents a unit that is integrated with the cargo at launch. It carries the cargo to its destination i.e. the assemblage. However, multiple CDVs are likely to be needed, assuming one per launch if expendable CDVs are used for the multi-launch mission. A space tug on the other hand is an in-space asset that locates the cargo, berths or docks to it, and transports it to the assemblage. It is an independent spacecraft that provides the in-space transportation as a service. There were technical merits to either choice but the iSAT study chose to work with CDVs rather than the space tug. The net cost of even multiple CDVs was estimated to be lower than a dedicated and more capable space tug. Similarly, CDVs exist as a capability today while space tugs are still in development. However, the Study recognized that the space tug may evolve as a better choice when they are demonstrated in space and a better understanding is obtained of commercially provided space tugs. Similarly, the space tug may also be favourable if the number of CDVs needed for the mission is high.

7.3 Assembly Agent:

The Study group had various options to discuss for the assembly agent. The Study group comprised of astronauts, robotics experts, developers of free-flying servicing vehicles, and expertise from ISS and Mars operations, and upcoming servicing missions. This resulted in a large trade space consisting of in-situ astronaut-based assembly, proximal although remote astronaut commanded assembly, free-flying servicer-based assembly similar to the Restore-L and RSGS missions, and embedded robotic systems such as the robotic arms on the ISS and those planned for the Lunar Gateway. The Study concluded that embedded robotic arms that can “walk” on the assemblage are the best option. Here “walking” represents use of standard interfaces on the assemblage for the robot to grapple and locomote from one interface to the other. This type of capability is already demonstrated by the arms on the ISS. Astronaut-based assembly, though high heritage, may be higher risk given the desired assembly and servicing location of either Cis-Lunar space or SE-L2. Designs would also have to be ruggedized and made human compatible at considerable cost to the mission. And finally, the kinds of interfaces may be difficult for human assembly: for example, multiple concurrent blind mates with high inertia modules. Free flyers were an interesting choice but limitations on fuel consumptions, potential for contamination, and need for multiple berthing operations were some of the challenges identified by the group. The high heritage of robotic arms from ISS and Mars missions, the simplicity and robustness of the arms, and the flexibility afforded by them made embedded “walking” robotic arms the assembly agent of choice.

The discussion also involved the mode of operations for assembly with choices involving astronaut-based assembly, high-bandwidth telerobotics, and supervised autonomy low-bandwidth telerobotics. High-bandwidth telerobotics represents the ground-based or space-based control stations that use joysticks or similar devises to have significant command and control of the assembly agent. Commands are sent at a low level of granularity with haptic feedback and either direct line-of-sight operations or remote imagery. Low-bandwidth telerobotics or supervised autonomy is the mechanism where a robot is given a limited set of commands or scripts (i.e. low bandwidth communication) and the robot autonomously undertakes the various underlying steps needed for each of the commands or scripts. For example, force control, vision-based localization, motion or path planning, collision avoidance, and other lower level functions are autonomously conducted by the robot. The operations for Mars missions involve low-bandwidth supervised autonomy telerobotics. The group chose to use low-bandwidth telerobotics as the nominal approach and recommended the option to have the ability for high-bandwidth telerobotics as a fall-back option.

7.4 Assembly Location and Assembly Platform:

This discussion rotated around the orbit at which the assembly would be carried out and what, if any, external platform would be used for the assembly destination. The ISS or a future Lunar Gateway represented exciting choices for an external platform that could be leveraged for assembling the observatory. However, these platforms were also limited by the orbit in which they operated. The Study group considered these two variables independently first and then together.

The SE-L2 location was selected as the operational environment for the observatory, although the assembly location choices were many ranging from LEO, GEO, HEO, Cis-Lunar, and at SE-L2. Environmental factors such as gravity gradients, thermal gradients, contamination, lighting conditions, along with logistical factors such as ease of circularization and subsequent transportation to SE-L2, availability of launch systems, total time to access the assembly location and frequency of launches, communication delays, availability of resources such as astronaut presence, and other factors were considered. The Cis-Lunar environment and the SE-L2 environment were both found to be feasible locations while the other locations had either an unfavourable technical issue or introduced high cost or detrimental risk posture. The Study chose the Cis-Lunar environment as the assembly location. The relative ease of access from Earth in comparison with the SE-L2 location (days compared to months) was one favourable factor. There also exists low delta-v (in the order of 10s-100s of m/s) pathways for easy access from the Cis-Lunar environment to SE-L2. This reduced complexity of transporting the assembled observatory between the two locations also made the Cis-Lunar environment a favourable location. Further, the current interest in the Cis-Lunar environment for the Artemis lunar exploration program holds potential for infrastructure (not just the Gateway) that could be leveraged. This includes frequent launches, presence of communication assets, growth in industry capabilities for that environment among others. This too factored into the choice of orbit. Note further that the team concluded that the communication delays at the Cis-Lunar and the SE-L2 environment would make it extremely challenging for high-bandwidth telerobotics from the ground. Hence communication delay did not serve as a basis for choice between these two locations.

The choice of orbits narrowed the choices for platforms from which the observatory could be assembled. The ISS, though a very attractive option by itself, was found to not be favourable due to challenges with the LEO environment (e.g. thermal environment, Earth albedo, gravity gradients, contamination and debris, delta-v for transportation to SE-L2). The future Lunar Gateway is planned to be in the Cis-Lunar environment. It is anticipated to have robotic arms, ability to berth cargo delivery vehicles, and continual crewed presence. However, the iSAT study decided to not use the Lunar Gateway as an external platform to assemble the observatory. The iSAT study team concluded that the observatory would likely have to be human-rated if it is assembled at the Gateway. This is likely to introduce significant design challenges and may likely result in the observatory being overdesigned to address the margins associated with human-rated systems. This would incur significant cost and development risk. Other considerations included stability, contamination, programmatic interdependence, among others.

The iSAT study team concluded that the best option would be to assemble the observatory from its native spacecraft bus. The observatory spacecraft would be equipped with berthing ports and ability to host the robotic arms needed for assembly. The observatory would be assembled starting with the spacecraft and adding modules to it. The spacecraft also serves as the source of power and communications for the observatory. Hence, assembling from the spacecraft provides these basic utilities natively. It also ensures that every step of the assembly is verified and validated as an intrinsic system without dependence on an external asset. This approach also ensures the design and programmatic decisions for the observatory are completely focussed on meeting the observatory requirements and do not need to accommodate requirements of an external platform. This would also reduce the overall cost and risk.

However, the iSAT team did consider the advantages of the Lunar Gateway and crewed presence. The team agreed that though the nominal assembly would take place through supervised autonomy, there may be off-nominal scenarios, validation steps, or other currently unforeseen scenarios where high-bandwidth telerobotics would be beneficial. In such cases, the presence of crew in the Cis-Lunar environment may be leveraged. The close proximity would overcome the communication delay issue and provide opportunity for high bandwidth telerobotic intervention. It was, however, agreed that EVA based assembly would not be a design option.

8. Concept of Operations

The observatory is designed as an assembly of separate modules with standardized interfaces. The modules are individually developed and tested on the ground. They are launched on one or more launch vehicles. As multiple launches are used, the modules are afforded higher volume and mass allocations than would be possible for a single launch observatory. These modules are equipped with grapples and interfaces for robotic manipulation, assembly, and adjustability to meet desired accuracy and stability requirements. These may also provide communication, power, and fluid (if needed) connections. Some module interfaces may also be reversible for servicing.

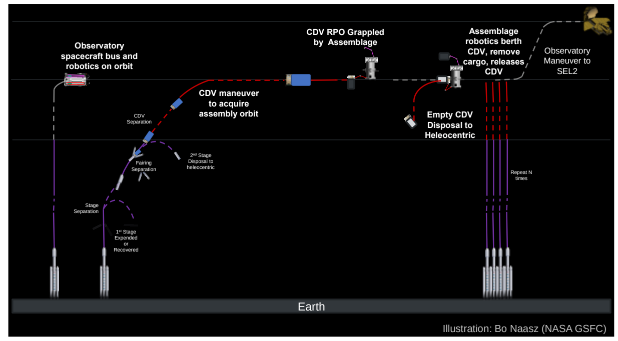

Figure 3. The multi-launch cadence of ISA concept of operations.

The first launch carries the spacecraft bus, two robotic arms for the assembly, and first set of modules. The spacecraft forms the foundation of the assemblage. In doing so, it removes the programmatic dependence on any additional platforms such as the ISS or NASA's proposed Lunar Gateway. Subsequent launches would have rendezvous and proximity operation (RPO) capable cargo delivery vehicles (CDVs) to deliver the modules to the assemblage. Dragon and Cygnus are representative examples of CDVs. Alternately, it is also possible to have a dedicated space tug (e.g. Mission Extension Vehicle) or even an intelligent upper stage that delivers the modules.

The robotic arms on-board the assemblage berth the CDV to the observatory spacecraft. The robotic arms unload individual modules from the CDV and relocate them to their assembly location. Similar to the robots on the ISS (or Gateway), the assembly robots are anticipated to be capable of mobility across the assemblage using its end effectors and pre-designed grapple points located on the assemblage. Using standard interfaces, supervised autonomy (similar to Mars rovers), vision guided localization, and force-controlled dexterous manipulation, the robots assemble the individual modules to the assemblage. The assembly steps are validated in-space (e.g. using metrology or telemetry from the modules themselves) with minor adjustments made by the robots to meet assembly specifications. Engineers on the ground would be in the loop throughout these steps. These steps are very similar to the instrument assembly approach already being conducted on the ISS (e.g. OCO-3 [32]).

This process of module launch, delivery to the assemblage and robotic assembly continues in iterative steps until the observatory is completely assembled.

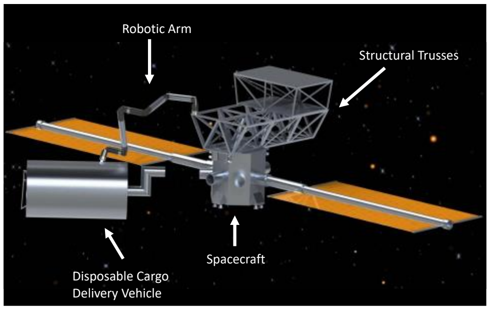

Figure 4. Artistic depiction of the berthing of the first CDV to the observatory spacecraft which has the initial structural modules already assembled.

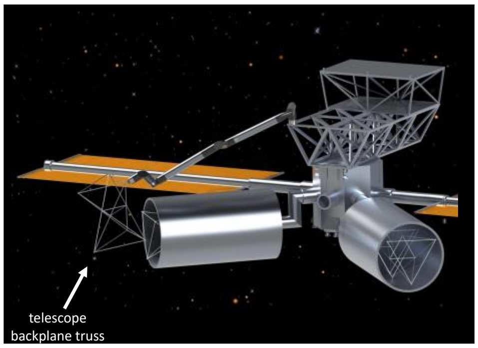

Figure 5. Artistic depiction of robotic unloading of modules from the CDV. Shown here is a truss module for the structure of the observatory

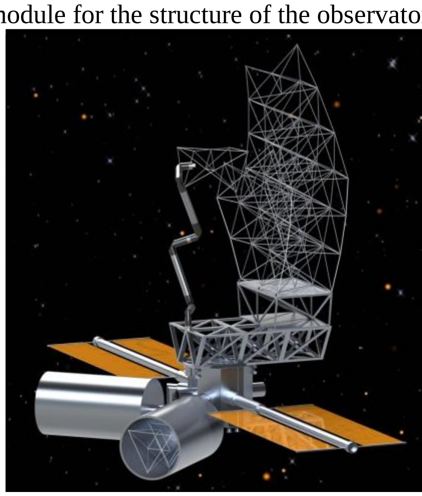
Figure 6. Artistic depiction of robotic assembly of the backplane truss from modular elements

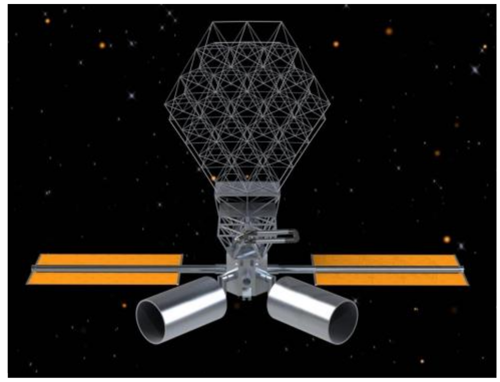
Figure 7. Artistic depiction of the completely assembled backplane

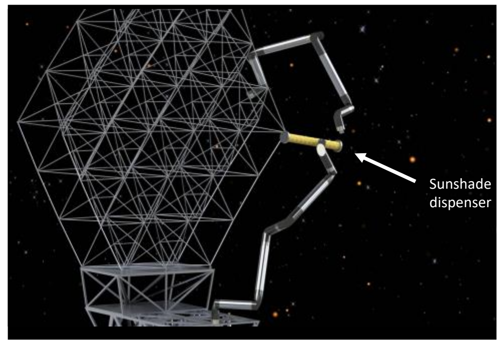

Figure 8. Artistic depiction of robotic deployment of the sunshade elements from its dispenser

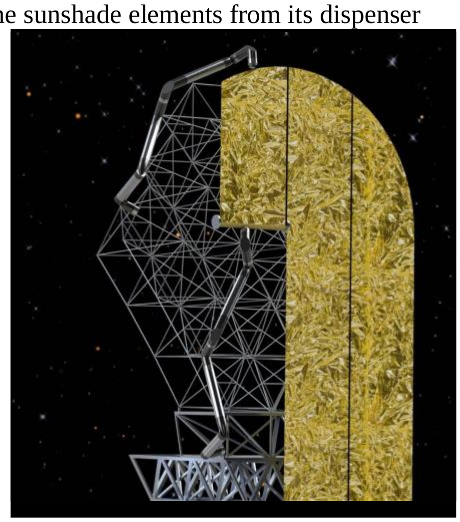
Figure 9. Artistic depiction of robotic assembly of the sunshade modules.

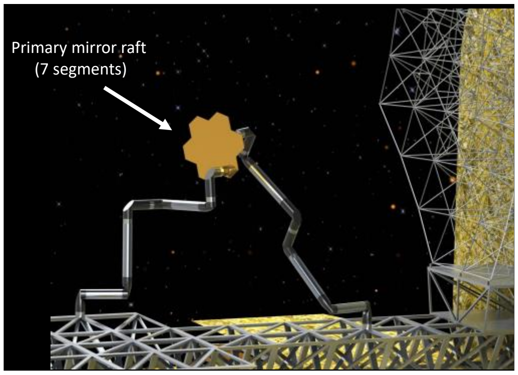

Figure 10. Artistic depiction of multi-robot collaboration in transporting the mirror modules

Figure 11. Artistic depiction of robotic assembly of the mirror modules

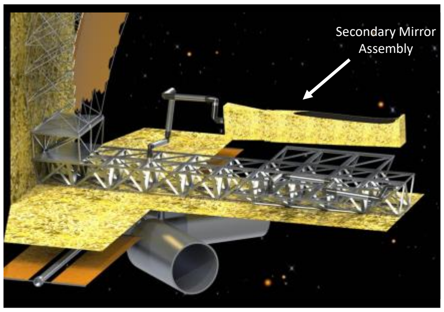

Figure 12. Artistic depiction of robotic assembly of the secondary mirror module

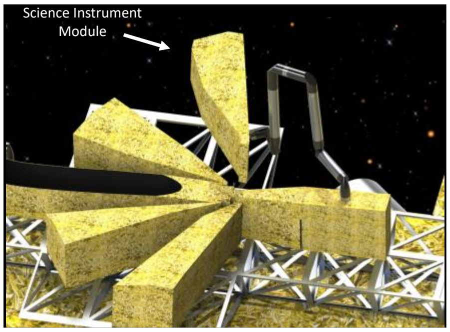

Figure 13. Artistic depiction of robotic assembly of an instrument module

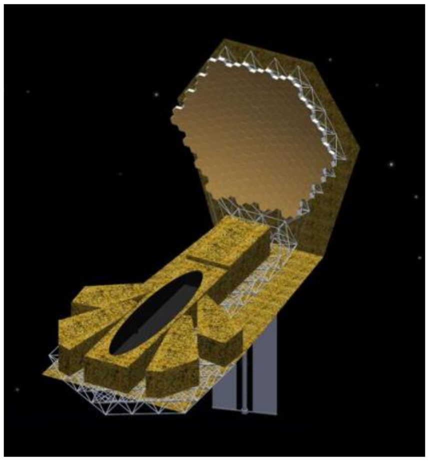

Figure 14. Artistic depiction of the assembled observatory with 20m aperture

9. Key Findings

The key findings from the Study are listed below:

Finding 1: With key capabilities demonstrated in space over the last decade, ISA has emerged as a viable approach for observatory assembly. Engineering development needs and technology gaps for specific observatory designs will have to be addressed.

Finding 2: ISA removes the constraint of fitting the entire observatory in a single, specific launch vehicle by enabling use of multiple launches. This enables observatory and instrument designs that better suit the science goals and not the mass and volume constraints of fitting in a single fairing.

Finding 3: The ISA approach is scalable and can enable observatory sizes that cannot be achieved by conventional, single-launch approaches. The largest filled-aperture telescope deployed from a future 8-10 meter-class fairing appears to be about 15 meters in size.

Finding 4: ISA offers an in-situ approach to servicing the observatory and replacing instruments by re-using the on-board robotics needed to assemble the observatory in space. No additional servicing infrastructure is required.

Finding 5: ISA changes the risk posture of observatory development and makes it potentially more manageable. Hence, ISA may be a preferred implementation approach compared to conventional, single-launch approaches for observatories, particularly those with 10m class or larger apertures.

Finding 6: ISA may offer opportunities for reducing the costs of conventional, single-launch observatories for aperture sizes 15 meters or less, particularly when including the servicing infrastructure in the mission. This will depend ultimately on the point design selected and its technology needs.

10. Representative Support for the Findings

In this section, the paper discusses representative rationale that support the findings presented above.

10.1 Finding 1: Viability of Approach

The key capabilities and technologies that enable ISA and their state of art have been discussed in sections 3. Over the last 10-15 years, some of the key ISA enabling technologies have undergone a veritable revolution and matured through demonstrations in space. NASA identified ISA as being at a "Tipping Point" of wide commercial infusion and made significant investments towards the public-private partnership-based IRMA program. The IRMA program is slated to have in-space demonstration(s) of robotic assembly in the next few years. NASA and DARPA have invested heavily in space missions for robotic servicing scheduled for launch in early to mid 2020s. Furthermore, the National Space Strategy 2018 has asked NASA to lead the exploration of capabilities for in-space assembly, servicing and manufacturing. Unlike past decades, the technology maturation and programmatic pull makes ISA relevant now.

The last decade has also seen the successful infusion of robotic instrument assembly on the ISS into NASA's Science Mission Directorate portfolio of science missions, particularly in Earth Science. OCO-3 and ECOSTRESS are the latest examples. The iSAT concept of operations has significant commonality with this approach of instrument installation. This includes the use of CDVs, RPO, use of robotic arms, installation of modular instrument using a standard interface, and in-space verification and validation of the robotic installation.

Despite the maturation of some of the key capabilities of ISA, there are going to be technological challenges in adapting and applying them to an observatory assembly. Capabilities which are specific to an observatory have challenges that need to be addressed. For example, modularization of the observatory would need large trade space analyses beyond what was conducted in the iSAT study. Interfaces to assemble these modules would have to be developed to meet the specific constraints of the observatory design. Ability to meet specific stability, alignment, contamination standards, specific robotic behaviours and their supervised autonomy capabilities, and other performance requirements would have to be defined and demonstrated for a specific observatory design. While component technologies exist, there are likely challenges in a system-level demonstration of autonomous robotic assembly of truss modules to form thermally stable, stiff, linear structures. Similarly, collaboration among multiple agents (two robots, two spacecraft, robot and spacecraft, ground and robot, ground and spacecraft etc.) are also likely to have specific technology challenges or gaps. It is not clear what kinds of stresses may be introduced on structures that get assembled when robots manipulate them or walk on them. How the micro-dynamics from these or other induced stresses impact overall observatory stability is an open question. Similarly, how well a robot may be able to manipulate soft goods needed for the sunshade is also not well understood. There are other similar specific questions that would need to be well understood.

However, the consensus finding of the SMEs in this Study was that closing the gaps and demonstrating them is achievable with today's capabilities. This will, however, need systematic investments to facilitate an adaptation of the key capabilities to the requirements of a specific observatory, and any associated demonstrations and tests.

10.2 Finding 2: Breaks "Tyranny of Launch Vehicle"

The constraint of fitting into the launch vehicle and surviving launch as an integrated system dominates the design of conventionally developed observatories. Observatories worth billions of dollars are designed to the constraints of a launch vehicle that costs only a few hundred million dollars. JWST costs more than $8 billion, but the design is catered to the constraints of its ~$300 million launch vehicle. Attempts to maximize the aperture size to a specific launch vehicle become more expensive and riskier as designs approach the vehicle's mass and volume limits of the fairing capacity. This is the "tyranny of the fairing". ISA offers the possibility to open up totally different strategies for architecting observatories. This is achieved through three key elements: (1) designing the observatory architecture and instruments as discrete modules, (2) launching the modules on multiple launch vehicles, and (3) assembling them robotically in-space. These elements de-couple the observatory and instrument designs from the mass and volume constraints of a single launch vehicle.

Larger mass and volume allocations with ISA can enable architectures and design choices of instruments and telescopes that better suite science goals, although may be more difficult, or not feasible, with a single-launch approach. For example, ISA can better enable slower, off-axis designs which are much longer than on-axis designs for the same aperture size but offer different science benefits (for e.g., reduced polarization effects and improved coronagraphy performance). Availability to larger mass and volume allocations can also enable observatories to use stiffer structures thereby improving stability. The observatory could even be architected to be evolvable i.e., capable of growing in aperture over time. This could result in early science returns. Instruments may be more numerous and capable, as they are independently launched and less constrained by mass and volume. Larger volumes could enable optical architectures that have fewer reflections and, hence, less throughput loss - critical for photon-limited science. Greater mass allocations may allow the instruments to be designed with simpler optical designs and forgo expensive light-weighting activities along with their model development and validation efforts. Prime focus instruments could also be possible with ISA.

10.3 Finding 3: Scalable

JWST perhaps represents the largest telescope that may be folded and launched from a 5 meter-class fairing of currently available launch vehicle. Observatories with aperture size larger than JWST that are developed using the conventional approach are unlikely to fit within currently available 5 meter-class launch systems.

As we look to future capabilities, the heavy lift systems hold promise for larger observatories than using the conventional development approach. Three emerging launch vehicles are baselining fairing diameters larger than the currently available 5 meter-class fairings: Blue Origin's New Glenn [33], SpaceX's Big Falcon Rocket [34], and NASA's Space Launch System (SLS) [35]. From data available to this Study, the SLS appears to offer the largest payload mass and volume capacity to date. The LUVOIR space telescope concept team did extensive packaging and system design work to successfully fit a 15-meter aperture UV/Optical/NIR observatory into the SLS Block 2 fairing. A larger fairing (10-meter) for use with the SLS Block 2 rocket is being considered as a possible future development, but its larger cross-section will likely reduce the Block 2's mass performance. Thus, apertures greater than 15 meter in diameter are unlikely to be deployed to SE-L2 with a single launch and will require some form of ISA. When considering off-axis designs, the size limit is perhaps even smaller, around 10-12 meters aperture size depending on a specific point design.

As ISA can use multiple launch vehicles and modular components, the fairing size does not limit the aperture size. The iSAT study developed concepts for off-axis apertures of 5, 10, 15, and 20 meters that may be assembled from modules launched using currently available 5 meter-class launch fairings. Observatories with apertures even larger than 20 meters are likely possible with ISA. ISA is inherently scalable and can enable future large observatories beyond what can be fit, even when folded, in a SLS or other future planned vehicles.

10.4 Finding 4: In Situ Servicing

The world has both marvelled at, and profited by, the benefits of HST servicing (instrument upgrades and observatory repairs). HST today is a more powerful and effective telescope than it ever has been since its initial launch due to its servicing program. JWST, three decades in development and costing greater than $8 billion, is not serviceable. Congress has mandated that future observatories be serviceable, where possible [36]. The four astrophysics large mission concepts proposed to the National Academies' Decadal Survey are all considering various aspects of robotic serviceability in their designs.

Unfortunately, there is currently no credible plan or resource for servicing these future observatories. NASA would need a separate program to develop a servicing capability with its own programmatic and schedule risks, technological challenges, and significant cost impact. Moreover, the servicer would need (i) a modular design for observatory's serviceable elements, (ii) interfaces for robotic grappling and assembly, (iii) RPO capabilities to get to the observatory, (iv) berthing mechanisms, and (v) a robotic system to conduct the servicing. This means it would have to develop almost all the elements needed for ISA. It would result in a redundancy of first developing the observatory with conventional, deployment-based approach and then additionally developing the capabilities needed for ISA to service it.

In the ISA approach, the robotic arms used for assembling the observatory can be used for in-situ servicing. If new modules are needed, they may be delivered using the same approach as used to deliver the modules for assembly. ISA does not need a separate servicer spacecraft to be developed. ISA, with its built-in robotic servicer, may provide a planned way to extend the observatory life and amortize its cost over many decades of scientific research.

In-space assembly of the observatory is also likely to make it easier to service than one developed using the single-launch, conventional approach. With the modular approach of ISA, servicing would be easier as it could be designed to be the reverse of the assembly process. This would also enable the design to be seamlessly verified for servicing. Moreover, serviceability of some of the deployments in the conventional designs can be extremely difficult, if not impossible. For example, a monolithic sunshade (i.e., so-called "soft goods") deployment failure may be extremely difficult to service. Using a modular sunshade with ISA and robotic servicing at the module level may be much simpler than a large monolith. The incremental assemble-then-validate approach of ISA also ensures any failure in a module can be replaced in a timely manner by an updated module in a subsequent launch. This prevents assembly anomalies from ending the mission as may be the case for failure in some of the critical deployment mechanism for deployment-based observatories. Further, ISA may also enable projects to carry a sparing approach, where appropriate, to raise overall reliability.

The use of on-board robotic system inherently provides significant flexibility and opportunity for in-situ and timely serviceability. Many space robotics missions (e.g. Shuttle flights, ISS, and the Mars missions) have used their robots for unanticipated servicing scenarios or anomaly resolution. The role of the robotic arm in debugging the Insight mission's instrument on Mars is a recent example. In some cases, the anomaly may be time sensitive. Consider, for example, an anomaly that exposes optical elements to adverse thermal environment. Timely mitigation with in-situ robotics may be the only option as it would take too long to respond with a new development of a subsequent servicer. The onboard servicing capability of ISA may inherently offer a lower risk posture for mission success.

10.5 Finding 5: More Manageable Risk Posture

JWST relies on 20 sequential deployment events, 40 deployable structures, and 178 release mechanisms, many of them in the sunshield. It may be difficult, if not impossible, to recover from failure or anomaly during deployment. Conventional, single-launch future observatories and their large sunshades may need even more deployment mechanisms. Despite having high reliability, the sheer number of these deployment mechanisms impacts the overall system reliability. Testing of all the different deployments is also expensive. It introduces schedule risk when there are anomalies. ISA may have orders of magnitude fewer of such mechanisms, if any. It will likely use robotically reversible and adjustable joining interfaces with an incremental assemble-and-verify approach, similar to instrument assembly on the ISS. More profoundly, ISA may also provide the ability to recover from faults or anomalies with in-situ servicing and ability to replace a failed module.

Current mission schedules have a single critical path and all elements enter the expensive design-build-test phases of the project at the same time. Funding fluctuations in these phases can have adverse schedule and cost outcomes. Maintaining a high level of funding for several years, as needed in these phases, may put strain on a NASA budget. Cost growth is typically encountered in these phases, making the issue further acute. An ISA mission may be planned in a phased approach to have multiple development paths. In such an approach, design-build-test phases are decoupled (e.g., multiple so-called "swim lanes") with separate launches that don't have to be executed concurrently. This offers the opportunity for NASA to flatten the mission funding profile, reduce the strain on annual budgets, and reduce the sensitivity to budget variations. This may result in longer development and implementation lifetimes, but it may be preferable in some circumstances.

With the conventional, single-launch approach, a launch failure may mean mission failure. As ISA uses multiple launches, loss of one vehicle would be a significant setback, but not complete mission failure. Dependence of the conventional approach on a specific launch vehicle, (e.g. on SLS), also introduces risk. Any issues with the availability of a specific vehicle (e.g., engineering issues or schedule delays), may adversely impact the observatory development schedule. ISA reduces this risk as it can leverage a range of different launch vehicles, including currently available launch vehicles.

ISA takes advantage of the risk benefits of modularization. Modularity encapsulates complexity at the module level and prevents it from being pervasive across the system. Hence, faults and anomalies can be more readily contained and not propagated through the system. It may also reduce the total number of interfaces and indirect coupling between elements. It enables performance quantification and verification at the module level rather than system level. Modularity eases integration and assembly, handling and transportation, planning and tracking, among others well known benefits. JWST has some distinct modules (e.g., the segments), but some aspects are not modular (e.g., the sunshield). One of the lessons learned was to strive for modularity in the design and maintain simplest possible interfaces including ability to swap out key risk items late in integration flow. In reality, for the current single-launch approach, modularity is often sacrificed to meet mass and volume margins. ISA necessitates modularity and enables it by providing higher mass and volume allocations. This will likely reduce risk in development. Furthermore, reuse of the same type of interface across the observatory will likely also reduce risk and cost.

With larger apertures, the cost, complexity, and time required to complete telescope and system-level assembly, integration, and testing (AIT) becomes increasingly challenging in the conventional approach. Performing these tests in the presence of gravity becomes particularly difficult (e.g., the sunshield deployment tests for JWST). It is also a single critical path as all flight elements have to come together for flight integration and tests. By eliminating complex post-launch deployments, using simpler module-level and interface testing, and allowing for reversible in-space assembly, the overall ISA paradigm may reduce reliance on system-level ground AIT. This may not only mitigate the cost/complexity of a ground AIT program, but the phased launch manifest of ISA may also eliminate critical path delays that can improve overall program risk posture, cost, and launch schedule.

10.6 Finding 6: Opportunities for Cost Saving

As discussed in section 5, in the Qualitative Analysis phase of the iSAT study a large group of subject matter experts evaluated the potential benefits and drawbacks of ISA and compared it the conventional single launch approach of deploying observatories. The group found that there may be opportunities for cost savings with ISA, particularly when also considering the cost of servicing the observatory. The group recognized that there are likely to be cost uppers from the use of multiple launch vehicles and cargo delivery vehicles. However, they listed a number of factors that may reduce the overall cost. A representative set of examples include:

- Higher mass and volume allocations simplify development
- Significantly reduced number of deployment mechanisms
- No system-level single critical path; parallel developments
- Simplified AIT
- Reduced “marching army” costs
- Reduced dependence on high-fidelity models and their validation
- No monolithic, large, soft goods, sunshade or sunshield; replaced by smaller, easier-to-test, modular elements
- Commodity of scale
- Resilience to implementation phase mass growth
- Reduced need for new test facilities
- Small modules are easier to handle and transport
- Distributed development across NASA and industry

To quantitatively verify the assessment of the Qualitative Analysis step, the iSAT study formed a large team (~40 people) of subject matter experts and conducted a detailed formulation effort. This effort investigated how the ISA mission may be planned, estimated the resources needed, and developed a nominal overall schedule. This team comprised of several discipline specific sub-teams viz. (1) optical systems, (2) structures, (3) thermal systems (including sunshade/sunshield) (4) robotics, (5) launch systems and in-space transportation, (6) spacecraft and (7) systems engineering. Each sub-team was supported by subject matter experts from different NASA and government centers, as well as different commercial companies and academia. The team represented significant past experience from ISS missions, HST and Servicing missions, Mars robotic missions, JWST and WFIRST, as well as planned missions for robotic servicing such as Restore-L and RSGS.

To understand the scalability, the team considered four different aperture diameters for its reference observatory - 5, 10, 15, and 20 meters. To keep the study consistent with the time and resources available, the team used the same architecture for the observatory modularization and assembly concept of operations for all four aperture sizes. The team recognized, however, that it is likely that there may be better point solutions for the different observatory architectures that could be explored in detail in subsequent activities.

The team broke down the observatory design and in-space assembly problem into its sub-disciplines with the systems sub-team playing the role of integrator of the information sets. Each sub-team looked at notional requirements (desirements) and developed an implementation plan for their element of the observatory. The implementation plan was set up per phase of the project life-cycle (A-E) and assessed the major activities to be carried out in each phase. The sub-teams did not undertake detailed design of their element. While there were some analyses carried out such as first order structural sizing and stability analyses, thermal loading analyses, robotics reachability analyses, the major emphasis was on planning the implementation phases. The sub-teams also examined interfaces and interdependence between the activities between their respective teams. Testbeds are a good example of such interdependencies where the sub-teams identified and planned testbeds collaboratively to meet the overall observatory system needs. Similarly, the sub-teams addressed the various interfaces between the modules of the observatory, the spacecraft, the CDVs, the robotic systems, and other subsystems.

The sub-teams also planned a notional launch manifest based on the use of commercial 5 meter-class fairings. The manifest planning involved a packing configuration study to best use the fairing capabilities while remaining consistent with the overall observatory assembly constraints. This, in turn, informed the modularity of the observatory and how each of the sub-teams sized and planned their respective elements. Through various iterations of launch configuration and packing, module sizing, assembly sequence planning, and resource and schedule planning, the team successfully came up with an implementation plan and launch manifest that met all the different constraints of the observatory design, launch, assembly, operations, and servicing.

The team then developed a notional project level schedule based on sub-team or sub-system level schedule. Each sub-team developed a detailed schedule of their own element. This schedule was informed by the activities that needed to be conducted in each phase of the project, resources needed, analogues from past experience (e.g. JWST backplane truss, optical elements, robotics from Mars missions and ISS), and consistency with the schedules of the other sub-teams to address the interdependencies. The overall project schedule was developed by the systems sub-team. Similarly, the sub-teams also developed notional Master Equipment List (MEL) and Power Equipment List (PEL) for their elements and these were integrated by the systems team into a detailed project level MEL and PEL. These had margins built into the elements and also at the project level in a manner consistent with common practice for space missions.

Finally, the sub-teams developed estimates for resources needed, including workforce, to meet the implementation plan. The resource needs were planned on a per-phase basis with traceability to the major activities in that phase as well as analogues for similar activities from past experiences. For example, the estimates for CDVs were informed by the Cygnus vehicle and the planned Power and Propulsion Element for the Lunar Gateway. Similarly, the robotic systems estimates were informed by the shuttle arm, ISS and Mars robotics, and planned servicing mission and Lunar Gateway robotic systems. The observatory modules estimates were informed by JWST experience. The spacecraft estimates were based on commercial GEO spacecraft estimates. There were similar analogues for other elements in the planning.

Based on the data generated by the team for the four different observatory sizes, the iSAT study conducted a relative, architecture-level, cost comparison against the conventional approach of single-launch and deployment of the observatory. The data for the single-launch conventional approach was generated by the A-team (A for architecture) from the JPL Innovation Foundry (which is also responsible for JPL's Team-X activities) [37] based on legacy parametric cost models, legacy data on subsystems, well-understood Cost Estimating Relations, and past experiences. The data for the ISA based observatories was based on the resource estimates developed in the Quantitative Analyses phase. The non-labour costs, including materials, and the labour rates used in this were augmented by large margins to account for uncertainties. However, the bounds on these estimates were informed by analogues from past and on-going missions.

The findings from the relative, architecture-level, cost comparison between the conventional single-launch approach and the ISA approach verified the postulations of the Qualitative Analysis. Note that the two analyses, were blind to each other - the Quantitative Analysis was not informed of the postulations of the Qualitative Analysis. The notable findings from this exercise for the four different observatory sizes were:

- The ISA approach showed opportunities for cost savings in the flight system element developments.
- However, the ISA approach incurs additional costs arising from the use of multiple launch vehicles, CDVs, and robotics.
- As flight systems elements are typically about 60-70% of mission estimates, ISA could present major net saving in cost in comparison with a comparable single-launch observatory.
- However, the uncertainty in both the single-launch conventional approach and the ISA approach estimates is fairly high. The two estimates were within each other's uncertainty bounds, when adding 2x and 3x margins for some of the element-level estimates for the ISA approach.
- It did not appear that ISA would reduce the overall cost by half nor would ISA be twice as expensive as the conventional approach.

When the cost estimates of the first servicing mission were included in the comparison, the iSAT study found the ISA approach estimates fared better relative to the conventional single-launch approach. This is because the ISA approach re-uses the in-situ robotic systems used for assembly to do the servicing. In contrast, the single-launch conventional approach would have to develop a new servicing capability. ISA may also reduce the scope of testing and verification needed for servicing in comparison to the single-launch conventional approach. This is because of the significant overlap between the potential servicing and assembly steps. In contrast, the single-launch conventional approach may not benefit from this overlap. Servicing the deployed observatory may actually be more complicated and expensive than servicing the assembled observatory.

11. Conclusions

The iSAT study finds that ISA is likely the only development approach for filled-aperture observatories with larger than 15 meter-class apertures even when considering future large launch vehicles like the SLS. The iSAT study showed that ISA changes the risk posture of observatory development, potentially making it easier to manage risks. This aspect may make it a preferred implementation approach compared to conventional, single-launch approach, particularly for 10 meter-class observatories and larger. For aperture sizes of 15 meters or less, ISA may offer opportunities for reducing the costs of conventional single-launch observatories, particularly when including servicing in mission scope. The cost and risk benefits need to be further evaluated for a specific observatory of interest and its technology needs. With its built-in servicing ability, ISA resolves the uncertainty associated with servicing of the observatory, and thus enables many decades of scientific findings.

When is it worth assembling observatories in space rather than deploying them from a single launch? The iSAT study found that the answer may be "now". Further, in-depth analyses are needed to validate this for a specific observatory of interest while considering prevalent technological and programmatic aspects.

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