When is it Worth Assembling Observatories in Space?

Astro2020 APC Whitepaper

Type of Activity: Space Based Project

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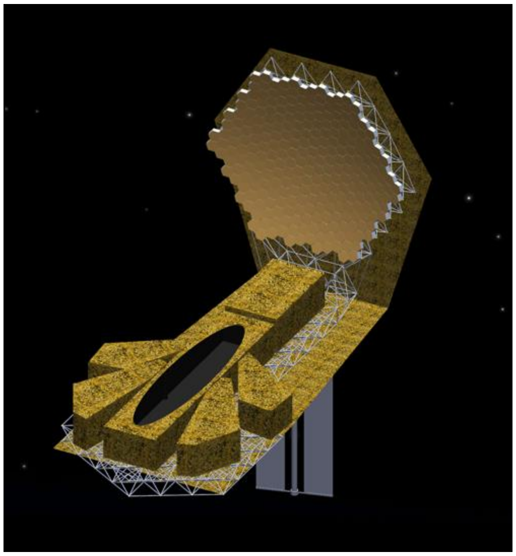

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EXECUTIVE SUMMARY

Since the last Decadal Survey, we have witnessed robotic arms move across the exterior of the ISS and install instruments[1], robots grapple and berth spacecraft[2], unmanned cargo vehicles autonomously reach the ISS[3], the cost of commercial rockets drive downward[4], and large rovers[5,6] commanded on the surface of Mars remotely and safely by humans. Can these capabilities, along with the successful experiences extending the life of Hubble Space Telescope[7] (HST), be leveraged to enable the next generation of large space telescopes to be assembled in space? To investigate the viability and benefits of in-Space Assembly (ISA), Dr. Paul Hertz, Director of NASA's Astrophysics Division, chartered the in-Space Assembled Telescope (iSAT) Study[8], asking "**When is it worth assembling space telescopes in space rather than building them on the Earth and deploying them autonomously from a single launch vehicle?**" This whitepaper summarizes the response.

The iSAT Study responded to this question using a five-step process, as shown in Figure 1, over 14 months and compared the benefits and challenges of ISA with conventional, single-launch approaches (deployed or monolithic).

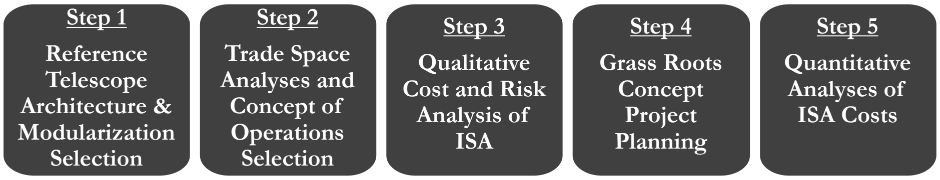

Fig. 1 The Five Steps of the NASA iSAT Study

The Key Findings from this Study are:

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 8-10m fairing appears to be about15m 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 15m or less, particularly when including the servicing infrastructure in the mission. This will depend ultimately on the point design selected and its technology needs.

If the Decadal Survey recommends a flagship-class observatory, we suggest it also recommend:

- **NASA conduct a detailed study of ISA implementation of the specific observatory and evaluate it against a baseline implementation approach**
- **NASA initiate a technology development program to reduce technology gaps associated with in-space assembled observatories**

A brief summary of relevant past efforts, the Study's reference ISA approach, and description of the iSAT study are presented first. The key findings are then discussed in detail before conclusions.

Past Observatory ISA Efforts: In-space assembly of large-aperture telescopes has, for at least a decade and a half, been evaluated as necessary to achieve future astronomical goals. More than a half-dozen significant reports and numerous publications on ISA are hosted on the iSAT web site archives[9], including the Thirty-Meter Space Telescope[10], workshops on large space structures[11], space assembly strategies[12], study of servicing and assembly options[13], a concept for demonstrating assembly techniques on the ISS[14], evolvable telescopes[15], and a modular space telescope design[16] among others. The NASA OpTIIX project[17] developed concept designs to robotically assemble a 1.5m telescope on the ISS. Laboratory technology development efforts have also been successfully carried out with notable examples including truss assembly[18,19], development of robotically manipulatable interfaces[20], and autonomous robotics[21].

Reference ISA Approach: A detailed concept of operations for the assembly of the iSAT reference observatory can be found here and the major steps are graphically shown in Figure 2. These steps are similar to the instrument assembly approach used on the ISS (e.g. OCO-3 [22]).

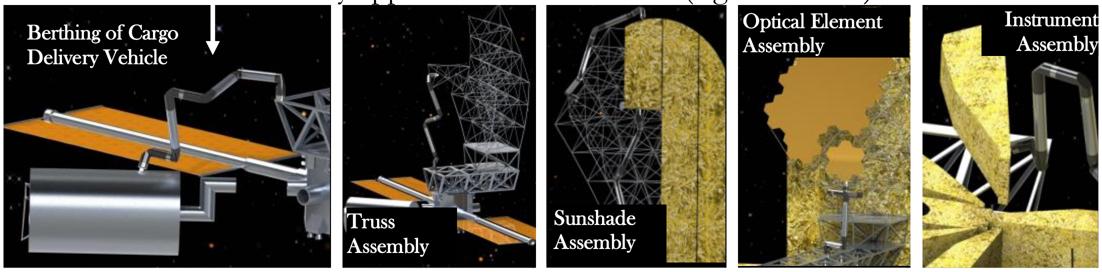

Fig 2. Artistic rendition of representative robotic assembly steps for the Study's iSAT reference concept.

Modularized Design of the Observatory: The observatory is designed as an assembly of separate modules with standardized interfaces. The modules are individually developed, tested on the ground, and launched from one or more launch vehicles. They are designed as precision structures with thermal control to meet stability requirements. These modules are equipped with grapples and interfaces for robotic manipulation, assembly, and adjustability to meet desired accuracy requirements. These may also provide communication, power, and fluid connections. Some module interfaces may also be reversible for servicing.

Launch and Cargo Delivery: The first launch carries the observatory spacecraft, two robotic arms, 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 International Space Station[23] (ISS) or a potential NASA Gateway[24]. Subsequent launches may have rendezvous and proximity operation (RPO) capable Cargo Delivery Vehicles (CDVs) or "smart upper stages" to deliver the modules to the assemblage. Alternately, it is also possible to have a dedicated space tug (e.g. Mission Extension Vehicle[25]).

Robotic Manipulation and Assembly: The robotic arms on-board the assemblage berth the CDV to the observatory spacecraft and then unload and relocate individual modules to their assembly location. Similar to the robots[26,27] on the ISS, the assembly robots may be designed to be capable of mobility across the assemblage using its end effectors and pre-designed grapple points. Using standard interfaces, supervised autonomy (similar to Mars rovers[5,6] or better), 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 may supervise these steps.

Servicing: This process of launching modules, delivery to the assemblage, and robotic assembly continues in iterative steps until the observatory is fully assembled. The arms remain with the observatory after assembly is completed. If subsequent servicing is needed, a new module is delivered using the same approach as used for assembly and the on-board robot arms conduct the servicing. No additional servicing infrastructure is needed.

In summary, the major technical differences from conventional, single-launch approaches are: (1) modularity, (2) multiple launches, (3) RPO, (4) CDVs, (5) robotic assembly, (6) in-space verification and validation (V&V) and adjustments, and (7) built-in servicer.

The iSAT Study benefitted from contributions of more than 70 subject matter experts (SMEs) from six different NASA Centers, fourteen commercial companies, and several government laboratories and academic institutions. The experience base included relevant missions such as HST[7], ISS, JWST[28], WFIRST[29], NASA's Restore-L[30], DARPA Robotic Servicing of Geosynchronous Satellites (RSGS[31]), and Mars robotic missions[5,6]. Study details can be found here. The different steps are shown in Figure 3 and the results of steps 1 and 2 are summarized. In step 4, about 40 Study SMEs made up seven sub-teams representing the key elements of the observatory (a) structures, (b) optics and instruments, (c) robotics, (d) thermal engineering and sunshade, (e) spacecraft, (f) launch systems, rendezvous and berthing, and (g) systems engineering. Working closely together over six months, each group developed a first order implementation plan spanning project 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.

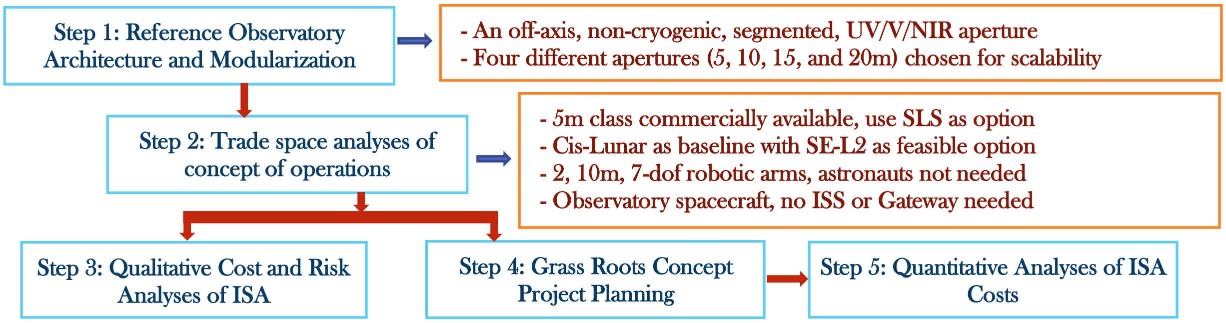

Figure 3: The Study began with a reference design and con-ops followed by the steps of evaluating ISA value

The key Findings of the Study, based on these cumulative set of activities, are summarized next with a representative set of supporting explanations.

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.

Support: Concepts for in-space assembly have been discussed for a long time, including a concept for assembly of JWST[32]. Hence, it is natural to ask, what developments have occurred over the last decade to make ISA relevant now? Since the last Decadal Survey, some of the key enabling capabilities of ISA have technologically matured by being demonstrated and used in space. The ISA paradigm is built on the following key capabilities: (i) modularity, (ii) multiple launches, (iii) RPO, (iv) CDVs, (v) robotic assembly, and (vi) in-space verification and validation (V&V). The current state-of-art in these components are summarized in Table 1 and representative examples are shown in Figure 3. A collection of publications on ISA is also hosted on the Study website.

The last decade has also seen the successful infusion of robotic instrument installation on the ISS into NASA's Science Mission Directorate portfolio of science missions, particularly in Earth Science. OCO-3[22] and ECOSTRESS[33] are the latest examples. The Study ISA concept has a lot of 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[34], and in-space verification and validation of the robotic installation.

NASA identified ISA as being at a "Tipping Point[35]" of wide commercial infusion and made significant investments towards the public-private partnership based In Space Robotic Manufacturing and Assembly program (IRMA)[36]. 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[30,31] 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[37]. Unlike past decades, the technology maturation and programmatic pull makes ISA relevant now.

#	ISA Key Capabilities	Status	Representative Examples	Readiness for Observatory ISA
1	Modular Elements	Flight Demonstrated	Instruments on HST, instruments installed on ISS	Low
		Active Development	JWST primary mirror segments	
2	Launch Vehicles	Flight Demonstrated	SpaceX Falcon, Falcon Heavy, ULA's Delta IV	High
		Active Development	SLS, Blue Origin, Starship, Vulcan Centaur	
3	RPO	Flight Demonstrated	DARPA Orbital Express, NASA OSIRIS-Rex, Cygnus, Dragon, Crew Dragon, ATV, HTV, Progress, Soyuz	High
4	CDVs	Flight Demonstrated	SpaceX Dragon, Cygnus from Northrop Grumman	High
5a	Space Robotics Hardware	Flight Demonstrated	Several robotic arms on ISS (e.g. Canadarm 2), Orbital Express robotic arm, Mars Rover arms, Shuttle arm	High
		Active Development	NASA Restore-L and DARPA RSGS robotic servicing arms, Canadarm 3, Maxar's Dragonfly arm, Mars 2020 rover	
5b	Space Robotics Software	Flight Demonstrated	Mars Rover Autonomy (e.g. MSL, MER), ISS, Orbital Express	Medium
		Active Development	Mars 2020, Mars Sample Return, NASA Restore-L, DARPA RSGS, NASA Tipping Point Demonstrations	
6	In-space Verification and Validation	Flight Demonstrated	Instruments on HST, instruments installed on ISS	Low
		Active Development	JWST primary mirror segments and wavefront control	

Table 1: Key capabilities needed for ISA. Some are at a credible maturity level for consideration for telescope mission observatories. Technology gaps and development needs remain specific to observatory assembly

Despite the maturation of some of the key capabilities of ISA, there are going to be technological challenges in adapting and applying it to an observatory assembly. Capabilities 2, 3, and 4, from Table 1, can be readily leveraged. However, capabilities 1 and 6, which are specific to an observatory, have challenges that need to be addressed. For example, modularization of the observatory would need a large trade space analyses beyond what was conducted in this Study. Interfaces to assemble these modules specific to the constraints of the observatory would have to be developed. Ability to meet specific stability, alignment, contamination standards, specific robotic behaviors and their supervised autonomy capabilities, and other performance requirements would have to be defined and demonstrated for a specific observatory design. The Study did not conduct a detailed technology gap analysis. However, it identified preliminary engineering development needs and technology gaps, some of which are shown in Table 2. 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.

- **Assembly of modules to form precise, linear, thermally stable trusses**
- **Multi-agent collaboration and autonomous assembly**
- **Manipulators walking on trusses while reducing induced stresses**
- **Manipulation of soft goods for to sunshade assembly**
- **Attitude control with moving center of mass during assembly**
- **Precise joining interfaces for robotic assembly and servicing**

Table 2: Representative Technological Challenges


Space X Dragon cargo resupply on ISS
Robotic Assembly on ISS
RPO shown on Orbital Express
Supervised Autonomy for Mars Rovers
NASA Restore-L robotic capabilities

Fig. 3: ISA technologies in use today form the foundation for ISA feasibility. Image credits: NASA and DARPA

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.

Support 1: Conventionally developed observatories are architected to the constraints of a single, specific vehicle's launch capacity. 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[38]. This is the "tyranny of the fairing"[39]. 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 units or 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. Both the future NASA Space Launch System (SLS)[40] and currently-existing commercial vehicles can be used for the multiple launches. The larger net mass and volume allocations made available for the payloads by multiple launches overcome the hard constraint of designing the entire observatory to fit in a single fairing.

Support 2: Larger mass and volume allocations with ISA can enable architectures and design choices of instruments and telescopes that better suite science goals but 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 and improved coronagraphy performance[40]). Availability to larger mass and volume allocations can also enable observatories to use stiffer structures thereby improving stability. More massive monolith telescopes can also be enabled by flying the primary mirror separately from the instruments. The observatory could even be architected to be evolvable[41] 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 forge ahead with simpler optical designs and forgo expensive light-weighting activities along with their model development and validation efforts. Prime focus instruments[42] could also be possible with ISA.

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 8-10m fairing appears to be about 15m in size.

Support: Three emerging launch vehicles are baselining fairing diameters larger than the currently available 5m class fairings: Blue Origin's New Glenn[43], SpaceX's Big Falcon Rocket[44] and NASA's SLS[22]. From data available to this Study, the SLS appears to offer the largest payload mass and volume capacity to date. The LUVOIR[45] space telescope concept team did extensive packaging and system design work to successfully fit a 15m aperture UV/Optical/NIR observatory into the SLS Block 2 fairing[46]. A larger fairing (10m) 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.

Hence, this fairing is unlikely to enable an even larger telescope aperture. Thus, apertures greater than 15m in diameter are unlikely be deployed to SE-L2 with a single launch and will require some form of ISA. As ISA can use multiple launch vehicles and modular components, the fairing size does not limit the aperture size. The iSAT Study worked out the conceptual details of assembling a 20m aperture using 5m class commercial launch vehicles by scaling the 15m aperture approach. ISA is inherently scalable and can enable future large observatories beyond what can be fit, even when folded, in a SLS or future planned vehicles.

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.

The world has both marveled at, and profited by, the benefits of HST servicing[47]. HST today is a more powerful and effective telescope than it ever has been since its initial launch due to its servicing. Will future observatories have the same opportunity of being serviced, and if so, how? ISA provides a unique opportunity for an in-space assembled observatory to be readily serviced, thus enabling the observatory cost to be amortized over many decades of scientific findings very much like the HST. This is discussed next with representative support for this Finding.

SUPPORT FOR THIS FINDING

Conventional, Single-launch Approach Needs an Additional Servicer; ISA Does Not

- Congress has mandated that future observatories be serviceable, where possible[48].
- The four large astrophysics mission concepts[45,49,50,51] are all including aspects of robotic serviceability.
- Currently, there is no credible plan or resource for servicing them. NASA would need a separate program to develop a servicing capability for these future observatories.
- Servicing would need (i) modular 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 for servicing.
- Result is redundancy: a) first developing the observatory with conventional, single-launch approach, and then b) developing the most of the capabilities needed for ISA to service it.
- In the ISA approach, the robotic arms used for assembling the observatory can be re-used for in-situ servicing. Similarly, delivery of new modules may re-use the CDV approach as used for assembly.

Assembled Modules May Be Easier to Service

- Serviceability of some of the deployments in the conventional designs can be extremely difficult, if not infeasible. For e.g., a monolithic sunshade deployment anomaly may be difficult to service, if at all.
- In-situ robotic servicing at the module level should be simpler with ISA
- The ISA incremental assemble-validate approach also ensures any failure in a module may be replaced in a timely manner by an updated module in a subsequent launch.
- With ISA, servicing may be simplified by architecting it to be a reversal of the assembly process. This allows design features for assembly to be re-used for servicing. This would also enable the design to be verified for servicing.
- ISA may also enable missions to maintain some on-orbit sparing capability, where appropriate.

In-situ Robotic Arms Provide Opportunistic Servicing and Anomaly Resolution

- Many space robotics missions (e.g. Shuttle flights[52], ISS, and the Mars missions) have used their robots for unanticipated servicing scenarios or anomaly resolution.
- In some cases, the anomaly may be time sensitive such as, an anomaly that exposes optical elements to an 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 observatory.
- ISA has on-board, built-in servicer that provides flexibility and opportunity to address these kinds of unforeseen servicing and anomaly resolution needs.

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.

In the qualitative analysis of the iSAT Study (Step 3), the Study SMEs arrived at consensus that the ratio of JWST's 6.5m aperture and observatory mass and volume to the 5m class launch payload capacity represented a combined cost, schedule, and success risk threshold for the conventional, single-launch approach. The SMEs estimated that observatories with a 10m class aperture size (and its large sunshade or shield) would represent a similar risk threshold for a future SLS launch vehicle. The consensus was that ISA may be a lower-risk approach at and beyond that threshold. Some of the representative supportive discussion for this are discussed next.

SUPPORT FOR THIS FINDING

ISA Mitigates Risks of Deployment Mechanisms

- JWST relies on 20 sequential deployment events, 40 deployable structures, and 178 release mechanisms[53], many of them in the sunshield.
    - It may be difficult, if at all possible, to recover from failure or anomaly during deployments.
- Conventional, single-launch future observatories and their large sunshades may need even more of such deployment mechanisms.
    - These mechanisms have high reliability, but the sheer number of them impacts the overall system reliability.
    - The rigorous testing of all the different deployment mechanisms is required and is expensive. It also introduces schedule risk when there are anomalies.
- ISA may have orders of magnitude fewer of such mechanisms.
    - ISA will likely use robotically reversible and adjustable joining interfaces with an incremental assemble-and-verify approach, similar to instrument assembly on the ISS.
- But most profoundly, ISA may also provide the ability to recover from faults or anomalies with in-situ servicing and ability to replace a failed module.

ISA Mitigates Single Critical Path Related Challenges

- 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[54].
    - Maintaining a high level of funding for several years, as needed in these phases, may put strain on the Astrophysics budget.
    - Cost growth[55] 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, i.e., decoupled design-build-test phases (e.g., multiple 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,
        - Reduce the sensitivity to budget variations.
    - This may result in longer development and implementation lifetimes, but this may be preferable in some circumstances.

Launch Failure May Not Be Mission Failure

- 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.

SUPPORT FOR THIS FINDING

ISA Offers Options to Manage Mass and Volume Growth Risks

- As challenges emerge during implementation and integration phases of a project, mass or volume growth is typically encountered in many conventionally single-launch space flight missions.
    - With a hard ceiling of launch capacity, this typically spirals into a "zero-sum game" of managing the growth by absorbing it across different flight elements' margins.
    - It can trigger numerous re-design-test-validate cycles.
    - This may impact schedule, eat into desired margins, and result in cost growth.
- ISA may provide higher mass and volume allocations through modular architecture and planned use of multiple launch vehicles.
    - As the flight system elements are decoupled through the use of modules, mass or volume growth in one or few modules may not impact the entire observatory development.
    - This breaks the "zero-sum game" of mass and volume limit.
- ISA may also uniquely provide the option to add additional launch(es), or change to a higher capacity launch, late in the project when deemed more cost effective than project-wide redesigns.

ISA Takes Advantage of the Risk Benefits of Modularization

- Modularity has many risk benefits:
    - Encapsulates complexity at the module level; prevents it from spreading through the system.
        - Faults and anomalies can be more readily contained.
    - Reduces the total number of interfaces and mitigates indirect coupling between elements.
    - Enables performance quantification and verification at the module level, not at system level.
    - Eases integration and assembly, handling and transportation, planning and tracking.
- JWST has some distinct modules (e.g., the primary segments); some elements are not modular (e.g., sunshield).
    - One of the lessons learned was to "strive for modularity in the design and maintain simplest possible interfaces inducing swap out key risk items late in integration flow"[57].
- In reality, the single-launch approaches often sacrifice modularity to meet mass and volume limits.
- ISA necessitates modularity and enables it by providing higher mass and volume allocations. It may thus leverage the different benefits of modularity more readily than a single-launch approach.

Simplifies the Assembly, Integration, and Test Process

- With larger apertures, the cost, complexity, and time required to complete telescope and system-level assembly, integration, and testing (AIT) becomes increasingly challenging.
- Performing these tests in the presence of gravity becomes particularly difficult.
    - For example, sunshield deployment tests for JWST[58].
- It is also a single critical path: all flight elements have to come together for flight integration and tests.
- By eliminating complex post-launch deployments, using simpler module and interface level testing, and reversible interfaces in the assembly, ISA 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 impact final program cost and schedule.

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

The qualitative analysis of the Study (Step 3) concluded that the ISA approach will likely offer cost benefits in the flight systems development. Some of the rationale behind this is summarized in Table 3. As flight systems (telescopes, instruments, and spacecraft) are typically about 60-70%[59] of mission estimates, ISA could present major net saving in cost in comparison with a comparable single-launch observatory. However, the ISA approach incurs additional costs arising from the use of multiple launch vehicles, CDVs, and robotics. To quantitatively understand the net effect at an architectural level, the Study conducted a cost estimation between ISA and single-launch approach for the reference observatories with 5, 10, and 15m apertures. Technology development and Pre-phase A cost estimates were not included in this effort for both approaches. The details of the quantitative estimation are summarized in the text boxes and the results are discussed next.

Potential opportunities for cost benefits with ISA

- 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 shield; 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

Table 3: ISA may provide opportunities for cost savings

Estimating Costs of Conventional, Single-Launch Observatories

- The Study funded JPL's A-team[60] (A stands for architecture) to conduct an independent cost estimation using conventional cost models
- Used the MEL developed for the three observatories of the iSAT study
- Used a telescope cost model[61], instrument costs from CADRe[62] using analogues, legacy mission data, cost to cost ratios for flagship class missions

Challenges of Costing ISA with Current Cost Models

- ISA is a fundamentally different implementation approach from a conventional, single launch observatory approach.
- The Study found that **the existing cost models are inadequate for estimating an ISA mission cost.**
  - These cost models are largely mass-dependent, rely on legacy data for missions constrained by a single launch vehicle's capacity, and do not consider many of the features unique to ISA.
- Hence, the Study conducted a bottoms-up, grass roots cost estimation of the ISA implementation. This was blind to the A-Team cost estimate findings.

Grass Roots Cost Estimation of the Three ISA Observatories

- Developed by a badge-less team of ~40 SMEs; experience from JWST and other relevant missions
- Used detailed phase A-E plan, mission schedule, MEL, PEL, launch manifest, and resource estimates.
- WBS 1-4 were cost to cost ratios (same as A-Team), instrument costs from CADRe, grass roots for optical system, structures, robotics and spacecraft. Analogues for CDVs[63], NASA Launch Services reference for launch vehicles.
- Grass roots resource estimates were increased by a factor of 2 to account for uncertainties and potential optimism in early grass roots costing.
- Access to prior estimates of servicing infrastructure, analogous to NASA Restore-L and DARPA RSGS
- Full details of basis of estimates and results can be found here.

The trends in the estimates from the A-team (single-launch approach) and grass roots ISA estimation are shown in Figure 4. **These are not total cost comparisons.** The trend in the estimates of the OTE and spacecraft have a lower rate of scaling for ISA than the single-launch approach. The telescope cost estimate trend line has a lower (cost beneficial) rate than the one reported in literature[59]. These trends for ISA reflect many of the opportunities listed in Table 3. For example, the spacecraft estimates for ISA benefitted from not having several hundred deployment mechanisms, and their testing and integration. Similarly, the telescope structure and optical elements benefitted from modular, parallel development and simplified AIT of many identical modules. The AIT process for the sunshade (counted under spacecraft estimates) was also significantly simplified, for example, from not having to test a massive, monolithic sunshade in Earth gravity. The ISA approach baselined smaller sunshade modules that were anticipated to be easier to test and integrate. The cost of robotics was not a major fraction of the overall costs. It also did not scale with aperture size as the same sized robotic arms could be used for the three observatories. For the 5m case, it was ~6% of total cost estimates and was a smaller fraction for the 10m and 15m cases. The cost of CDVs and multiple launches were significant cost increases for ISA. This narrowed the gap in the trends in the total estimates between the two approaches.

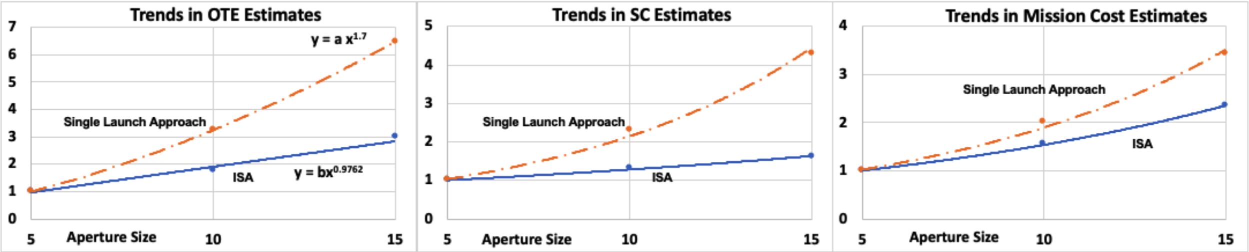

Fig 4. In each of the plots, the 10m and 15m cost estimates are normalized by the 5m estimates for the corresponding implementation approach. The single-launch approach estimates are shown in dotted line while the ISA is shown in solid line. The 5m estimates for ISA were different from the single-launch approach.

As seen here, when comparing the total cost estimates for the two approaches, cost savings in the flight system with ISA overcame the costs incurred by the robotics, multiple launches, and the CDVs. With 100% margin placed on the ISA grass roots resource estimates for flight systems, the 10m and 15m aperture observatory cost estimates for ISA were less than the single-launch approach while the 5m was higher. However, when considering the potential uncertainties in the underlying approaches of this initial analysis, **the only meaningful conclusion is that the cost estimates are within each other's uncertainty bounds** for the two implementation approaches. A more detailed analysis is needed for a specific observatory of interest.

However, if servicing is included in the observatory mission scope, ISA provides another potential opportunity for cost savings. As the single-launch approach needs an external servicing infrastructure, the cost estimate of a servicer would have to be added to its mission estimates. The cost of the servicer would include robotics, RPO capabilities, and an additional spacecraft. ISA may not incur these costs as it can re-use the in-situ robotic arms used for assembly (Finding 4).

The Study recognizes that the results will likely vary with different observatory designs and other assumptions. Hence, a conservative conclusion is that ISA may provide opportunities for cost reduction that need to be carefully evaluated for a specific observatory and its technology needs.

Conclusions: The iSAT Study finds that ISA is likely the only development approach for filled-aperture observatories with larger than 15m aperture even when considering the SLS. 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 10m class observatories and larger. For aperture sizes 15m 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.

The Study suggests that if the Decadal Survey recommends a large space observatory, it also recommend:

- NASA conduct a detailed study of ISA implementation of the specific observatory and trade it against a baseline implementation approach
- NASA initiate a technology development program to reduce technology gaps associated with in-space assembled observatories.