The Case for In-Space Assembly of Telescopes to Advance Exoplanet Science

A Whitepaper in support of the Exoplanet Science Strategy

Authors:

Rudranarayan Mukherjee, Jet Propulsion Laboratory, California Institute of Technology
Rudranarayan.M.Mukherjee@jpl.nasa.gov
818-354-2677

Nick Siegler, Jet Propulsion Laboratory, California Institute of Technology
Bradley M. Peterson, The Ohio State University/Space Telescope Science Institute
Gordon Roesler, Defense Advanced Research Projects Agency
John Grunsfeld, NASA Goddard Space Flight Center (emeritus)
Harley Thronson, NASA Goddard Space Flight Center
Matt Greenhouse, NASA Goddard Space Flight Center
Ron Polidan, PSST Consulting, LLC
Howard MacEwen, Reviresco LLC

For references cited in this Whitepaper, please see:
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1.0 Introduction: This whitepaper makes the case that robotic In-Space Assembly (ISA) should be studied and developed by NASA as a potential approach (1) to break the space telescope cost model, (2) to overcome limitations of a single fairing size, and (3) to reduce the risks associated with a single launch and complex deployment. We compare ISA against the existing paradigm of deployment from a single fairing and discuss the important developments over the last decade that underscore the feasibility of realizing the benefits of ISA. We also suggest a few steps that may be considered towards evaluating ISA and developing it as a new paradigm for large space assets. While our commentary is applicable to different astrophysics assets (e.g. starshades and interferometers), this whitepaper focuses on telescopes without loss of generality.

2.0 What is ISA? ISA is the assembly of modules in space to form larger functional elements[1-2]. The International Space Station (ISS) stands as the greatest example: the largest human-made body in low Earth orbit[3] (LEO). Currently, instruments and other payloads are regularly attached to the ISS using an onboard robotic system, effectively demonstrating assembly[4]. The essential idea of in-space robotic assembly of telescopes and other assets is to design them from the start as an ensemble of modular components that have purpose built standard interfaces by which they can be assembled robotically (with or without in-situ human presence). These components can either be packed individually and launched in a single vehicle or launched in multiple vehicles using smaller commercial launches. The assembly could be with supervised autonomy (akin to Mars rovers[5-6]), high-bandwidth telerobotics (akin to ISS), or with in-situ human supervision (akin to robotic surgery[7]). Instruments could also be launched separately as complete systems and periodically updated. Unlike terrestrial robotic assembly with massive tether lines and bolted joints, the in-space assembled telescope could have standard interfaces similar to quick-connects or USB ports. The highly successful Hubble Space Telescope (HST) servicing missions[8] used this technique for the wide field instruments. The components of each module would be assembled on the ground, enabling finer assembly techniques with humans or machines. Each module could be independently tested and verified.

The overall structural accuracy, precision, and stability requirements for a telescope are stringent[9] and it is natural to question if ISA can meet these requirements. Typical robotic assembly on ground or on the ISS has approximately sub-centimeter level of accuracy in repeated manipulations. However, recent development in precision positioning systems have demonstrated centimeter-level travel range with nanometer-level resolution (e.g., NEXLINE linear drives[10]). Hence, incorporating adjustability and correctability within error budget allocation and system design can potentially loosen requirements for robotic assembly to the order of sub-centimeter to achieve the desired wavefront error stability requirements. On the HST servicing missions[8] the interfaces were designed to achieve stringent tolerances at optical wavelengths proving that wavefront error stability can be achieved in modular systems.

3.0 What makes it feasible? There have been breakthrough developments over the past decade in (1) the capabilities of robotics, (2) commercialization and reduction in the cost of launch vehicles[11], (3) demonstrated capabilities for precision autonomous rendezvous and docking[12], and (4) the possible availability in the next decade of a cis-lunar platform called the Lunar Orbital Platform-Gateway[13] ("Gateway" for short). We believe these developments will only continue to become more capable and, along with creative architectural approaches in design and assembly, may enable future space telescopes by lowering cost and risk.

3.1 Robotics: The last decade has seen a revolution in the field of robotics with significant investments made by NASA, the Department of Defense, the commercial sector, and academic institutions worldwide[14-15]. Consider the following examples.

Robots on Mars: The Mars Rovers[5-6] and the Phoenix Lander[16] are a huge success story for semi-autonomous robotic systems developed and deployed by NASA. For more than a decade, the rovers have travelled dozens of miles on the surface of Mars, taken revealing images of the Martian landscape, drilled into scientifically interesting rocks, and taken geological samples that have enabled breakthrough science. The supervised autonomous robotic capabilities demonstrated by these missions have grown with every mission. While these are examples of planetary surface exploration, the core algorithms and robotic autonomy developed for these systems are cross-cutting and applicable to robotic assembly of telescopes and other assets (see [17] as e.g. of applying these to robotically assemble a 3m back plane truss from modular elements).

Robotic Servicing Missions: DARPA, NASA and commercial contractors have demonstrated rendezvous, docking and servicing of avionics on the Orbital Express Mission[12,18], including a robotic arm and autonomous operations. DARPA's Robotic Servicing of Geosynchronous Satellites (RSGS) mission[19] is developing technologies for in-space servicing. This includes close inspection of a spacecraft, rendezvous and berthing, robotic manipulation for anomaly resolution (e.g., failed deployment) on the spacecraft being serviced, and the attachment of an external payload on the spacecraft. RSGS is developing a sophisticated robotic payload consisting of force-torque sensors equipped on two seven-DOF arms (Front-end Robotics Enabling Near-Term Demonstration arms[20-21]), a perception sensor suite (LIDAR and cameras), a tool change-out mechanism, different robot end-effector tools, and an ability to berth secondary payloads. NASA's Restore-L mission[22-23] is developing technologies to refuel Landsat-7[24] in LEO using a servicer analogous to the RSGS servicer. Restore-L is developing tools for refueling spacecraft and relevant robotic and sensing capabilities for in-space servicing. The technologies being matured by these missions pave the way for future ISA missions.

Robotics on ISS: The ISS hosts a highly capable telerobotic system consisting of the Canadarm2[25] and the Special Purpose Dextrous Manipulator (SPDM)[26], which have telerobotically assembled payloads on the ISS. The robotic system berths in-coming resupply vehicles, detaches the payload from the vehicle, moves it to the appropriate position, and assembles[4] it to the ISS's structure using a standard interface[27]. Telerobotic operations on the ISS have also manipulated electronic cards and other utility elements. The series of NASA Robotic Refueling Mission demonstrations on ISS exercised the ability of SPDM to use modular tools to cut safety wires, remove caps, turn valves and practice fluid transfers with an ISS payload. The tool complement included specialized tools to exercise a variety of connectors and HST like latches and interfaces.

Terrestrial Robotics: Robotic surgery[7] is a classic example of the advances, benefits, and success of robotics in a high-profile application. Recent years has also seen an enormous interest in autonomy in a diversity of terrestrial applications such as self-driving cars[28] and drones[29]. Consider the following as examples of recent programs relevant to ISA:

- DARPA's Autonomous Robotic Manipulation[30] and their subsequent Robotic Challenge[31] developed core technologies for autonomous robotic behaviors including sensing, force-controlled manipulation, motion planning, and state estimation, among others.

Robots autonomously drove vehicles, manipulated human tools, and performed autonomous behaviors such as stair climbing, door opening and valve turning, among others.

- NASA's Space Technology Mission Directorate (STMD) Tipping Point Program is developing robotic ISA capabilities**[32]** by leveraging the growing interest and capabilities of the commercial sector. The program includes (a) Public-Private Partnership for Robotic In-Space Manufacturing and Assembly of Spacecraft and Space Structures (Orbital ATK), (b) Versatile In-Space Robotic Precision Manufacturing and Assembly System (Made in Space, Inc.), and (c) Dragonfly: On-Orbit Robotic Installation and Reconfiguration of Large Solid RF Reflectors (Space Systems Loral (SSL)). Each of the lead companies listed has also partnered with additional capable commercial companies.

Commercial Sector: Much of the robotic hardware used in past space missions was developed by commercial entities under contract with government agencies or laboratories. In the recent past, the commercial sector has demonstrated growing interest and capabilities that have the potential to enable ISA. For example, (1) the DARPA RSGS program is a public-private collaboration**[33]** between DARPA and SSL, where SSL is paying for the spacecraft while DARPA funds the robotic payload, and (2) Orbital ATK is developing the robotic in orbit life-extension and maneuvering services for GEO spacecraft using its Mission Extension Vehicle**[34]**.

3.2 Access to space: The last decade has seen impressive advances by the commercial sector in launch capabilities**[11]**. Access to the ISS using commercial launch vehicles has now been demonstrated by two aerospace companies: SpaceX and Orbital ATK. Several companies have also successfully developed smaller, dramatically cost-effective launch vehicles, thus creating a new paradigm for commercial space access. The recent successful launch of SpaceX's Falcon Heavy**[35]** not only captivated the public, but openes up opportunities for telescope designs that are assembled from elements delivered to orbit by lower-cost vehicles.

3.3 Lunar Orbital Platform-Gateway: The National Space Council recommended Gateway**[36]** holds the promise of robotic and crewed presence together in the cis-lunar environment, including periodic launch access and resupply. As was the case with HST, where relative ease of access enabled servicing and regular instrument upgrade, the Gateway can be a venue for a similar approach to assembling and servicing. Furthermore, the second Sun-Earth Lagrange point (SEL2**[37]**), an attractive venue for telescopes, has a notably low delta-v from the cis-lunar environment (tens of m/s). This opens up a low-fuel and low-cost mission architecture option for a Gateway-enabled assembled telescope at cis-lunar to travel to SEL2 and subsequently return to the Gateway for servicing and upgrades. In light of the fact that Congress has mandated**[38]** that, when feasible, future telescopes must be serviceable, the Gateway could potentially fill that objective. The overall cost and risk posture could potentially be even more favorable as the robotics, crew presence, and resupply vehicles may be leveraged from other NASA investments. Crewed supervision of the robotic assembly, close inspection, and potential intervention for anomaly resolution, also reduces perceived risk with robotic assembly.

4.0 Benefits of ISA: The benefits to science of large-aperture space telescopes are well-established**[39]**. They include important advances in both the search for exoplanets and general astrophysics. However, our current paradigm for building space telescopes results in observatories costing several billion dollars, with costs increasing with aperture**[40]**. Furthermore, for current conventional space observatory designs, size and mass are constrained by what can be transported into space in a single launch. The following are some ways in which ISA could overcome the long list of challenges in current designs for the future space observatories.

Launch Vehicle Dependence: ISA can enable telescope sizes that are not feasible with the deployment approach. For deployed observatories, such as the James Webb Space Telescope (JWST**[41]**), everything has to fit within a single fairing. Hence, the telescope aperture is size-limited by the fairing. The current paradigm cannot, therefore, take advantage of commercially available smaller and cheaper vehicles. The dependence on heavy-lift launch vehicles significantly increases the cost and risk posture of future telescopes developed using current designs. For example, three of the four NASA funded Science and Technology Definition Team (STDT) concept studies**[42]** baseline large apertures that use the planned Space Launch System (SLS**[43]**) with descope options of smaller aperture (with lower science return) if the SLS is unavailable. ISA is not dependent on a fairing size nor a specific launch vehicle. As the telescope is designed in modules that are incrementally assembled, ISA can take advantage of better packing in a single fairing or multiple launches where modules are sequentially supplied to the assembly location. Components and sub-assemblies can be designed to fit into launch vehicles of different sizes, particularly the cost-effective commercial vehicles.

One-Time Deployment Risk: The current approach of self-deployment (e.g., JWST) carries the risk of failure stemming from anomalies during its one-time deployment. The lesson of HST is clear: with no servicing capabilities available, such failure could lead to mission failure. In ISA, deployment risks are mitigated through incremental assembly using standard, reversible, adjustable interfaces. Use of spares, careful supervision via monitoring and safety protocols, reversible robotic behaviors and other operational approaches may reduce the risk of assembly. The use of a robotic system also allows the possibility of post-assembly corrections or adjustments to meet desired performance.

Evolution with Time: Telescopes that are self-deployed cannot grow in aperture. The deployed telescopes are also limited in number and size of instruments hosted by the observatory. With ISA, the telescope itself could be designed to be evolvable**[44]**, say starting with a 3 – 5 meter aperture and growing in stages over time with low-cost commercial servicing launches to 20 meter or larger. Similarly, the telescope could be designed to host more and diverse instruments than may be feasible with a single launch in a deployed approach. These instruments could be launched subsequently on lower-cost commercial vehicles and robotically installed. Moreover, instruments that are larger than the fairing size could also be designed if the instruments themselves are also assembled in space.

Launch Loads: In current designs where all components are integrated into their final system configurations and folded into the fairing, large design margins must be carried to survive launch loads. As components cannot be individually launch-locked, the entire system must be substantially ruggedized**[45]**. This reduces effective mass and space available to the payloads, and represents a significant cost in the overall design and construction. For ISA, modules could be designed to standard packing volumes and launch-locked individually. Hence, only the individual modules, not the entire telescope, would have to be ruggedized against launch stresses. This may allow new designs and use of new technologies that are not feasible in the current paradigm.

Integration and Test Facilities: The current design paradigm requires significant investments in terrestrial test facilities. As telescope observatory sizes grow, new facilities have to be designed and constructed or old ones refurbished at significant costs to accommodate the telescope and the detailed deployment schemes. The complexity of packing the 6.5-meter JWST into its fairing and planning for its deployment has required impressive engineering ingenuity. However, it also involved significant complexity, cost, and risk. This could change with ISA. For ISA, each module would be independently tested and verified. This would allow integration and testing to occur in existing facilities and at a scale that reduces cost and complexity. Through standardization[46] and modularity in place of unique parts, as is currently the case, cost is expected to be dominated by recurring engineering rather than higher-cost non-recurring engineering. Spares can also be fabricated and launched to reduce overall risk. If launched sequentially, in-space testing may also be feasible, thereby limiting costly mistakes (if any) to components and not the entire telescope.

5.0 Why Now? There are four NASA-chartered future space telescope concepts being studied and designed for consideration by the National Academies' 2020 Decadal Survey. Of these, three depend on the SLS, whose future is currently uncertain. However, the recent successes of commercial launch vehicles underscores potential opportunities for significant cost savings and programmatic risk reduction if the telescopes could avail themselves of the ISA approach. The telescope designs could be significantly different if they could be modularized, launched on a few of the new generation vehicles and assembled in space. Furthermore, if an evaluation of ISA found favorable risk and cost benefits, any required technology developments and demonstrations should start in the near future to enable a mission in the foreseeable future (pending 2020 Decadal Survey recommendations). The ISS could be an excellent venue for such new technologies and risk-reduction efforts. However, the future of ISS is uncertain beyond about 2025. There is, thus, a limited-time opportunity for any relevant ISA technology activities on the ISS. The cis-lunar Gateway is currently in concept design phase and there is also a limited time window to inform its design of ISA opportunities and requirements. The RSGS robotic servicer is expected to be operational in the early 2020s. If ISA experiments were formulated and developed within the next few years, the RSGS servicer could serve as a means for facilitating ISA technology demonstrations beyond its primary mission. Thus, embarking on a path to studying ISA and design of telescopes using robotic assembly in the next few years provides an opportunity to design and develop ISA experiments that can occur in the mid 2020s using the ISS, RSGS servicer, or any Gateway capabilities.

6.0 Recommendation: In-Space Assembly offers the possibility of significant risk and cost benefits through (1) modularity in components, (2) standardized interfaces, (3) smaller, easily launched components, (4) use of lower-cost, commercial vehicles, (5) reversible, supervised and safe robotics with potential astronaut involvement, (6) incremental builds and inherent serviceability, (7) opportunities for more instruments and upgrades, and (8) possible reduction in integration and testing complexity. While there is significant interest and promise in ISA, there has yet to be a comprehensive evaluation for designing and developing a space telescope via this new approach. We have not yet demonstrated the achievability of the purported benefits nor have we studied all the factors that may impact cost and risk. We believe that NASA should conduct design and trade studies to investigate the benefits, if any, of ISA of large-aperture telescopes. If the findings of the study are favorable, it could be followed by a technology roadmap identifying the key technology gaps and the demonstration path to closing them. Otherwise, we will continue to realize one space telescope every generation at large costs with their own unique risks and limited by launch vehicle fairings.