

NOTE: This document was prepared by a team that participated in the 2018 Workshop on Autonomy for Future NASA Science Missions. It is for informational purposes to inform discussions regarding the use of autonomy in notional science missions and does not specify Agency plans or directives.

2018 Workshop on Autonomy for Future NASA Science Missions: Astrophysics Design Reference Mission Reports

Table of Contents

Introduction	2
The Astrophysics Design Reference Mission Report	3
Astrophysics Design Reference Mission Report Summary	14

NOTE: This document was prepared by a team that participated in the 2018 Workshop on Autonomy for Future NASA Science Missions. It is for informational purposes to inform discussions regarding the use of autonomy in notional science missions and does not specify Agency plans or directives.

Introduction

Autonomy is changing our world; commercial enterprises and academic institutions are developing and deploying drones, robots, self-driving vehicles and other autonomous capabilities to great effect here on Earth. Autonomous technologies will also play a critical and enabling role in future NASA science missions, and the Agency requires a specific strategy to leverage these advances and infuse them into its missions. To address this need, NASA sponsored the 2018 Workshop on Autonomy for NASA Science Missions, held at Carnegie Mellon University, October 10-11, 2018.

The Workshop goals included:

- Identifying emerging autonomy technologies (10-15 years) that will:
 - Enable or enhance mission capabilities
 - Reduce risk
 - Reduce cost
- Identifying potential collaborations, partnerships, or linkages involving government, industry, and/or academia to enable these technologies

Capturing crosscutting autonomy technology requirements for future NASA missions

Over 90 individuals from industry, academia, and NASA participated in the workshop, which included [presentations by keynote speakers, panel discussions, and small group discussions](#).

To provide structure for workshop discussions and post-workshop analysis, NASA established eight teams to examine the following Design Reference Mission (DRM) areas: Astrophysics, Earth Science, Heliophysics, Mars, Moon, Ocean Worlds, Small Bodies and Venus. Each DRM team was led by a scientist and a technologist, and team members consisted of workshop participants with relevant experience and interest. NASA asked each team to develop one or more mission scenarios that would be enabled by infusion of autonomous technology. The Agency provided guidance to support these team discussions; in particular, NASA urged the DRM teams to “think out of the box” and to consider bold missions that would be enabled by autonomous technology to provide valuable science results. Each DRM team developed mission scenarios that included defined science objectives, capability and technology needs, system requirements, and a concept of operations. Teams also identified gaps where autonomy technologies and other supporting technologies need to be developed and/or infused to enable each mission.

The DRM teams conducted small group discussions at the workshop and then presented a summary of their findings to all workshop attendees. Each DRM team continued to refine its mission scenarios after the workshop, creating both a full report and a summary report to document team findings. DRM teams also reported results at the December 2019 meeting of the American Geophysical Union.

This document contains the full report and summary report generated by the Astrophysics DRM team. [Full and summary reports generated by all eight DRM teams, plus a summary of workshop results are available online.](#)

The Astrophysics Design Reference Mission Report

Part I: Abstract

Astrophysics Overview

As we persevere in our quest to answer the fundamental questions of science by peering into the heart of the universe, we strive for ever larger apertures to see better than what we can see today. In a domain of science where every photon counts, the size of the aperture is directly correlated to better science. But past experiences have shown that developing a large observatory to fit, even when folded, into a single launch fairing of an existing or a future planned launch vehicle has various technological, programmatic, schedule, and cost challenges. Is there a way to mitigate these challenges for future observatories and improve the cost and risk postures of their implementations? Further, servicing these observatories in space to extend their lifetimes and update instruments for many decades of scientific returns is also a challenging aspect. How will future observatories have the same opportunity of being serviced? To address these issues, NASA and other government entities are expressing growing interest in exploring the value proposition of in-space robotic assembly and servicing for large space assets including optical telescopes. This interest is also reciprocated by industry through internal investments and public-private partnerships.

Design Reference Mission

We study the autonomous in-space robotic assembly and servicing of a 20-m, filled-aperture, segmented, ultraviolet/visible/near-infrared, non-cryogenic observatory from its modular components in cislunar orbit. The mission is to use multiple launches for the modules. The observatory is to have instruments updated at its operational environment i.e., SE-L2. Mission components include the observatory spacecraft, robotic systems for assembly and servicing, and cargo delivery vehicles (that bring the modules to the assemblage) that will work together to assemble the observatory. We explore how autonomy can enable this DRM scenario.

Critical Autonomy Capabilities

We find that the success of this DRM is predicated on the successful development of both system-level and functional-level autonomy. Functional-level autonomy corresponds to the robotic behaviors associated with the detailed assembly steps while the system-level autonomy orchestrates these functional-level steps by monitoring, tracking, and reasoning over a large state-space of the overall system and environmental effects. Among different autonomy features, we focused on the following key autonomous aspects:

- Autonomous Onboard System Manager.
- Autonomous Maneuvers, Mobility and Manipulation.
- Autonomous In-space Verification/Validation.
- Autonomous Onboard Anomaly Detection.

A few representative key autonomy technologies needed for this DRM scenario are:

- Dexterous, precise manipulation, manipulation of soft goods, manipulation with minimal induced stresses

NOTE: This document was prepared by a team that participated in the 2018 Workshop on Autonomy for Future NASA Science Missions. It is for informational purposes to inform discussions regarding the use of autonomy in notional science missions and does not specify Agency plans or directives.

- Sensing and perception for contact-based, precision assembly
- Anomaly detection and fault response
- Distributed actuation, sensing, and control
- Multi-agent coordination, planning, and control

Findings

The Astrophysics DRM team finds that the following actions and activities would facilitate implementation of the mission scenario described above:

- Consider funding a technology-gap analysis and technology roadmap activity with emphasis on identifying autonomy capabilities that may be leveraged from other space or terrestrial applications.
- Consider setting up virtual and physical test beds in laboratory settings for technology development and risk reduction demonstrations with equal emphasis on system- and functional-level autonomy.
- Consider in-space demonstrations or risk-reduction efforts using small spacecraft or existing assets (e.g., inside and outside the International Space Station [ISS]).

Part II: The Case for In-Space Assembly of Large Observatories

In-space assembly has emerged as a timely and credible approach over the last decade. How well it can be mapped to assembly of an observatory remains a challenge^{1,2}. Following are some key features to consider that relate to in-space assembly of large observatories.

- With key capabilities demonstrated in space over the last decade, in-space assembly (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.
- 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.
- 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. Anything larger will likely need ISA.
- ISA offers an in situ approach to servicing the observatory and replacing instruments by reusing the onboard robotics needed to assemble the observatory in space. Conventional, single-launch approaches need an external additional servicer to be developed. ISA does not need additional servicing infrastructure.

¹ Mukherjee, R., et al. "The Case for In-Space Assembly of Telescopes to Advance Exoplanet Science." https://exoplanets.nasa.gov/internal_resources/839/. Accessed 16 January 2020.

² Mukherjee, R., et al. "When is it Worth Assembling Observatories in Space?" https://exoplanets.nasa.gov/internal_resources/1254/. Accessed 16 January 2020.

NOTE: This document was prepared by a team that participated in the 2018 Workshop on Autonomy for Future NASA Science Missions. It is for informational purposes to inform discussions regarding the use of autonomy in notional science missions and does not specify Agency plans or directives.

- ISA changes the risk posture of observatory development and makes it potentially more manageable.
- ISA may offer opportunities for reducing the costs of conventional, single-launch observatories particularly when including the servicing infrastructure in the mission. This will depend ultimately on the point design selected and its technology needs.

Current State of Art: Concepts for in-space assembly have been discussed for a long time, including a concept for assembly of the James Webb Space Telescope (JWST). 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) rendezvous and proximity operation (RPO), (iv) Cargo Delivery Vehicles (CDVs), (v) robotic assembly, and (vi) in-space verification and validation (V&V). The current state-of-art in these components is summarized in Table 1.

#	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: Component capabilities needed for ISA are described here. However, technologies specific to assembling an observatory need to be studied in detail. (Reproduced from the white paper summarizing the results of the In-Space Assembled Telescope [iSAT] Study³.)

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. The Orbiting Carbon Observatory 3 (OCO-3) and the ECOSystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) are the latest examples. The Study ISA concept has a lot of commonality with this approach of instrument installation, including the use of CDVs, RPO, use of robotic arms,

³ Mukherjee, R., et al. "When is it Worth Assembling Observatories in Space?" https://exoplanets.nasa.gov/internal_resources/1254/. Accessed 16 January 2020.

NOTE: This document was prepared by a team that participated in the 2018 Workshop on Autonomy for Future NASA Science Missions. It is for informational purposes to inform discussions regarding the use of autonomy in notional science missions and does not specify Agency plans or directives.

installation of modular instruments using a standard interface, and in-space verification and validation of the robotic installation.

NASA identified ISA as being at a “Tipping Point” of wide commercial infusion and made significant investments towards the public-private-partnership-based In Space Robotic Manufacturing and Assembly program (IRMA). The IRMA program is slated to have in-space demonstration(s) of robotic assembly in the next few years. NASA and the Defense Advanced Research Projects Agency (DARPA) have invested heavily in space missions for robotic servicing scheduled for launch in the 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.

One of the key missing capabilities is autonomy. While assembly via astronauts or high bandwidth, human-in-the-loop telerobotics has been demonstrated in the past, this DRM scenario is predicated on the use of autonomous robotic assembly because of the following concerns, among others.

- The time delay due to orbit location (Sun-Earth–L2 and Earth-Moon–L2)
- The large state-space of variables that has to be tracked and reasoned over during assembly
- The deliberate contact-based assembly and in situ verification and validation needed
- The dimensions and inertias of the modules
- The multiple concurrent blind mates that are needed for assembly
- The sensitivity to disturbances and contamination of the assemblage
- The overall mission cost and risk posture

Part III: The Design Reference Mission

DRM Scenario: In-space Assembly of Large Observatories

NASA SMD has chartered a study, the In-Space Assembled Telescope (iSAT) study, to explore the value proposition of in-space assembly of future telescopes. Among other steps, this ongoing study has:

- engaged a large community of practitioners,
- developed a reference telescope architecture,
- designed a reference telescope in terms of modular components for in-space assembly,
- evaluated different orbits for assembly and operations,
- explored different robotic systems for assembly, and
- developed a reference concept of operations.

This study leverages experience from past (e.g., Hubble Space Telescope [HST]) and ongoing astrophysics missions (e.g., JWST) as well as robotics missions (e.g., ISS, Mars robotics, Restore-L, Robotic Servicing of Geosynchronous Satellites [RSGS]) among others. It evaluated the opportunities in cost and risk postures for in-space assembled telescopes of sizes 5m, 10m, 15m and 20m. This DRM leverages the findings of the SMD iSAT study to explore the opportunities presented by autonomy in facilitating the DRM scenario.

The Concept of Operations:

NOTE: This document was prepared by a team that participated in the 2018 Workshop on Autonomy for Future NASA Science Missions. It is for informational purposes to inform discussions regarding the use of autonomy in notional science missions and does not specify Agency plans or directives.

A detailed concept of operations for the assembly of the iSAT reference observatory can be found in the iSAT ConOps Storyboard⁴ and the major steps are graphically shown in Figure 1 below. These steps are similar to the instrument assembly approach used on the ISS (e.g., OCO-3).

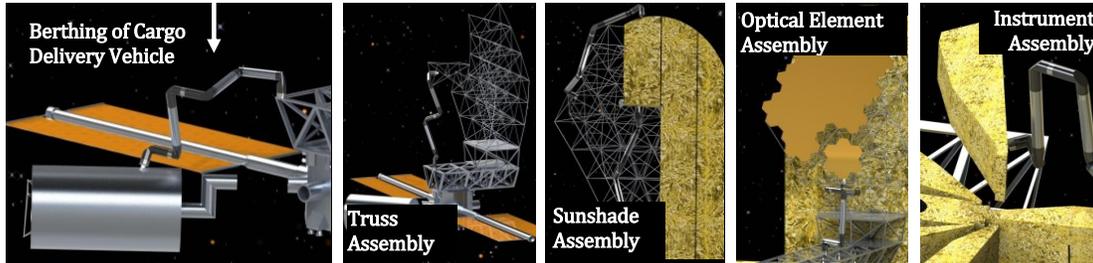


Fig 1. Artistic rendition of representative robotic assembly steps for the Study's iSAT reference concept.

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. They 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 (ISS) or a potential NASA Gateway. 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).

Robotic Manipulation and Assembly: The robotic arms onboard the assemblage berth the CDV to the observatory spacecraft and then unload and relocate individual modules to their assembly locations. Similar to the robots 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 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

⁴ Mukherjee, R., et al. “iSAT ConOps Graphical Storyboard: 20 m Segmented UV/V/NIR Telescope.” https://exoplanets.nasa.gov/internal_resources/1171/. Accessed 16 January 2020.

NOTE: This document was prepared by a team that participated in the 2018 Workshop on Autonomy for Future NASA Science Missions. It is for informational purposes to inform discussions regarding the use of autonomy in notional science missions and does not specify Agency plans or directives.

approach as used for assembly and the onboard 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.

We envision the need for different autonomous behaviors, examples of which include, but are not limited to:

- rendezvous and berthing,
- manipulation of the modules in unloading from the fairing,
- mobility over the assemblage to reach different assembly locations,
- force-controlled, vision-based, dexterous manipulation for assembling the modules,
- manipulation of soft goods in assembling a large sunshade from modular elements,
- attitude control of the combined assemblage (spacecraft and stack) during assembly,
- metrology-guided adjustments to the assembly,
- inspection of the modules and subassemblies,
- servicing via refueling or instrument replacement, and
- the overall verification and validation of the assembly.

While a detailed technology gap analysis and road mapping activity for in-space assembly of observatories has not been conducted, and we suggest such an activity be funded as the next step, following are some key technology challenges specific to observatory assembly.

- 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, and
- precise joining interfaces for robotic assembly and servicing.

Autonomy Capabilities Needed

During the Autonomy Workshop breakout sessions, the DRM team discussed the autonomy technology needs, status or readiness of the technologies, and the criticality of the technology and used this information to identify three key thematic areas of capability need. Within each thematic area, the team listed different component autonomy technologies. This activity was informed by the Autonomous Systems Taxonomy developed by the NASA Autonomous Systems Capability Leadership Team. The results are discussed below, and the reader is encouraged to be mindful that new autonomy needs may emerge as this DRM scenario is studied in more granularity through the iSAT study or future efforts.

NOTE: This document was prepared by a team that participated in the 2018 Workshop on Autonomy for Future NASA Science Missions. It is for informational purposes to inform discussions regarding the use of autonomy in notional science missions and does not specify Agency plans or directives.

Autonomous technologies needed for this capability:	Other supporting technologies needed	Related/relevant R&D projects	Potential challenges/risks and key points/questions
<ul style="list-style-type: none"> • Anomaly Detection • Fault Response • Sensing and Perception • State Estimation and Monitoring • Knowledge and Model Building • Motion Planning • Dexterous, Precision Manipulation • Gossamer Structure Manipulation • Soft Goods Manipulation • Force-Torque Control • Situational and Self Awareness • Algorithms in sensor fusion • Distributed actuation • Sensing and control • Planning/Execution • Hierarchical tasknet • Tasknet V&V • Framework for system-level autonomy interfaces 	<ul style="list-style-type: none"> • Systems Engineering for autonomy, i.e., what are requirements specific to autonomy, how is it architected, implemented, verified and validated? • Robotics-informed “joining” hardware • End Effectors for robots • Perception Sensors • Computing for vision processing • Modeling and Simulation • Anomaly Detection (enhancing) • Framework-compliant controllers and SW • Non-Destructive Evaluation (NDE) approaches • Metrology • Active Optics • Modular deployable components, particularly soft goods 	<ul style="list-style-type: none"> • NASA Restore-L • DARPA RSGS • Experimental Satellite System-11 (XSS-11) (RPO) • Tipping Point (IRMA) • Mars Robotics Missions • ISS robotics • Ground based telescope assembly • DoD and commercial activities in multi-agent systems • Autonomous boats • Deep Space-1 • Earth Observing-1 • Arcsecond Space Telescope Enabling Research in Astrophysics (ASTERIA) Technology Development 	<ul style="list-style-type: none"> • Can robots autonomously assemble stiff, thermally stable, structures from modules? • Can the system manage the large state-space of variables and facilitate the different functional autonomy level steps needed while managing resources and monitoring environmental factors? • Can the autonomous robotic systems detect and recover from anomalies without causing catastrophic damage to the system? • Can a synergistic autonomy architecture be implemented that is inherently scalable in terms of the number of variables it manages or tracks, as well as be hierarchical, i.e., range from system-level down to detailed functional-level autonomy? • What is the right balance of virtual, in-laboratory, and in-space testing and demonstration needed to assure autonomy?

1. Autonomous Onboard System Manager.

In-space assembly and servicing will require planning for coordination between many different agents (e.g., spacecraft, robots, delivery vehicles), management of resources and environmental effects, and

NOTE: This document was prepared by a team that participated in the 2018 Workshop on Autonomy for Future NASA Science Missions. It is for informational purposes to inform discussions regarding the use of autonomy in notional science missions and does not specify Agency plans or directives.

ensuring system-level performance by sequencing and monitoring many different functional-level autonomous behaviors. This is an enabling feature.

This is an **Enabling** capability: “Integrate capabilities with the flight system.” There are multiple factors that drive the necessity of an onboard “spacecraft manager” in order to support in-space assembly. This spacecraft manager is a Planner/Executive software for spacecraft routines and a set of interface requirements to ensure that the spacecraft manager has sufficient information to control the different aspects of the spacecraft.

First, spacecraft are currently operated using command sequences, where each command is associated with an execution time. For an autonomous spacecraft, sequences are too brittle to be feasible, as operational anomalies, like a robotic action taking a longer period of time, or failures, like a missed grasping operation, will mean that the commands the spacecraft is executing do not correspond to the actual circumstances the sequence or command was designed for. System-level autonomy uses task networks, or tasknets, to operate a spacecraft. This is a different paradigm where each command is associated with a set of states that are required for successful execution. For instance, a task for attaching a reflector will only be executed once the position state requirement of the reflector is actually met.

The second factor driving the necessity of system-level autonomy is resource management. Spacecraft are complex, with commands being executed by different subsystems that all utilize the same resources like energy, time, attitude, etc. Currently, resource management is handled by spacecraft mission planners who develop command sequences. However, if there are delays associated with anomalies or failures, then it is possible that commands would begin to use resources in an unpredictable way and endanger the mission. For instance, an anomaly in ISA results can cause delay, leading to excess power use during eclipse and energy depletion. In contrast, system-level autonomy would command robotic controllers in small task steps, like individual manipulations, each time requesting resource requirements from the controller. It would then schedule these ISA tasks in a manner that does not disrupt spacecraft health and safety.

Third is the requirement of graceful spacecraft safing that results in function preservation. This is met by using tasknets and resource management in conjunction with onboard anomaly detection. Contingency tasknets can be designed that respond to detected anomaly states, which are then scheduled or immediately executed. Moreover, these contingency tasknets can respond to operational anomalies. In the case of a slow reflector panel assembly that may take longer to execute than a single orbit, the Executive software may schedule the contingent action to safely stow the robotic arm until the spacecraft is out of eclipse by first requesting a safe stow point from the robotics controller.

2. Autonomous Maneuvers, Mobility and Manipulation.

The complement of the system-level manager is the many different functional-level autonomous behaviors needed to assemble and service the observatory. Robotic systems have to autonomously “Go where needed” and “Manipulate what is needed.” Autonomous orbital maneuvers for spacecraft berthing and attitude control, autonomous robotic mobility over the assemblage to access different locations, and autonomous manipulation (including soft goods) in assembling different types of modules of the observatory are key enabling features. These contact-based behaviors have to be successfully executed subject to a large state-space of variables that need to be monitored, tracked, or controlled.

NOTE: This document was prepared by a team that participated in the 2018 Workshop on Autonomy for Future NASA Science Missions. It is for informational purposes to inform discussions regarding the use of autonomy in notional science missions and does not specify Agency plans or directives.

This is an **Enabling** capability. Autonomous orbital maneuvers for spacecraft berthing and attitude control, autonomous robotic mobility over the assemblage to access different locations, and autonomous manipulation in assembling different types of modules of the telescope are key enabling features of this DRM.

Autonomous orbital maneuvers for far-field rendezvous, near-field rendezvous, and terminal capture for berthing are a needed capability for supplying the assemblage with different modules. These modules may be delivered to the assembly site from different types of launch systems ranging from propulsive Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA) rings to Cygnus-type systems. These systems may have varying levels of rendezvous and proximity operations (RPO) capabilities with different levels of control authority and sensing. Autonomy capabilities will be needed for RPO and berthing of these supply vehicles to the telescope assemblage. Along with safe operations, autonomous capabilities will be needed to minimize the disturbances from these behaviors. Similarly, autonomy capabilities will be needed for attitude control of the assemblage, as well as the stack arising from the berthing of the supply vehicle to the assemblage. This may be a distributed actuation problem requiring a kind of multi-agent collaboration between the telescope spacecraft and the supply vehicle. Autonomously controlling the stack attitude also becomes important due to the changing center of mass (cm) as the robot repositions modules (or itself) along the assemblage.

The DRM has baselined long-reach “walking” robotic manipulators. These are manipulators are much like the Canadarm on the ISS. It is expected that the robots for this DRM would be able to carry modules from the fairing to their assembly location by “inch-worming” over the assemblage by grappling the assemblage at specially designed interfaces. These grappling behaviors would involve perception-guided force-controlled manipulations with different types of contact loads.

The manipulators would have to access the supply fairing to access the delivery module. The manipulators would then have to safely carry the payload to its assembly location. The manipulator also must attain a configuration where it can have the freedom of workspace and dexterity to assemble the modules. During the mobility of the manipulator by itself, or the manipulator while carrying a payload, the overall cm of the assemblage may move, thereby impacting the attitude control. Thus, autonomous coordination between the manipulators and the spacecraft will be required during mobility. Manipulator mobility may also be required in areas with potential obstacles, e.g., truss work under assembly. This may arise when moving a payload. A manipulator has to autonomously plan for the mobility of not only itself, but the different payload modules it may be carrying.

The manipulators would also have to autonomously manipulate all the payloads during the different phases of assembly including rigid elements as well as soft goods such as sun-shade elements. The manipulators may have to enable several concurrent contacts and force-controlled assembly of the payloads. These assembly interfaces may be hard-hard (e.g., truss to truss), soft-hard (e.g., sunshade elements to truss) and even soft-soft (e.g., stray-light-blocking soft goods). Multi-sensor-informed, autonomous, dexterous manipulation of these force-controlled interactions between payloads with different interfaces is a key enabler. The manipulator should autonomously handle a variety of materials, such gossamer structures, as well as soft goods uncertainties arising from environmental factors (e.g., lighting conditions) and properties intrinsic to the manipulator or payload (e.g., thermal drift, manufacturing tolerances). These manipulations have to be precise to meet the tolerances allocated from

NOTE: This document was prepared by a team that participated in the 2018 Workshop on Autonomy for Future NASA Science Missions. It is for informational purposes to inform discussions regarding the use of autonomy in notional science missions and does not specify Agency plans or directives.

the optical requirement of the telescope. The manipulators may also have to reach crowded workspaces to adjust the assemblage to achieve the desired tolerances. The manipulators may have to conduct a variety of perception-guided, force-controlled “joining” behaviors, some of which may be actuated while others may be passive.

3. Autonomous In-space Verification/Validation

Autonomy is needed to “Check your work.” An observatory assembly has strict requirements for precision of module placement, structural stability, operational thermal control, among many others. In addition to the precise assembly, the validation of assembly should be continual and enabled by incorporating different kinds of sensors and autonomous behaviors.

This is an **Enabling** capability. A telescope assembly has strict requirements for precision of element placement, structural rigidity, operational material temperature, and resonant characteristics. In addition to the precise assembly of structural and optical elements already mentioned, the validation of construction should be continuous and enabled by incorporating non-traditional sensors on the assembling robot. These sensor payloads can largely be borrowed from the field of Non-Destructive Evaluation (e.g., laser-excited ultrasonics, thermography, model-based photogrammetry, etc.), but require novel sensor fusion techniques to be incorporated into anomaly detection and manipulation planning.

In-space V&V can be separated into two categories, Operational and Diagnostic. Operational V&V allows the assembling agent to better detect anomalies during assembly steps by providing sensory feedback used during manipulation planning or control. Diagnostic V&V allows the agent to act as a servicing agent during fault recovery or during the long lifetime of the telescope—either autonomously or by leveraging human-commanded diagnostic behaviors (e.g., “Take *this* measurement of *these* joints”).

Ground V&V campaigns will need to be conducted of all assembly modules and the assembly agent itself. As an additional requirement, the results of these V&V campaigns will likely need to be used by the assembly agent to completely characterize the acceptable range of sensor readings, thus enabling the kind of assured anomaly detection that is required for large-scale telescope assembly in space.

4. Autonomous Onboard Anomaly Detection.

This scenario involves deliberate contact between autonomous agents and modules, some of which may have fragile components. It is critical that the system be robustly autonomous to ensure that the contact-based events perform within the bounds of nominal behaviors via continuous and autonomous anomaly detection. Furthermore, it is paramount that the system autonomously and gracefully transitions from different anomalous situations to safe states (i.e., safing) where engineers on the ground can intervene to recover. While autonomous recovery would be an ultimate goal, autonomous detection and graceful safing is a key requirement.

This is an **Enabling** capability: “Do no harm.” This DRM comprises of many different kinds of behaviors demonstrated by the spacecraft, the robotic system, and multi-agent interactions—i.e., between spacecraft, robot, and resupply vehicle. Many of these interactions involve deliberate contact with fragile components (e.g., reflectors) during assembly and adjustments. These interactions would be significantly dependent on different types of sensors, their calibrations, fusion of multiple sensors and impact of the environment on the sensors (e.g., lighting conditions, thermal drift). These interactions would also involve

NOTE: This document was prepared by a team that participated in the 2018 Workshop on Autonomy for Future NASA Science Missions. It is for informational purposes to inform discussions regarding the use of autonomy in notional science missions and does not specify Agency plans or directives.

control of different types of actuators (e.g., robot joint actuators, thrusters, ACS systems), coordination between these actuators, and environmental impact on these actuators. This is a many-element problem involving diverse types of elements (multi-system, individual system, coordination of sensors and actuators, down to individual sensors and actuators) that all have to work together to achieve nominal behaviors. As the interactions between all these hierarchical elements involve repeated and deliberate contact, any off-nominal scenario or anomaly can be catastrophic to the assemblage. Furthermore, as the assembly may involve non-reversible joints, damage to the assembly from an anomalous contact may be unrecoverable. Hence, it becomes paramount that the system be robustly autonomous in ensuring that it is performing within the bounds of nominal behaviors via continuous and autonomous anomaly detection. While autonomous recovery would be an ultimate goal, autonomous detection and graceful safing is a key requirement.

Two levels of anomaly detection and safing could be implemented based on the granularity of the autonomous behaviors. The first is short-term autonomy mode, e.g., a single, element-level behavior after which assembly robots await human responses or commands. During this phase, the system would autonomously detect an anomaly, safe itself gracefully, inform ground systems, and wait for recovery instructions. Example: the system should be able to assemble two modules together through vision-based localization and force control. It should be able to detect off-nominal forces, loss in calibration, inadequate lighting, or visibility, among other factors. And the system should autonomously stop its behavior at a juncture where it is safe to do so. Abrupt stopping may actually be more harmful.

The second type of anomaly detection and safing concerns long-term autonomy. Here the system is expected to carry out a number of different behaviors autonomously that are mutually dependent or involve more discrete planning. For example, consider an aggregate behavior where the robot is tasked to autonomously deploy a structural module and then assemble it to the assemblage with one instruction from the ground system. During this phase, the system would be responsible for autonomously detecting variations in the scene and adapt its behaviors accordingly. It would also be able to autonomously detect an impending “system-level” anomaly even if the element-level behaviors are nominal, while still providing the same responsiveness to anomalies of individual element-level behaviors. An example of this type would be autonomous capabilities that sense and aggregate dimensional tolerances of components to determine that the next component will not fit. In this case, the robot would go back and adjust the assembly before assembling the next module.

Element-level behaviors (the first type above) are enabling. System-level behaviors (the second type) are enhancing. An autonomous system without the first type of anomaly recovery is impractical for this DRM. The second type, when appropriately verified and validated, would significantly reduce the overall cost and risk posture of an ISA DRM.

Part IV: Findings

The Astrophysics DRM team finds that the following actions and activities would facilitate implementation of the mission scenario described above:

- Consider funding a technology-gap analysis and technology roadmap activity with emphasis on identifying autonomy capabilities that may be leveraged from other space or terrestrial applications.

NOTE: This document was prepared by a team that participated in the 2018 Workshop on Autonomy for Future NASA Science Missions. It is for informational purposes to inform discussions regarding the use of autonomy in notional science missions and does not specify Agency plans or directives.

- Consider setting up virtual and physical test beds in laboratory settings for technology development and risk reduction demonstrations with equal emphasis on system- and functional-level autonomy.
- Consider in-space demonstrations or risk-reduction efforts using small spacecraft or existing assets (e.g., inside and outside the ISS).

NASA is already investing in the area of in-space assembly and servicing through, for example, the Restore-L project and the In Space Robotic Manufacturing and Assembly program (IRMA). However, these programs are unlikely to embrace the full capabilities of autonomous robotic assembly due to their deployment in Low Earth Orbit and the availability of a short time delay. Hence, this DRM team suggests that specific technologies for autonomous assembly be explored further and matured through test beds and demonstrations.

Primary Author and Point of Contact: Rudranarayan Mukherjee (NASA/JPL)

The material presented in this document has been based primarily on the findings of the iSAT study (that was conducted by the team identified below) with additional inputs from the DRM team.

Astrophysics DRM Team:

D. Allen (NASA/LaRC), N. Bosanac, (Univ of Colorado), L. Callahan (NASA/GSFC), J. Chow (Lockheed Martin), S. Chung (NASA/JPL), P. Hughes NASA/GSFC), J. V. Hook (NASA/JPL), R. Amini (NASA/JPL)

iSAT Study Team:

N. Siegler (JPL/Caltech), H. Thronson (NASA/GSFC), K. Aaron (JPL/Caltech), J. Arenberg (NGC), P. Backes (JPL/Caltech), A. Barto (Ball), K. Belvin (NASA/LaRC), L. Bowman (NASA/LaRC), D. Calero (NASA/KSC), W. Doggett (NASA/LaRC), J. Dorsey (NASA/LaRC), M. East (L3 Harris), D. Folta (NASA/GSFC), M. Fuller (NGC), S. Glassner (Northeastern), J. Grunsfeld (NASA retired), K. Havey (L3 Harris), R. Hellekson (NGC), G. Henshaw (NRL), J. Hoffman (MIT), S. Jefferies (NASA/LaRC), J. S. Knight (Ball), P. Lightsey (Ball), J. Lymer (Maxar), E. Mamajek (JPL/Caltech), D. McGuffey (NASA/GSFC), D. Miller (Aerospace/MIT), K. Mehalick (NASA/GSFC), B. Naasz (NASA/GSFC), A. Nordt (LMC), K. Patton (NGC retired), C. Peters (NASA/GSFC), M. Perrin (STScI), B. M. Peterson (OSU/STSci), J. Pitman (Heliospace), R. Polidan (PSST), A. Qureshi (Maxar), D. Redding (JPL/Caltech), K. Ruta (NASA/JSC), H. P. Stahl (NASA/MSFC), G. Roesler (Robots in Space), R. Shishko (JPL/Caltech), A. Tadros (Maxar), A. Van Otten (NGC), W. Vincent (NRL), K. Warfield (JPL/Caltech), S. Wiens (LMC), J. Wood (LMC)

Astrophysics Design Reference Mission Report Summary

In the Exoplanet Science Strategy Report⁵, the National Academies recommend that “NASA should lead a large strategic direct imaging mission capable of measuring the reflected-light

⁵ National Academies of Sciences, Engineering, and Medicine. *Exoplanet Science Strategy*. Washington, DC: The National Academies Press. [<https://doi.org/10.17226/25187>] 2018.

NOTE: This document was prepared by a team that participated in the 2018 Workshop on Autonomy for Future NASA Science Missions. It is for informational purposes to inform discussions regarding the use of autonomy in notional science missions and does not specify Agency plans or directives.

spectra of temperate terrestrial planets orbiting Sun-like stars.” For direct imaging of exoplanets, the size of the telescope aperture is directly correlated with the probability of finding Earth-like exoplanets—the bigger the aperture, the better the probability. In other areas of astrophysics, larger aperture has direct correlation to better science, as well. Past experiences have shown that developing a large observatory to fit—even when folded—into a single launch fairing of an existing or a future planned launch vehicle involves various technological, programmatic, schedule, and cost challenges. Is there a way to mitigate these challenges and improve the cost and risk postures of future observatory implementations? Furthermore, servicing these observatories in space to extend their lifetimes and update instruments to provide many decades of scientific returns is also challenging. The world has both marveled at and profited by the benefits of Hubble Space Telescope (HST) servicing. How will NASA ensure future observatories have similar opportunities to be serviced? To address these issues, NASA and other government entities are expressing growing interest in exploring the value proposition of in-space robotic assembly and servicing for large space assets including optical telescopes. This interest is also reciprocated by industry through internal investments and public-private partnerships.

The Astrophysics DRM team explored the role of autonomy in enabling robotic assembly of an optical telescope in cislunar space with delivery, operations, and servicing at the Sun-Earth Lagrange Point (SE-L2). Onboard autonomy with minimal human supervision plays a central role in this DRM scenario. While NASA has experience with in-space assembly via astronauts or high-bandwidth, human-in-the-loop telerobotics, the following concerns, among others, make autonomous operations—with minimal human supervision via telemetry—a key enabling feature:

- The time delay due to orbit location (Sun-Earth–L2 and Earth-Moon–L2)
- The large state-space of variables that must be tracked and reasoned over during assembly
- The deliberate contact-based assembly and in situ verification and validation needed
- The dimensions and inertias of the modules
- The multiple concurrent blind mates that are needed for assembly
- The sensitivity to disturbances and contamination of the assemblage
- The overall mission cost and risk posture

The Astrophysics DRM team suggests the following autonomous DRM scenario.

DRM Scenario: In-space Assembly of Large Telescopes

The overall reference mission concept is as follows. A 20-m, filled-aperture, segmented, non-cryogenic ultraviolet/visible/near-infrared observatory will be assembled from its modular components in cislunar orbit using autonomous robotics. The mission will use multiple launches for the modules. The observatory instruments will be updated in the operational environment, i.e., SE-L2. Mission components include the observatory spacecraft, robotic systems for

NOTE: This document was prepared by a team that participated in the 2018 Workshop on Autonomy for Future NASA Science Missions. It is for informational purposes to inform discussions regarding the use of autonomy in notional science missions and does not specify Agency plans or directives.

assembly and servicing, and cargo delivery vehicles (that bring the modules to the assemblage) that will work together to assemble and service the observatory.

This DRM scenario requires a level of autonomy that is not currently available. Advancements in autonomy technology are required for this mission scenario to perform the following:

Autonomous Onboard System Management: In-space assembly and servicing will require planning to coordinate many different agents (e.g., spacecraft, robots, delivery vehicles), manage resources and environmental effects, and ensure system level performance by sequencing and monitoring many different functional-level autonomous behaviors. This capability is an enabling feature.

Autonomous Maneuvers, Mobility, and Manipulation: The complement of system-level management is management of the many different functional-level autonomous behaviors needed to assemble and service the observatory. Robotic systems have to autonomously “go where needed” and “manipulate what is needed.” Autonomous orbital maneuvers for spacecraft berthing and attitude control, autonomous robotic mobility over the assemblage to access different locations, and autonomous manipulation (including soft goods) to assemble different types of observatory modules are key enabling features. These contact-based behaviors have to be successfully executed, subject to a large state-space of variables that need to be monitored, tracked, or controlled.

Autonomous In-space Verification/Validation: Autonomy is needed to “check your work.” An observatory assembly has strict requirements for precision of module placement, structural stability, and operational thermal control, etc. In addition to the precise assembly, the validation of assembly should be continual and enabled by incorporating different kinds of sensors and autonomous behaviors.

Autonomous Onboard Anomaly Detection: This mission scenario involves deliberate contact between autonomous agents and modules, some of which may have fragile components. It is critical that the system is robust and employs continuous and autonomous anomaly detection to ensure that the contact-based events are performed within the bounds of nominal behaviors. Furthermore, it is paramount that the system autonomously and gracefully transitions from different anomalous situations to safe states (i.e., safing) where engineers on the ground can intervene to recover. While autonomous recovery is an ultimate goal, autonomous detection and graceful safing is a key requirement.

To enable autonomy in this DRM scenario, advancements in the following supporting technology areas are required:

- Systems engineering for autonomy
- Modular design principles for the observatory, particularly soft goods for sunshades
- Robotics-informed “joining” interfaces

NOTE: This document was prepared by a team that participated in the 2018 Workshop on Autonomy for Future NASA Science Missions. It is for informational purposes to inform discussions regarding the use of autonomy in notional science missions and does not specify Agency plans or directives.

- Perception sensors and metrology
- Computing, particularly for computer vision
- Modeling and simulation
- Non-destructive testing approaches

Findings

The Astrophysics DRM team finds that the following actions and activities would facilitate implementation of the DRM scenario described above:

1. Fund a technology-gap analysis and technology roadmap activity with emphasis on identifying autonomy capabilities that may be leveraged from other space or terrestrial applications
2. Set up virtual and physical test beds in laboratory settings for technology development and risk reduction demonstrations with equal emphasis on system- and functional-level autonomy
3. Implement in-space demonstrations or risk-reduction efforts using small spacecraft or existing assets (e.g., inside and outside the ISS)