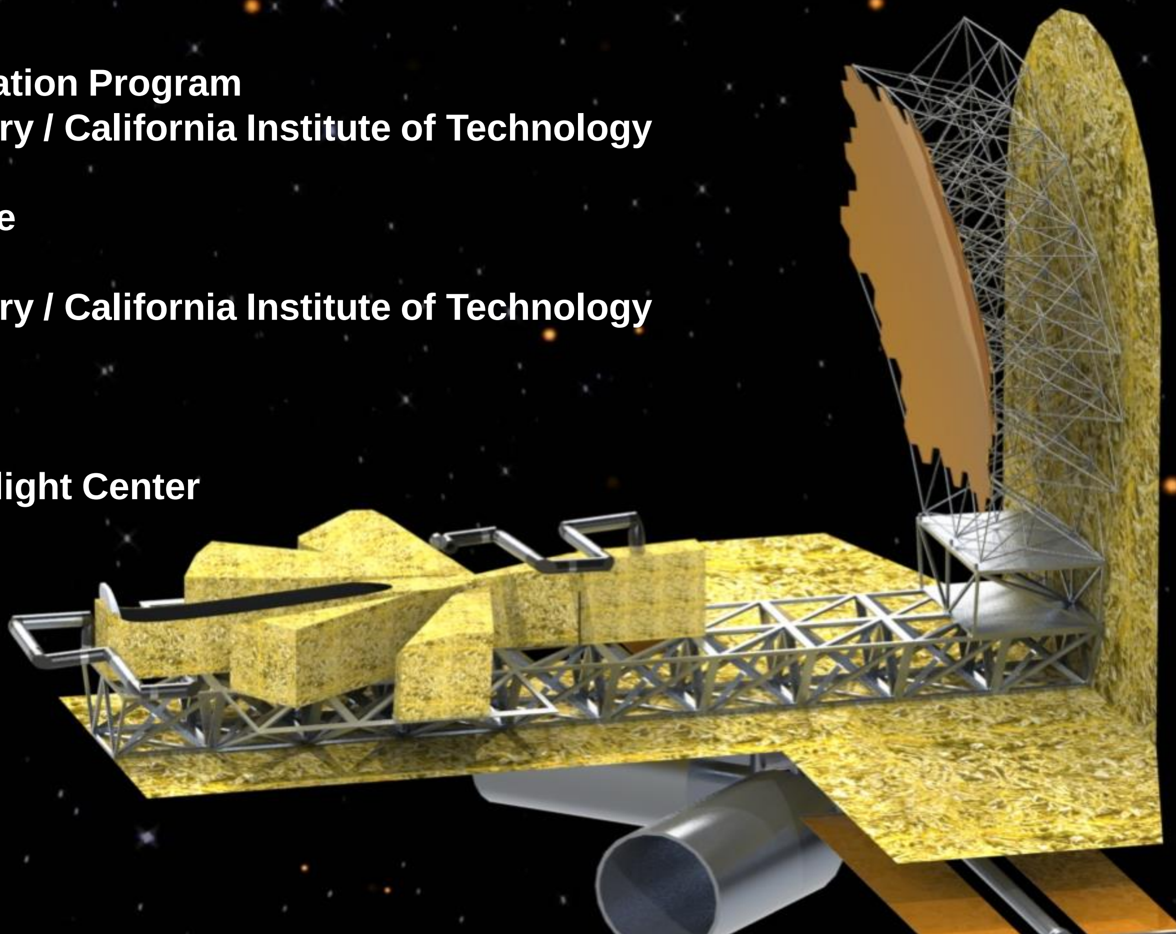
NASA-Chartered In-Space Assembled Telescope Study: Final Report

Nick Siegler
Chief Technologist
NASA Exoplanet Exploration Program
Jet Propulsion Laboratory / California Institute of Technology

Rudranarayan Mukherjee
Robotics Technologist
Jet Propulsion Laboratory / California Institute of Technology

Harley Thronson
Senior Scientist
NASA Goddard Space Flight Center

July 2019



The cost information contained in this document is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech.

CL#19-4130

Outline

1. Study Effort
2. Reference Observatory
3. Study Findings
4. Study Suggestions
5. Support Slides for Findings
6. Final Thoughts

Study Effort

Exoplanet Science Strategy Report

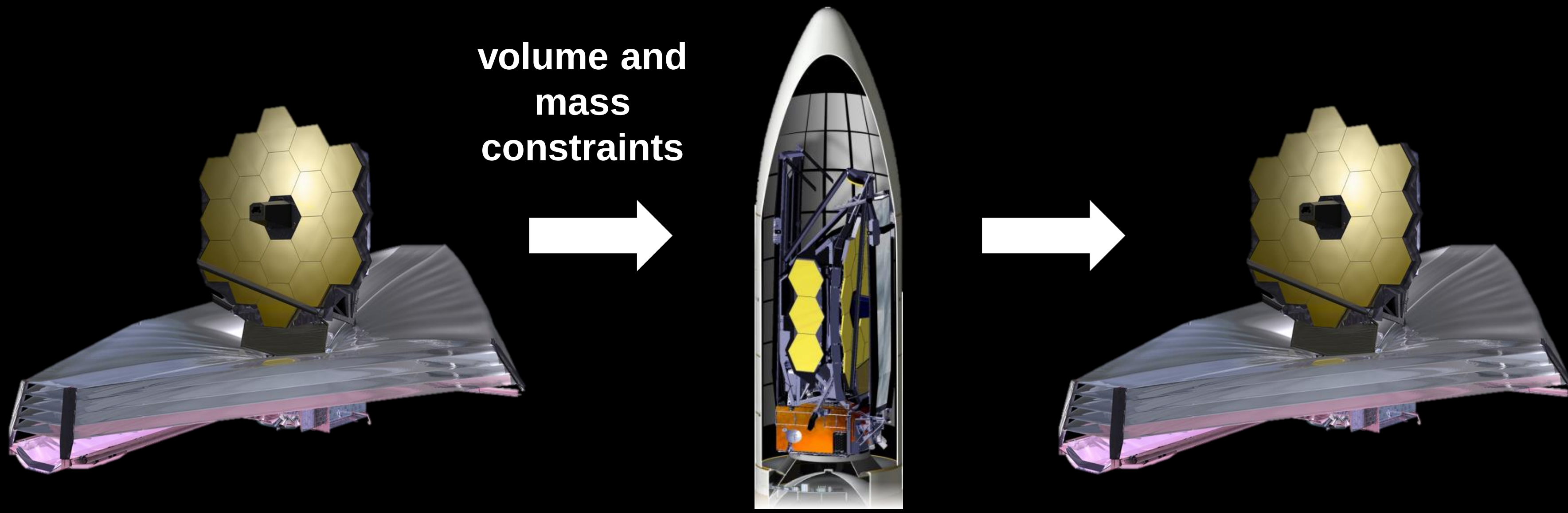
Released September 5, 2018 by the National Academies

Recommendation #1:

NASA should lead a <u>large</u> strategic direct imaging mission capable of measuring the reflected-light spectra of temperate terrestrial planets orbiting Sun-like stars.

David Charbonneau (Harvard) Scott Gaudi (Ohio State University)

Existing Large Observatory Paradigm: Constraints



- **Severe packaging and mass constraints on JWST**
  - Over 20 sequential deployment events, 40 deployable structures, 178 release mechanisms – all of which must work.
  - Numerous light-weighting iterations to meet LV mass constraints
  - Complex modeling development and validation efforts
- **No servicing capabilities**
  - No fault recovery if anomaly during commissioning or operations
  - No instrument upgrading to extend useable life (already ~ 10 yrs old at launch)

Study Objective and Deliverables

Dr. Paul Hertz
Director
Astrophysics Division
Science Mission Directorate
NASA Headquarters

- **Study Objective:**
  - ***"When is it worth assembling space telescopes in space rather than building them on the Earth and deploying them autonomously from single launch vehicles?"***

- **Deliverables:**

  An Astro 2020 Decadal Survey whitepaper by July 2019 assessing:

  1. the telescope size at which iSA is necessary (*an enabling capability*)
  2. the telescope size at which iSA is cheaper or lower risk with respect to current launch vehicle deployment techniques (*an enhancing capability*)

- **Decadal Survey Statement of Task:**
  - *Consider ongoing and planned activities and capabilities in other organizational units of NASA, including (but not limited to) in-space assembly and servicing and existing and planned research platforms in Earth orbit and cis-lunar space.*

iSAT Charter

In-Space Assembled Telescope (iSAT) Study
5/19/2018 v8

Charter

Authors:
Nick Siegler, NASA ExEP, Jet Propulsion Laboratory, California Institute of Technology
Harley Thronson, NASA PCOS/COR, NASA Goddard Space Flight Center
Rudra Mukherjee, Jet Propulsion Laboratory, California Institute of Technology

A. Background

Large aperture telescopes benefit all astrophysics as well as planetary and Earth science. They provide unprecedented spatial resolution, spectral coverage, and signal to noise advancing all of these science areas. Envisioning the need for future large segmented telescopes to one day exceed the fairing size of existing or even planned launch vehicles, NASA will need to begin considering the in-space assembly (iSA) of these future assets. In addition, robotically assembling space telescopes in space rather than deploying them from single launch vehicles offers the possibility, in some circumstances, of reduced cost and risk for even smaller telescopes. This possibility, however, has not been proven. Therefore, following discussions within NASA's Science Mission Directorate (SMD) and Astrophysics Division (APD), the SMD Chief Technologist and APD Division Director have commissioned a study to assess the cost and risk benefits, if any, of the iSA of space telescopes. In particular, the study must answer the question: ***"When is it worth (or advantageous) to assemble space telescopes in space rather than to build them on the Earth and deploy them autonomously from individual launch vehicles?"*** This document charters the plan for the study deliverables, process, and membership. The goal for completion of the study is May 2019 culminating in a submitted whitepaper to the National Academies' 2020 Astronomy & Astrophysics Decadal Survey.

B. Deliverables

The in-Space Assembly Telescope (iSAT) Study Working Group is chartered by the NASA SMD Chief Technologist and APD Director to deliver by the goal of May 2019 a whitepaper assessing:

1. the telescope size at which iSA is necessary (an enabling capability)
2. the telescope size at which iSA is cheaper or lower risk with respect to traditional single launch vehicle deployment (an enhancing capability)
3. the important factors that impact the answers (e.g., existence of HEO-funded infrastructure, architecture of space telescope (segments or other), cryogenic or not, coronagraph capable (stability) or not, etc.)

1

https://exoplanets.nasa.gov/exep/technology/in-space-assembly/iSAT_study/

Study Assumptions

1. Reference telescope:
   - Non-cryogenic operating at UV/V/NIR assembled in space
   - Four sizes between 5 – 20 m
2. Driving requirements:
   - Structural stability required by coronagraphy of exo-planets
3. Operational destination:
   - Sun-Earth L2
4. Launch vehicles:
   - Use of 5 m-class LV fairings
5. Number of reference concepts to study:
   - Only one
   - Not a down select, not a recommendation

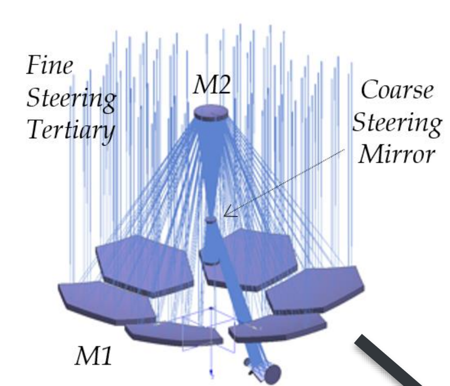
Study Activities

Activity 2a: Qualitative assessment of the benefits/disadvantages

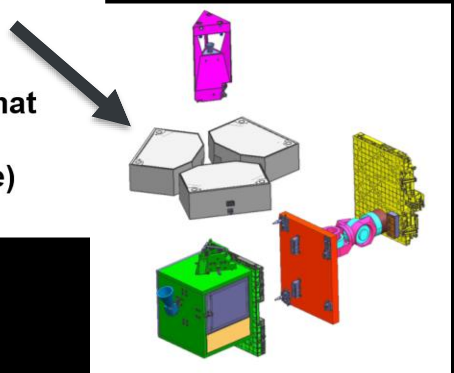
Activity 2b: Quantitative estimate of the costs and identify risks

Activity 1b: Assembly and Infrastructure

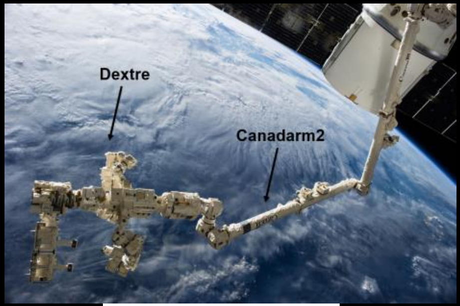
Activity 1a: Modularization and Testing

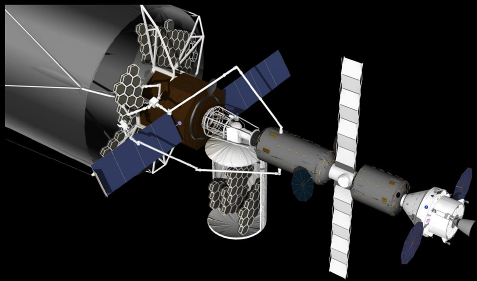


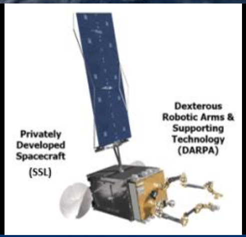
3 Mirror Anastigmat Telescope (1.45 m aperture)

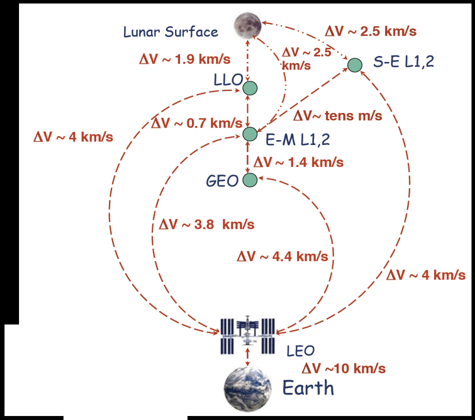


6 launch modules for assembly









Detailed Process Approach

Five steps

- Step 1a: A systematic approach was used to select a reference telescope and its modularization strategy for apertures between 5-20 m.
- Step 1b: A systematic approach was used to select reference assembly orbit, assembly agent (astronaut vs robot), assembly platform, launch vehicles, and notional con-ops

A two-pronged costing (and risk) approach:

❖ Two separate teams initially blind to each other's findings; then converged to check consistency to get verification.

- Step 2a: A qualitative approach based on experiences and lessons learned, including JWST, ISS, HST, Restore-L, Orbital Express, RSGS
- Step 2b: A quantitative approach based on a grass-roots costing exercise and risk assessment by SMEs from various subsystems:
    - Define assembly conops, Phase A-E schedules
    - Implementation plans, including testing, V&V, and integration
    - Resource needs and budget, MEL, PEL, launch manifest
- Step 2c: Independent parametric cost estimate for conventional

Study Participants

Name	Institution	Expertise
1. Ali Azizi	NASA JPL	Metrology
2. Larry Dewell	LMC	Pointing/Stability/Control
3. Oscar Salazar	NASA JPL	Pointing/Stability/Control
4. Phil Stahl	NASA MSFC	Telescopes
5. Jon Arenberg	NGAS	Thermal/Sunshade
6. Doug McGuffey	NASA GSFC	Telescopes/SE
7. Kim Aaron	NASA JPL	Structures
8. Dave Redding	NASA JPL	Telescopes
9. Bill Doggett	NASA LaRC	Structures
10. Al Tadros	Maxar	Robotics
11. Bob Hellekson	NGIS	Telescope Systems
12. Eric Mamajek	NASA JPL	Astrophysicist
13. Shanti Rao	NASA JPL	Optical Design
14. Matthew East	L3 Harris	Mirror Segments
15. Mike Rodgers	NASA JPL	Optical Design
16. Ray Ohl	NASA GSFC	Optical AIT
17. Sergio Pellegrino	Caltech	Technologist
18. Tere Smith	NASA JPL	AIT
19. Paul Backes	NASA JPL	Robotics
20. Jim Breckenridge	Caltech	Optical Design
21. Allison Barto	Ball	SE/optical testing
22. David Stubbs	LMC	Telescopes/Design
23. John Dorsey	NASA LaRC	Structures
24. Jeff Sokol	Ball	Mechanical/AIT
25. Atif Qureshi	SSL	Robotics SE
26. Carlton Peters	NASA GSFC	Thermal
27. Kan Yang	NASA GSFC	Thermal
28. Paul Lightsey	Ball	SE
29. Kim Mehalick	NASA GSFC	Thermal/Sunshade
30. Bo Naasz	NASA GSFC	RPO
31. Keith Havey	L3 Harris	Mirror Segments
32. Harley Thronson	NASA GSFC	Mission Concepts
33. Scott Knight	Ball	Optics

Name	Institution	Expertise
34. John Lymer	Maxar	Robotics
35. Glen Henshaw	NRL	Robotics
36. Gordon Roesler	ex-DARPA	Robotic Assembly
37. Rudra Mukherjee	NASA JPL	Robotics
38. Mike Fuller	NGIS	Spacecraft
39. Ken Ruta	NASA JSC	Robotics
40. Dave Miller	MIT	System Assembly
41. Joe Pitman	Heliospace	Structures
42. Keith Belvin	NASA LaRC	Structures
43. Sharon Jeffries	NASA LaRC	Systems Eng
44. Dave Folta	NASA GSFC	Orbital Dynamicist
45. Lynn Bowman	NASA LaRC	Programmatic
46. John Grunsfeld	ex-NASA	Astronaut
47. Alison Nordt	LMC	Programmatic
48. Bill Vincent	NRL	Programmatic
49. Diana Calero	NASA KSC	Launch Vehicles
50. Brad Peterson	OSU	Astrophysicist
51. Kevin DiMarzio	Made in Space	Fabrication
52. Matt Greenhouse	NASA GSFC	Astrophysicist
53. Max Fagin	Made in Space	Fabrication
54. Bobby Biggs	LMC	Fabrication
55. Alex Ignatiev	U Houston	Coatings
56. Rob Hoyt	Tethers	Fabrication
57. Scott Rohrbach	NASA GSFC	Scattered Light
62. Jason Herman	Honeybee	Robotics
63. Stuart Wiens	LMC	Spacecraft
64. Josh Woods	LMC	Spacecraft
65. Austin Van Otten	NGAS	Structures
66. Marshal Perrin	STScI	Astrophysicist
67. Jeff Hoffman	MIT	Astronaut
68. Keith Warfield	NASA JPL	Costing
69. Ron Polidan	PSST	Astrophysicist
70. Howard Macewen	Self	Aerospace
71. Samantha Glassner	NEU	Student
72. Nick Siegler	NASA JPL	Technologist

Study Participants

Name	Institution	Expertise
1. Ali Azizi	NASA JPL	Metrology
2. Larry Dewell	LMC	Pointing/Stability/Control
24. Jeff Sokol	Ball	Mechanical/AIT
25. Atif Qureshi	SSL	Robotics SE
26. Carlton Peters	NASA GSFC	Thermal
27. Kan Yang	NASA GSFC	Thermal
28. Paul Lightsey	Ball	SE
29. Kim Mehalick	NASA GSFC	Thermal/Sunshade
30. Bo Naasz	NASA GSFC	RPO
31. Keith Havey	L3 Harris	Mirror Segments
32. Harley Thronson	NASA GSFC	Mission Concepts
33. Scott Knight	Ball	Optics

Key Commercial Companies

- Lockheed
- Ball
- NGIS (O-ATK)
- NGAS
- SSL
- L3 Harris
- several consultants

Study Involvement

- 72 participants
- 6 NASA Centers
- 14 private companies
- 2 gov't agencies
- 5 universities

Name	Institution	Expertise
34. John Lymer		
35. Glen Henshaw		
36. Gordon Roesle		
37. Rudra Mukher		
38. Mike Fuller		
39. Ken Ruta		
40. Dave Miller		
41. Joe Pitman		
55. Alex Ignatiev		
56. Rob Hoyt		
57. Scott Rohrbach		
62. Jason Herman		
63. Stuart Wiens		
64. Josh Woods		
65. Austin Van Ott		
66. Marshal Perrin		
67. Jeff Hoffman		
68. Keith Warfield		
69. Ron Polidan		
70. Howard Macev		
71. Samantha Glassner	NEU	Student
72. Nick Siegler	NASA JPL	Technologist

SMEs

Missions: JWST, HST, ISS, Restore-L, RSGS, NASA Tipping Point, APD STDTs, Gateway

Disciplines:

- RPO
- telescope optics
- robotics
- structures
- sunshade
- instruments
- I&T + V&V
- launch vehicles
- orbital dynamics

New Steering Committee Study Members

Transitioning from telescope focus to robotic assembly and systems focus

1. Dave Redding	JPL
2. Joe Pitman	consultant
3. Scott Knight	Ball
4. Bill Doggett	NASA LaRC
5. Matt Greenhouse	NASA GSFC
6. Ben Reed	NASA GSFC
7. Gordon Roesler	DARPA (ret)
8. John Grunsfeld	NASA (ret)
9. Keith Belvin	NASA STMD
10. Brad Peterson	STScI/OSU
11. Florence Tan	NASA SMD
12. Ray Bell	Lockheed
13. Nasser Barghouty	NASA APD
14. Dave Miller	MIT
15. Keith Warfield	NASA ExEP
16. Bill Vincent	NRL
17. Bo Naasz	NASA GSFC
18. Erica Rogers	NASA OCT

Four Face-to-Face Meetings

… and multiple weekly telecons

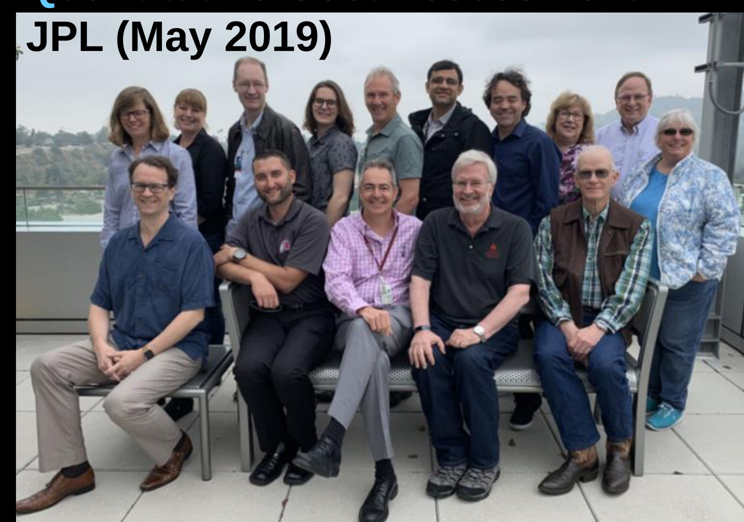
Telescopes: Caltech (June 2018)

Robotics, Orbits, LVs, Assembly Platforms: LaRC (Oct 2018)

Qualitative Cost, Risk Assessments: JPL (Feb 2019)

Quantitative Cost Assessment

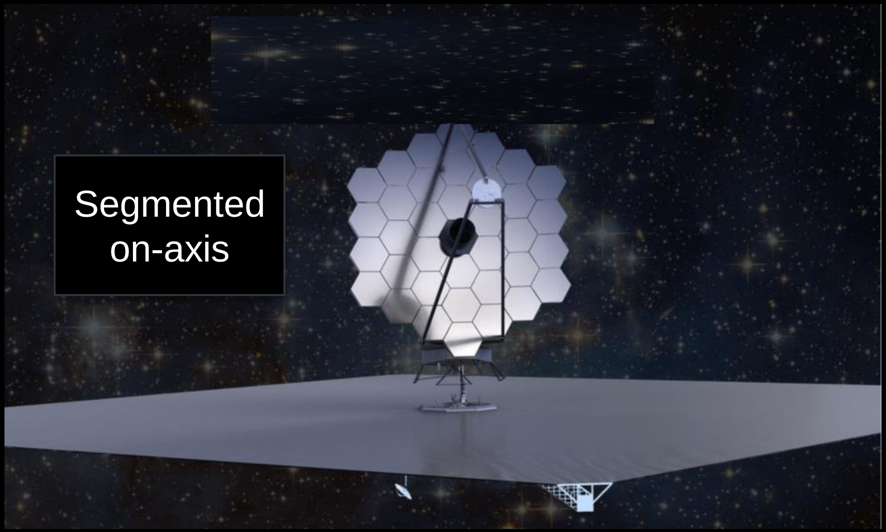
JPL (May 2019)



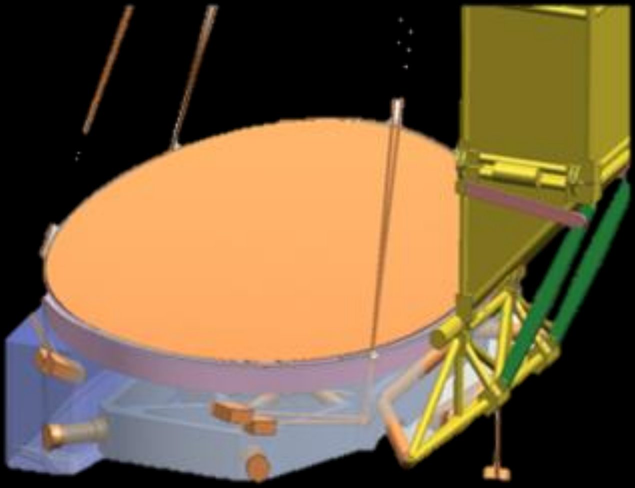
Reference Observatory

Telescope Architecture Candidates

Telescope Concepts Considered

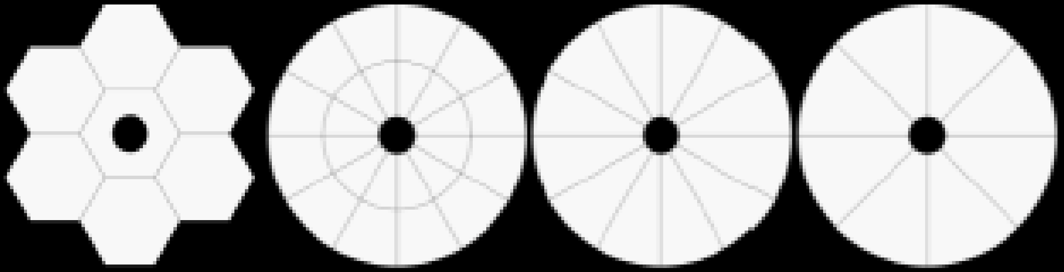


Elliptical, off-axis

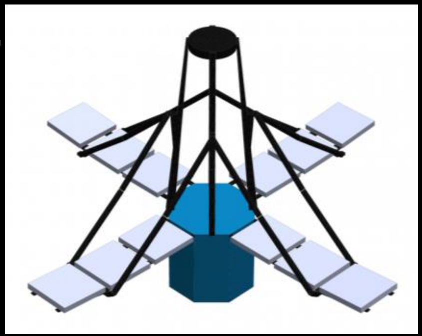


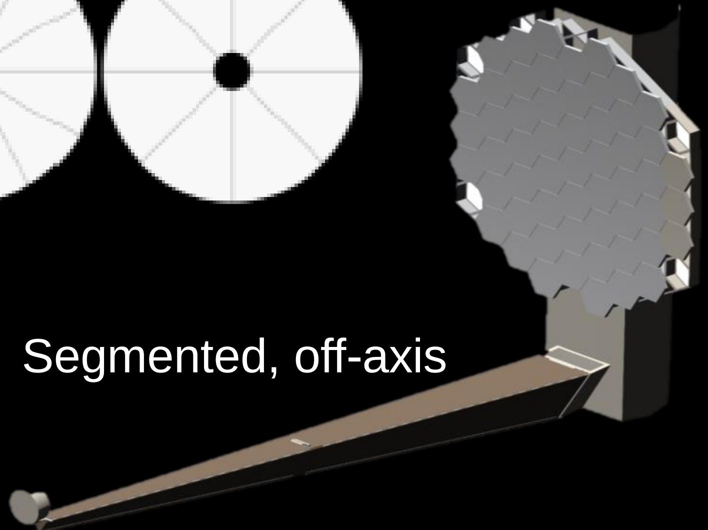
5 m segments

Pie-shaped segments



Sparse,



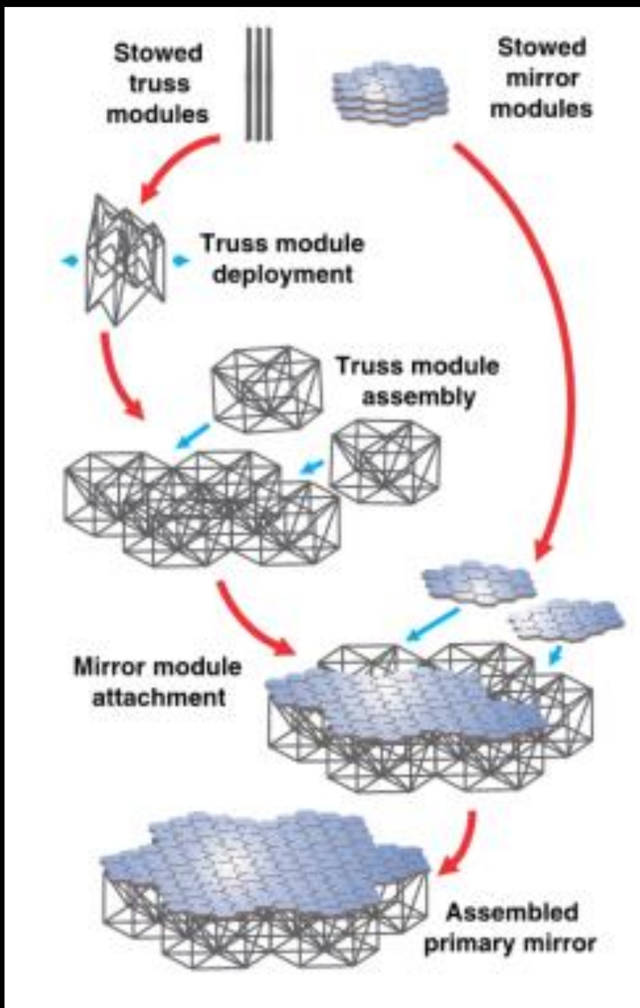


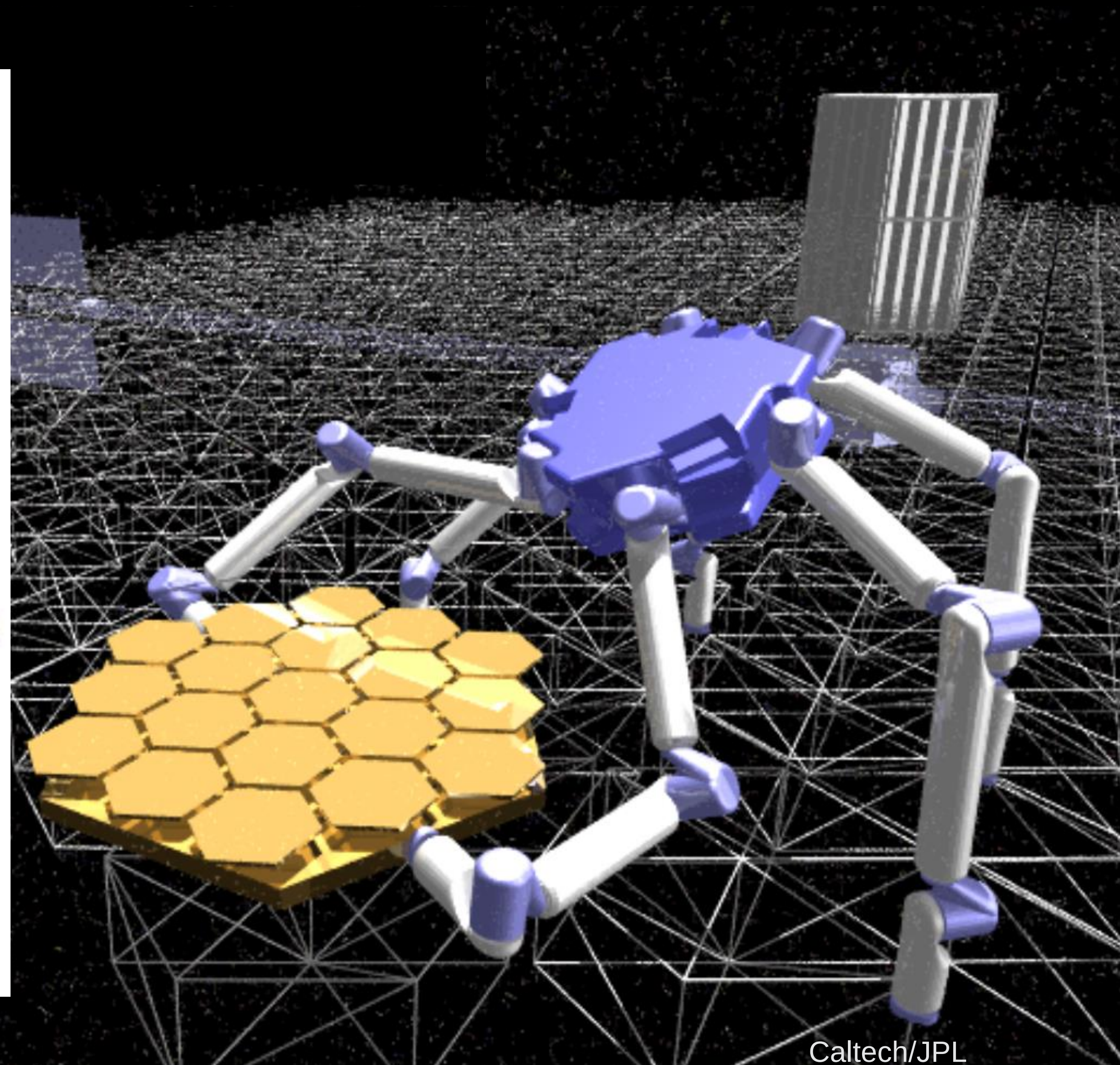
Segmented, off-axis

Robot Candidates

Multi-Limbed Robot

Caltech/JPL; Lee et al. (2016)



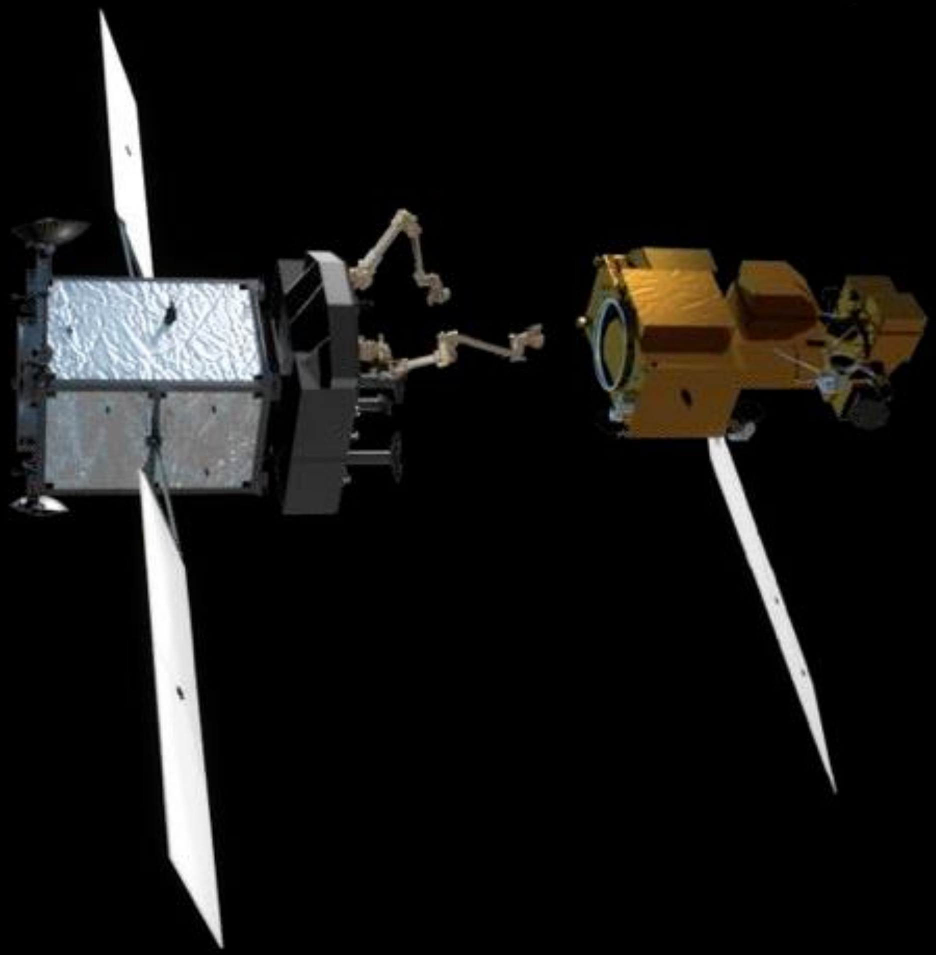


Free-Flying Robots

NASA's Restore-L

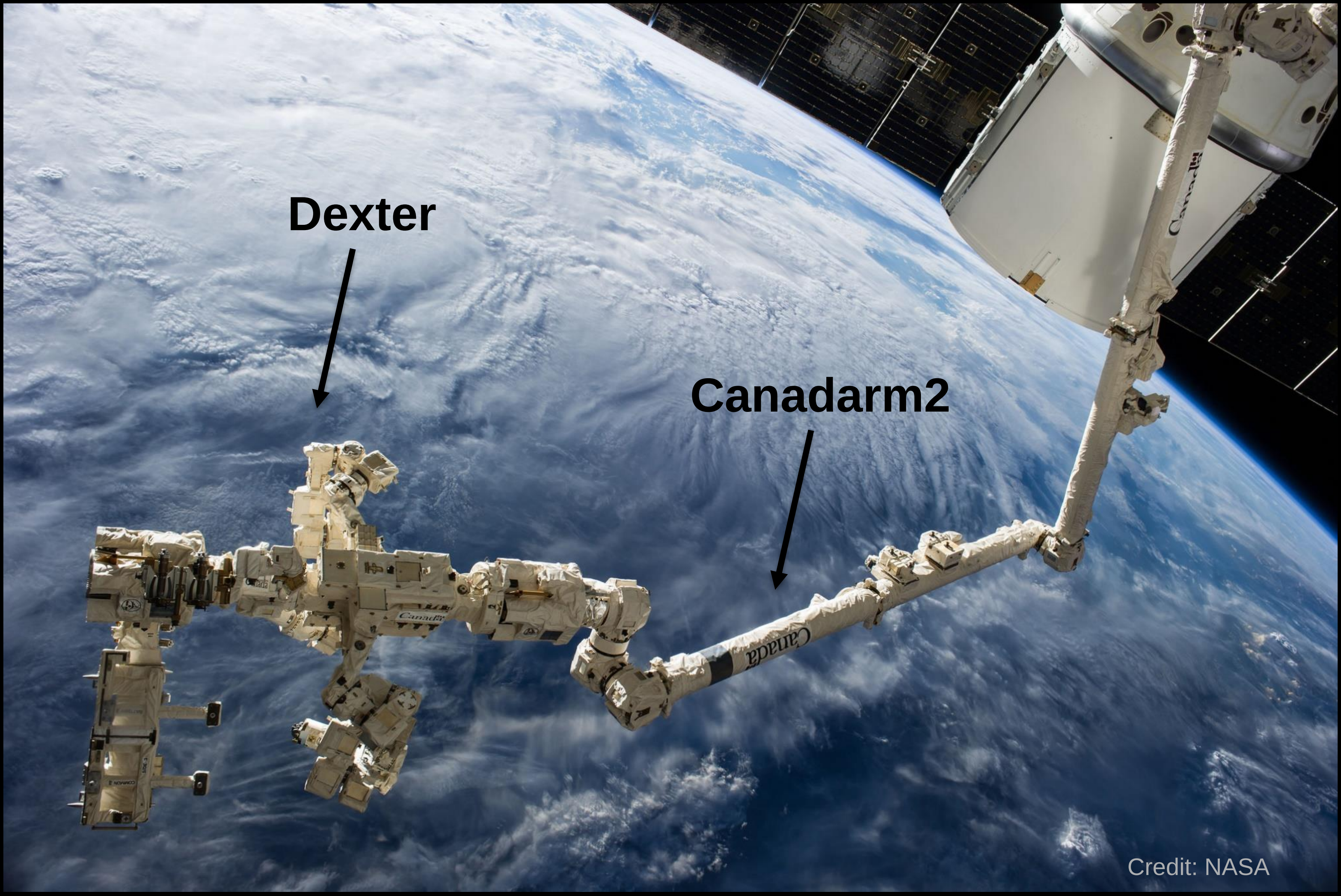
DARPA/SSL's Robotic Servicing of Geosynchronous Satellites

Orbital ATK's Mission Extension Vehicle



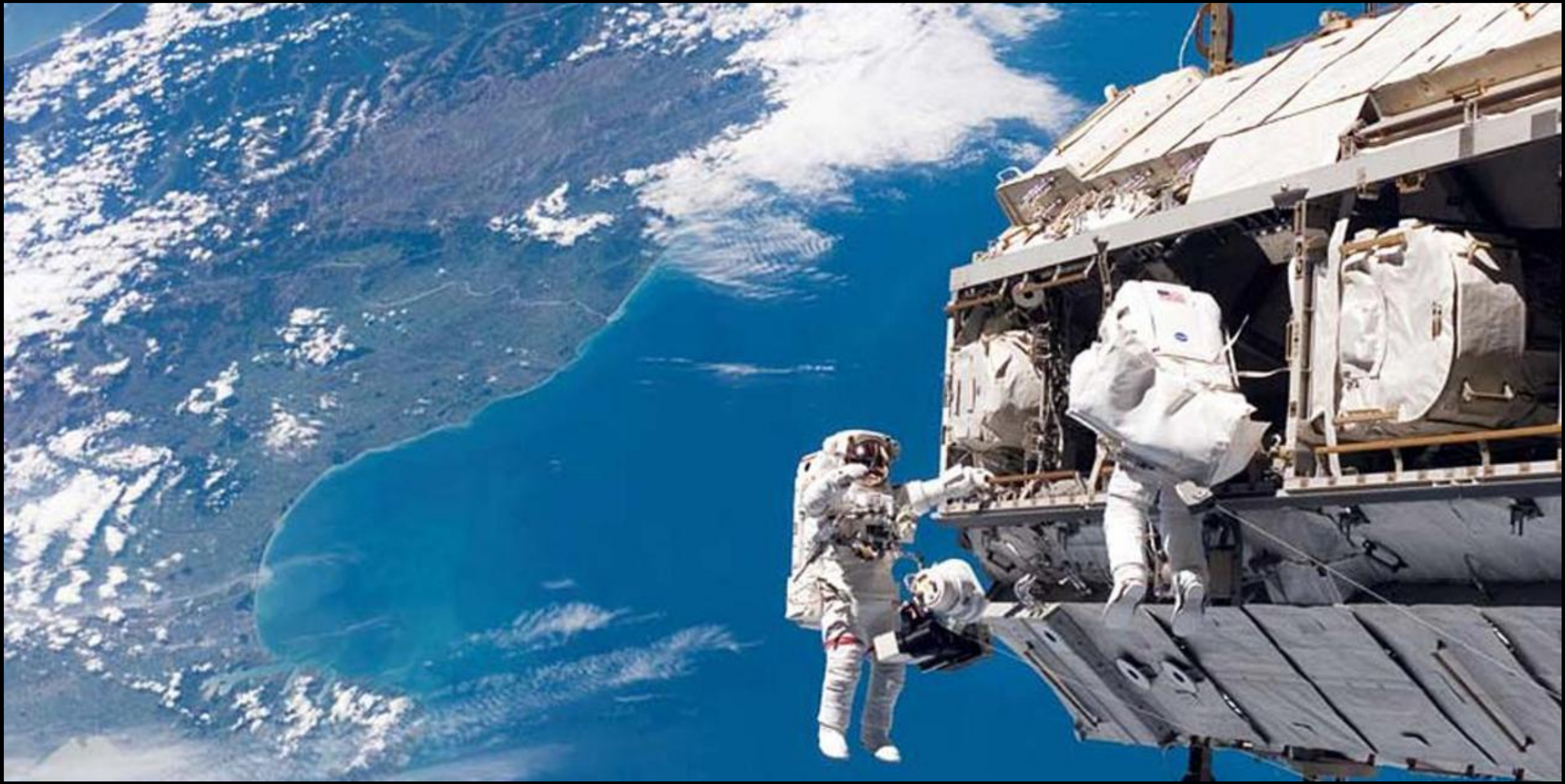
Credit: NASA

Robotic Arm
ISS's DEXTER and Canadarm2



Astronauts

Can play an important role in iSA, to be defined



Credit: NASA

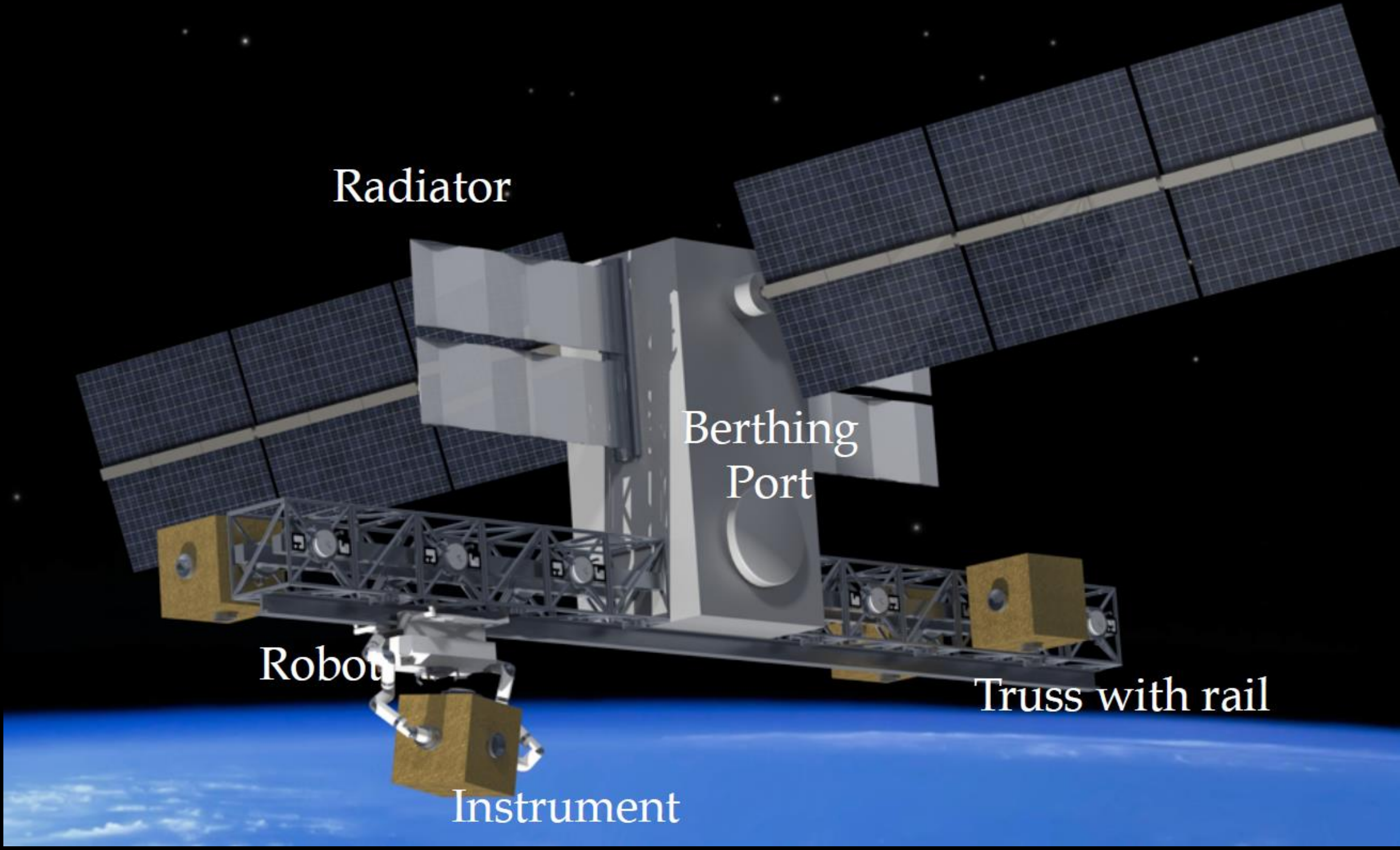
Assembly Platform Candidates

International Space Station
LEO


Image: NASA

Earth Sciences Space Station

Sun Synchronous Orbit



Gateway
cis-Lunar orbit

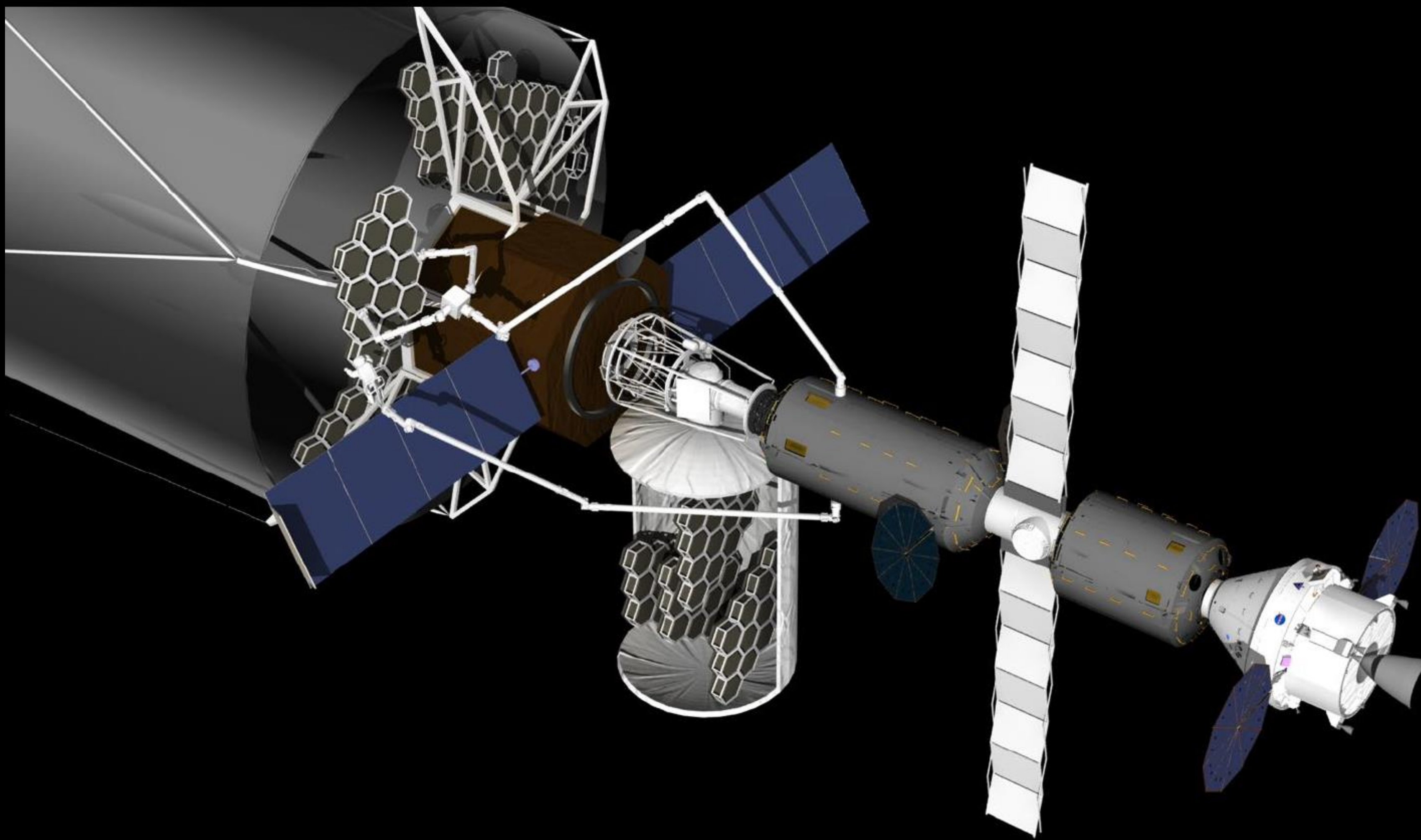


Illustration: NASA

Bring Your Own Assembly Platform

Free-fliers with specialized robotic arms docked to spacecraft bus

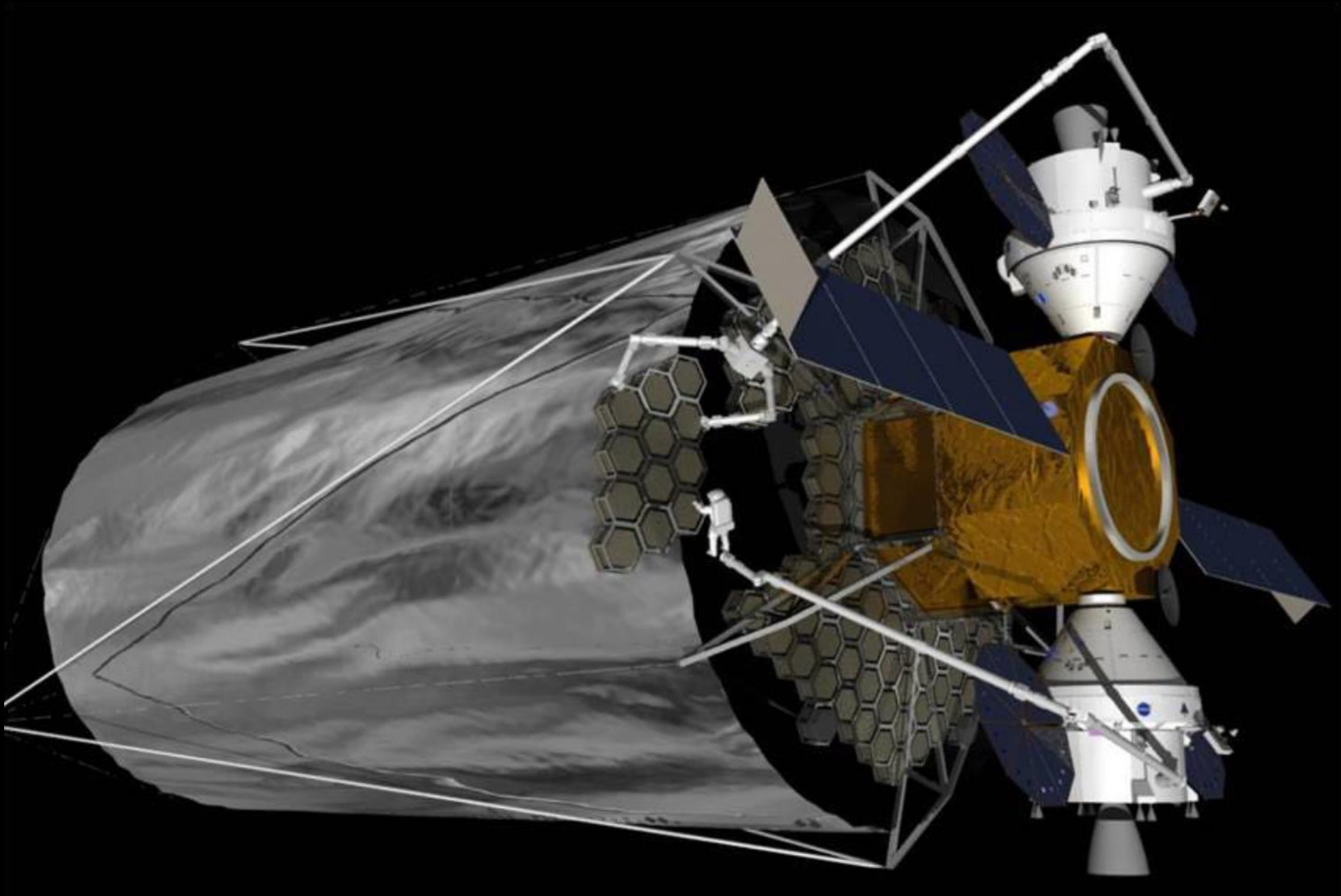
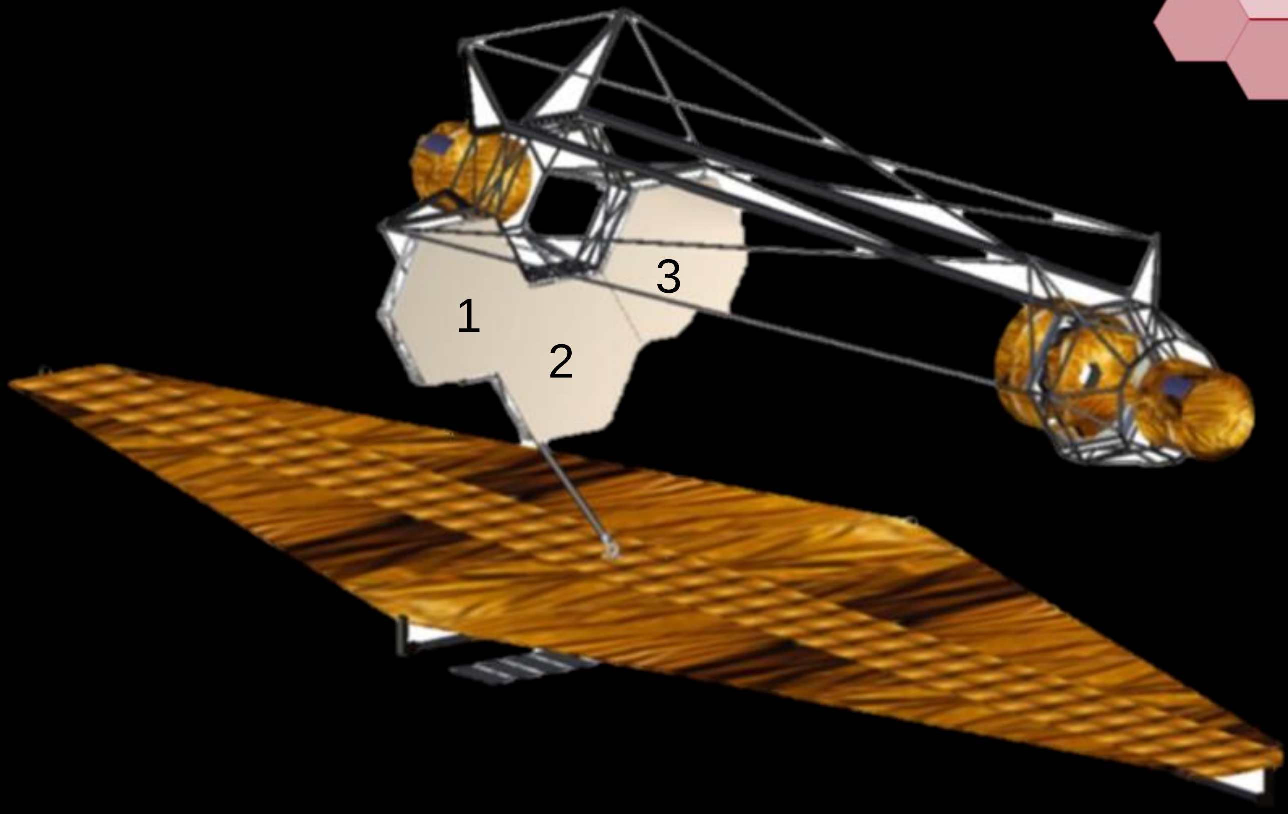
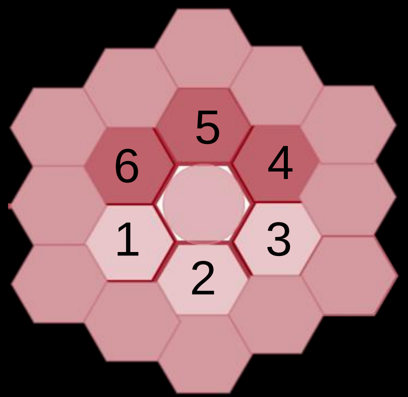


Illustration: NASA

Evolvable Space Telescope

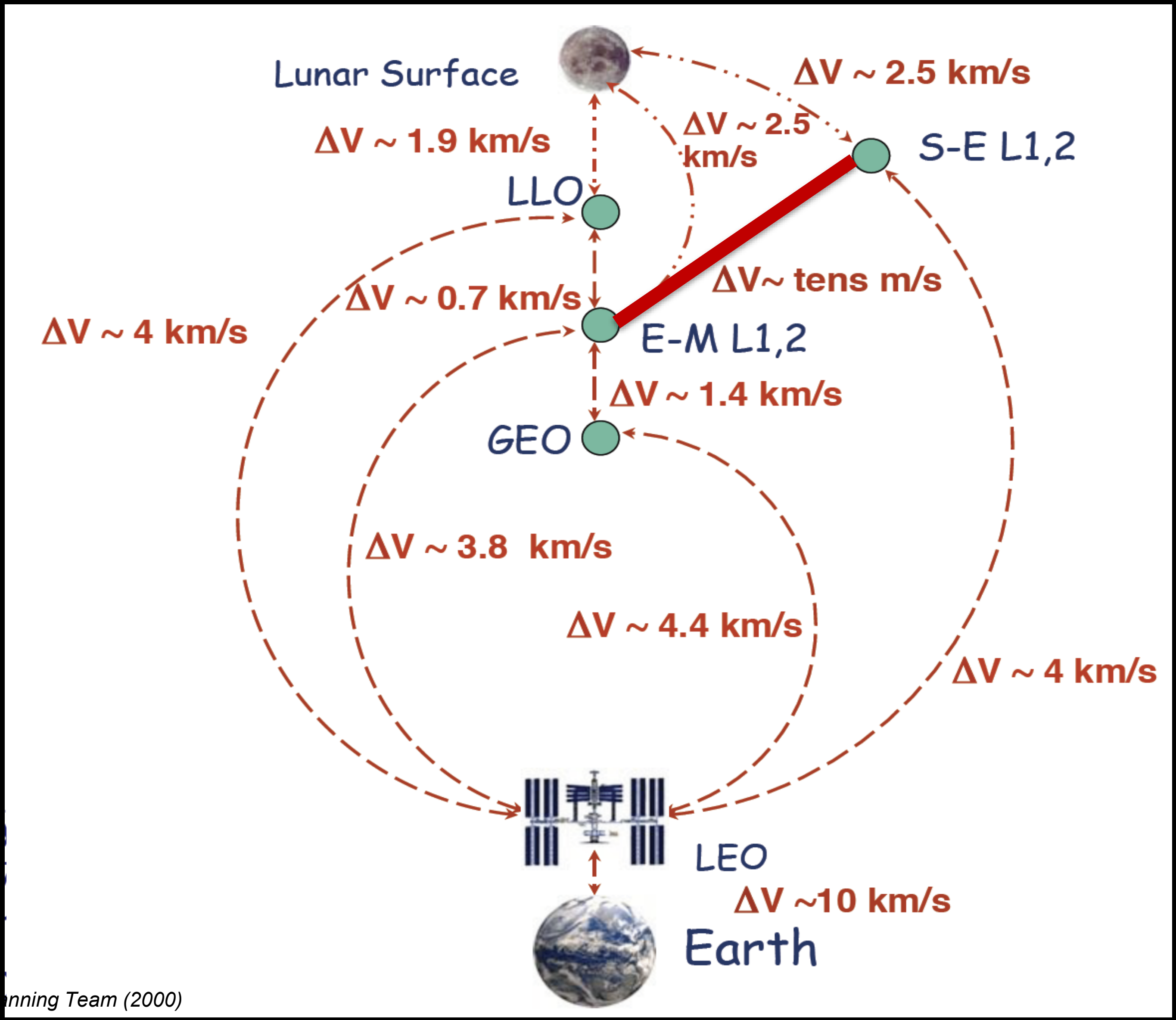
Northrop Grumman





Orbit Candidates

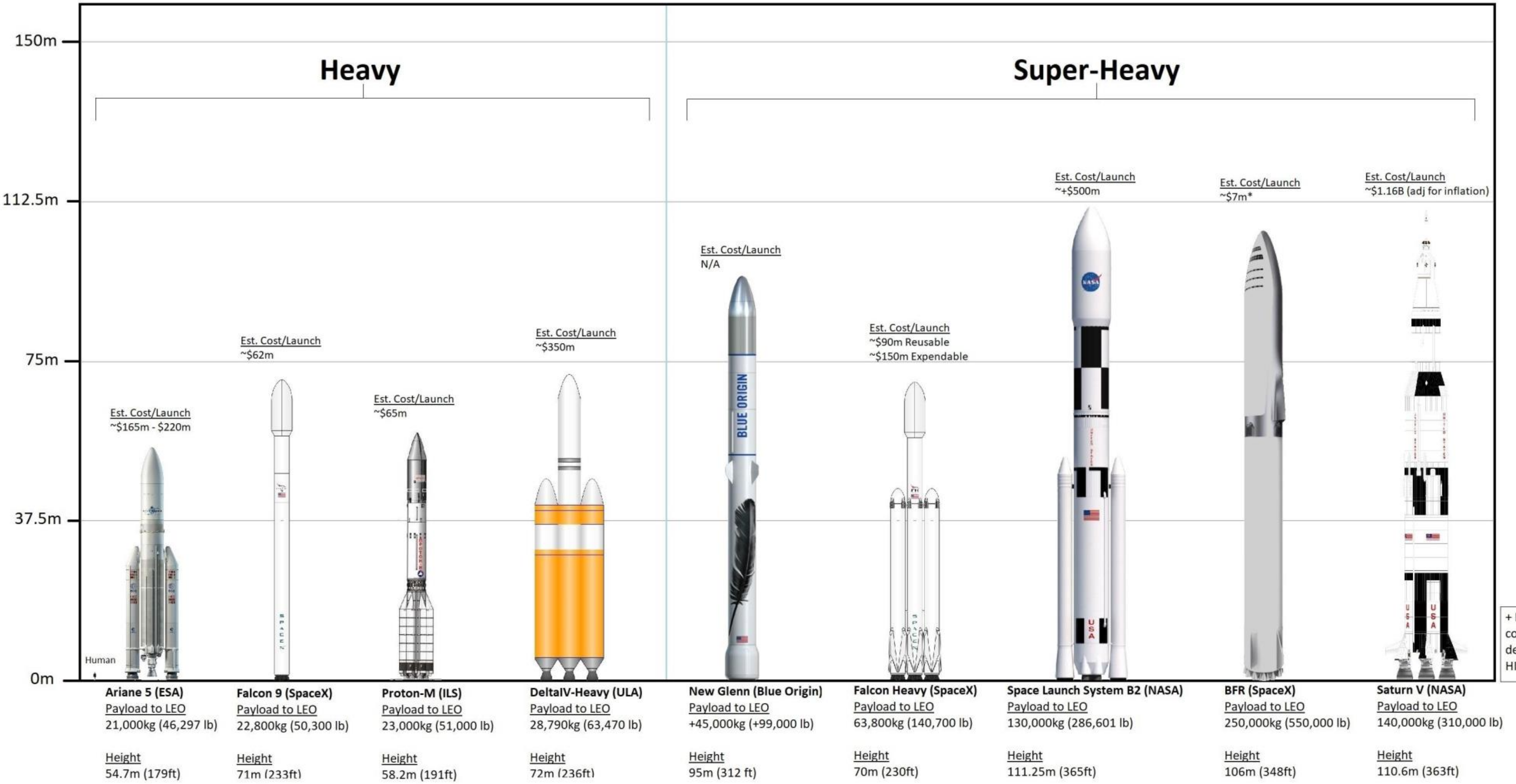
Delta v's



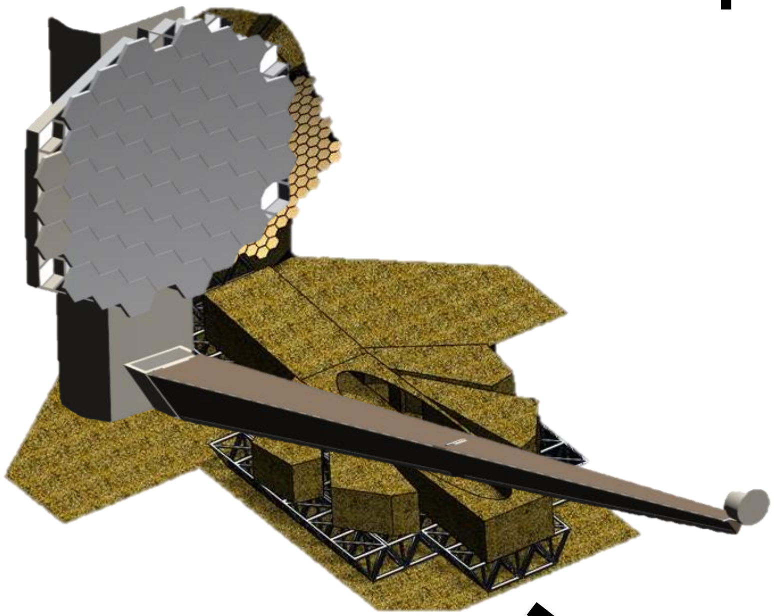
Lunar Surface
ΔV ~ 2.5 km/s
ΔV ~ 1.9 km/s
ΔV ~ 2.5 km/s
S-E L1,2
LLO
ΔV~ tens m/s
ΔV ~ 0.7 km/s
ΔV ~ 4 km/s
E-M L1,2
ΔV ~ 1.4 km/s
GEO
ΔV ~ 3.8 km/s
ΔV ~ 4.4 km/s
ΔV ~ 4 km/s
LEO
ΔV ~10 km/s
Earth
nning Team (2000)

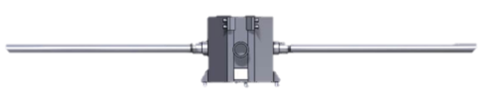
Launch Vehicle Candidates

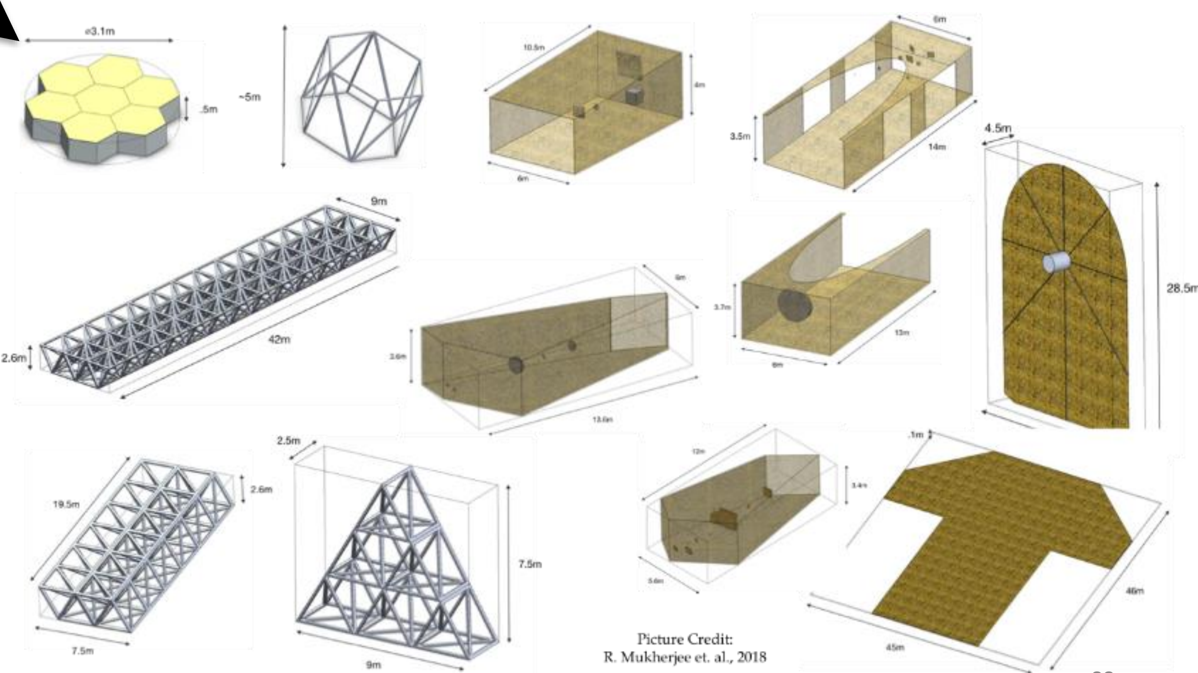
Candidate Launch Vehicles



Modularization of a Space Telescope



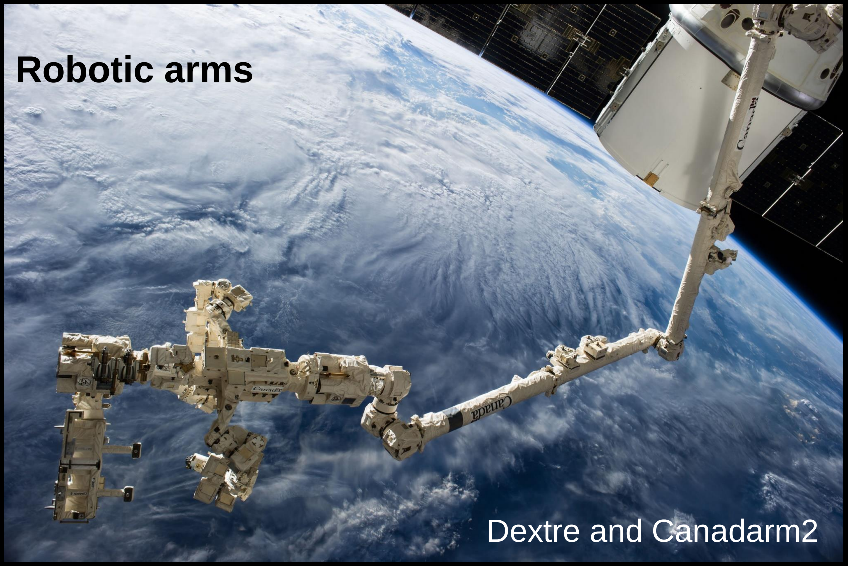




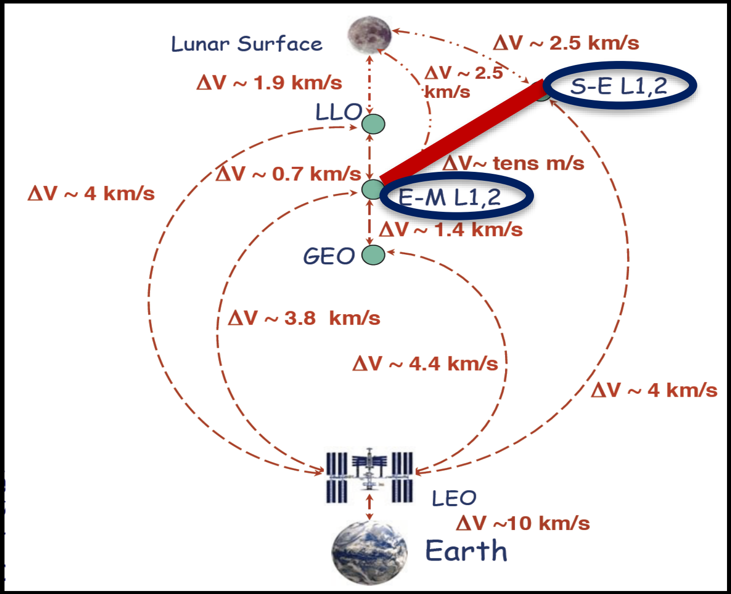
Picture Credit:
R. Mukherjee et. al., 2018

Selected Reference Mission Concept

Assembly Agent



Assembly Orbit



Launch Vehicles

ULA's Delta IV Heavy | **ULA's Atlas V** | **SpaceX's Falcon Heavy**

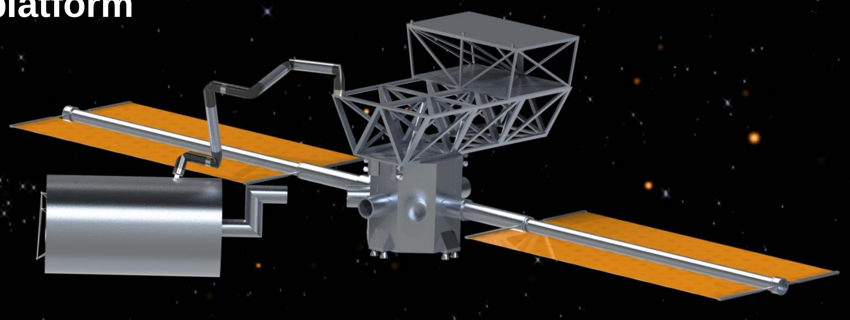
Photo: United Launch Alliance

Photo: United Launch Alliance

Photo: SpaceX

Assembly Platform

Telescope's spacecraft bus as the assembly platform



Delivery ConOps

Disposable Cargo Delivery Vehicle (CDV)

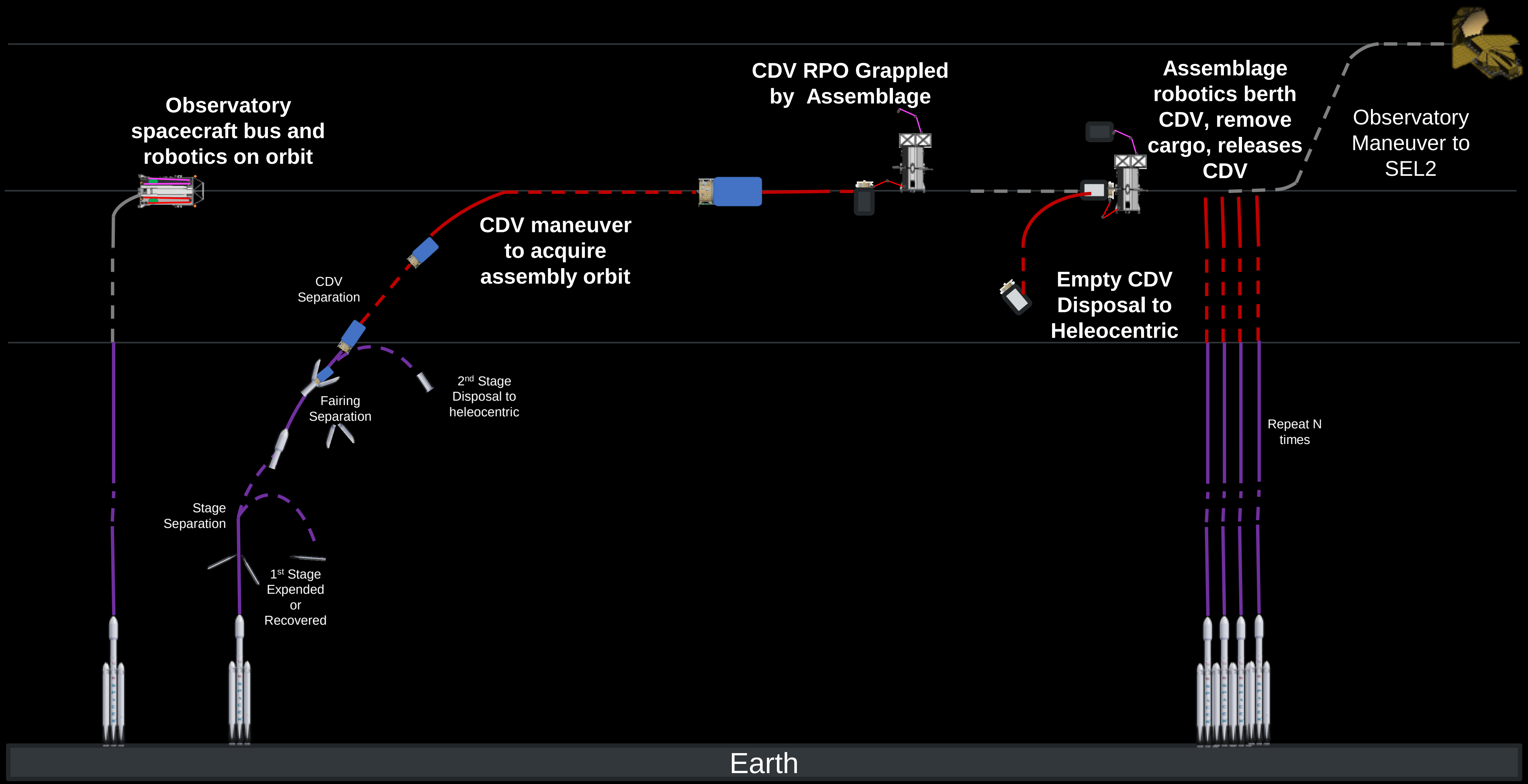


Illustration: Bo Naasz (NASA GSFC)

Delivery Via Disposable Cargo Delivery Vehicle

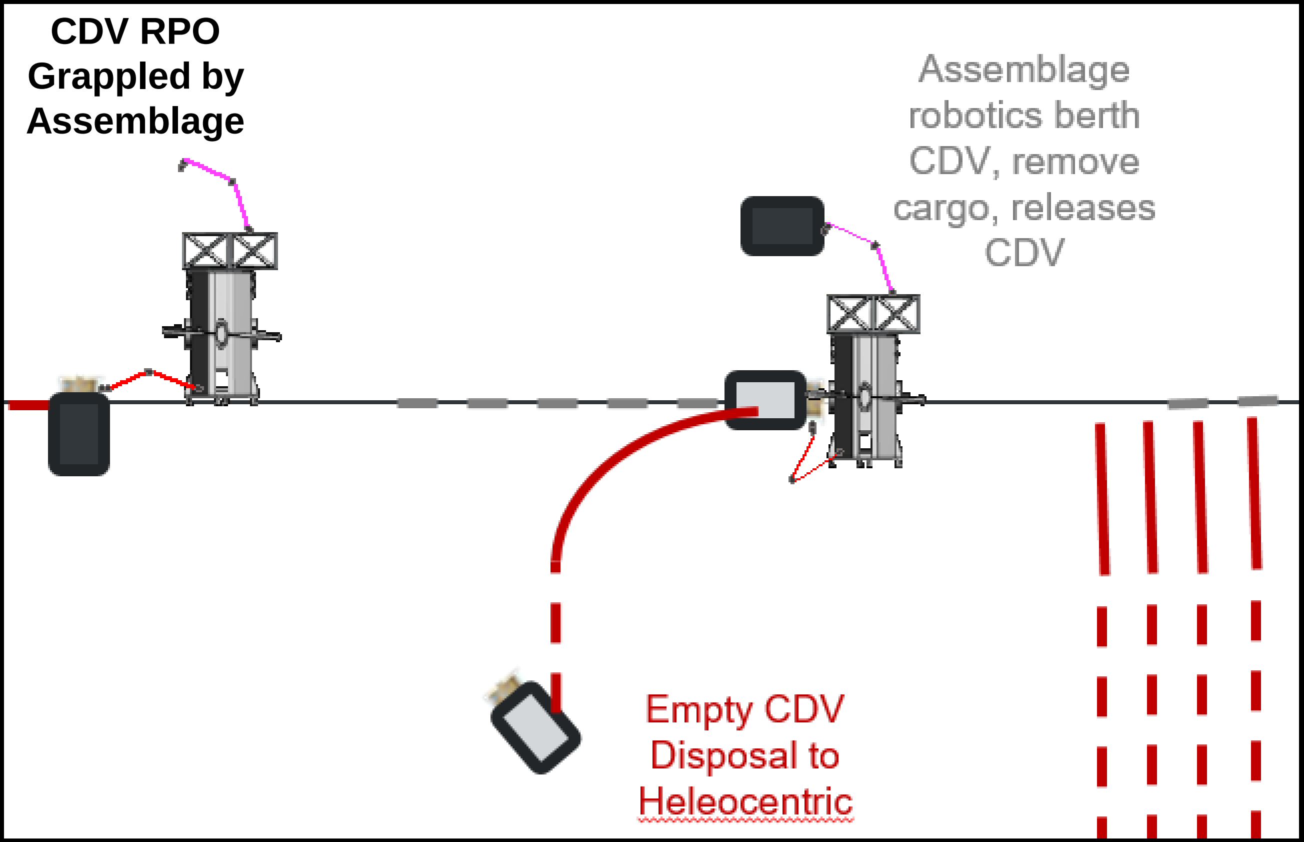
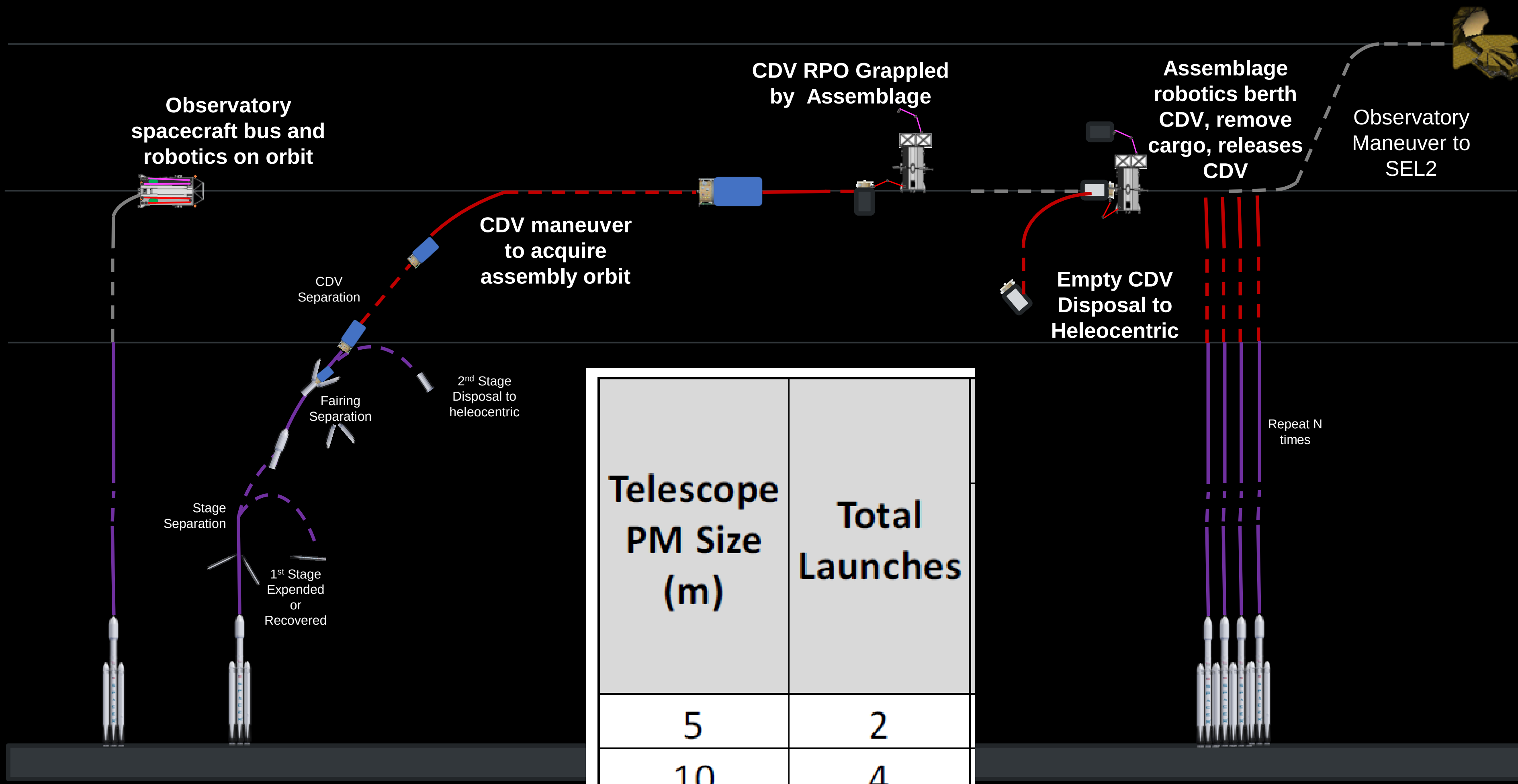


Illustration: Bo Naasz (NASA GSFC)

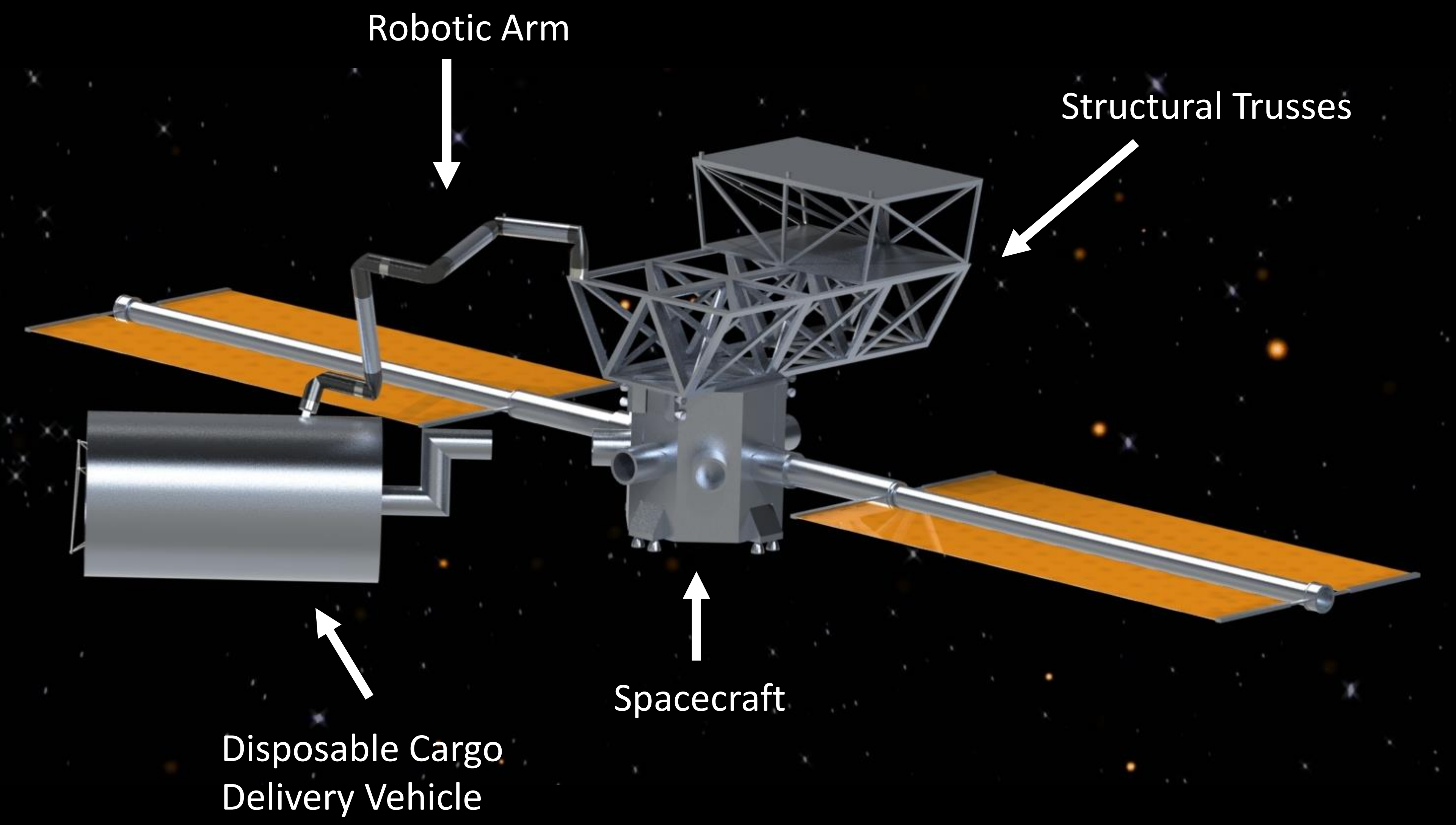
Delivery ConOps

Disposable Cargo Delivery Vehicle (CDV)

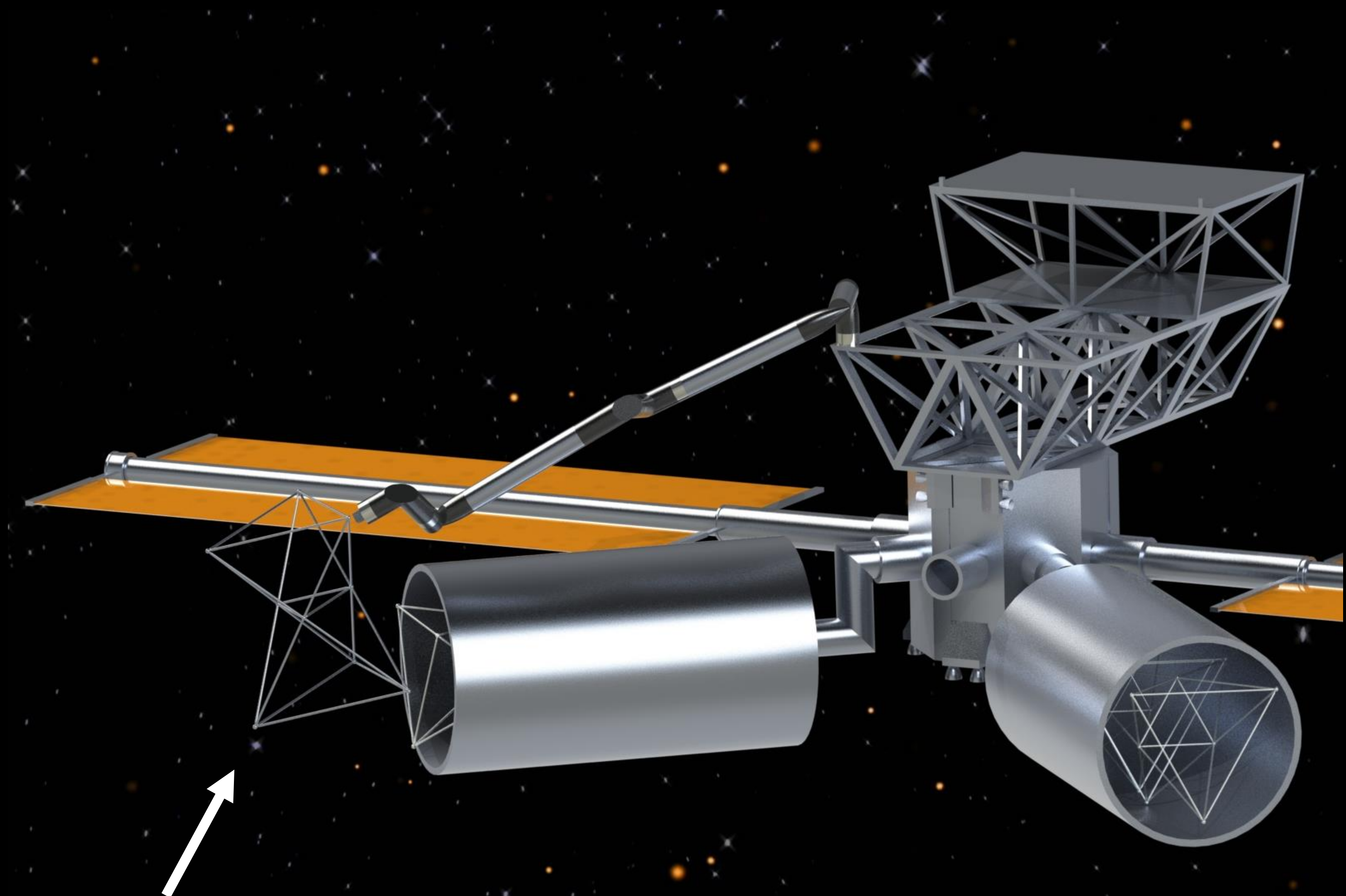


Telescope PM Size (m)	Total Launches
5	2
10	4
15	7
20	12

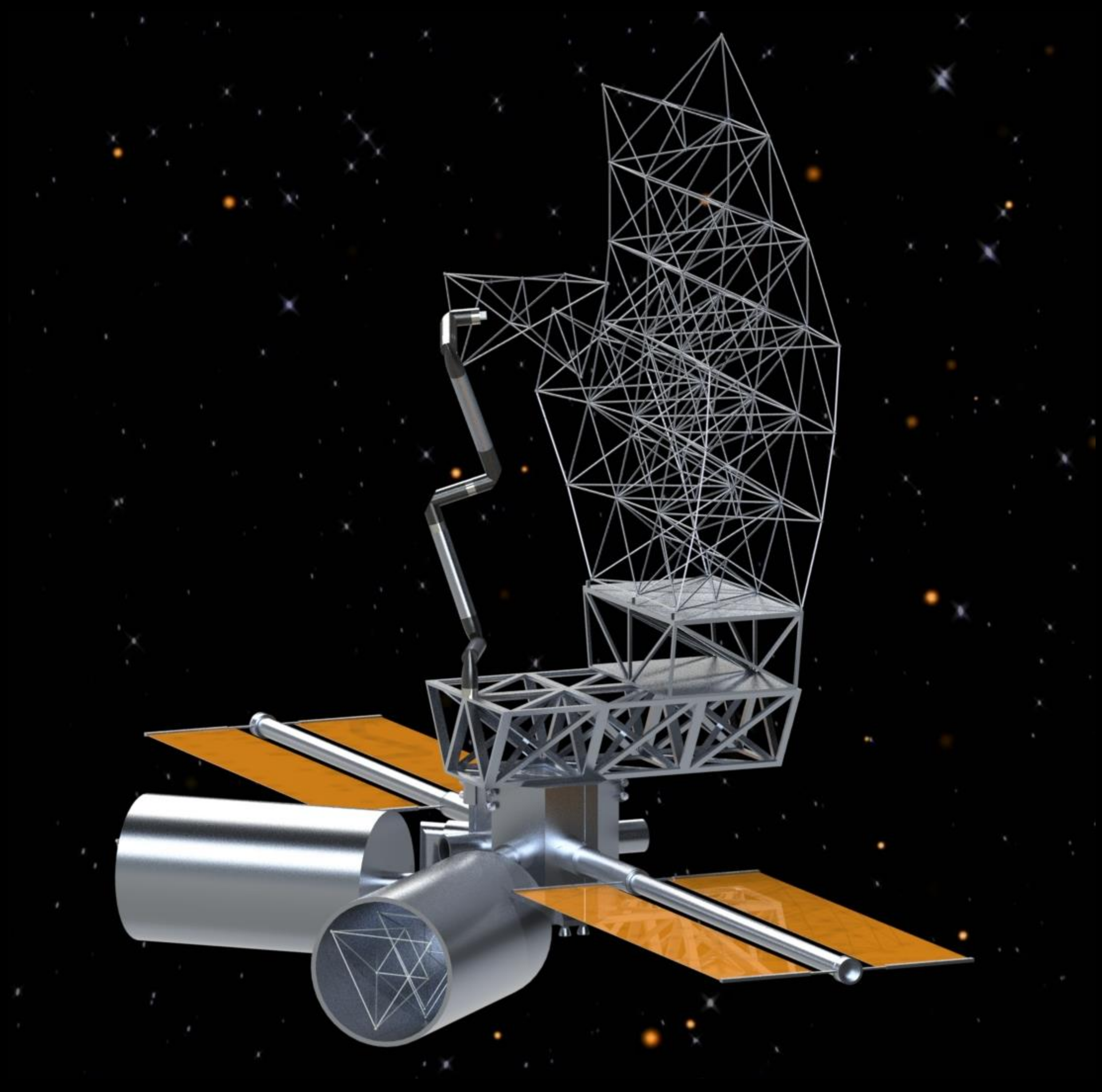
Illustration: Bo Naasz (NASA GSFC)

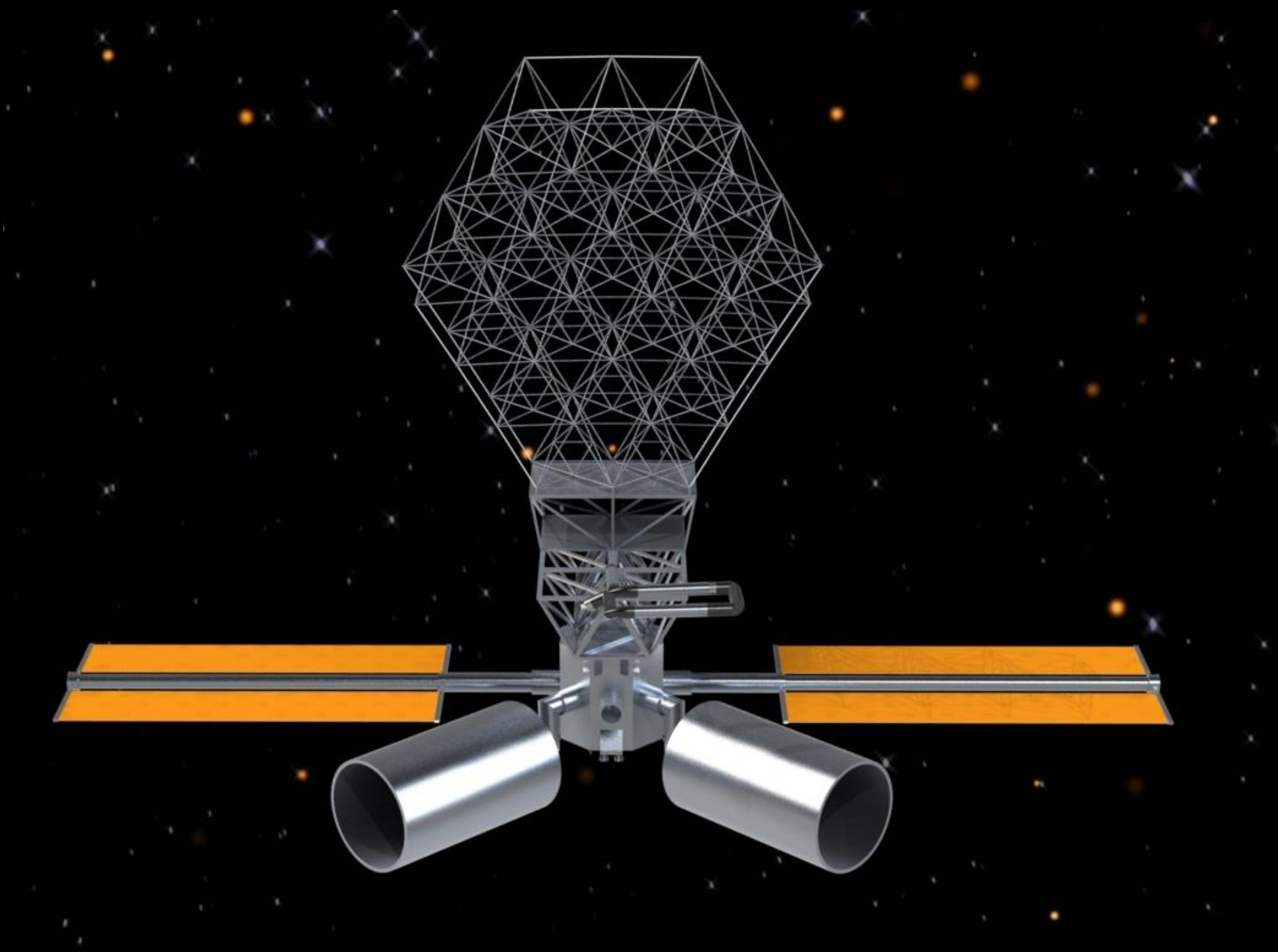


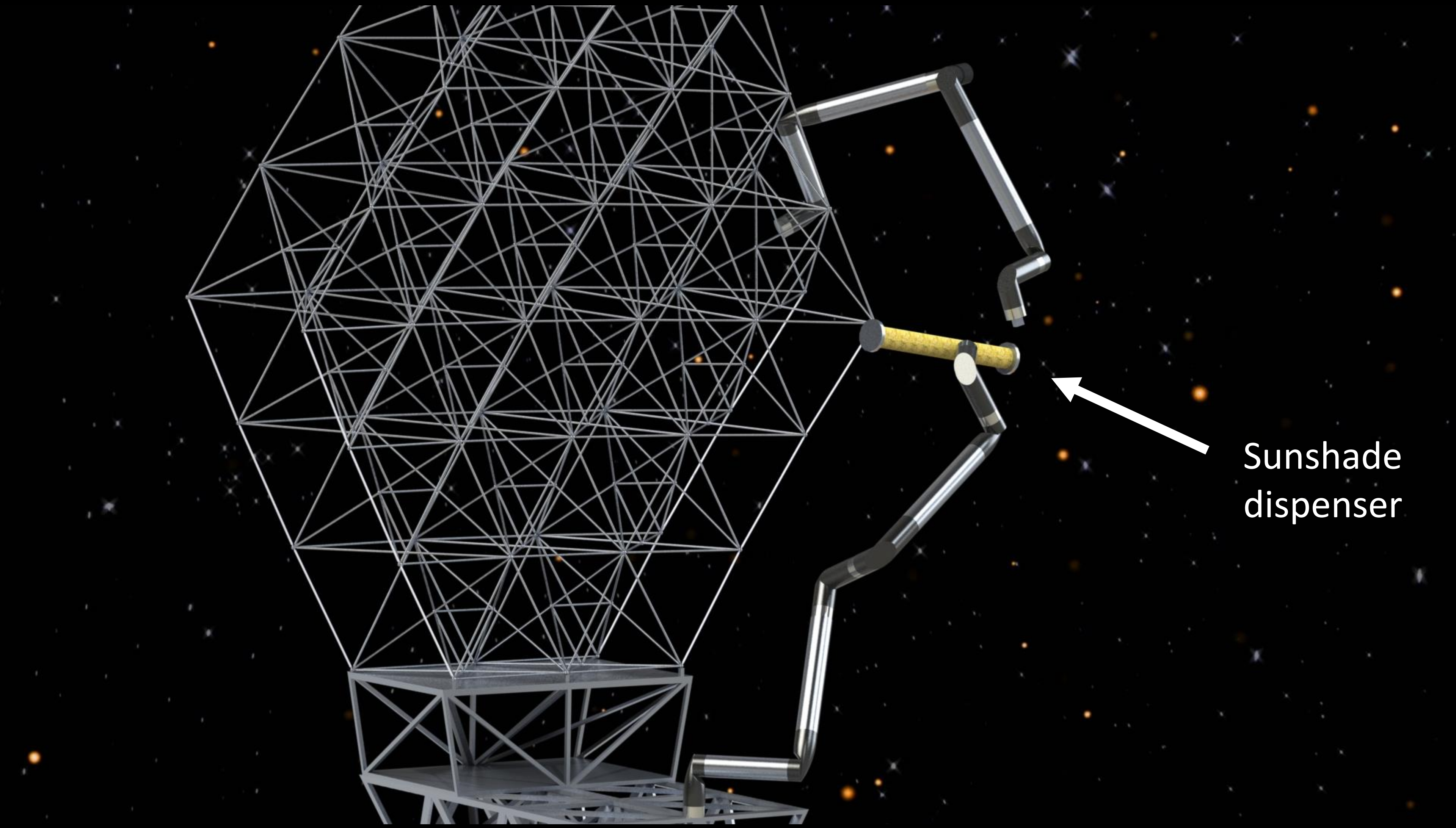
All illustrations from R. Mukherjee and D. Mick (NASA/JPL/Caltech)

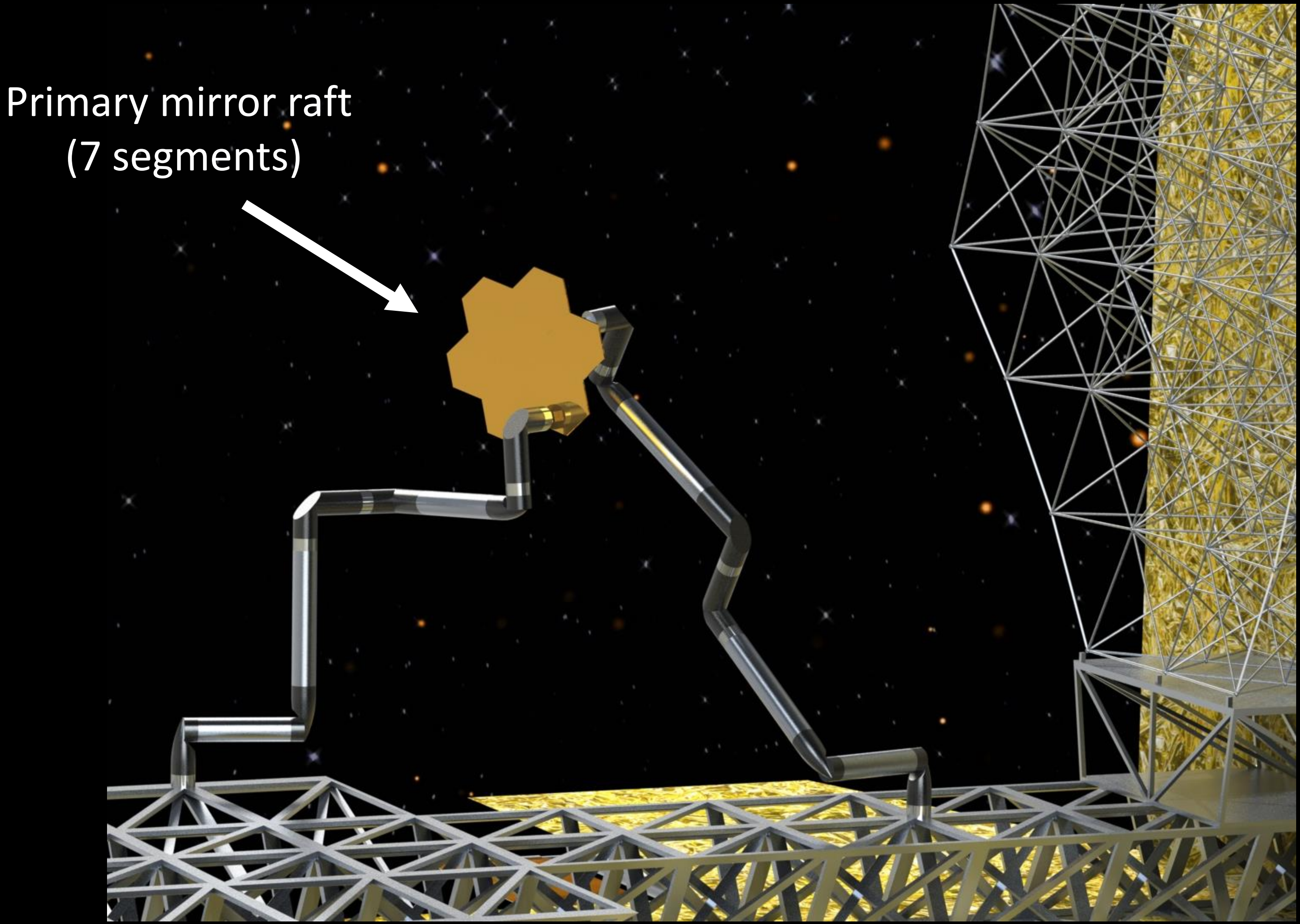


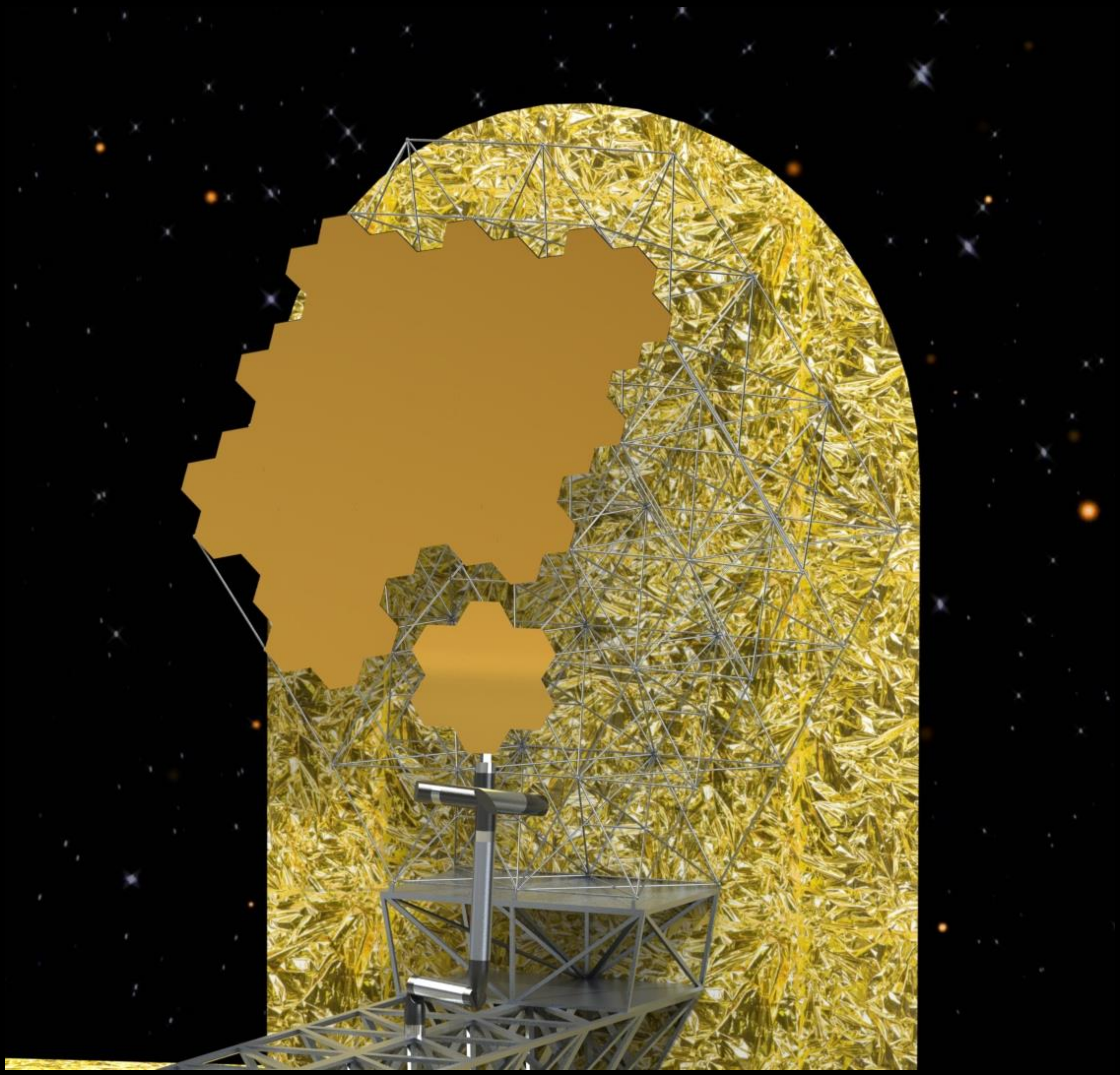
telescope
backplane truss

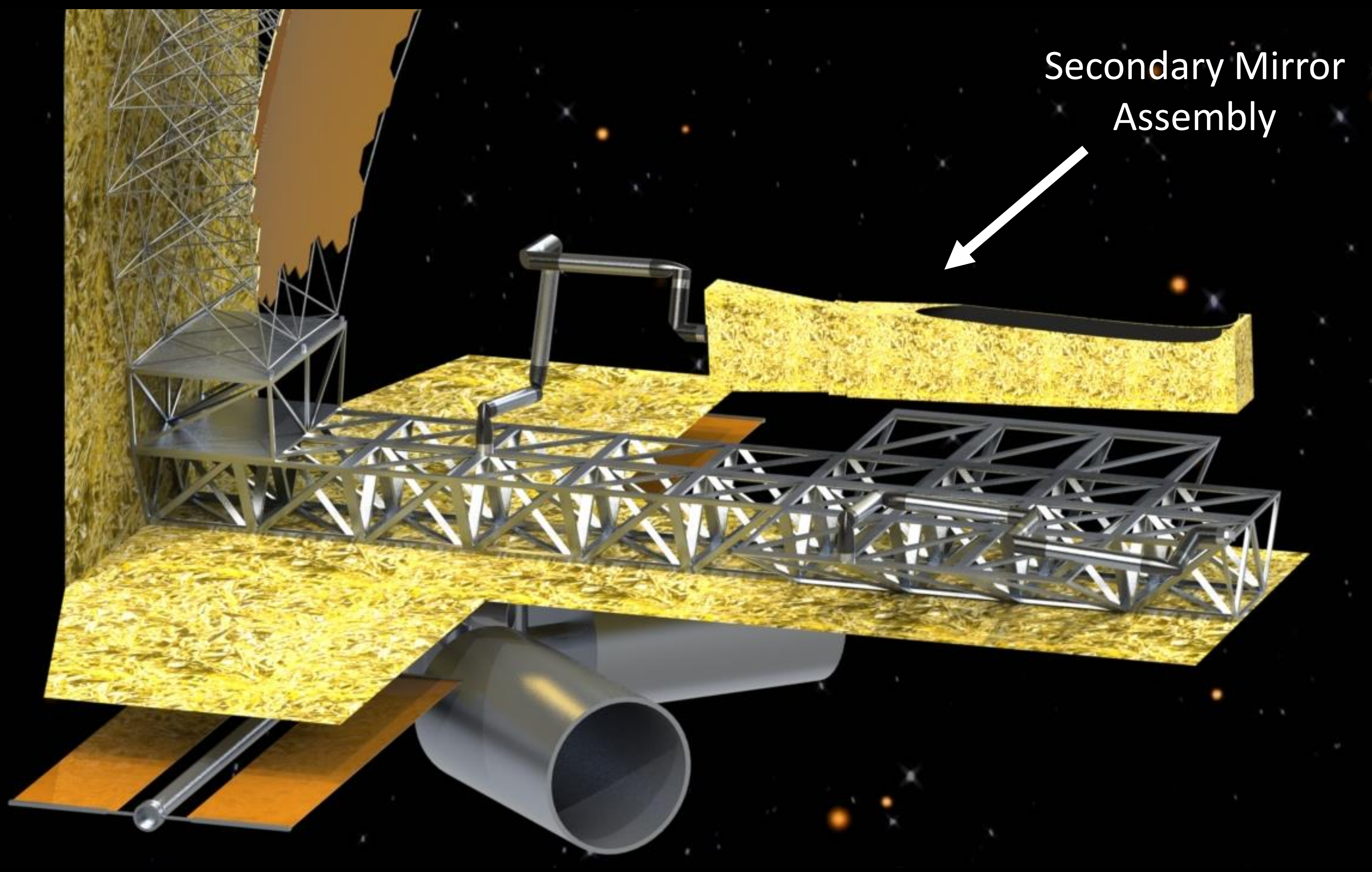


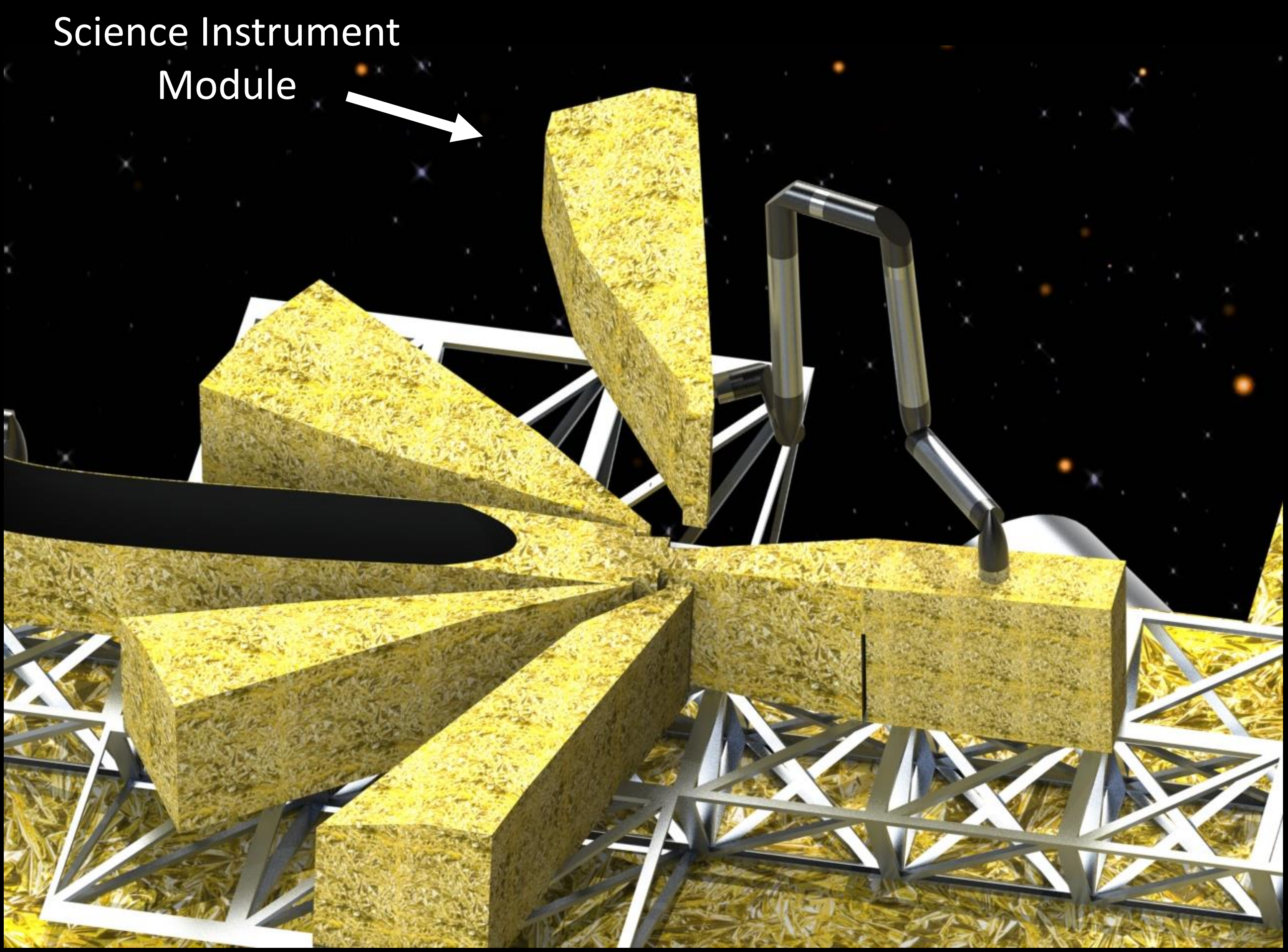



Sunshade
dispenser

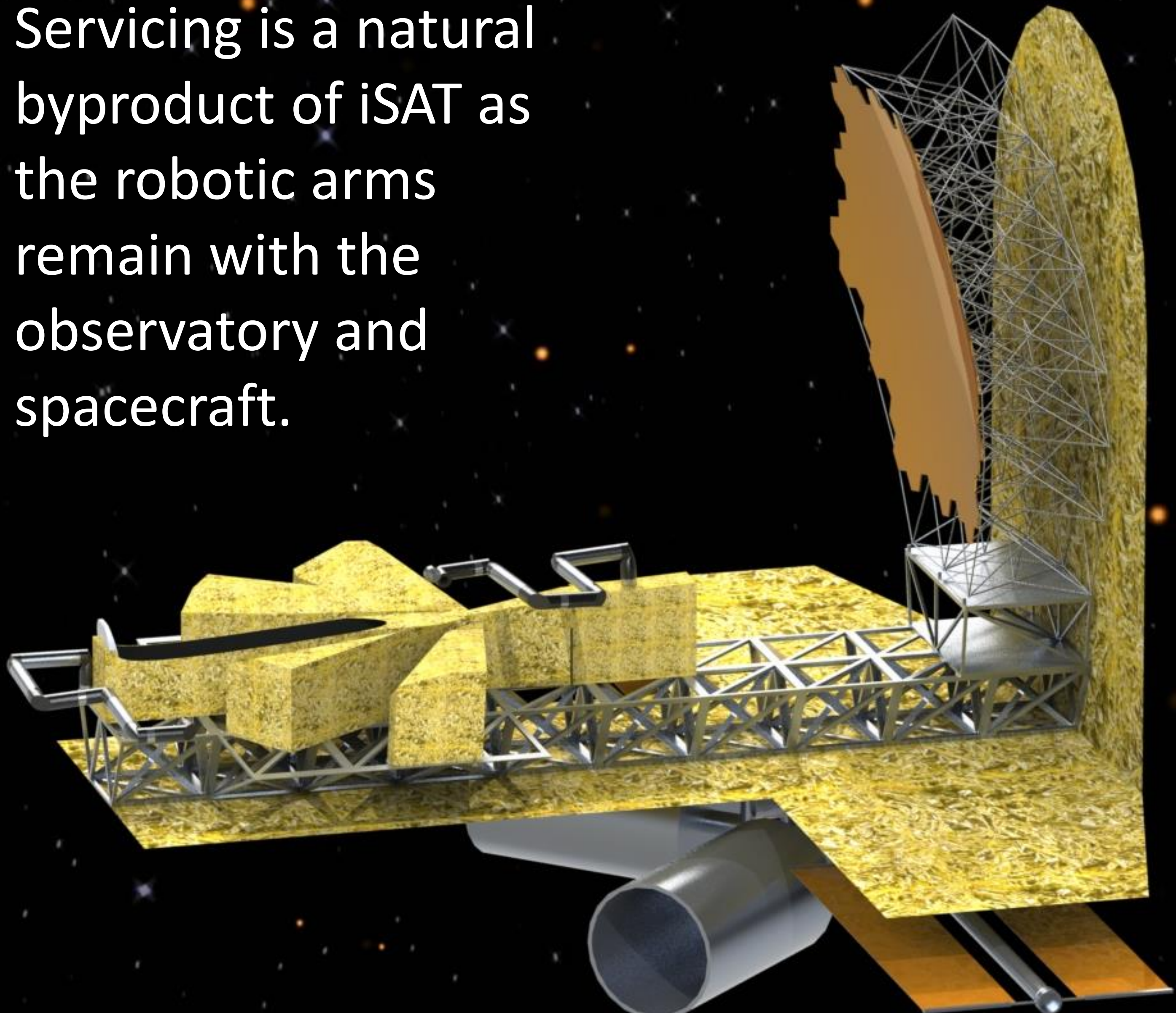

Primary mirror raft
(7 segments)




Secondary Mirror
Assembly


Science Instrument
Module

Servicing is a natural byproduct of iSAT as the robotic arms remain with the observatory and spacecraft.



Study Findings

Key Aspects of the iSAT Paradigm

1) Modularized flight elements: encapsulation of complexity, standardized interfaces, more readily assembled/serviceable, tailor to LV fairing size

2) Multiple launches: leverages existing commercial medium-lift capabilities for lower cost, more flexibility, greater margins

3) Cargo delivery vehicles to deliver modules to the assembly site; leverages ISS experience

4) Rendezvous and proximity operations: Robotic arm grappling and berthing as demonstrated at the ISS

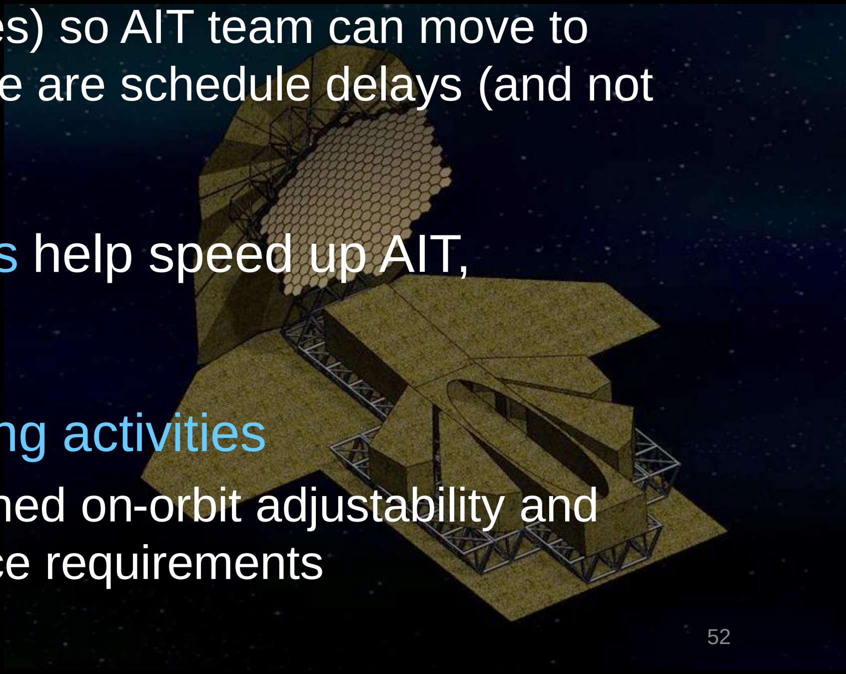
5) Supervised autonomous robotic arms: ISS-qualified arms; ensures executed commands are correct before launching subsequent steps

6) In-space V&V: Combination of "smart" module diagnostics, onboard metrology, model validation

7) Servicing: Follows same paradigm – no explicit servicer needed

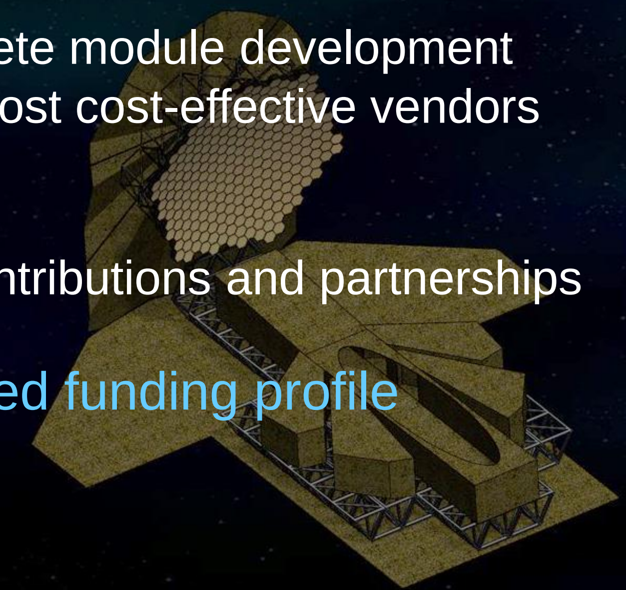
Key Cost Benefits Enabled by iSA (1 of 2)

- Relaxes mass and volume constraints
  - Reduces engineering design complexity and time (i.e. cost)
  - Eliminates complex folding designs, reduces mass iterations, less need for complex modeling
- More versatile scheduling
  - More work conducted in parallel
  - Multiple parallel deliveries (swim lanes) so AIT team can move to different module deliveries when there are schedule delays (and not turn into a large marching army)
- Modules with standardized interfaces help speed up AIT, especially during anomaly resolution
- Eliminates costly systems-level testing activities
  - Enabled by greater degrees of designed on-orbit adjustability and correctability to meet system tolerance requirements



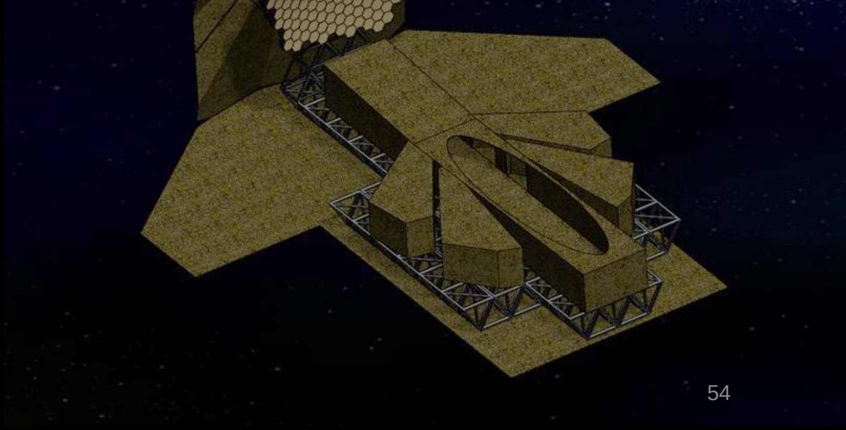
Key Cost Benefits Enabled by iSA (2 of 2)

- Diminishes cost and schedule impacts from late-stage hardware re-design changes and iterations.
- Reduces need for ruggedizing the system and its interfaces to survive launch
- Less need for new and larger ground test facilities
- Spread the wealth: Can distribute and compete module development work across NASA and industrial base to the most cost-effective vendors and facilities
- Share the wealth: Enhances international contributions and partnerships
- More readily enables prescribed or flattened funding profile programs



Key Science Benefits Enabled by iSA

- No "Tyranny of the fairing"
  - Telescope diameters and configurations that achieve science goals not possible with apertures constrained by single launches
  - Instruments may be more capable as they are independently launched and less constrained by mass and volume
- Telescopes can evolve and last decades
  - Continuous stream of planned instrument upgrades (e.g., HST)
  - Can plan for refueling and preventive maintenance missions that extend useable lifetime
  - Can authorize unexpected repair missions
- No explicit servicer needed
  - Cost and science benefits



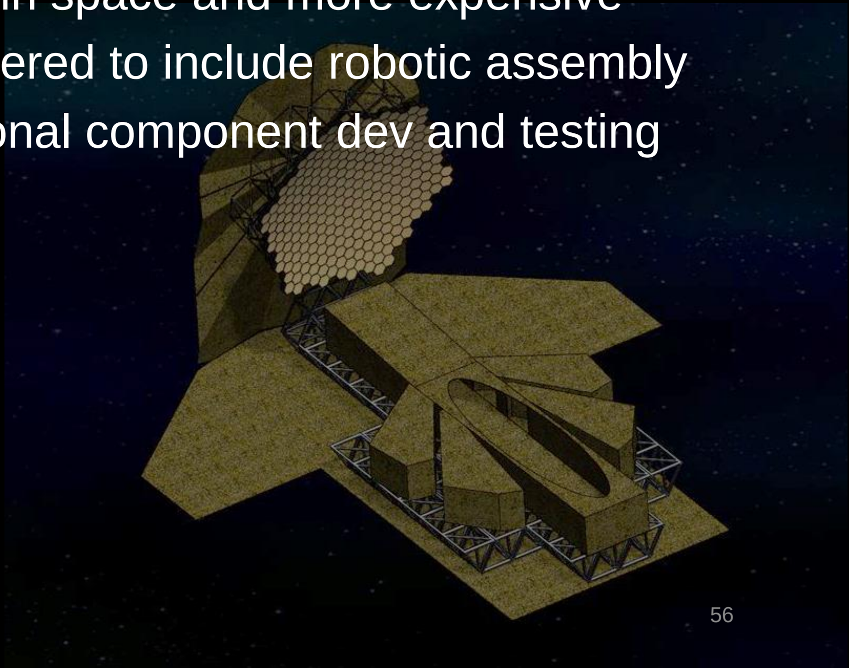
Key Risk Benefits Enabled by iSA

- Eliminates complex autonomous self-deployments
- Mitigates the risks associated with a single LV or deployment anomaly
  - Faulty modules can be replaced during commissioning
  - Or, with servicing, during operations.
  - *Launch failure need not be mission failure.*
- Modularization enables faults and anomalies to be more readily contained and not propagated.
- Multiple LV vendors reduces programmatic risk of depending on a specific vendor in case of over-subscription or anomaly.

iSAT will also have Challenges/Drawbacks

– **iSAT operations not required in single LV deployment approach:**

- Phases A and B likely longer durations
- Space AI&T is a new engineering development
- Robotic arms autonomy software development
- Robotic arm testbeds demonstrating assembly and sequences
- In-space rendezvous and capture operations
- iSA contamination issues
- Fewer anomaly resolution options while in space and more expensive
- Ground Data Systems will have to be altered to include robotic assembly
- Multi-decade lifetime may require additional component dev and testing



NASA OCT Joint Agency iSA Capability Needs

Item	Capability	Rank	Score
7.3	Fail-safe modes of behaviour on failure detection	1	100%
10.3	Modular design	2	96%
14.1	Soft docking / berthing of modules	3	91%
13.1	A limited number of standard mechanical, electrical, thermal and fluid connection approaches with well-characterized properties	4	89%
6.1	Standard protocols and ports to accommodate visiting vehicles and communications traffic	5	87%
5.1	Means of verifying the continuity of interface connections / disconnections	6	84%
10.5	Design for servicability	7	84%
5.5	Modeling and simulation for verification and validation	8	83%
5.6	Modeling and simulation for assembly sequencing / planning	8	83%
4.1	Ability to reversibly assemble structural, electrical and fluid connections	10	82%
6.2	Standard but secure communications protocols to accommodate interaction with other (TBD) associated systems	11	80%
5.7	Quantitative performance prediction for autonomous systems	12	79%
10.4	Design for assembly	13	78%
2.5	Ability to assemble high stiffness structures	14	78%
8.2	Known precision limits of any and all assembly agent elements across the assembly site's environmental envelope	15	77%
2.1	Robotic assembly with joining	16	76%
3.1	Abiity to route electrical power and data across assembled joints	17	76%
4.2	Ability to disconnect structure, electrical, and fluid connections without propagating damage to other system components	18	73%
3.3	Ability to route fiber optical conductors across joints	19	71%
7.1	Intelligence to make stereotyped decisions correctly without human input	20	68%


Credit: U.S. Naval Research Lab (NRL)

NASA OCT Joint Agency Capability Needs

				ISAT Readiness	
Item	Capability	Rank	Score	Tech	Rationale
7.3	Fail-safe modes of behaviour on failure detection	1	100%		Standard Phase C/D engineering
10.3	Modular design	2	96%		Leverage HST & ISS modular design experience
14.1	Soft docking / berthing of modules	3	91%		Leverage HST & ISS TRL9 Common Berthing Mechanisms
13.1	A limited number of standard mechanical, electrical, thermal and fluid connection approaches with well-characterized properties	4	89%		Leverage HST, ISS, Restore-L, RSGS I/F's. Define ISAT modules to simplify I/F req'ts.
6.1	Standard protocols and ports to accommodate visiting vehicles and communications traffic	5	87%		Leverage existing HST & ISS I/F's. Develop as standard engineering in phase C/D.
5.1	Means of verifying the continuity of interface connections / disconnections	6	84%		Leverage HST, ISS, Restore-L, RSGS I/F's. Could benefit from smart switch technology.
10.5	Design for servicability	7	84%		Leverage and expand HST & ISS design of ORU's. Optimize modularity/serviceability in Phase A.
5.5	Modeling and simulation for verification and validation	8	83%		Leverage JWST, HST SM ModSim experiences
5.6	Modeling and simulation for assembly sequencing / planning	8	83%		Leverage ISS experience
4.1	Ability to reversibly assemble structural, electrical and fluid connections	10	82%		Leverage HST, ISS, Restore-L, RSGS I/F's. Define ISAT modules to simplify I/F req'ts.
6.2	Standard but secure communications protocols to accommodate interaction with other (TBD) associated systems	11	80%		Leverage HST and ISS secure ops protocols. Leverage DOD secure comms capabilites.
5.7	Quantitative performance prediction for autonomous systems	12	79%		Leverage Planetary missions and Safe mode ops
10.4	Design for assembly	13	78%		Leverage ISS assembly design experience
2.5	Ability to assemble high stiffness structures	14	78%		Leverage ISAT multiple LV's approach to provide additional mass for design to stiffness req'ts
8.2	Known precision limits of any and all assembly agent elements across the assembly site's environmental envelope	15	77%		Leverage ISS robotics (MT, SSRMS, SPDM). Constrain modular design and I/F's to capabilities.
2.1	Robotic assembly with joining	16	76%		Leverage ISS, STS, Restore-L, RSGS robotics
3.1	Abiity to route electrical power and data across assembled joints	17	76%		Leverage ISS PDGF and PVGF.
4.2	Ability to disconnect structure, electrical, and fluid connections without propagating damage to other system components	18	73%		Leverage HST, ISS, Restore-L, RSGS I/F's. Could benefit from smart switch technology.
3.3	Ability to route fiber optical conductors across joints	19	71%		Leverage ISS PVGF and commercial telecon FO switching technology.
7.1	Intelligence to make stereotyped decisions correctly without human input	20	68%		Leverage telerobotics from ISS, STS, Restore-L, RSGS

LEGEND		Expected normal space flight systems development effort
		Some additional pre-A technology or engineering prudent
		Risk prudent to mitigate and balance prior to entering Phase A

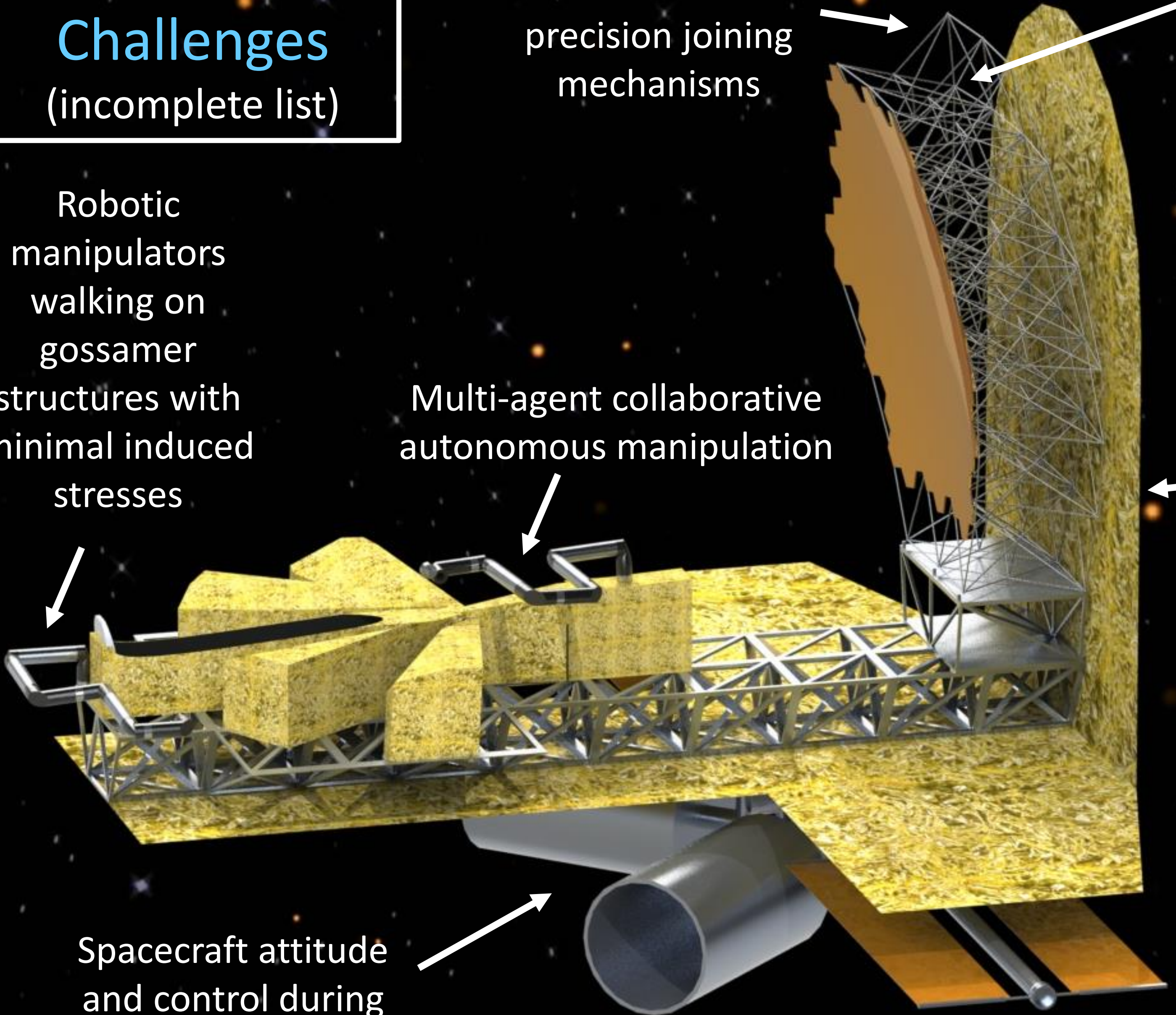
Technology Readiness

#	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	

- Capability needs 2, 3, 4 , 5a have all achieved a high-level of iSAT readiness through space demonstrations.
- Capability need 5b has achieved a medium-level of iSAT readiness through space demonstrations.
- Capability needs 1 and 6 currently have low readiness and will require the most focused investment for a specific observatory design

iSAT Technical Challenges

(incomplete list)



iSAT Study Findings

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 best suit the science goals and not the mass and volume constraints of fitting in a single fairing.

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

iSAT Study Findings

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 single-launch observatories and makes it potentially more manageable. Hence, ISA may be a preferred implementation approach compared to single-launch approach for observatories, particularly those with 10m class or larger apertures.

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

Study Suggestions

Suggestions to the Decadal Survey

If the Astro2020 Decadal Survey recommends a large space observatory, we suggest it also recommend:

(1) *NASA (a) conduct a detailed study of an ISA implementation of the specific observatory and (b) trade it against the conventional single-launch approach*

and

(2) *NASA initiate a technology development program to reduce the technology gaps associated with in space assembled observatories.*

Final Thoughts

Final Thoughts

- iSA has made significant progress over the last 15 years to the point it can now be considered by the Agency as an alternative implementation approach to realize large telescopes.
- The least mature aspects are the ones related to the observatory itself and not on the "basic" aspects of iSA which through space demonstrations have achieved high technology readiness (multiple launches, cargo delivery vehicles, rendezvous and proximity operations, and robotic arms).
- This Study found an iSA implementation approach that is largely self-sustained (uses the observatory's own spacecraft) and does not depend on future space platforms (e.g. Gateway), future rockets (e.g. SLS), or the need for astronauts. But these assets could all be incorporated with potential benefits.
- During the last Decadal Survey, iSA was not on the Astrophysics Division's radar. This Study concludes that iSA has indeed matured since that time and should now be part of the Agency's option space in building the future.

Support Slides for Findings

Finding 1: Technology Readiness

With key capabilities demonstrated in space over the last decade, ISA has emerged as a viable approach for observatory assembly. Engineering development and technology gaps for specific observatory designs will need to be addressed, however, no technical show stoppers have been identified.

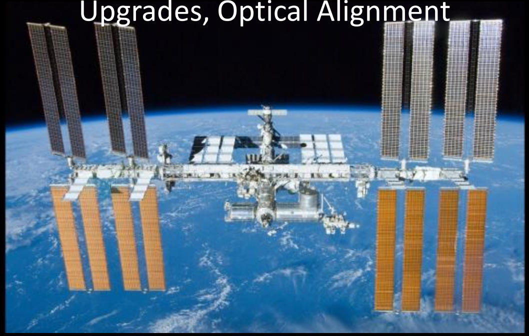
- Development needs that extend today's ISA capabilities to the level needed for future observatories include both engineering and technology considerations.
- The Study performed an initial cursory assessment of a draft list of such needs but did not attempt to define these needs.
  - Not within the scope of this assessment and would require a specific observatory point design to properly frame the development needs.
  - This is a recommended future activity.
- While ISA capabilities have advanced significantly, their application to ISA of space telescopes is the least mature.

Finding 1: Technology Readiness

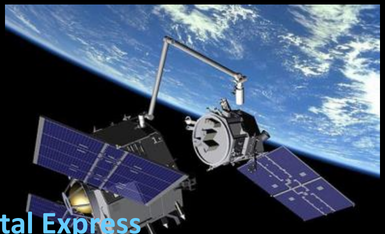
iSAT Leverages Many TRL 9 Capabilities

Past Capability Advances

HST Servicing – Inspects, Repairs, Upgrades, Optical Alignment



ISS Assembly – Modularity, Multiple LV's, Robotic Arms

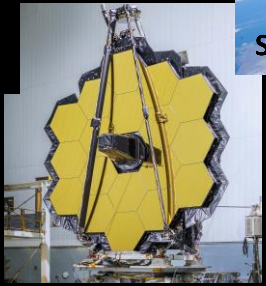


Orbital Express
Autonomous Rendezvous and Soft Capture, Removal/installation of ORUs, Fluid Transfer

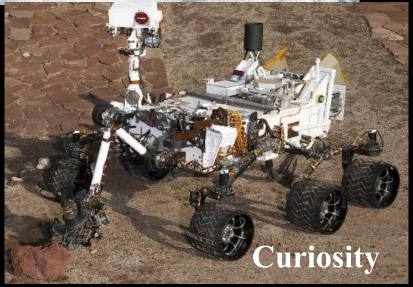
Ongoing Capability Improvements

ISS Servicing and Assembly – Robotic Repairs, Autonomous Docking, Instrument Assembly

Space X Dragon Resupply



JWST:
Segmented Optics
WFS&C Phasing

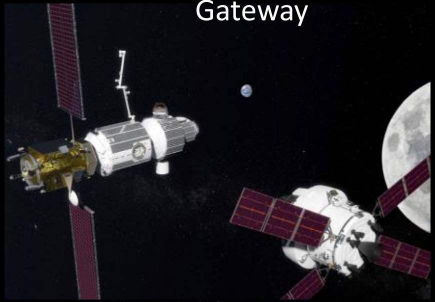


Supervised Autonomy Robotics

Commercial LEO – Infrastructure Buildup, Support Services

Future Capability

Advanced Servicing – Autonomy, Telerobotics, Refueling, Servicing



Gateway

Restore-L

Mars Sample Return

Key Aspects of the iSAT Paradigm

1) Modularized flight elements: encapsulation of complexity, standardized interfaces, more readily assembled/serviceable, tailor to LV fairing size

2) Multiple launches: leverages existing commercial medium-lift capabilities for lower cost, more flexibility, greater margins

3) Cargo delivery vehicles to deliver modules to the assembly site; leverages ISS experience

4) Rendezvous and proximity operations: Robotic arm grappling and berthing as demonstrated at the ISS

5) Supervised autonomous robotic arms: ISS-qualified arms; ensures executed commands are correct before launching subsequent steps

6) In-space V&V: Combination of "smart" module diagnostics, onboard metrology, model validation

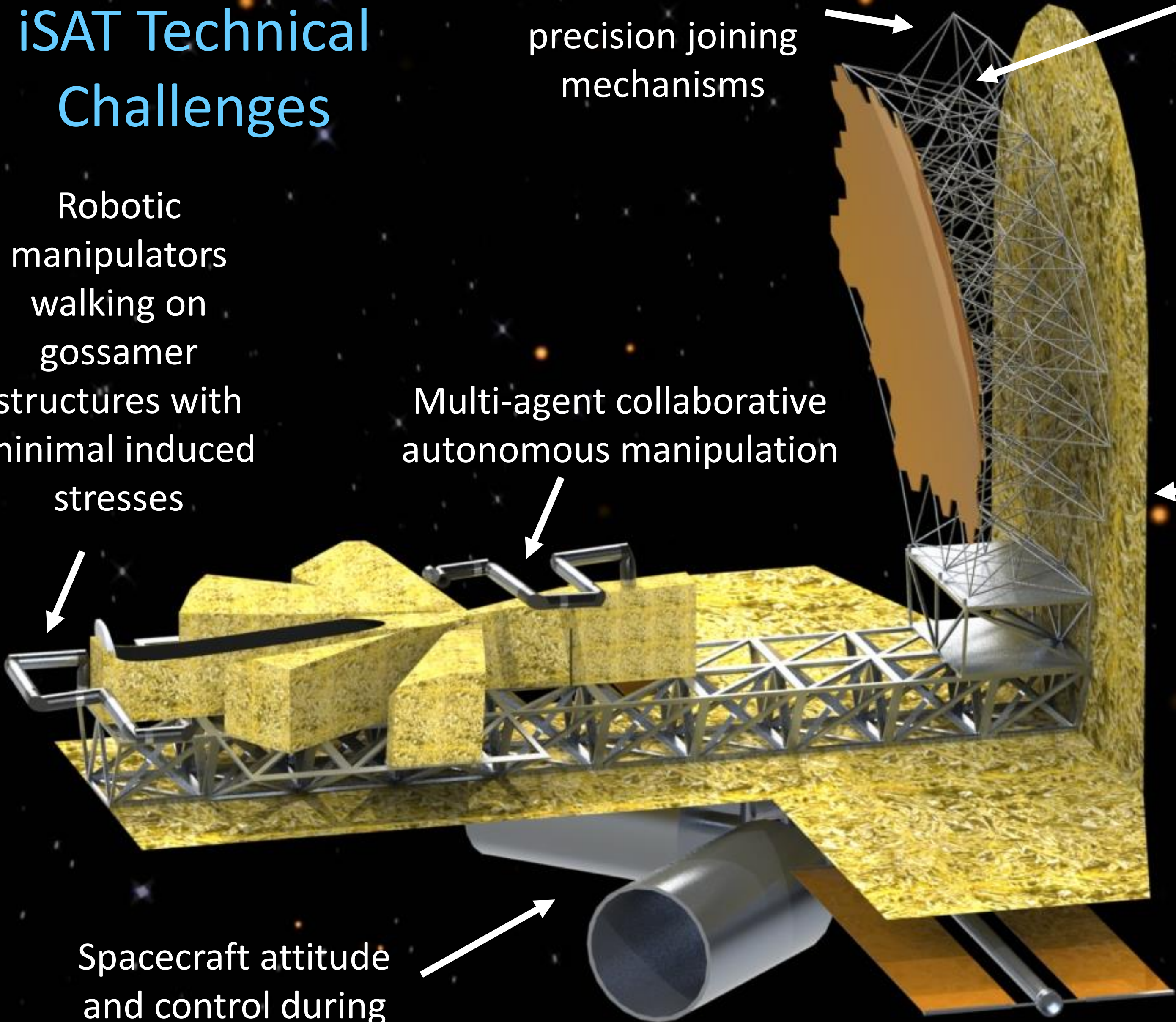
7) Servicing: Follows same paradigm – no explicit servicer needed

Technology Readiness

#	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	

- Capability needs 2, 3, 4 , 5a have all achieved a high-level of iSAT readiness through space demonstrations.
- Capability need 5b has achieved a medium-level of iSAT readiness through space demonstrations.
- Capability needs 1 and 6 currently have low readiness and will require the most focused investment for a specific observatory design

Examples of iSAT Technical Challenges



Finding 2: Reduces System Complexity

ISA is a paradigm shift that removes the "Tyranny of the rocket fairing". This enables observatory and instrument designs that best suit the science goals and not the mass and volume constraints of fitting in a single fairing.

- No "Tyranny of the rocket fairing"
  - Telescope diameters and configurations that achieve science goals not possible with apertures constrained by single launches
  - Instruments may be more capable as they are independently launched and less constrained by mass and volume

Finding 2: Reduces System Complexity

ISA is a paradigm shift that removes the "Tyranny of the rocket fairing". This enables observatory and instrument designs that best suit the science goals and not the mass and volume constraints of fitting in a single fairing.

- The mass and volume constraint of a single launch vehicle imposes a hard ceiling which is met in the conventional approach at significant cost and high engineering and programmatic risk.
  - JWST is a remarkable engineering feat of fitting such a large volume at such a low mass into a single fairing.
  - It has accepted the risk of using hundreds of deployment mechanisms, long delays in its implementation, verification and validation phases, and significant cost growths.
  - 1.0 ratio

Finding 2: Reduces System Complexity

Fragile elements had to be tightly packed

design decisions needed extensive validation

High fidelity models and extensive testing for validation

iterations of labor-intensive, customized model-test-validate iterations for light weighting

AIT needed disassembly to get access

thermal design had to use a highly complicated folded sunshield

ISA enables use of multiple launches

Off axis designs

optical layouts with fewer reflections,

slower (and longer) telescopes,

more instruments,

prime focus instruments,

higher stability

The observatory could also be evolvable.

Finding 3: Enabling Approach

The ISA approach is scalable and can enable observatory sizes that cannot be achieved by conventional single-launch approaches. The largest conventionally developed filled-aperture telescope deployed from a future 8-10m fairing appears to be 15m in size.

- Super Heavy Lift Launch Vehicles offer 15m telescope apertures
  - SpaceX’s Big Falcon Rocket and NASA’s SLS offer 8-10m fairings
- Apertures greater than 15m in diameter cannot be deployed to a Sun-Earth L2 orbit with a single launch
- ISA is a scalable approach and no inherent issue in going larger than 15m class aperture

When is iSA enabling?

Paul's first question

Study answer: When the observatory, even folded, no longer fits into the launch vehicle's fairing.

Given that ISA enables scaling to large aperture sizes, the answer depends on the size of a given rocket's launch vehicle.

- for example, our Study showed a 20 m observatory with multiple 5 m-class fairings is feasible.

Launch Vehicle	Fairing Size Interior Diameter (m)	Estimated Maximum Telescope Aperture (m)	Comment
NASA SLS Block 2	8	15	Block 2 realization appears unlikely
NASA SLS Block 1B	8	13-15	Upgraded engines could provide more lift
SpaceX Big Falcon Rocket	9	15	
Blue Origin New Glenn	7	< 15	
SpaceX Falcon Heavy	5	~ 8	Only one on this list currently available
ULA Vulcan	5	~ 8	

Finding 4: Servicing Benefits

ISA offers an 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.

- Congress has mandated: "future observatories be serviceable, where possible”
  - Currently no credible plan or resource
  - NASA would need a separate program
- Serviceability of some of the deployments in the conventional designs can be extremely difficult, if not impossible.
  - A monolithic sunshade (soft goods) deployment failure may be extremely difficult to service.

- ISA does not need a separate servicer spacecraft to be developed.
  - New modules may be delivered using the same approach for delivering the modules for assembly
  - The robotic arms used for assembling the observatory can be used for in-situ servicing.
- Even difficult soft goods like sunshades can be modularized.

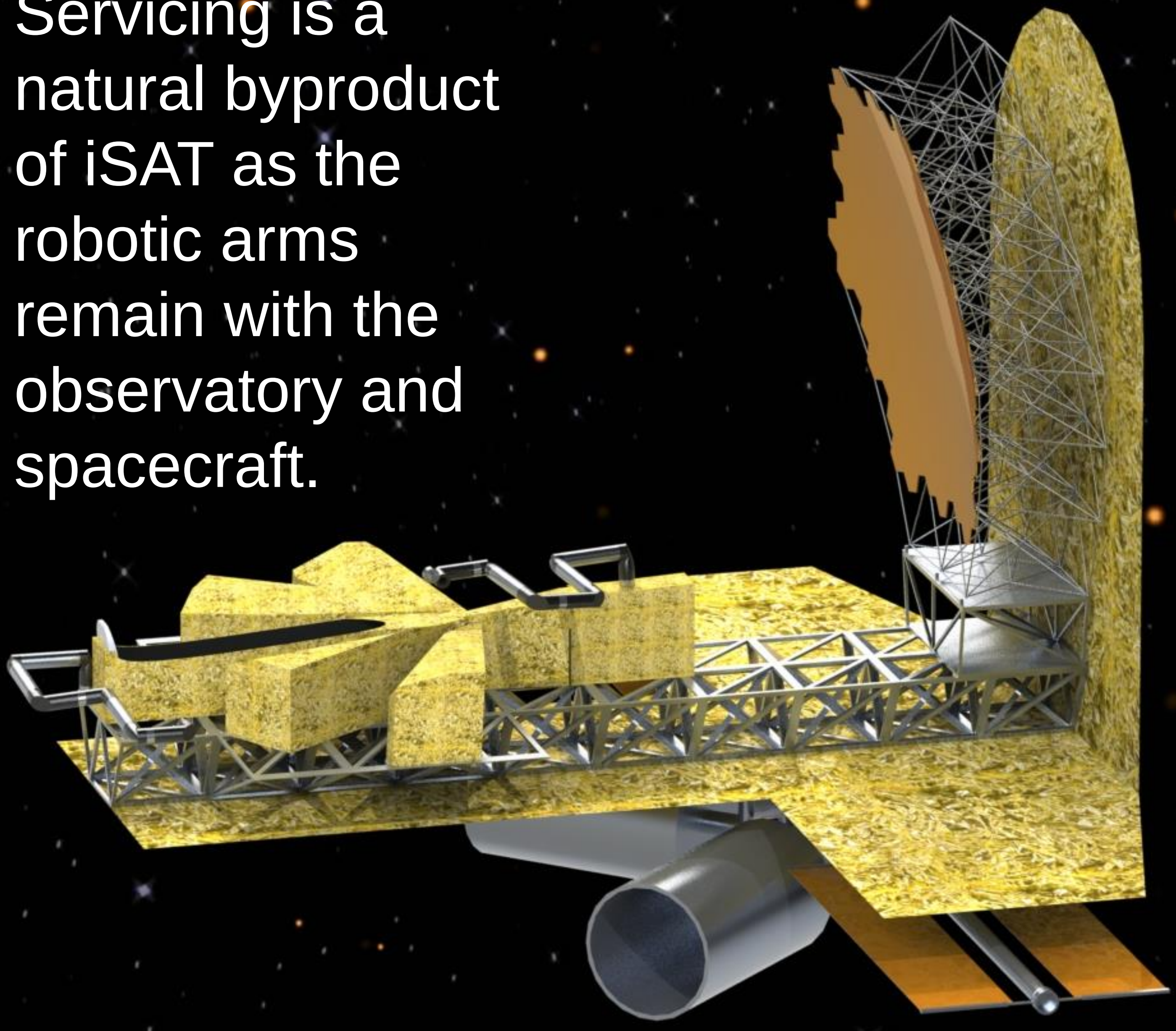
Finding 4: Servicing Benefits

ISA offers an 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.

With a servicing solution in hand, telescopes can evolve and last multiple decades enabling:

- A continuous stream of planned instrument upgrades (e.g., HST)
- Planned refueling and preventive maintenance missions
- Unexpected repair missions
- Amortized mission costs over decades

Servicing is a natural byproduct of iSAT as the robotic arms remain with the observatory and spacecraft.



Finding 5: More Manageable Risks

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

- Eliminates complex autonomous self-deployments
    - JWST relies on 20 sequential deployment events, 40 deployable structures, and 178 release mechanisms. They all have to work.
- Mitigates the risks associated with a single launch vehicle
    - *Launch failure need not be mission failure.*
- Modularization enables faults and anomalies to be more readily contained and not propagated.
- Multiple LV vendors reduces programmatic risk of depending on a specific vendor in case of over-subscription or anomaly.

Additional Support for Finding 5

- Future observatories and their large sunshades may need even more deployment mechanisms.
- These mechanisms have high reliability but the sheer number of them impacts the overall system reliability.
- Rigorous testing of all the different deployment mechanisms is expensive, and introduces schedule risk

- Large sunshades may either be assembled in space with no deployment mechanisms or hybridized (a combination of space assembly and lower-risk deployments)
- Modules can be robotically reversible and contain adjustable joining interfaces
- iSA uses an incremental assemble-and-verify approach

Additional Support for Finding 5

- Current mission schedules have a single critical path.
- An ISA mission may be planned in a phased approach to have multiple delivery paths.

- Late deliveries can result in large standing armies.
- Reduces inter-dependence, bottlenecks, and resulting standing marching armies

- Maintaining peak funding for several years may put considerable strain on the Astrophysics budget.
- iSA offers an opportunity to flatten the funding profile, when beneficial, reducing the strain on the annual Astrophysics budget.

Additional Support for Finding 5

- Late project phase mass or volume growth is typical in conventional development.
- With a hard ceiling, spirals into zero-sum game of spreading the growth across flight elements potentially impacting schedule, eat into desired margins, and result in cost growth and schedule risk.
- Cost, complexity, and time required for system-level AIT and deployment demonstrations
- Tests in the presence of gravity becomes particularly challenging

- Larger mass and volume allocations through the use of multiple launches
- Provides the option to change launch vehicle or add a new launch late in the project
- ISA may reduce reliance on system-level ground AIT:
  - eliminating complex pre- and post- launch deployments,
  - using simpler module-level and interface testing, allowing for reversible iSA and reduced systems testing
- iSA occurs in the operational 0-g environment.

Finding 5: More Manageable Risks

Qualitative Assessment Activity Results

- The Study SMEs arrived at consensus that the ratio of JWST's 6.5 m aperture to 5 m-class launch fairing capacity represented a combined cost, schedule, and success risk threshold for the conventional, single-launch approach.

- The SMEs estimated that observatories with a 10 m-class aperture would represent a similar risk threshold for a future SLS launch vehicle.
  - For e.g, the technical challenges and risk associated with JWST's large deployed sunshield remain today and future sunshades will only get larger for larger observatories.

- The consensus was that ISA may be a lower-risk approach at and beyond that threshold.

Finding 6: Cost Benefits

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

1. Qualitative activity using lessons learned and SME recommendations to drive cost down indicate likely cost savings.
2. Existing cost models shown to be inadequate for ISA.
3. Quantitative bottoms-up costing exercise conducted in parallel to compare to qualitative.
4. The cost of the development effort to advance the unique aspects of an ISAT technology program to flight readiness was not included in the costs analysis.

Cost Estimation

ISA will incur additional cost compared to a conventional, single launch observatory. These include:

- Modularity, multiple launches, cargo delivery vehicles, rendezvous and proximity operations, assembly robotics

ISA will likely offer opportunities for cost savings in the development of flight system elements such as the telescope, instruments, spacecraft

- These elements typically represent 60-70% of mission costs. Hence, this can be a source of significant savings.
- Flight system assembly, I&T are other areas of potential savings.

→ What is the net effect?

Relative cost comparison between single-launch vehicle observatory and iSAT. Green represents WBS elements where ISA may provide cost benefits while red represents elements where ISA may have a cost increase in comparison to a conventional, single-launch approach

WBS 1-3 Mng. SE. SMA	WBS 4 SCI	WBS 5.1 Telescope Structure	WBS 5.2 Telescope Optics	WBS 5.3 Sunshade	WBS 5.4 Inst	WBS 5.5 Robotics	WBS 6 SC	WBS 7-9 MOS/GDS	LV	CDV	Ops	WBS 10 SI&T

Cost Estimation

Developed and compared estimates of conventional single-launch vs ISA same architecture but 3 different aperture size (5, 10, 15m).

Used current cost models for conventionally developed observatories

- an architectural study undertaken by JPL's A-Team
- Same MEL as ISA
- CERs using established models
- and scaling laws

Our Study conducted a grass roots cost estimation for ISA

- detailed phase A-E plan,
- schedule,
- MEL, PEL,
- launch manifest
- resource plans

The cost information contained in this document is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech.

These cost estimates and approaches are from the iSAT Study and have not been reviewed by JPL for institutional approval.

Estimating Conventional Single Launch Costs

Using Traditional Cost Models

WBS/Element	Title	Calculation Method (Inputs)
1	Project Management (PM)	% (of 5A, 5B, 6A, 6B, 6C costs) – w/ % stretched operations for ISATs
2	Project Systems Engineering (PSE)	% (of 5A, 5B, 6A, 6B, 6C costs) – w/ % stretched operations for ISATs
3	Safety & Mission Assurance (SMA)	% (of 5A, 5B, 6A, 6B, 6C costs) – w/ % stretched operations for ISATs
4	Science (SCI)	% (of 5B Costs Only)
5A	Optical Telescope Element (OTE)	Phil Stahl Model (Dia., Temp., Diffraction wavelength, Segment Size) 15% reduction for ISAT (no full scale I&T on the ground)
5B	Instrument(s) Element (IE)	NASA Instrument Cost Model aka NICM (mass, power, type)
6A	Spacecraft Element (SCE)	$/kg (SCE mass) SCE mass as % of (mass of : OTE, IE, & RAE) OTE mass scaled as a power of the aperture from JWST mass
6B	Robotic Assembly Element (RAE)	Weighted $/kg Structure Cost Estimating Relationship from SMAD for Structure Spacecraft Cost Estimating Relationship from SMAD for "Smart Mass"
6C	Cargo Delivery Element (CDE)	$/kg (mass scaled from CYGNUS by cargo carrying capacity) 85% learning curve assumed for multiple units
7	Mission Operations System (MOS)	% (of 5A, 5B, 6A, 6B, 6C costs) – w/ % stretched operations for ISATs
8	Launch Vehicle Services (LVS)	LSP Catalog. # of launches based on Mass Only [no volume considerations]
9A	Ground Data System (GDS)	% (of 5A, 5B, 6A, 6B, 6C costs) – w/ % stretched operations for ISATs
9B	Science Data System (SDS)	% (of 5B costs Only) – w/ % stretched operations for ISATs
10	Systems Integration & Test (SI&T)	% of costs of elements integrated on the ground 5A, 5B, 6A, & 6B for GOATs 6A, & 6B only for ISATs
	Reserves	% of everything above EXCEPT WBS 8 Launch Vehicle Services
	TOTAL	Total of everything above

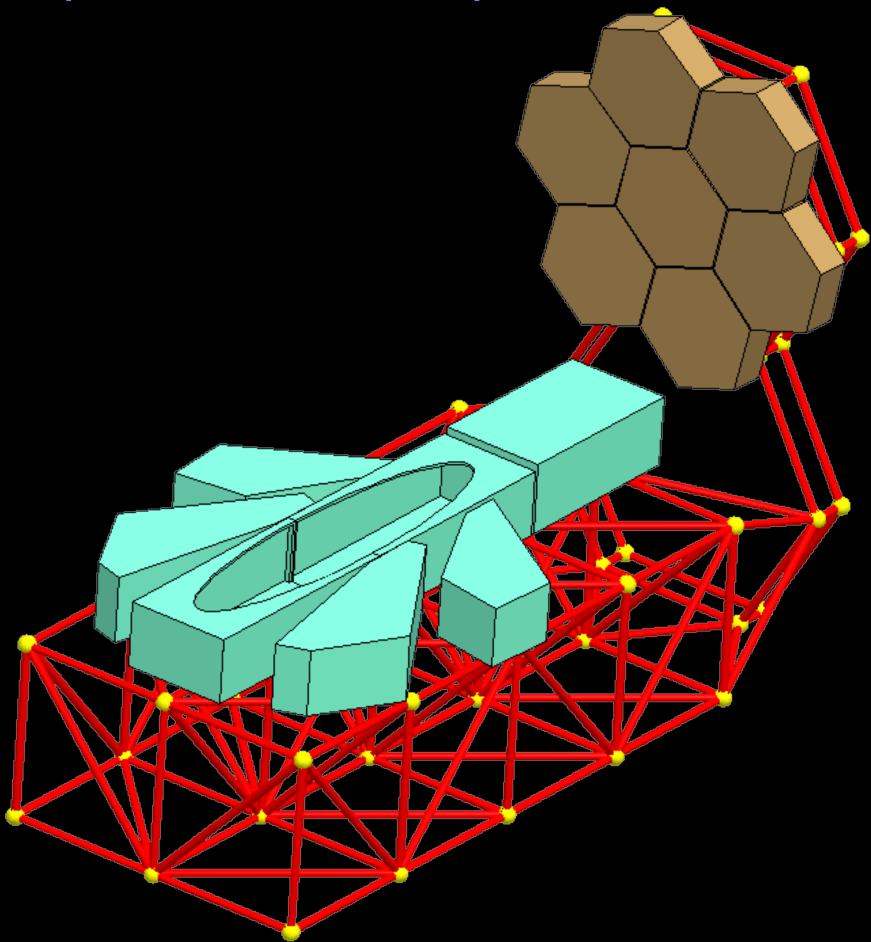
iSAT Grass Roots Estimation

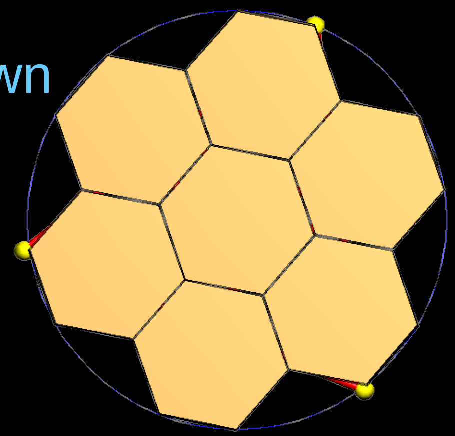
WBS Element	Basis of Estimate
WBS 1-3: Proj. Mgmt, Sys Eng (incl. Mission Design), SMA	Cost-to-Cost Ratio Based on Flagship class missions
WBS 4: Science	Cost-to-Cost Ratio Based on Flagship class missions
WBS 5.1 Telescope Structure	Grass roots for labor, per unit non-labor estimates:**$10M**
WBS 5.2 Telescope Optics	Grass roots for labor, per unit non-labor estimates: **$100M**
WBS 5.3 Telescope Sunshade	Grass roots for labor, per unit non-labor estimates: **30%** of labor
WBS 5.4 Instruments	CADRe based on analogues (HDI, ECLIPS, LUMOS, Pollux)
WBS 5.5 Robotics (2 arms)	Labor: Grass roots for labor, analogues (Gateway, Restore-L, RSGS, Mars), Non-Labor: estimate of **$100M** per arm
WBS 6: Spacecraft	Grass roots estimate, **$1B, $1.5B** and **$2B** for 3 sizes
WBS 7 & 9: MOS/GDS	Cost-to-Cost Ratio Based on Flagship class missions
Reserves	Consistent with A-Team (30%). Does not include LV and CDS,
WBS 8.1 Launch Systems	Input from NASA Launch Service Program (NLSII PPBE input)
WBS8.2 Cargo Delivery Vehicle	Grass roots estimate from analogues (Cygnus, Dragon)
Operations	$80M/year assembly ops cost added to mission operations
Servicer	From Analogues (DARPA RSGS and Restore-L)
Tech Dev and Pre-Phase A	**Did Not Estimate**

- Used $500k per person per year for labor; unit modules for truss and optics shown in next slide
- Multiplied labor estimates by factor of 2 to account for optimism in grass roots i.e. 100% margin for all three sizes
- Includes scaling effect with aperture size on non-labor costs, including materials
- Does not include learning curve for repeat modules

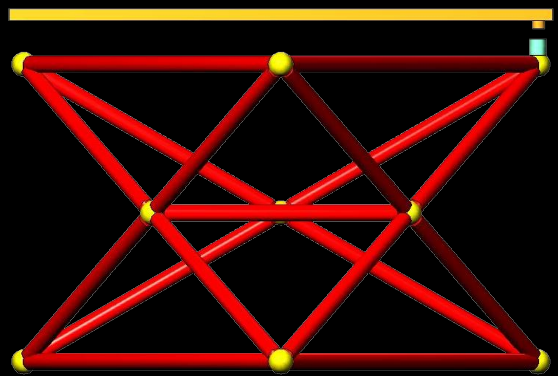
What is a unit module?

Example of truss and optical unit module are shown





Unit Module for Optical Raft



Unit Module for Truss

The cost information contained in this document is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech.

These cost estimates and approaches are from the iSAT Study and have not been reviewed by JPL for institutional approval.

Grass Roots Costing
Creating List of Representative Activities

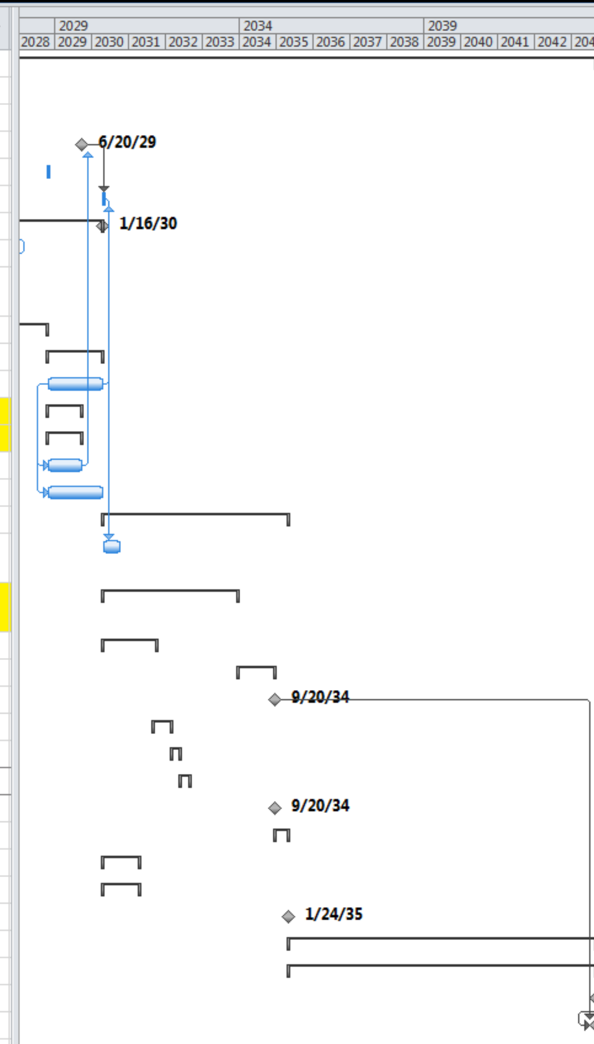
Example of Activities Per Phase shown for Thermal Subsystem

Thermal ICD, thermal specification finalization
Thermal Subsystem Risks, waivers and/or deviation status
Technology development tested and completed
Detailed Spacecraft Thermal Design/Architecture
Thermal model including simplified components with corresponding power
Finalized trade studies and outcomes for Spacecraft/Observatory
Thermal Analyses for Observatory utilizing flight orbit for full complement of cases including Launch, ascent, early operations and/or transition orbits
Thermal Predictions for Spacecraft and Observatory (temperature, heater power, gradients, etc.)
Integrated Modeling (STOP) Thermal inputs for bounding cases
Early delivery of Spacecraft model/boundaries for OTE and Instrument Analyses
Preliminary Thermal Vacuum and Balance Tests configurations and concepts identified including required GSE and facilities
Thermal Hardware identified (MLI, heaters, sensors, heat pipes, etc.) including installation process and testing identified
Mass estimates

Grass Roots Estimation:
Creating a Notional Payload Schedule

Example of a Schedule per Payload Element

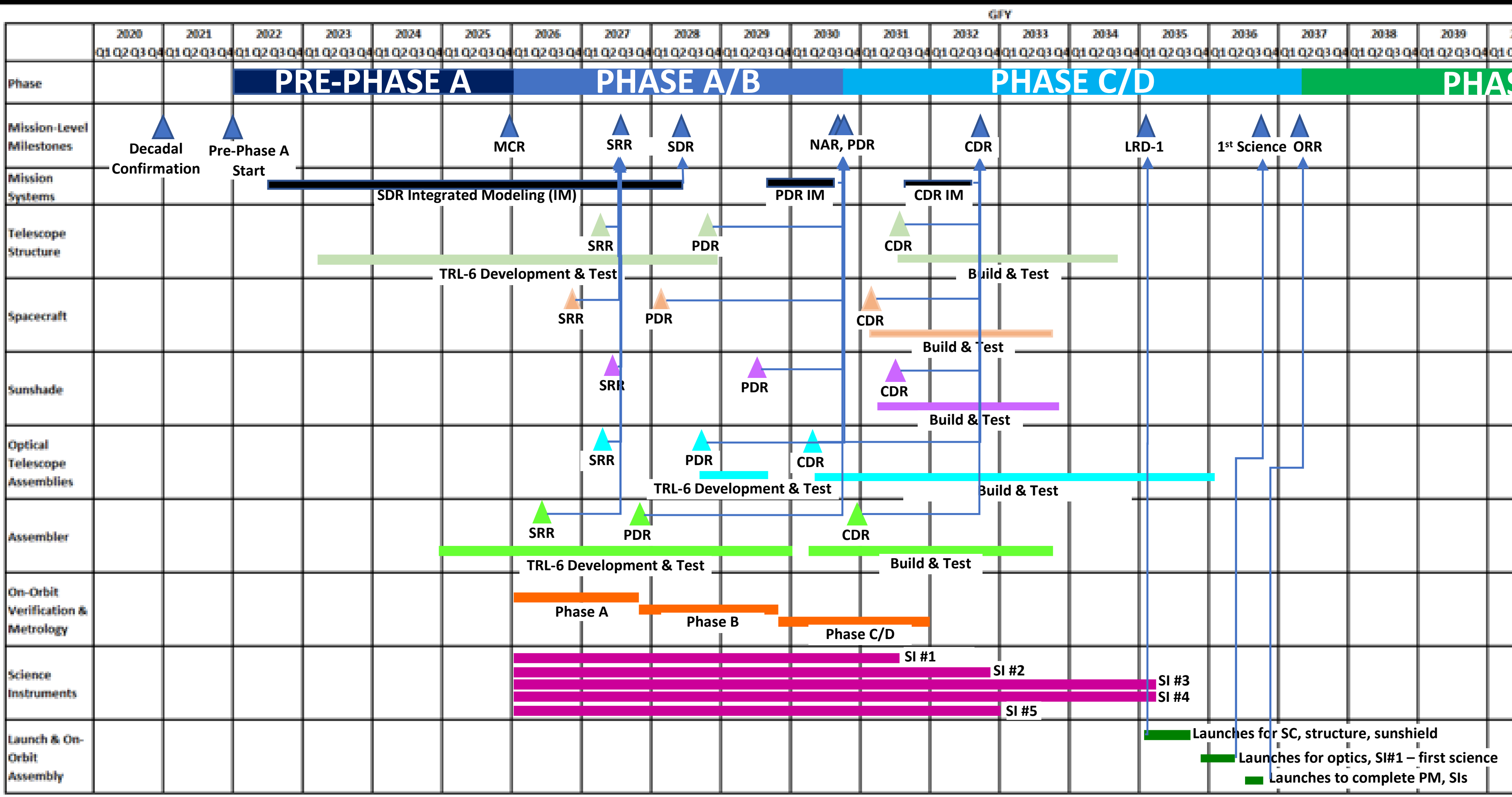
WBS	Task Name	Duration	Total Slack	Start	Finish
1.5	**iSAT Optical Telescope Assemblies**	**4607 days**	**528 days**	**Wed 10/1/25**	**Thu 5/28/43**
1.5.1	OTE Program Start	0 days	761 days	Wed 10/1/25	Wed 10/1/25
1.5.2	OTE SRR	1 day	761 days	Wed 1/20/27	Wed 1/20/27
1.5.3	OTE TRL-6 Demo Complete	0 days	911 days	Wed 6/20/29	Wed 6/20/29
1.5.4	OTE PDR	1 day	1893 days	Thu 7/20/28	Thu 7/20/28
1.5.5	OTE CDR	1 day	761 days	Thu 1/17/30	Thu 1/17/30
1.5.6	**OTE Phase A/B**	**1121 days**	**761 days**	**Wed 10/1/25**	**Wed 1/16/30**
1.5.6.1	Level 1 > 2 > 3 OTE Concept & Requirements	520 days	761 days	Wed 10/1/25	Tue 9/28/27
1.5.6.2	Risk Reduction Studies (Latches, metrology, RBA, production)	520 days	972 days	Wed 10/1/25	Tue 9/28/27
1.5.6.3	**PDR Phase**	**390 days**	**761 days**	**Thu 1/21/27**	**Wed 7/19/28**
1.5.6.4	**CDR Phase**	**390 days**	**761 days**	**Thu 7/20/28**	**Wed 1/16/30**
1.5.6.4.1	Final OTE Subsystems Design	390 days	761 days	Thu 7/20/28	Wed 1/16/30
1.5.6.4.2	**EM Technology Demonstrations**	**240 days**	**911 days**	**Thu 7/20/28**	**Wed 6/20/29**
1.5.6.4.2.1	**PMSA**	**240 days**	**911 days**	**Thu 7/20/28**	**Wed 6/20/29**
1.5.6.4.2.2	EM Latches, System Metrology	240 days	911 days	Thu 7/20/28	Wed 6/20/29
1.5.6.4.3	Production Lines Design and Long Lead Procure	390 days	4014 days	Thu 7/20/28	Wed 1/16/30
1.5.7	**OTE Production (Rafts 1-3, SMA, Aft Optics)**	**1309 days**	**761 days**	**Thu 1/17/30**	**Wed 1/24/35**
1.5.7.1	Complete parallel production lines (single line is ready)	120 days	810 days	Fri 1/18/30	Thu 7/4/30
1.5.7.2	**Multi-RAFT Assembly & Handling Pathfinder (1 EM raft, 2 simulators)**	**953 days**	**168 days**	**Thu 1/17/30**	**Tue 9/13/33**
1.5.7.3	**Raft #1 Subassemblies**	**381 days**	**761 days**	**Fri 1/18/30**	**Fri 7/4/31**
1.5.7.4	**Raft #1 Assembly Integration & Test**	**266 days**	**168 days**	**Wed 9/14/33**	**Wed 9/20/34**
1.5.7.5	End of 5m Program	0 days	2794 days	Wed 9/20/34	Wed 9/20/34
1.5.7.6	**Raft #2 Subassemblies**	**126 days**	**767 days**	**Fri 6/6/31**	**Fri 11/28/31**
1.5.7.7	**Raft #2 Assembly Integration & Test**	**64 days**	**767 days**	**Mon 12/1/31**	**Thu 2/26/32**
1.5.7.8	**Raft #3 All Elements**	**70 days**	**767 days**	**Fri 2/27/32**	**Thu 6/3/32**
1.5.7.9	Completion of RAFTS 1-3 I&T (milestone)	0 days	168 days	Wed 9/20/34	Wed 9/20/34
1.5.7.10	**Multi-Raft Assembly Demonstrations**	**90 days**	**168 days**	**Thu 9/21/34**	**Wed 1/24/35**
1.5.7.11	**Secondary Mirror Assembly**	**260 days**	**1217 days**	**Fri 1/18/30**	**Thu 1/16/31**
1.5.7.12	**Aft Optics & Instrument Interface**	**260 days**	**1217 days**	**Fri 1/18/30**	**Thu 1/16/31**
1.5.8	Initial Phase Complete (Rafts 1-3, SMA, Aft Optics)	0 days	168 days	Wed 1/24/35	Wed 1/24/35
1.5.9	**OTE Final Production (10m , 15m, 20m)**	**2176 days**	**168 days**	**Thu 1/25/35**	**Thu 5/28/43**
1.5.9.1	**Final Production Phase (20m / rafts 4-37)**	**2176 days**	**168 days**	**Thu 1/25/35**	**Thu 5/28/43**
1.5.9.2	20m OTE Production Complete	0 days	528 days	Thu 5/28/43	Thu 5/28/43
1.5.10	OTE Program Complete	0 days	528 days	Thu 5/28/43	Thu 5/28/43



The cost information contained in this document is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech.
These cost estimates and approaches are from the iSAT Study and have not been reviewed by JPL for institutional approval.

Grass Roots Estimation: Creating a Notional Overall Schedule

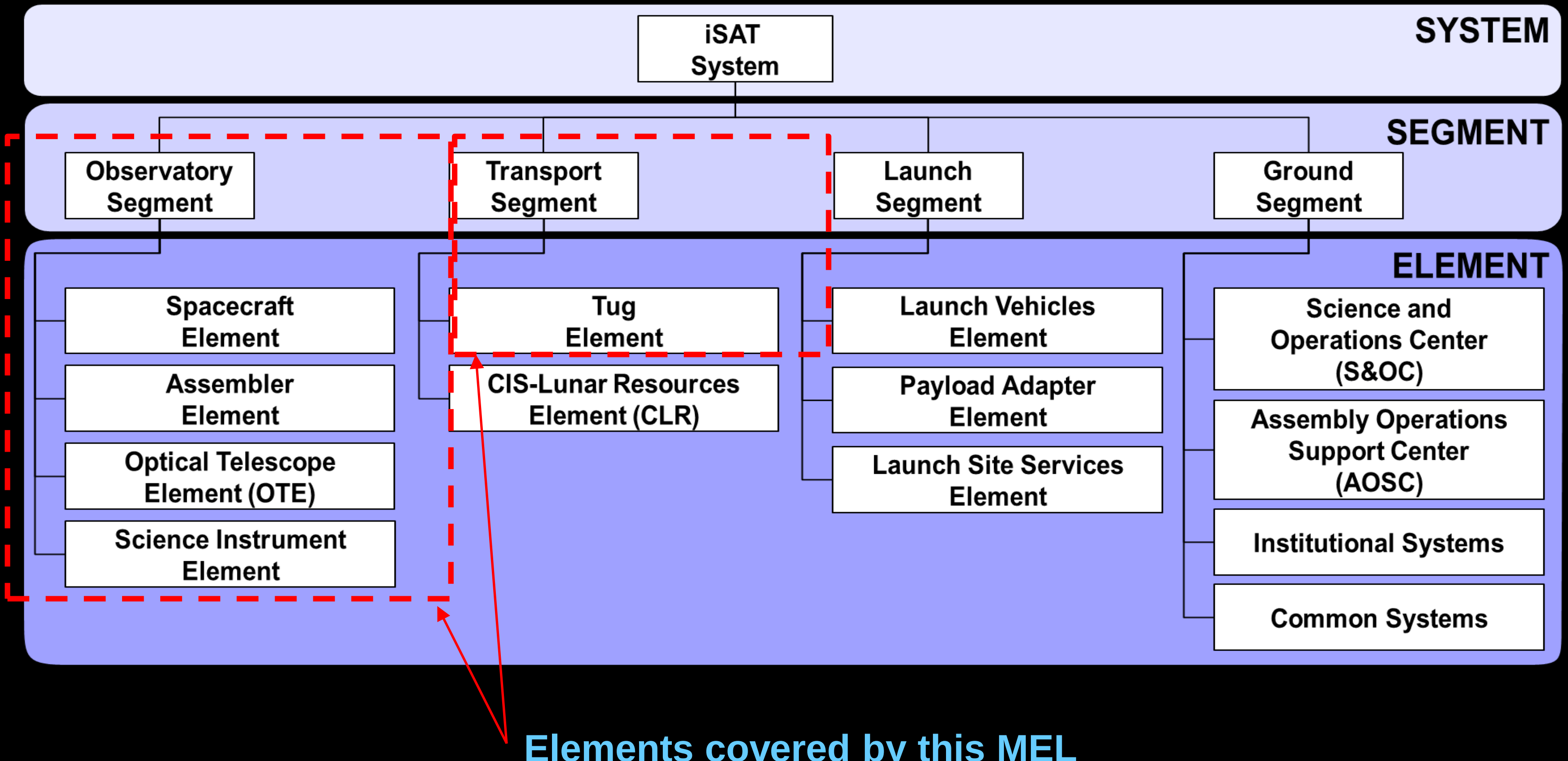
Example of a Schedule per Payload Element



The cost information contained in this document is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech.

These cost estimates and approaches are from the iSAT Study and have not been reviewed by JPL for institutional approval.

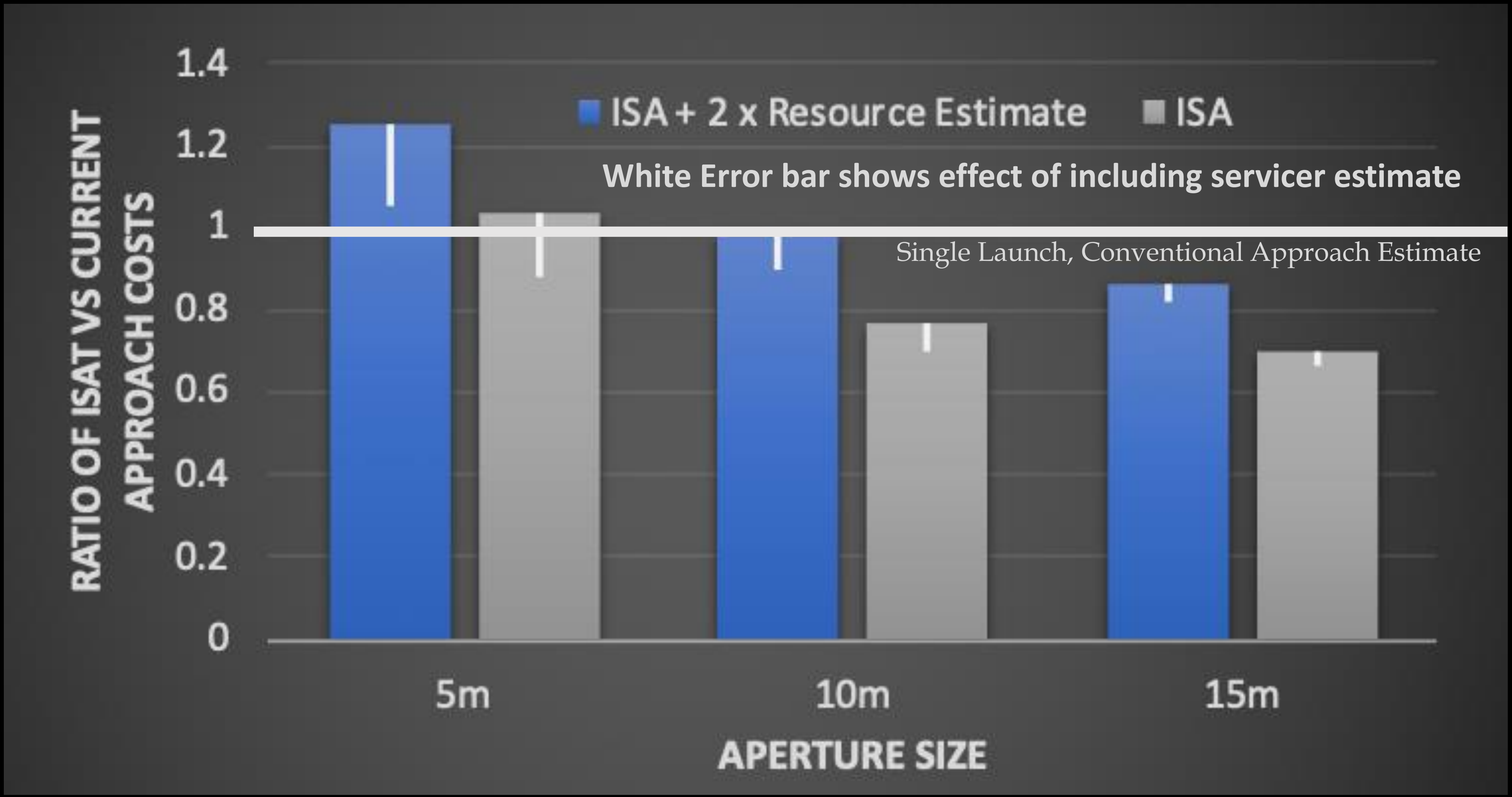
Grass Roots Estimation:
Creating a Notional MEL



WBS Element	Basis of Estimate
WBS 1-3: Proj. Mgmt, Sys Eng (incl. Mission Design), SMA	Cost-to-Cost Ratio Based on Flagship class missions
WBS 4: Science	Cost-to-Cost Ratio Based on Flagship class missions
WBS 5.1 Telescope Structure	Grass roots for labor, per unit non-labor estimates:**$10M**
WBS 5.2 Telescope Optics	Grass roots for labor, per unit non-labor estimates: **$100M**
WBS 5.3 Telescope Sunshade	Grass roots for labor, per unit non-labor estimates: **30%** of labor
WBS 5.4 Instruments	CADRe based on analogues (HDI, ECLIPS, LUMOS, Pollux)
WBS 5.5 Robotics (2 arms)	Labor: Grass roots for labor, analogues (Gateway, Restore-L, RSGS, Mars), Non-Labor: estimate of **$100M** per arm
WBS 6: Spacecraft	Grass roots estimate, **$1B, $1.5B** and **$2B** for 3 sizes
WBS 7 & 9: MOS/GDS	Cost-to-Cost Ratio Based on Flagship class missions
Reserves	Consistent with A-Team (30%). Does not include LV and CDS,
WBS 8.1 Launch Systems	Input from NASA Launch Service Program (NLSII PPBE input)
WBS8.2 Cargo Delivery Vehicle	Grass roots estimate from analogues (Cygnus, Dragon)
Operations	$80M/year assembly ops cost added to mission operations
Servicer	From Analogues (DARPA RSGS and Restore-L)
Tech Dev and Pre-Phase A	**Did Not Estimate**

- Used $500k per person per year for labor; unit modules for truss and optics shown in next slide
- Multiplied labor estimates by factor of 2 to account for optimism in grass roots i.e. 100% margin for all three sizes
- Includes scaling effect with aperture size on non-labor costs, including materials
- Does not include learning curve for repeat modules

Cost Estimation



The cost estimates are normalized by the cost estimate of the single-launch observatory i.e., for each aperture size, the estimate of the conventional, single launch observatory is **1**.

Costs to advance ISA technology to flight readiness for space telescopes is not included.