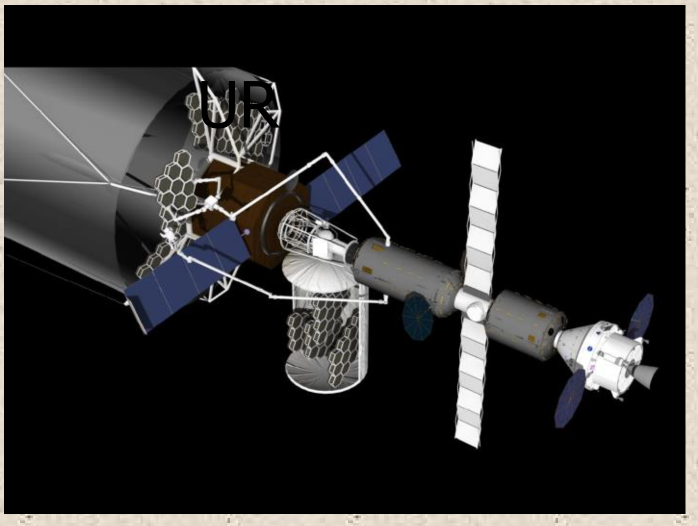
Technical Interchange Meeting on Future Capabilities in-Space Servicing and Assembly (iSSA): Opportunities for Future Astrophysics Missions

NASA Goddard Space Flight Center
November 1 – 3, 2017

Summary, Findings, and Observations



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

CL#17-6653

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"One of the ways to cope with [pressure on the federal discretionary budget]—not to solve it—is to look for synergies between exploration and science. So for example, let's look at the "Deep Space Gateway," a space station near the moon, which NASA has proposed. What kinds of astrophysics or lunar science might be done using that?"

Scott Pace
Executive Secretary
National Space Council
November 6, 2017

https://www.scientificamerican.com/article/q-a-plotting-u-s-space-policy-with-white-house-adviser-scott-pace/

"…we are now 'hitting a wall' in terms of the ability to build the missions we are considering, and thus novel methods may be needed, such as on-orbit assembly."

– Scott Gaudi
Chair, Astrophysics Advisory Committee
Ohio State University

"For the $'s invested in JWST we should have gotten something back in terms of infrastructure, servicing capabilities, ability to extend lifetime. Let's consider this for the next large astrophysics mission."

– TIM participant

"The science observations enabled by 15 m space telescopes, the current limiting size for a telescope aperture in an SLS Block II, will revolutionize our knowledge of the cosmos. And as is science's practice, it will also generate the next set of questions requiring, in some cases, even larger space telescopes. 15 m cannot be NASA's ultimate aperture size ceiling. In-space assembly, and servicing, will be humanity's next giant leap."

– TIM participant

TIM Participants

Community Technical Interchange Meeting on Future Capabilities in Space Servicing and Assembly:

Opportunities for Future Astrophysics Missions

NASA GSFC November 1 – 3, 2017

70+ participants from government, industry, and academia

Planning team chair: Harley Thronson (NASA GSFC)

Planning Team

Harley Thronson (NASA GSFC), Chair
Keith Belvin (NASA HQ STMD)
Lynn Bowman (NASA LaRC)
Ben Bussey (NASA HQ HEOMD)
Ruth Carter (NASA GSFC)
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Nicholas Siegler (NASA JPL)
H. Phillip Stahl (NASA MSFC)
Keith Warfield (HabEx/NASA JPL)

Participants List (1 of 2)

Name	Affiliation
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4. David Bodkin	Orbital ATK
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6. Jacob Bleacher	NASA GSFC
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14. Timothy Collins	NASA LaRC
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31. John Grunsfeld	NASA GSFC
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34. Steve Harrison	Made In Space, Inc.
35. Peter Hughes	NASA GSFC
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37. Gabriel Karpati	NASA GSFC
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Participants List (2 of 2)

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72. Keith Warfield	NASA JPL
73. Ryan Whitley	NASA JSC
74. Stuart Wiens	Lockheed Martin
75. Rob Zitz	SSL

- 30 NASA Centers
- 29 Industry
- 7 NASA HQ
- 4 academia
- 4 STScI
- 1 DARPA

Background, Ground Rules, Assumptions, and Agenda

BACKGROUND

Significant advances are taking place in the coming decades that have the potential to enable high-priority astrophysics space missions:

1. **Significant reduction in cost of medium-lift launch vehicles**
2. **Continued advances in robotic/telerobotic servicing and assembly capabilities**
3. **Deployment in cis-lunar space of an intermittently-occupied Deep Space Gateway facility**
4. **Advances in scientific instrument technologies**
5. **Congressional language for future space assets to be serviceable**

In this context, 70+ professionals representing three major communities (astronomers, developers of future space robotics systems, and NASA- and industry-led designers of a cis-lunar habitat) came together on November 1-3, 2017 at NASA GSFC to participate in a technical interchange meeting (TIM). This TIM is hopefully the first in a series that will continue to bring together different stakeholders to coordinate resources and plans that will one day enable revolutionary exploration and science capabilities.

WORKSHOP ASSUMPTIONS

- Serviceability of all future major space observatories is a requirement.
- Priority science goals will be developed via the National Academies' Decadal Survey process.
- The ISS will be available through at least 2024.
- An intermittently occupied deep-space Gateway will be operational in cis-lunar space in the mid- to late-2020s.
- The SLS Block 1B will be available in the mid-2020s and the Block 2 in the late-2020s and beyond.
- Commercial launch vehicles approximately equivalent to the Falcon Heavy will be available throughout the time period considered here.
- A free-flying GEO-based robotic servicing platform will be available in the mid-2020s and beyond.

WORKSHOP GROUND RULES

- Except unless otherwise stated, all participating individuals speak only for themselves, not their home affiliation or institution.
- Other than the formal presentations (mainly Day One and the morning of Day Two), we will follow the "Las Vegas rule": what is said at the TIM remains at the TIM, unless permission is given.

DAY ONE: November 1

0830 – 0900: Morning light refreshments

0900 – 0940: Introductions, workshop structure and goals (H. Thronson)

0940 – 1000: Satellite servicing/assembly: A future path (J. Grunsfeld)

1000 – 1020: HabEx (UV/Vis/NIR general astrophysics/search for habitable exoplanets; K. Warfield)

1020 – 1040: LUVOIR (UV/Vis/NIR general astrophysics/search for habitable exoplanets; M. Bolcar)

BREAK (15 min)

1055 – 1115: Lynx (X-ray mission; J. Gaskin)

1115 – 1135: Origins Space Telescope (mid- and far-IR telescope; R. Carter)

1135 – 1245: Working lunch and tutorial on Sun-Earth-Moon orbital dynamics (D. Folta) and In-space assembly and servicing for an interferometer (D. Leisawitz)

1245 – 1305: The Starshade (N. Siegler)

1305 – 1325: Space telescope assembly considerations and next steps (L. Feinberg)

1325 – 1405: Future major mission panel discussion [40 min]

BREAK (15 min)

1420 – 1440: Beyond the “Strategic Missions”: SMD Astrophysics 30-year Roadmap (K. Sheth) [20 min]

1440 – 1455: Lunar far-side telerobotics surface operations (R. Macdowall) [15 min]

1455 – 1535: Space robotics servicing and assembly I: GSFC SSPD (B. Reed), JPL (R. Mukherjee) [20 min each]

1535 – 1555: Space robotics servicing and assembly II: LaRC (L. Bowman), SSL Dragonfly, Orbital ATK CIRAS

1555 – 1615: NASA STMD technology investments in servicing and assembly (K. Belvin)

1615 – 1700: Preview of Days 2 and 3

DAY TWO: November 2

MORNING

0830 – 0900: Light refreshments

0900 – 0910: Welcome back: orientation to Day Two (H. Thronson)

0910 – 0930: Robotic Servicer in GEO: Opportunity for Assembly Experiments? (G. Roesler)

0930 – 1000: NASA and The Gateway – Design requirements, milestones, operations, role of industry (J. Guidi)

1000 – 1100: Engagement with the Gateway developers: NASA, Lockheed Martin, Orbital ATK, Aerojet Rocketdyne/Sierra Nevada, Nanoracks/SSL

1100 – 1130: Taking stock and initiating community engagement

1130 – 1300: Working Lunch and Summary of Spring DSG Workshop (B. Bussey), Erica Rogers (multi-agency iSA strategy development), 2020 Decadal Survey (Alan Boss)

1300 – 1700: BREAKOUT SESSIONS: DEVELOPING ANSWERS TO WORKSHOP DELIVERABLES

SEE FOLLOWING PAGE

DAY TWO: November 2

AFTERNOON

1300 – 1700: BREAKOUT SESSIONS: DEVELOPING ANSWERS TO WORKSHOP DELIVERABLES

Four breakout teams, each of ~20 members, will adjourn for about two hours to assess and develop responses to selected topics summarized in TIM Deliverables on Slide 3. The topics will be selected from the presentations given and discussion undertaken earlier in the TIM.

Example topics are

1. How will future large observatories be serviced?
2. How does in-space servicing or assembly allow innovative optical designs?
3. What science goals are enabled by space assembly?
4. How do the different options for servicing and assembly compare in (very approximate) cost and technical/programmatic risk?

In addition, all four teams will develop responses to four questions:

1. What additions, augmentations, and/or enhancements to a hypothetical Gateway appear to be most significant for a capability to service or assemble a future major space observatory?
2. What are valuable precursor or demonstration activities?
3. What are valuable joint or coordinated design activities among NASA and industry Gateway designer, developers of future robotic systems, and teams assessing future major space astrophysics systems?
4. Why now?

The results of these deliberations will be presented and discussed in plenary, which will lead to further development or reassessment on Day Three.

DAY THREE: November 3

<u>Morning</u>

0830 – 0900: Light refreshments

0900 – 1400: Open discussion, summary

ADJOURN NLT 1400

Some Key Highlight Slides

Enduring Quests, Daring Visions: NASA APD's 30 Year Roadmap

Technological Needs

SEVERAL new technologies need to be developed to support such a mission. These include:

- ***Optics deployment and co-phasing***: An 8–16 m telescope will require a segmented approach, and advanced options for optics deployment, such as robotic assembly may prove attractive. The wavefront accuracy and stability requirement is particularly challenging for exoplanet imaging, and may drive aperture format. For example, a single large segment may be surrounded with smaller

New Technology Mirrors, On-orbit Fabrication and Assembly Technologies

EXCEPT for the enormous sophistication of the HST, Spitzer, and JWST, our methods of building space telescopes have not progressed much beyond building and testing a ground-based telescope and rocketing it into space. This is particularly problematic because a telescope designed for zero-gravity is extremely difficult to test at 1 g, where it will never operate, to say nothing of contamination issues, and the vulnerability of a precisely assembled hardware to survive a violent ride into space. The key to bigger and better space telescopes may rely, instead, on assembling and testing telescopes on-orbit, from subcomponents produced on Earth, and perhaps in the visionary period, from actually producing many components in space using so-called 'smart materials,' advanced robotics, and possibly astronauts.

Enduring Quests, Daring Visions: NASA APD's 30 Year Roadmap

6.5 Technology Summary

	Formative Era					Visionary Era			
	GW Surveyor	CMB-pol Surveyor	FIR Surveyor	LUVOIR Surveyor	X-ray Surveyor	GW Mapper	Cosmic Dawn Mapper	ExoEarth Mapper	Black Hole Mapper
Formation flying									
Interferometry: precision metrology									
X-ray interferometry									
High-contrast imaging techniques									
Optics deployment and assembly									

Essential Goals

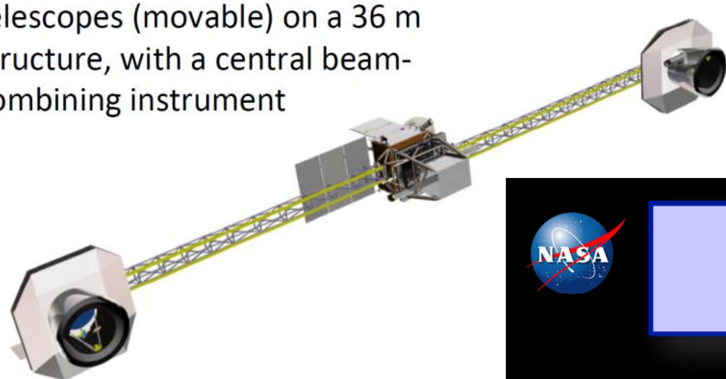
Beneficial Goals

In-space servicing and assembly is expected to be an important enabler for FIR, UVOIR, and possibly X-ray missions within the next 30 years.

David Leisawitz (NASA GSFC)

SPIRIT concept

Two 1-m diameter cryo-cooled telescopes (movable) on a 36 m structure, with a central beam-combining instrument



SPIRIT concept: NASA Goddard Space Flight Center

Interferometry space telescopes can be an application for in-space servicing and assembly.

With assembly in space …

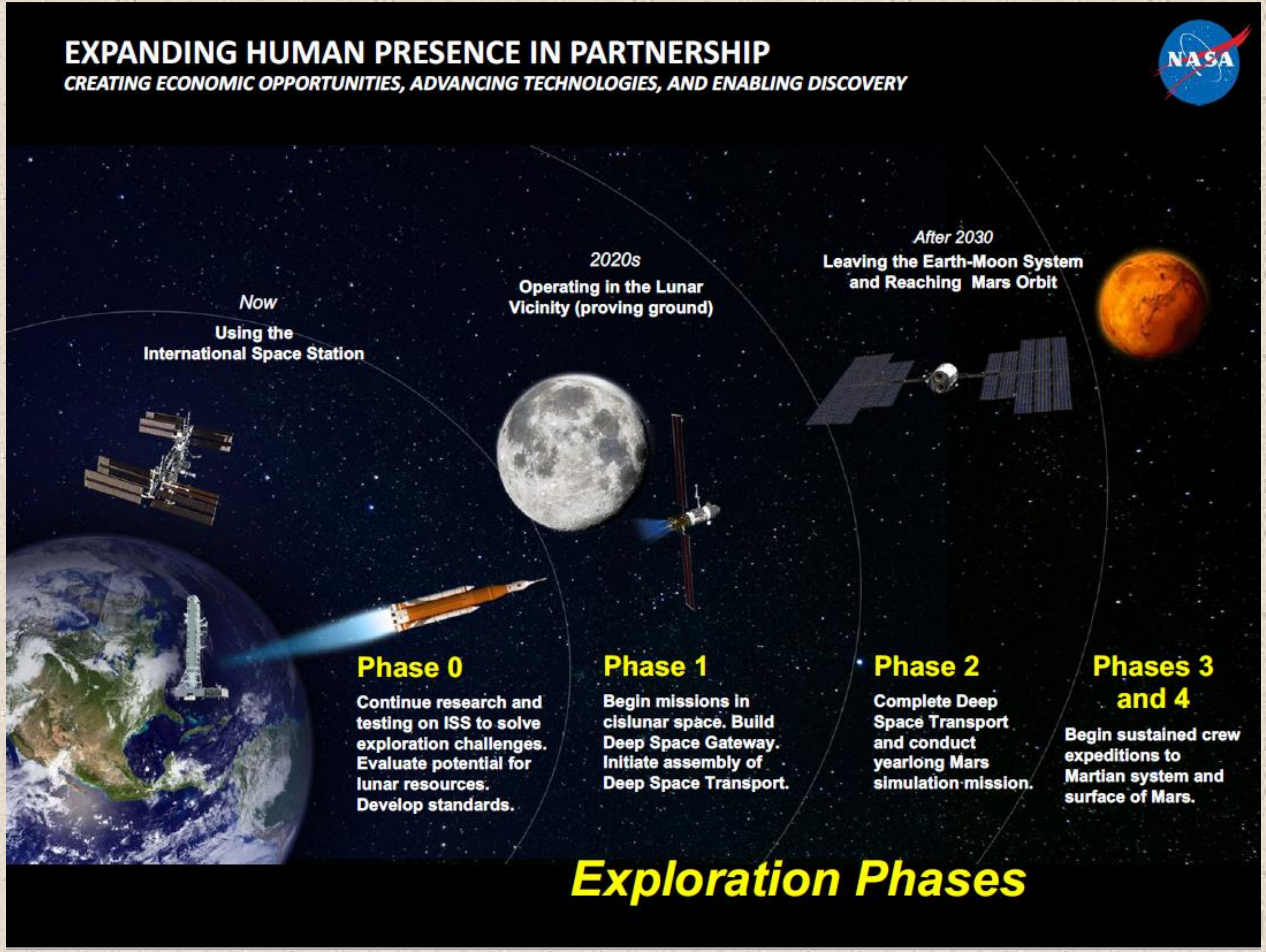
- Could launch boom as cargo, deploy or assemble in space, then follow with other components of flight system, attach to boom, and send to Sun-Earth L2.
  - Wouldn't have to trade sensitivity for angular resolution – optimize both to satisfy science requirements.
  - Could eliminate resource-consuming launch support structure.
  - Alignment and functional testing at Gateway eliminates need for large system environmental test on the ground, reducing cost and risk.
- Could be robotic, astronaut-assisted, or both.

John Guidi (NASA HQ - HEOMD)

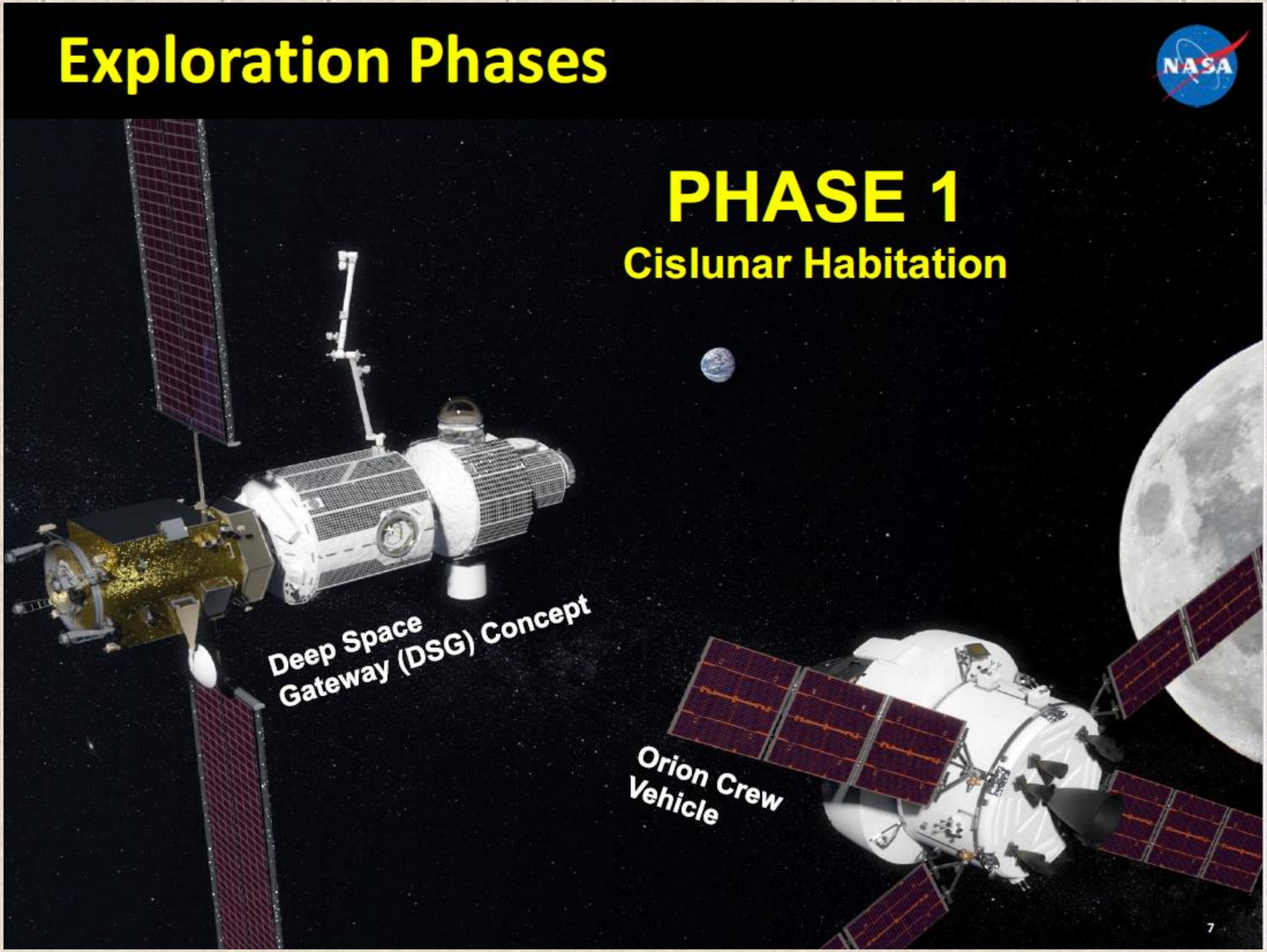
Deep Space Gateway Functionality

- **Assumptions**
  - Deep Space Gateway provides ability to support multiple NASA, U.S. commercial, science and international partner objectives in Phase 1 and beyond
  - The Gateway is designed for deep space environments
    - Supports (with Orion docked) crew of 4 for a minimum of 30 days
    - Gateway utilization activities during crewed and uncrewed operations
    - Supports buildup of the Deep Space Transport
- **Current emphasis on defining early Phase 1 elements**
  - Gateway Power Propulsion Element (PPE)
  - Gateway Habitat
  - Utilization planning (science, technology, partnership goals)
- **Future work to refine later elements; early feasibility trades complete**
  - Airlock, logistics strategy
  - Deep Space Transport development/testing requirements

John Guidi (NASA HQ - HEOMD)



John Guidi (NASA HQ - HEOMD)



Gateway expected to be uncrewed 90% of the time

- iSSA is an opportunity for their infrastructure to be further utilized

Lynn Bowman (NASA LaRC)

Problem:

A) Single-Launch Design Paradigm

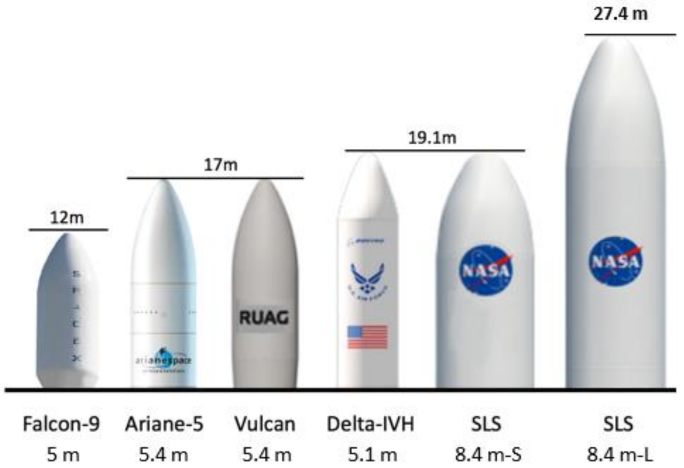
- **Limits Performance**
  - Technology fixed early in design cycle
  - Volume and mass limited by vehicle choice
  - No upgrades after launch
- **On-orbit technology is decades behind SOA**
- **Launch or on-orbit Failure = Mission Failure**

B) Every large system is a point design

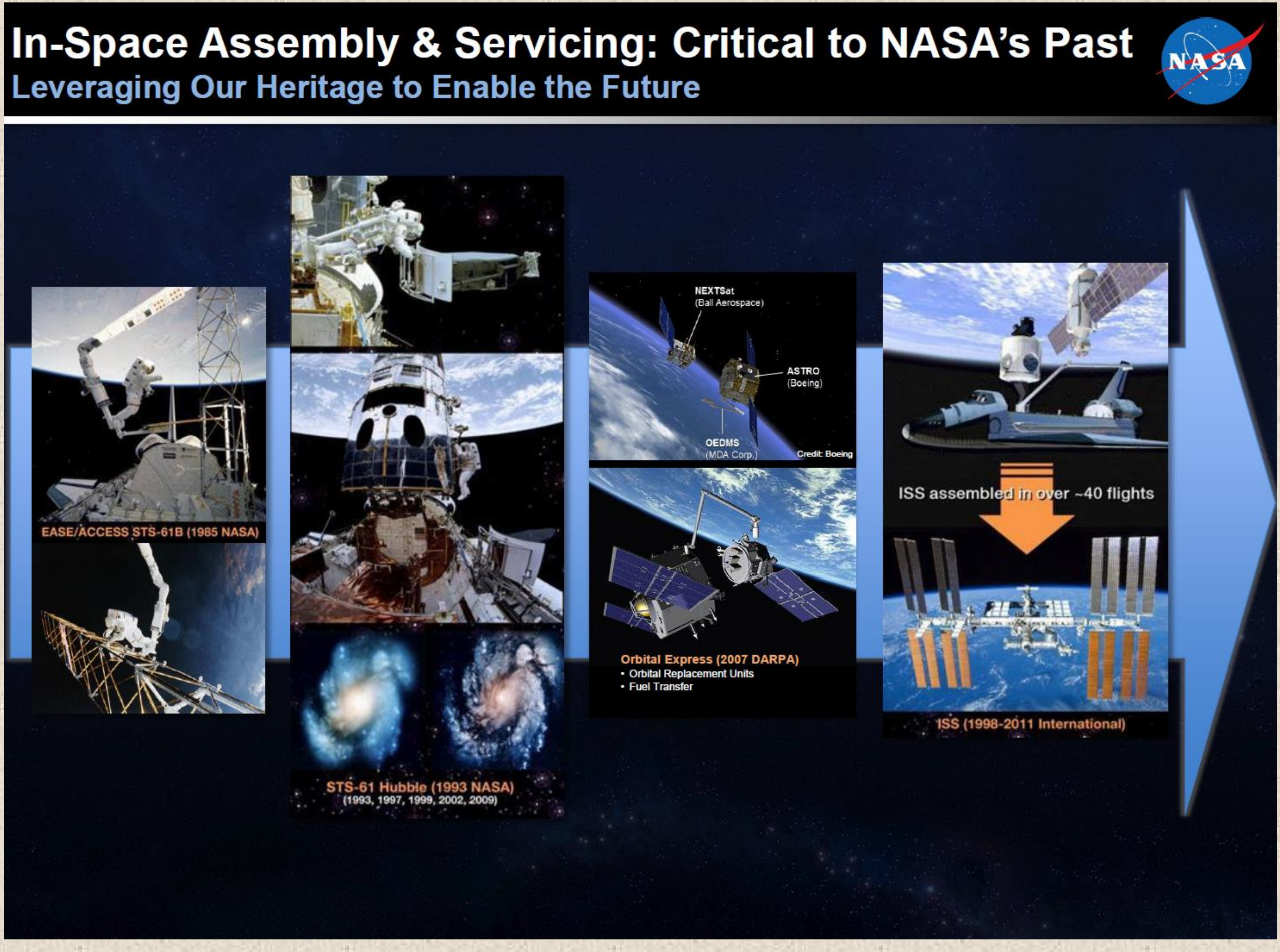
- **Little commonality with previous systems**
- **High development costs**
- **Extensive and unique/new testing of the system**
- **Slow emplacement of new capabilities**

Opportunity: **Emerging new launch paradigm consisting of multiple and frequent launch options**

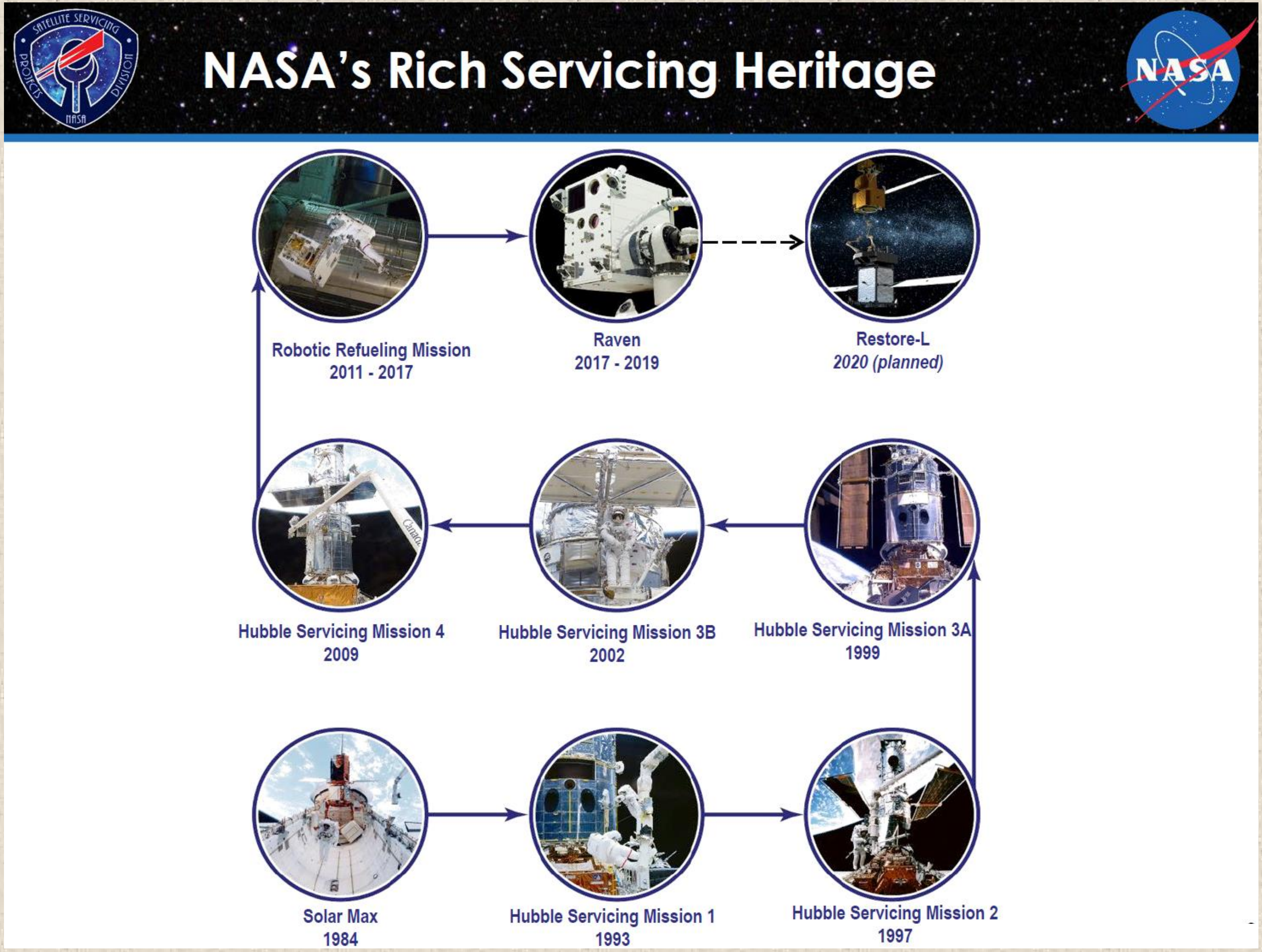
Need: **A new cross-cutting system design paradigm that exploits the new launch paradigm**



Lynn Bowman (NASA LaRC)



Ben Reed (NASA GSFC)



Keith Belvin (NASA STMD)

Key Agency Structures and Materials Technology/Capability Needs

1) *Human-Rated Composite Structures for Launch, Transit, Deep-Space Vehicles and Habitation*

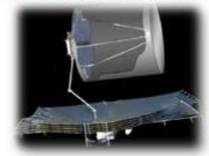
Capability Challenge

- 5-m class habitable structures
- 10m-class launch vehicle structures
- >30% mass reduction potential over metallic designs

Driving need

- Early exploration missions: Proving ground – Earth independent
- Launch vehicle structures - SLS Universal Stage Adapter for EM2 and Upper Stage Lox tank for EM3/EM4 early 2020's
- Cislunar habitats mid-2020's, Mars Hab/MAV 2030's

2) *In-Space Manufacturing, Assembly, and Servicing of Large-scale Precision And Non-Precision Structures*



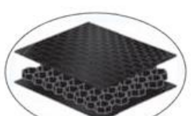
Capability Challenge

- ≥ 50 m modular solar arrays, < 1kg/m²
- ≥ 10-12 m diameter aperture with 10s of picometers stability
- Factor of 2 life extension for exploration vehicles
- Hardware in the loop simulation for assembly agent V&V.

Driving need

- Large solar arrays needed for SEP vehicles in 2028 per the EMC
- Large aperture telescopes – 2030-2040 (LUVOIR)
- iSA and iSM technology to TRL 6 prior to mission formulation

3) *Lightweight, Multifunctional Materials, Manufacturing & Structures for Deep-Space Exploration Systems*



Capability Challenge

- Mass reduction of >30% compared to unintegrated systems.
- Example: integrating radiation protection and thermal control
- Deployable and Softgood structural systems with < 1/6 volume
- Advanced materials > stiffness (150 GPa/[g/cm3]), strength (3 GPa/[g/cm3]) and fracture toughness (0.3 N/mm)

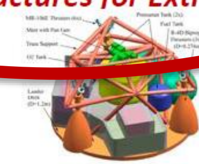
Driving Need

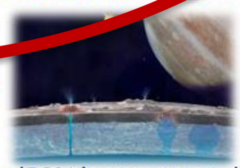
Europa – 2020's

Habitats needed for the Phobos/Mars Orbit Mission - 2033

Active structural control for large-aperture telescopes - 2035

4) *Materials and Structures for Extreme Environments*





Capability Challenge

- High Temp Carbon-Carbon Rocket Nozzles (50% less mass and 50% more thermal margin over SOA metallic nozzles)
- Cold Temp Mechanisms operating at ~50K
- Seals and Coatings for dust environments
- Radiation Shielding material systems.

Driving need

- Initial exploration missions - Proving ground – Earth independent
- SLS Upper Stage nozzle extension for EM3/EM4 early 2020's
- Mars Descent Vehicles mid 2020's - 2030's
- Europa missions beginning in mid 2020's

2017 (POC: kenny@nasa.gov)

Keith Belvin (NASA STMD)

Engineering Design and Technology For Resilience

Previous 10-15 years
Fixed, focused, governed

- Highly specialized platforms
- Fixed capabilities
- Costly
- Focused mission portfolio
- Long development time

Point Solutions for Asymmetric Warfare

Moving from Custom Build to Composability and Integration

Now.....The Future
Modular, adaptable, autonomous

- Flexible platforms
- Adaptable to capabilities
- Affordable
- Resilient to new threats
- Short development time

Composable, Agile Solutions for Multiple Missions and Threats

Jeffery P. Holland, PhD, PE (SES)
Engineered Resilient Systems (ERS) Community of Interest (COI) Lead
Director, US Army Engineer Research and Development Center (ERDC)
Director, Research and Development, US Army Corps of Engineers

2017 (POC: kenny@nasa.gov)

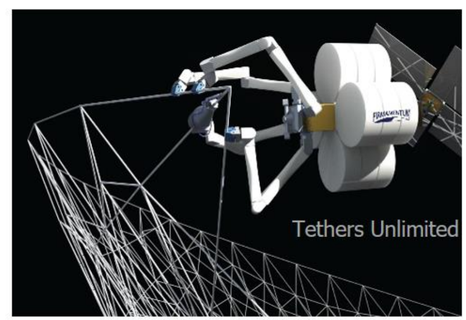
Keith Belvin (NASA STMD)

Gordon Roesler (DARPA)

The potential of space robotics

GEO today
- ***Single fairing constraint***
- ***No response to failures***
- ***Fixed capabilities***

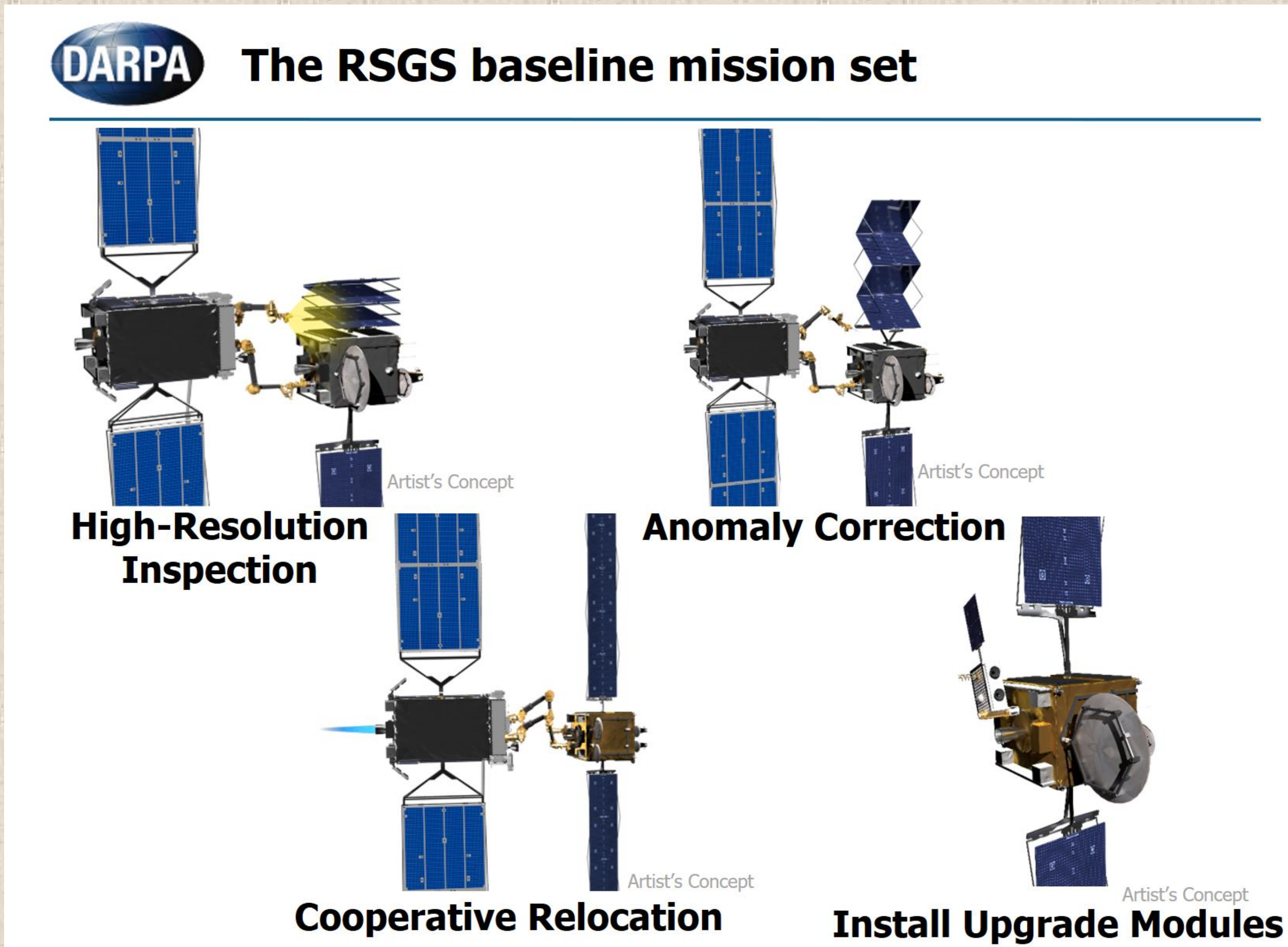
GEO future
- ***On-orbit assembly***
- ***On-orbit servicing***
- ***On-orbit upgrades***



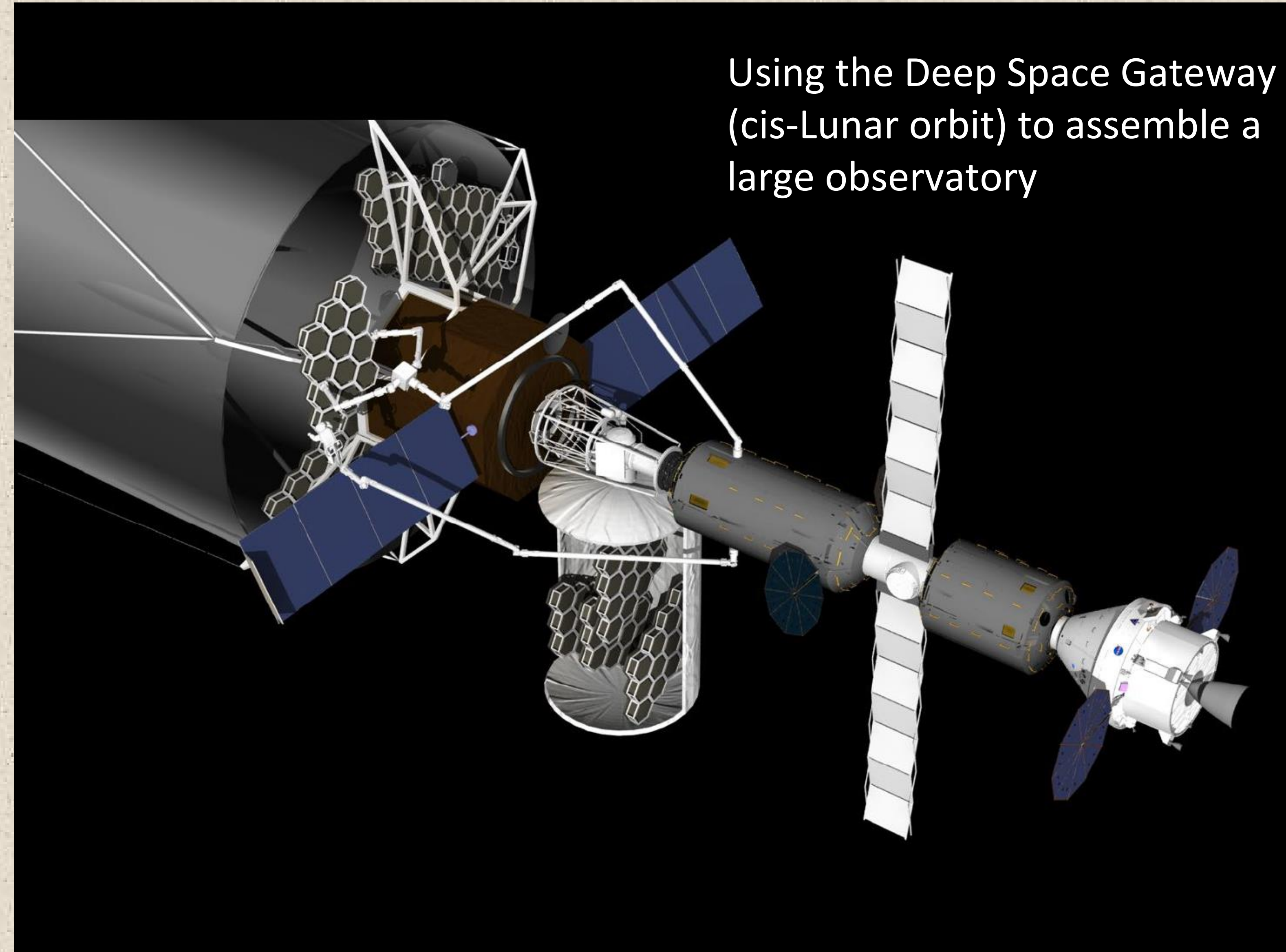
Robotics enables a *transformation of space*

Commercial driver: ability to change payloads on orbit so as not to carry expired assets on their financial ledgers

Gordon Roesler (DARPA)



John Grunsfeld (NASA GSFC)



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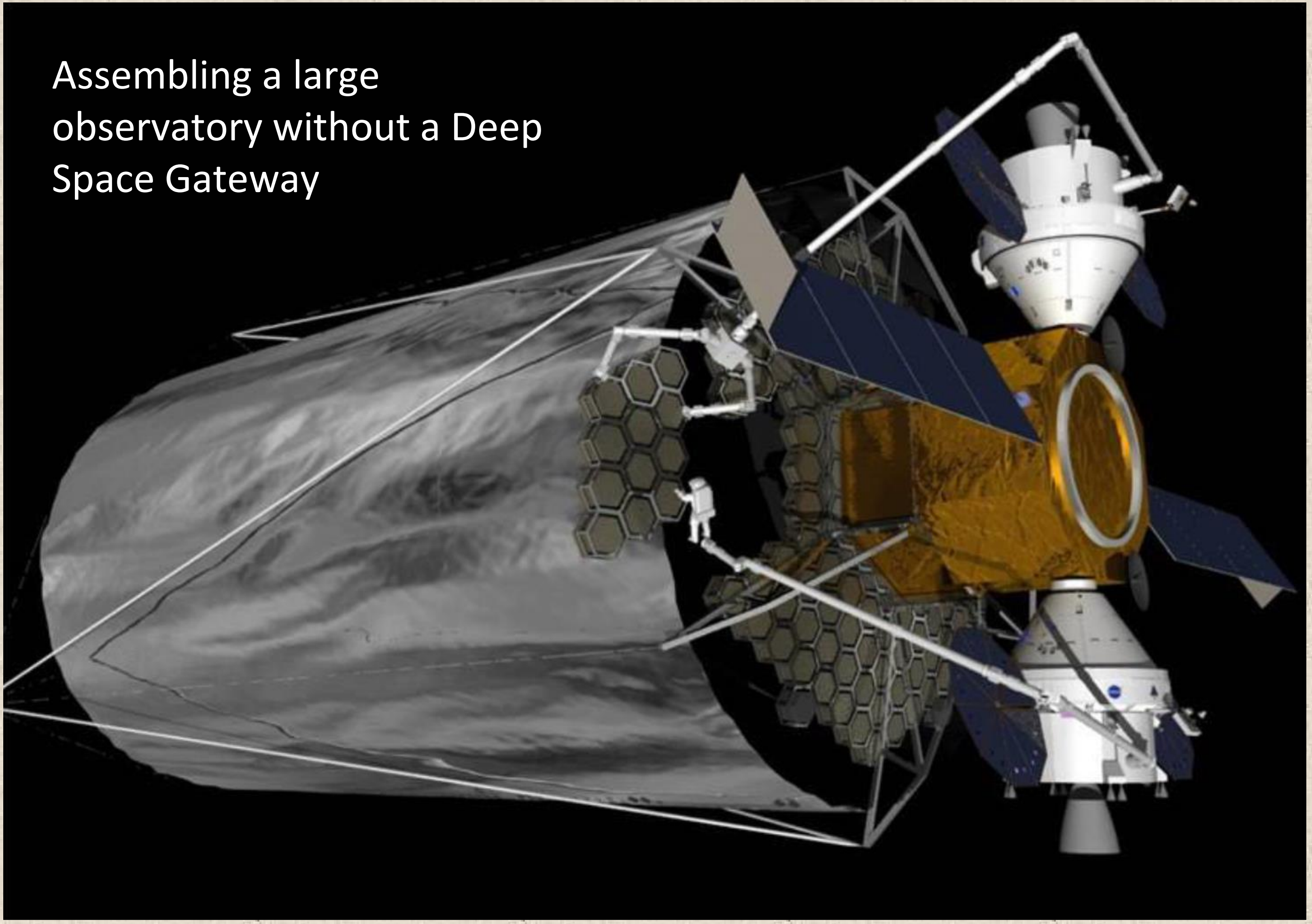
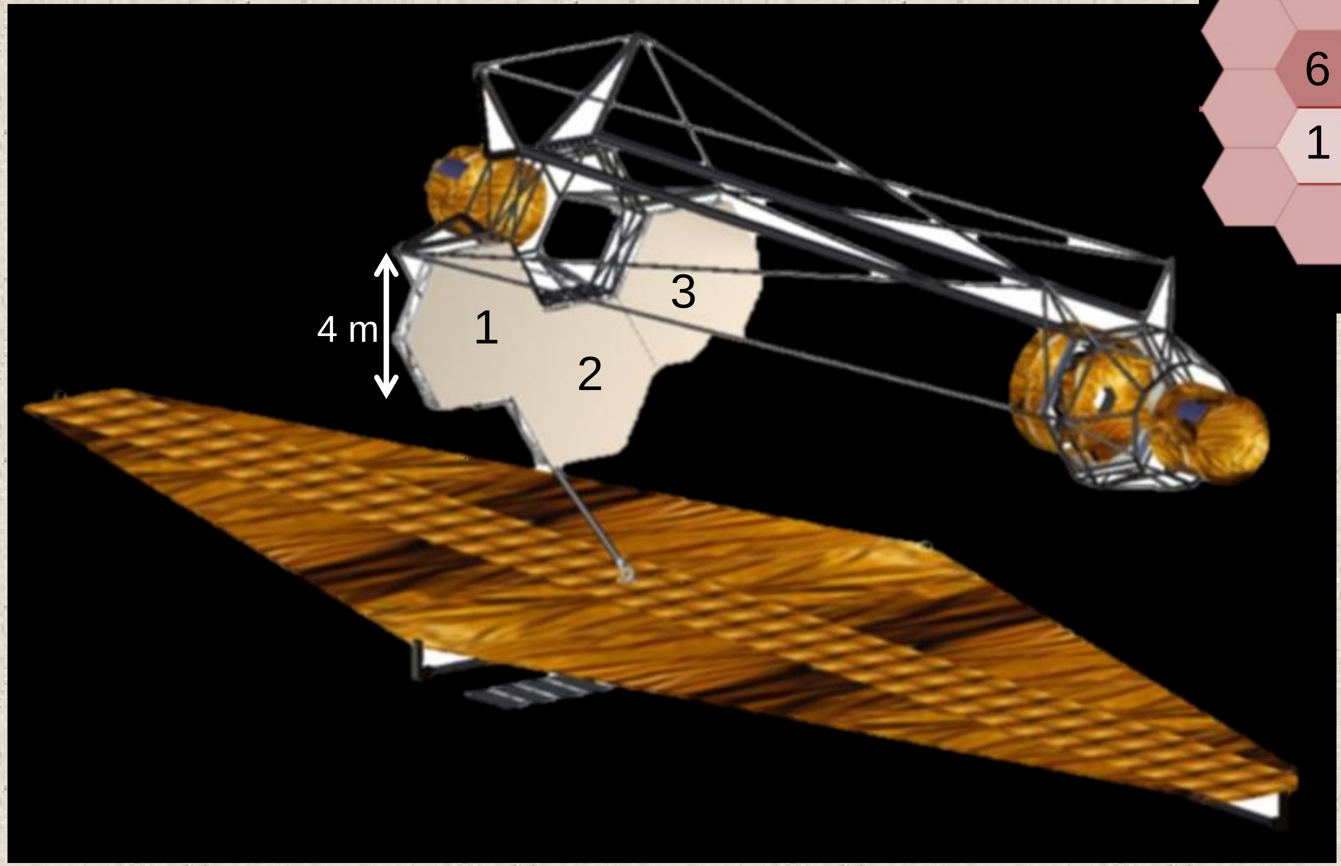
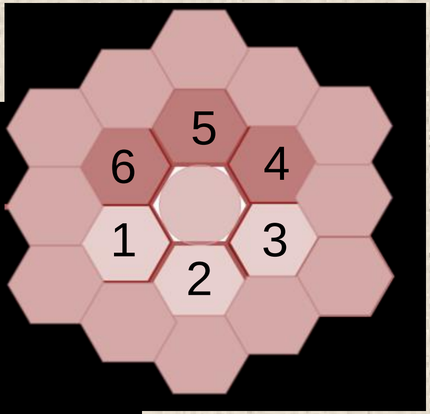


John Grunsfeld (NASA GSFC)

Telescopes that incrementally evolve

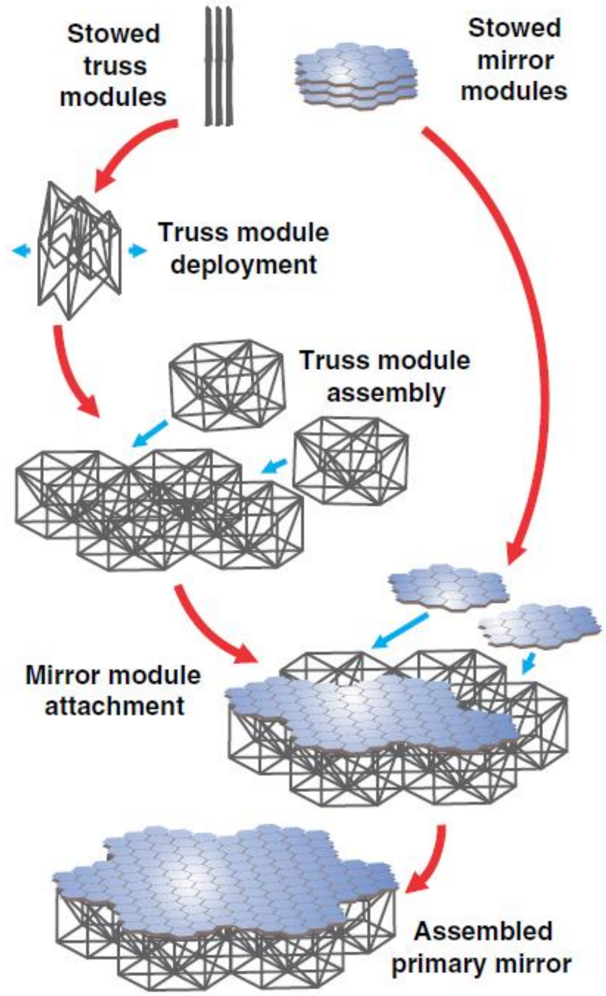


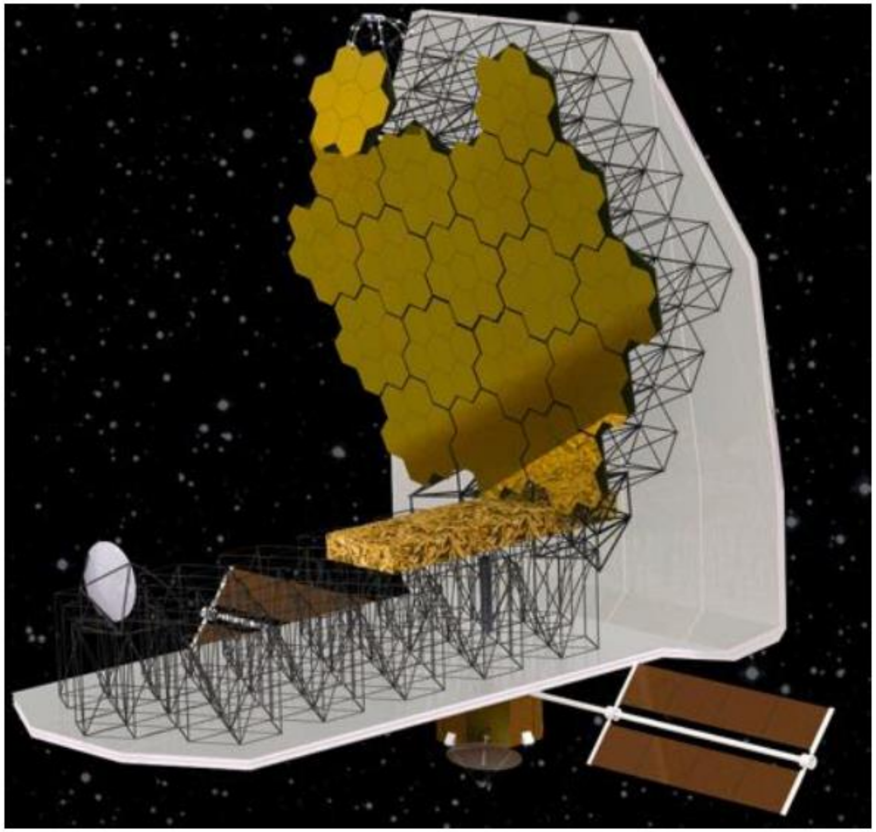


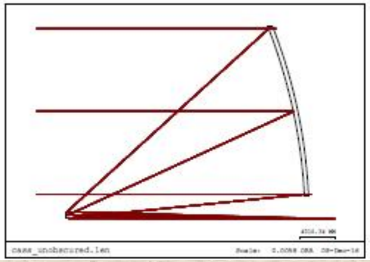
Polidan et al. 2016

Rudra Mukherjee (NASA JPL)

In Space Telescope Assembly Robotics







Unobscured Ritchey-Chretien

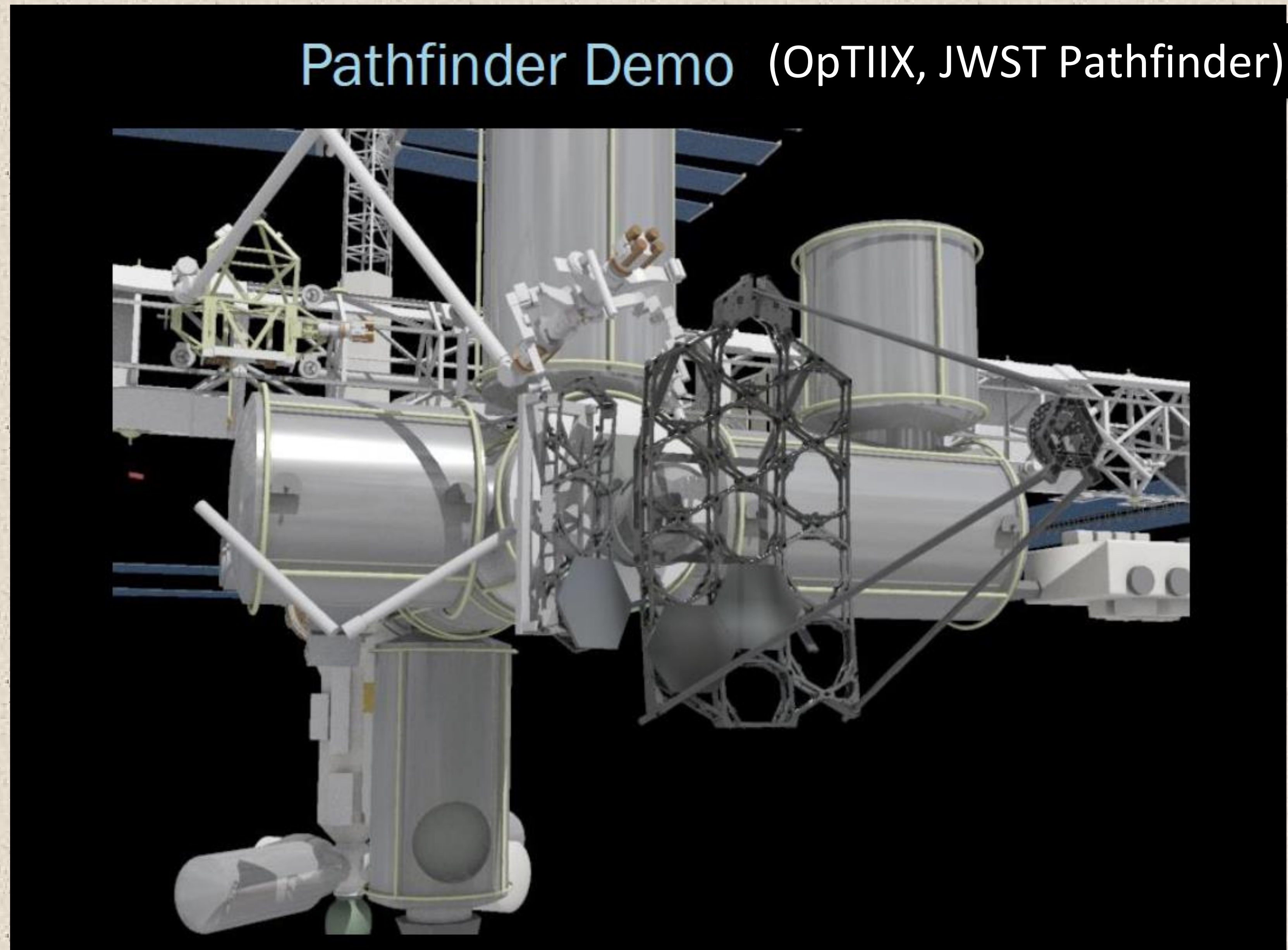
FOV 24.5x24.5 arc-sec.

Covers 8K x 8K x 12 micron FPA

Lee et al. 2016 (Caltech/JPL)

Telescopes assembled from modular deployable trusses

Lee Feinberg (NASA GSFC)



Key Acronyms

APD = Astrophysics Division (NASA)
DARPA = Defense Advanced Research Projects Agency
DSG = Deep Space Gateway
GSFC = Goddard Space Flight Center (NASA)
HEOMD = Human Exploration and Operations Mission Directorate (NASA)
iSA = in-Space Assembly
ISS = International Space Station
iSSA = in-Space Servicing and Assembly*
PAG = Process Analysis Group (NASA)
RSGS = Robotic Servicing of Geosynchronous Satellites (DARPA)
SOA = State of Art
SLS = Space Launch System
SMD = Science Mission Directorate (NASA)
STMD = Science & Technology Mission Directorate (NASA)
TIM = Technology Interchange Meeting
TRL = Technology Readiness Level

* Servicing = repair, replacement, upgrade, refuel, re-position

Questions Addressed During the TIM

Questions Addressed During the TIM

1. How does iSSA enable innovative instrument and telescope designs?
2. What astronomical goals are enabled by space assembly?
3. How does iSSA reduce cost and risk, both technical and programmatic?
4. How will future large observatories be serviced?
5. What additions, augmentations, and/or enhancements to a Gateway would be most valuable for servicing and assembling a future space observatory?
6. What are possible precursor demonstration activities?
7. What are useful coordinated activities?
8. Why now?

#1) How does iSSA enable innovative instrument and telescope designs? (1 of 2)

- **iSA <u>enables</u> space telescope designs that are not limited by launch vehicle fairing size and mass constraints.**
  - Examples: > 15 m aperture telescopes and long-baseline interferometers
  - 15 m is the reported maximum-size telescope aperture that fits in the fairing of a future SLS Block II
- **iSA <u>enables</u> space observatories and large structures to be designed with architectures too complex to be reliably deployed autonomously.**
  - Examples: large JWST-like segmented telescopes, interferometers, starshades
- **iSS <u>extends</u> the lifetime of observatories.**
  - Potentially enabling a Great Observatories paradigm (persistent assets)
  - Spacecraft could be refueled, subsystems could be replaced or upgraded
  - Mirrors could be recoated and decontaminated
  - Starshade membrane and edges could be repaired after micrometeoroid damage
- **iSS <u>enhances</u> our capability to more rapidly respond to new science questions through the replacement and upgrade of payload instruments**
  - "HST is a better observatory today than when it first launched"
  - Instrument technology is ~ 10-15 yr old by launch (technology lag)

#1) How does iSSA enable innovative instrument and telescope designs? (2 of 2)

- **iSSA <u>enables</u> telescope architectures that can grow in aperture size over time and hence, <u>enhancing</u> science through greater resolution and signal-to-noise**
  - “evolvable observatories”, “Pay as you go”

- **iSA <u>enables</u> the use of new materials in space, for example ultra-low weight optics, that cannot be adequately tested at 1 g or safely survive launch environment in an integrated state.**

#2) What astronomical goals are enabled by space assembly? (1 of 2)

- **iSA <u>enables</u> future large space telescopes, long baseline interferometers, and starshades that will provide unprecedented spatial and spectral resolution and signal to noise in the UV, V, NIR, and MIR.**
  - SLS Block II fairing permits a deployable 15 m aperture telescope

- **iSSA <u>enables</u> multiple generations of instrumentation for future observatories, opening new science capabilities and facilitating longer lifetimes for observatories.**

- **Examples include greater capabilities in (1) the search for life and (2) unlocking further secrets of the Universe:**

1) Searching for Life Elsewhere
- Increased yield of characterized Earth-like planets in the HZ of Sun-like stars
- Increased spectral resolution of spectral signatures, some of which may be of biological origin in the UV through MIR
- Observations of daily and seasonal light spectral variations due to changes in surface features as the planet rotates and orbits
- High-resolution, multi-wavelength remote sensing capabilities for Solar System objects that can enhance and extend planetary science missions

#2) What astronomical goals are enabled by space assembly? (2 of 2)

2) Discovering the Secrets of the Universe

- Constrain the nature of dark matter and map its distribution through ultra-precise astrometry
- Observing stars at all masses as individual objects beyond the Local Group to understand their formation and evolution in all environments
- Observing galaxies at star cluster scales (< 50 pc) across all cosmic time
- Observe atomic history across the full range of temperature and density, and track the rise of the periodic table
- Observe gravitational wave precursors (binaries) just prior to collision

Suggestions:
Reach out to the APD PAGs to solicit astrophysics topics that could be enabled with a Gateway infrastructure and a presence on the Moon and present initial findings at the February HEOMD Gateway Science Workshop.

#3) How does iSSA reduce cost and risk, both technical and programmatic? (1 of 4)

- **Beyond cost and risk, iSA is an <u>enabling</u> capability for the realization of large telescopes and interferometers in the not-too-distant future.**
  - At some aperture size (~ 17-20 m), even the next generation of LV fairing sizes will not be large enough to enable an autonomous telescope deployment
- **The case for "iSA of large observatories (4-15 m apertures and greater) being less expensive than autonomous deployment" has to date <u>not</u> been made.**
  - Potential cost savings may very likely be offset with new sets of unknown challenges (see next slide).
  - A more detailed study of how a large observatory would be built in space could examine this issue to the next level of needed fidelity.
- **By extending the lifetime of future NASA observatories, the cost of fewer new observatories results in a lower total cost amortized over more years.**

#3) How does iSSA reduce cost and risk, both technical and programmatic? (2 of 4)

Potential cost savings offered through iSSA:

- **Eliminates engineering design work and testing required to (1) creatively fit large structures into existing fairings and (2) autonomously deploy**
  - JWST invested a significant effort into designing and testing the telescope's folded wing design; even more for the observatory deployment with 40 deployable structures and 178 release mechanisms (all of which must work for the deployment to be successful)
- **Moves architecture away from "every new telescope is a new point design"**
  - Greater commonality with previous system reducing development costs
- **Reduces "ruggedization" to survive launch environment**
- **Reduces need for new and unique ground test facilities**
  - JWST required new ground facilities to be built
- **Reduces need for hardware redundancy**
- **Leverages existing and less-costly medium-lift launch vehicles**
- **New instruments can be swapped out without additional observatories**
- **Leverages investments in human space flight facilities**

#3) How does iSSA reduce cost and risk, both technical and programmatic? (3 of 4)

Potential new challenges may also INCREASE costs:

- **Would a full-scale, robotically-assembled telescope have to be demonstrated on the ground to mitigate concerns and risks? And then disassembled?**
- **Potential additional cost for any astronauts in the loop**
- **New robotic capabilities will be required as part of iSSA that would not be required in the autonomous deployment approach.**
- **Sending multiple modules into space will require new containers and interfaces each having to undergo environmental testing.**
- **New Earth-based problems yet unknown in standardization and assembly, as well as new unknown problems created in space, will likely need to be solved.**

#3) How does iSSA reduce cost and risk, both technical and programmatic? (4 of 4)

Risk reduction opportunities arising from iSSA

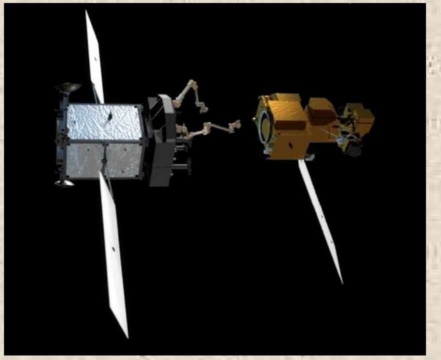
- **Reducing risk becomes increasingly more important as mission costs increase.**
- **Future larger observatories are likely to require more complex deployment schemes. iSSA can mitigate risk of failure by:**
  - Modularizing the design enabling repair and replacement of faulty sections
  - Designing servicing capabilities (robotic and/or human) into the architecture
  - Minimizing single-point failures
  - Enabling end-to-end testing (often not possible on ground)
- **iSA does not require next-generation launch vehicles**
  - Several future mission concepts under study rely on the SLS Block II (a potential programmatic uncertainty)
- **Launch failure need not be equivalent to mission failure**

Suggestion: Commission a design reference study that describes how a large aperture telescope would be assembled in space. The result can later be compared to the cost and risk of an autonomous deployment.

#4) How will future large observatories be serviced? (1 of 2)

- **As Sun-Earth L2 is the likely operational destination for many science missions, servicing could be performed in situ or in an orbit in the lunar vicinity.**
  - Earth-Sun L2 ←→ cis-lunar has a delta-v of 10's of m/s
  - LEO, GEO are other options but have large delta-v and are outside of their operational environment

- **Servicing observatories at Sun-Earth L2 may be preferred if operations are relatively <u>simple.</u>**
  - Simplicity – cooperative architecture aided by high levels of modularity
    - Re-fueling, swapping out instrument payloads, replacing solar arrays and batteries
  - Servicing can be conduced by a free flyer (e.g. DARPA RSGS, Restore-L)
  - Due to relatively long latencies operations would be semi-autonomous



#4) How will future large observatories be serviced? (2 of 2)

- **If servicing operations are relatively <u>complex</u>, then the mission can transfer from Sun-Earth L2 and be serviced at an accessible orbit in the lunar vicinity (e.g. Earth-Moon L1).**
  - Human and robotic support may be both important
  - Can leverage existence of an in-space assembly infrastructure (e.g. DSG)

#5) What additions, augmentations, and/or enhancements to a Gateway would be most valuable for servicing and assembling a future space observatory?

- **The design assembly study proposed by this TIM will be required to answer this question. Such a study would assess, for example:**
  - Autonomous and dexterous external robotic arms capable of assembling and servicing future observatories in the presence and absence of astronauts
    - Servicing includes capturing, berthing, docking, re-fueling, instrument swapping, subsystem replacement, etc
  - Ability to free-fly near Gateway (keep-away region, multiple sites?)
- **Capability for multiple astronaut EVAs for about 2 people over 2 weeks**
- **Defined ports, power, propulsion, attitude control**
- **Contamination mitigation**
- **Photogrammetry capabilities**

Suggestion: Conduct the aforementioned engineering design study to produce an early prioritized list of preliminary needs and requirements to be submitted for consideration to HEOMD before end CY19, best in summer 2018.

#6) What are possible precursor demonstration activities?

- **Valuable servicing demonstrations already planned:**
  - DARPA RSGS program and NASA Restore-L
- **Possible precursor assembly demonstrations on the ISS:**
  - Vibration isolation
    - floating systems are hard to demo in 1-g
  - Robotic assembly of a small segmented telescope (e.g. JWST Pathfinder, OpTIIX)
    - backplane
    - segment integration (power, alignment)
    - 0-g effects on mirror sag, alignments, and assembly feed back into models
- **Contamination analysis on a cis-lunar station**
- **Robotic arms dexterity tests on the ground relevant to telescope assembly**
- **Given the direction of the commercial sector at GEO, experiment packages to GEO to demonstrate assembly concepts may be worth considering.**
  - DARPA-RSGS expected to have a commercial free-flyer and dexterous robotic capability infrastructure

Suggestion: The aforementioned engineering design study will identify capability needs and technology gaps and produce a list of technologies that could be demonstrated to close these gaps.

#7) What are useful coordinated activities?

- **To take advantage of possible iSSA benefits, cooperation among the three NASA Directorates will be essential (SMD/STMD/HEOMD).**
  - Look for opportunities for coordination and strategic planning.
    - STMD already doing valuable work in this area
  - Coordinate towards standards, common tools, and interfaces
  - Ensure future infrastructure and capabilities are sufficiently versatile to use for multiple systems and missions

- **NASA should consider partnering with other government agencies and industry, US and foreign.**
  - Science & Technology Partnership Forum consortium between NASA, NRO, Air Force is an excellent start (DARPA also involved)
  - CONFERS is a joint DARPA/NASA consortium to establish common safety standards and regulations

Suggestions:

1. With an eye towards coordination, NASA may want to initiate an iSSA coordination group between the three Mission Directorates and perhaps with international space agencies as well.
2. Results from the iSSA TIMS and the fore-mentioned Design Study may be valuable inputs to the National Academies' Decadal Survey for the science and exploration opportunities opened up for the Agency.

#8) Why Now?

- **There are large future space observatories being studied and designed today to be serviceable but the servicing capabilities do not currently exist.**
- **There are large future space telescopes being studied and designed today that are limited by current and future launch vehicle fairing sizes.**
  - *"We are now hitting a wall [towards what is possible]"*
- **Potential space telescope missions planned to be serviced and/or assembled in the 2030s need to start their technology activities in the 2020s.**
- **A valuable venue for assembly demonstrations, the ISS, may be decommissioned in the mid-2020s.**
- **There is a near-term opportunity to inform the 2020 Decadal Survey about the potential benefits of iSSA as a potential implementation approach for future large apertures and the current SOA.**
- **There is at present a window of opportunity through 2019 to recommend augmentations to the DSG team before their designs are frozen.**
  - *March-July 2018 is the optimal window*

TIM Findings

The TIM Findings (1 of 2)

1. **iSSA is an important and enabling capability that has clear applications to near-term APD objectives**

2. **The current paradigm of telescope design (deployed or monolithic) does not contribute to the design of subsequent large-aperture space telescopes. Hence, the cost model for large telescopes is unlikely to change unless there is a paradigm shift.**

3. **There is a revolution in the TRL of robotics on the ground**
   – DARPA RSGS and NASA Restore-L are embodiments of this for space demonstrations and have legacy from the 15+ years of Mars and ISS robotics

4. **NASA STMD is already funding various iSSA Tipping Point efforts that can be built on for future iSSA**

5. **DARPA RSGS is a game changer**

6. **The ISS is potentially an ideal testing platform for many iSA technology development activities but is planned to be decommissioned mid-next decade**

The TIM Findings (2 of 2)

7. **The 2010 Decadal made no mention of iSSA**
   – Is this just an implementation issue?

8. **The "serviceability" of future telescopes is ambiguous as there is recognition that there are no ready servicers**
   – Consideration ought to be given on how to leverage existing servicer work (RSGS, Restore-L) including the opportunities enabled by a DSG

9. **Industry has very strong interest in iSSA and can play an important role**

10. **Large future space observatory concepts depend on availability of SLS Block II**
    – Some STDTs are relying on it

11. **A completed NASA Gateway infrastructure potentially offers a unique facility in which SMD may be able to leverage the iSSA of future large telescopes.**

Breaking the Cost Curve

(Zurbuchen's Question)

The need for ever-increasing telescope apertures in space to answer the Universe's most challenging mysteries will continue, as will the desire to change the payload instruments that process that light.

The current paradigm of telescope design (deployed or monolithic) does not contribute to the design of future large-aperture space telescopes (those that exceed their launch vehicle's fairing size). Hence, the cost model for large telescopes is unlikely to change unless there is a paradigm shift.

Future steps to break the cost curve may include:

- replacing the instrument payloads with newer more advanced ones
- upgrading spacecraft subsystems as they wear and age
- refueling to extend their lifetimes,
- repairing when needed, and
- incrementally enlarging the apertures over time

The potential benefits of iSSA of large future telescopes requires studying in more detail.

Summary of TIM Suggestions

TIM Suggestions (1 of 2)

1. **Commission a design study to understand how large-aperture telescopes could be assembled and serviced in space**
   - *Suggest joint SMD/STMD/HEOMD study with industry and academia participation*
   - *Multi-disciplinary, multi-institutional*
   - *Initiate the study in time for initial results to be available to Gateway and robotics designers within 2018, but certainly before end 2019.*

A. Produce several iSA concepts and prioritize them

B. Select one implementation concept for a deeper engineering study
   - *identify capability needs, SOA, and technology gaps and produce a list of technologies that could be demonstrated to close these gaps*
   - *assess opportunities for engineering demonstrations that may be deployed on the ISS within the next few years.*
   - *determine balance of human and robotic support*
   - *understand servicing options*
   - *produce an early list of preliminary interface consideration to the DSG*

C. Estimate the cost and understand scaling laws to compare costs/risks to an autonomously deployed telescope

TIM Suggestions (2 of 2)

2. **Reach out to the APD PAGs to solicit astrophysics topics that could be enabled with a Gateway and present initial findings at the February HEOMD Gateway Science Workshop.**
    - Already underway

3. **NASA may want to initiate an iSSA coordination group between the three Mission Directorates and perhaps with international space agencies as well.**

4. **Consideration ought to be given on how to leverage existing servicer (RSGS, Restore-L) work and the DSG work to meet the serviceability needs of future SMD mission concepts.**

5. **Consider providing input to the 2020 Decadal Survey about iSSA as a potential implementation approach for future large apertures.**

6. **The GSFC-hosted TIM should be considered the first of a series, with a follow-on held in CY18.**

Expressed Criticisms

- **Impediment: *"No one wants to add cost to their individual mission to pay for serviceability."***
  - iSSA needs leadership, long-term vision, and commitment to take hold.
  - DARPA for years lamented that there were no serviceable satellites but that was because there was no servicing capabilities. Hence, the RSGS
  - If NASA won't lead who will?

- ***"Not clear if SMD really needs an assembly and servicing infrastructure in orbit rather than just building a one-off in conjunction with a recommended mission."***
  - *[But SMD may not be able to afford it alone either]*

- **No mention of servicing or in-space assembly in the 2010 Astronomy & Astrophysics Decadal Survey**

- ***"This is all 10+ years out. How do we keep America engaged in the interim?"***

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The journey of a thousand miles begins with one step.

- Lao Tzu

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