Achieving Future Major Astronomical Goals in Space: Promises And Challenges of Servicing and In-Space Assembly of Very Large Apertures

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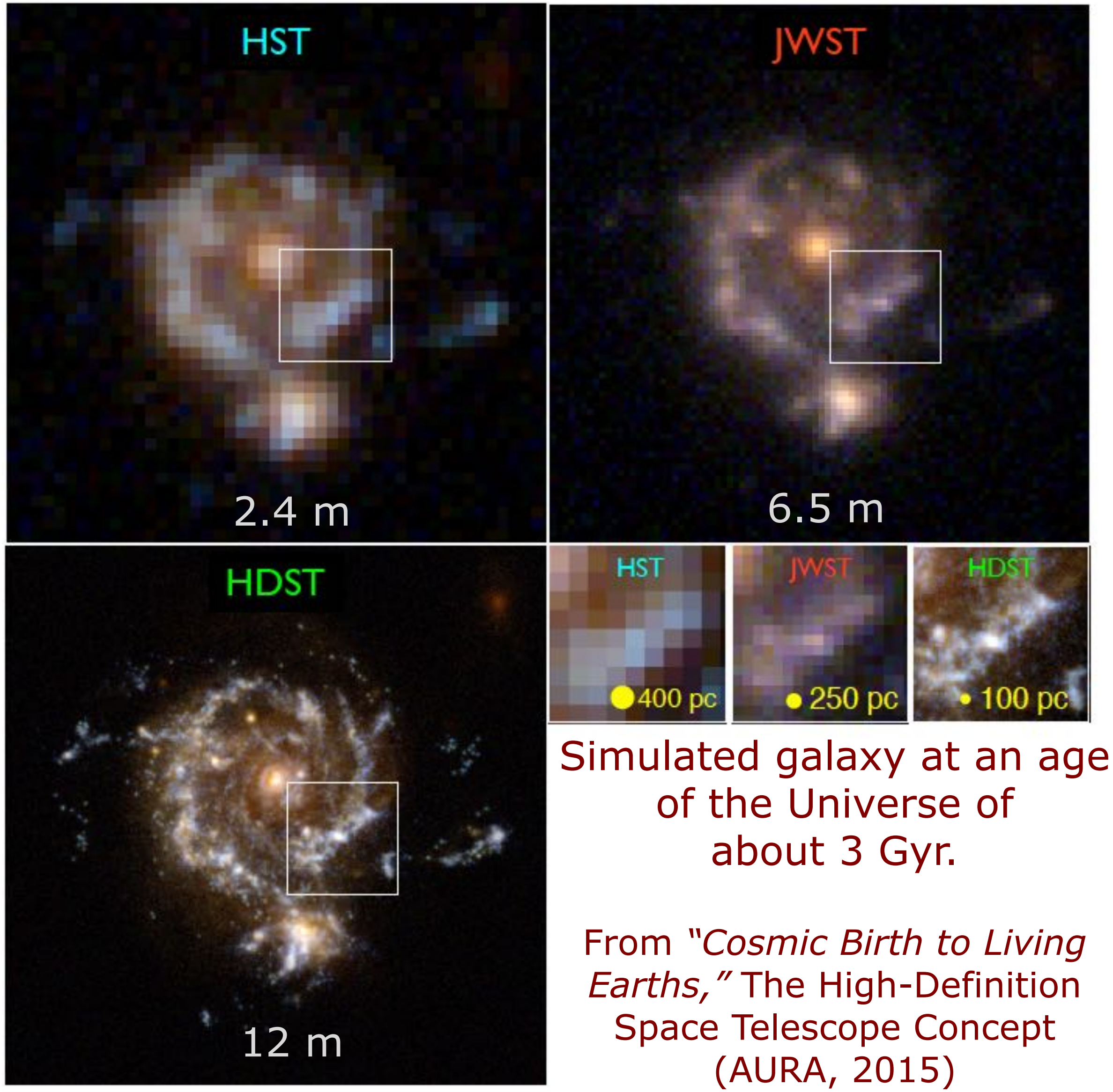
NASA Goddard Space Flight Center

AND

The Future Assembly/Servicing Study Team (FASST)

Supported by the NASA HQ Science Mission Directorate, Astrophysics Division

Motivation: Cosmic Revelations Increase Rapidly with Telescope Aperture



Simulated galaxy at an age of the Universe of about 3 Gyr.

From *"Cosmic Birth to Living Earths,"* The High-Definition Space Telescope Concept (AURA, 2015)

With spatial resolutions achievable by apertures in excess of ~10 meters, regions of active star formation in extremely distant galaxies can be separated from the older stellar populations.

The evolution over cosmic time of the star formation in galaxies can be studied in detail.

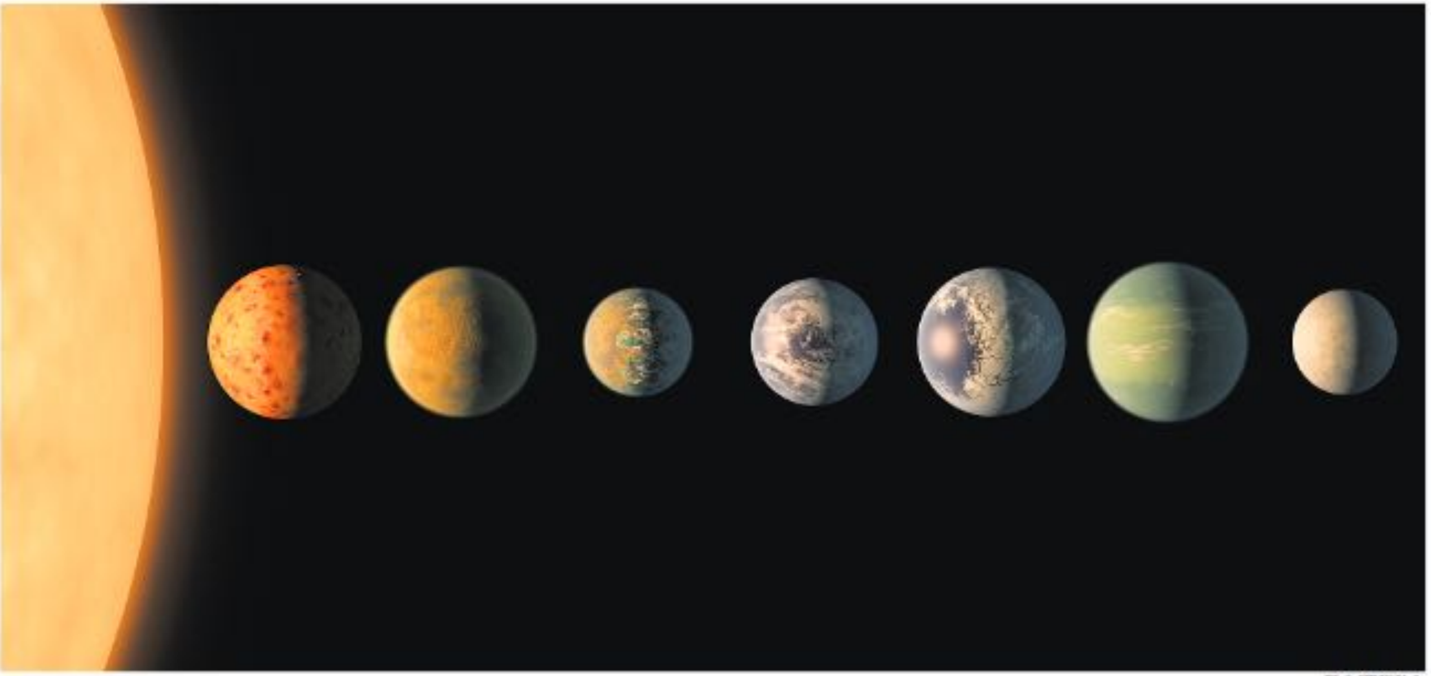
Moreover, the dynamic structure of very young galaxies, include the presence of dwarf and colliding companions, can be revealed.

Motivation: Enormous Public Interest in Exoplanets: *Are We Alone?*

"All the News That's Fit to Print"

The New York Times

VOL. CLXVI . . . No. 57,517 © 2017 The New York Times Company NEW YORK, THURSDAY, FEBRUARY 23, 2017



JPL-CALTECH/NASA

A rendering of newly discovered Earth-size planets orbiting a dwarf star named Trappist-1 about 40 light-years from Earth. Some of them could have surface water.

Circling a Star Not Far Away,

Uber's Culture Of Gutsiness

Migrants Hide, Fearing Capture on 'Any Corner'

By VIVIAN YEE

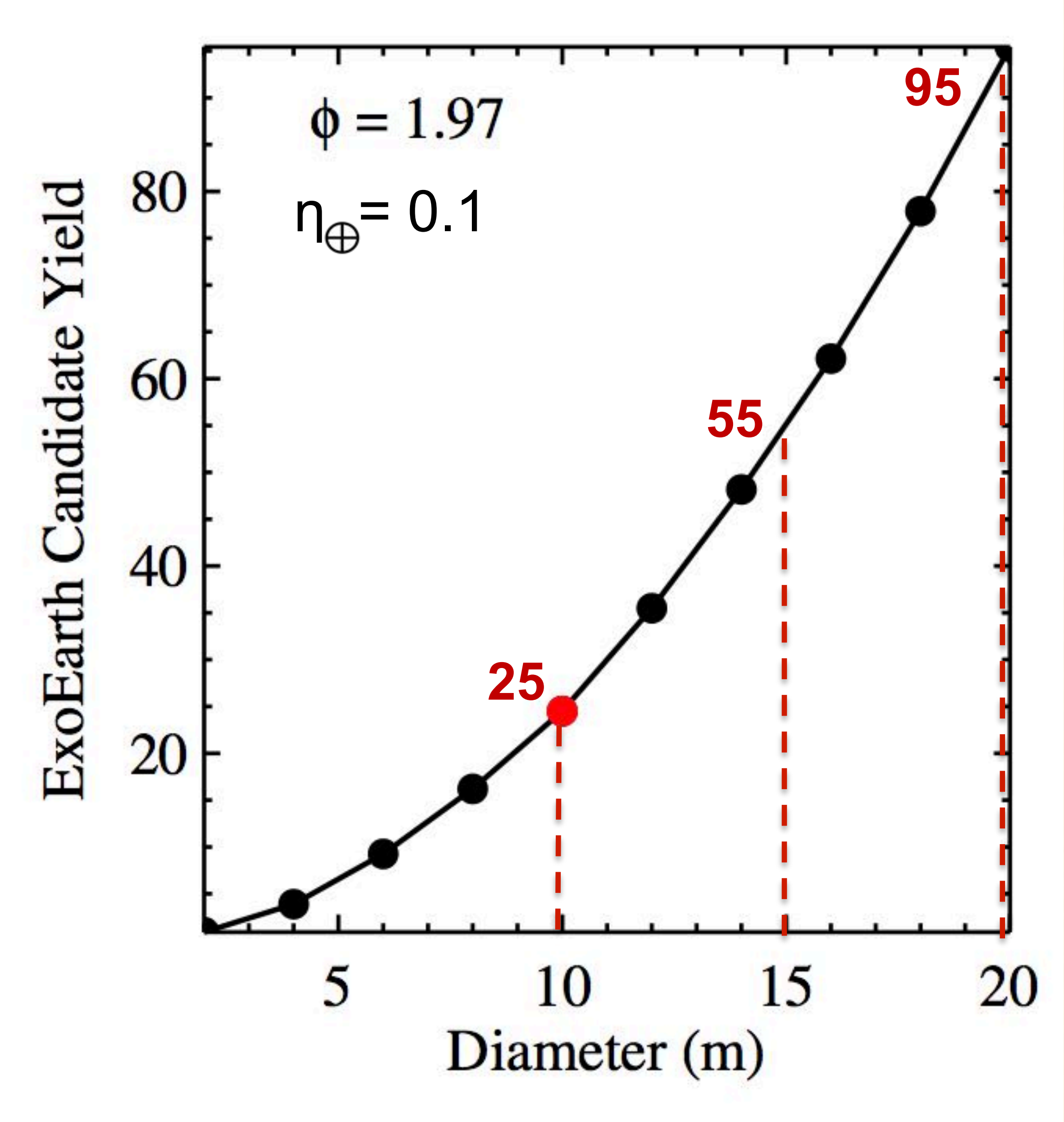
IMMIGRATION A police depart-

duras.

If deportation has always been

Multiple Thursday presentations on searches for exoplanets and required technologies.

Exo-Planet Discoveries Increase Rapidly with Telescope Aperture



Number of candidate exo-Earths increases approximately as *D^2*.

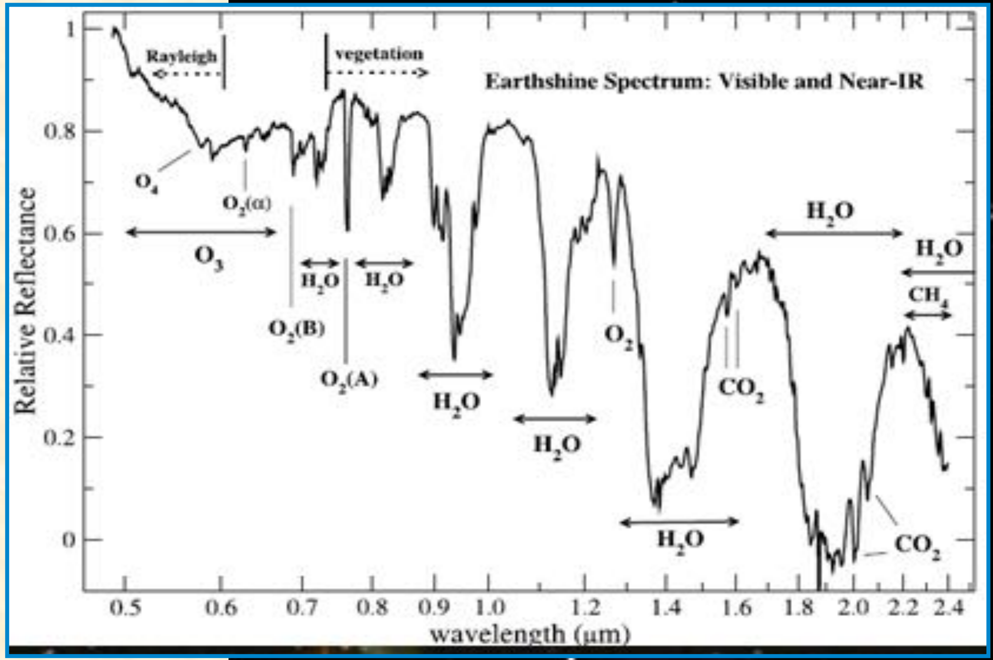
Increasing sample size will increase likelihood of discovery of an exo-Earth . . .or else put credible limits on their existence.

With ~30 candidates and η_{Life} = 0.1, one life-bearing world should be detected with a confidence of ~95%.

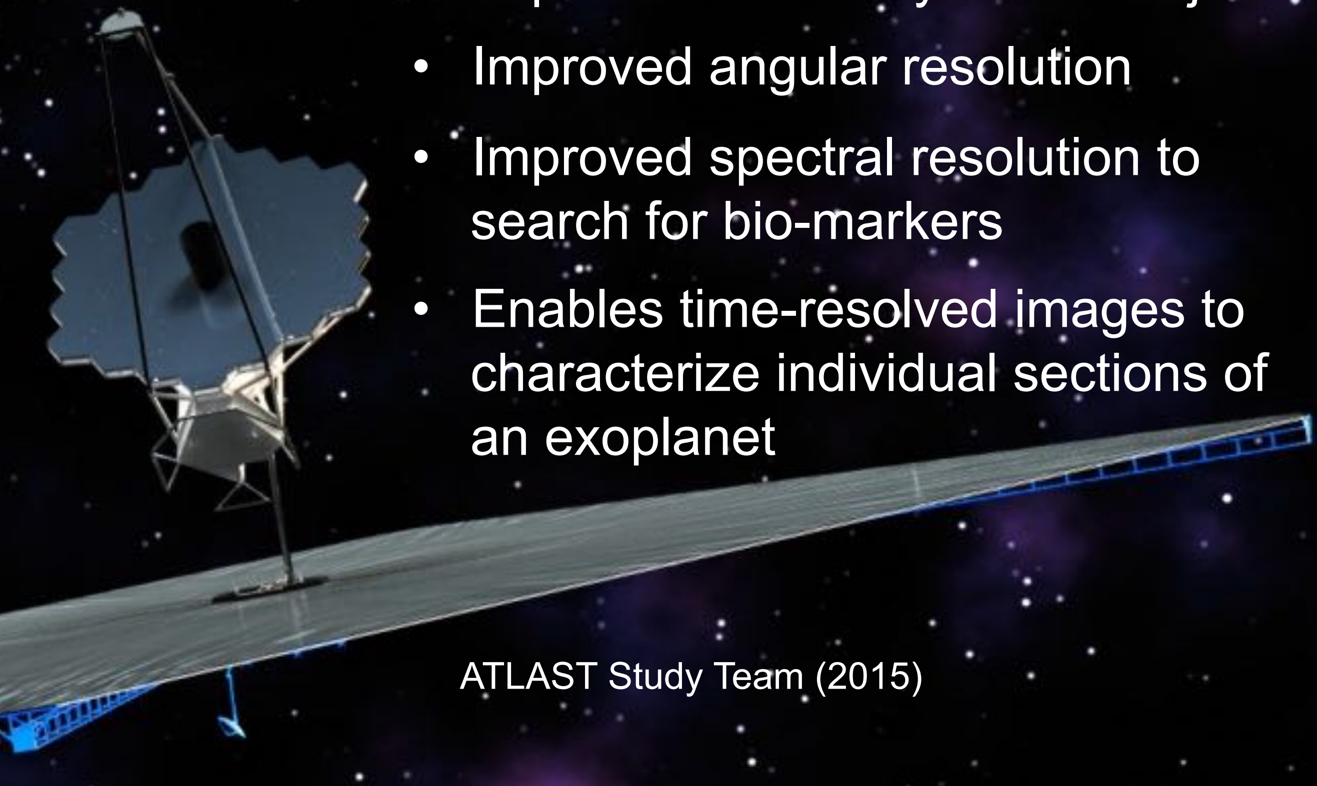
In addition, a large aperture will reduce the integration time to obtain diagnostic spectra.

Calculated number of candidate exoEarths in the solar neighborhood observed with a coronagraph, assuming the fraction of Sun-like stars orbited by an Earth-size planet in the HZ is 0.1 (Stark *et alia,* 2015).

That is, In the Search for Life Bigger is Way, Way Better



M. Turnbull *et alia* (2006)



- Improved sensitivity to faint objects
- Improved angular resolution
- Improved spectral resolution to search for bio-markers
- Enables time-resolved images to characterize individual sections of an exoplanet

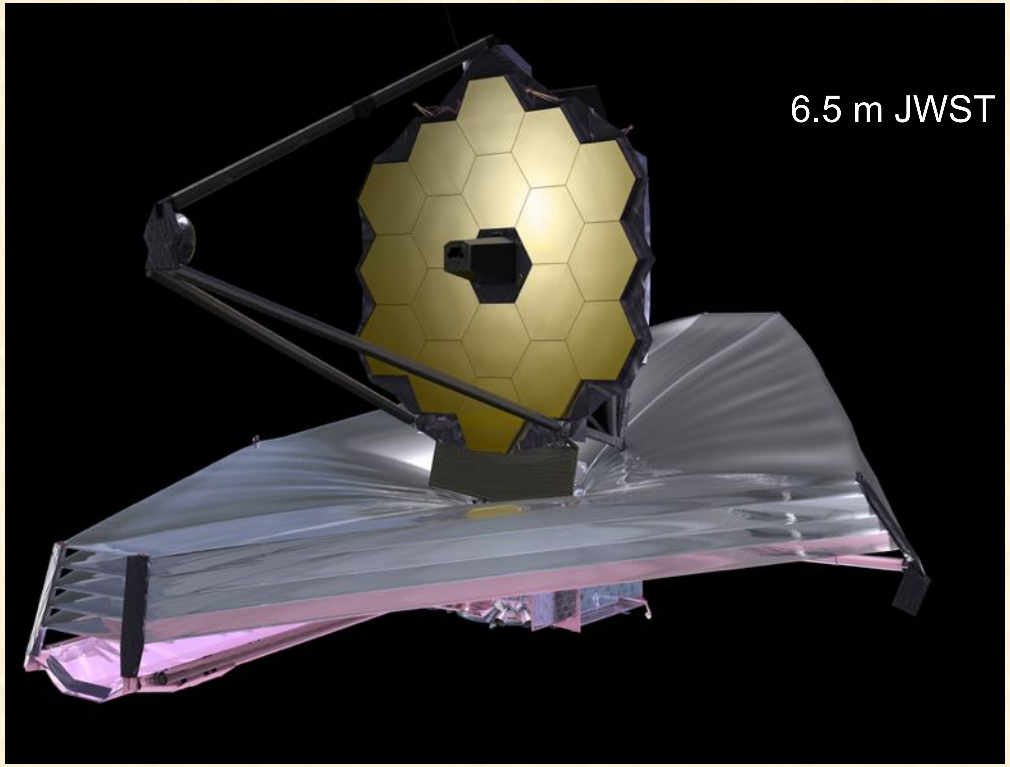
ATLAST Study Team (2015)

Exo-Earths will be *by far* the faintest celestial objects ever observed.

For Self-Deployment: Telescope Size Currently Limited by LV

"…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 (OSU) Chair, Astrophysics Advisory Committee

JWST within Ariane 5 (4.6 m fairing)



Falcon Heavy (5.2 m fairing) ~ 9 m telescope
SLS Block IB (5.2 & 8.4 m fairings) ~ 12 m telescope
SLS Block 2 (8.4 & 10 m fairings) ~ 15 m telescope
? > 15 m telescope

Before I Discuss Capabilities, Acknowledgements

Future Assembly/Servicing Study Team (FASST) Co-Authors

Nicholas Siegler (Exoplanet Exploration Program Office, Caltech/JPL), FASST *Co-Chair*

Lynn Bowman (NASA LaRC), Matthew Greenhouse (NASA GSFC), John Grunsfeld (NASA GSFC), Sharon Jefferies (NASA LaRC), Rudranarayan Mukherjee (Caltech/JPL), Bradley Peterson (OSU/STScI), and Ronald Polidan (PSSC, LLC)

Thank You to Colleagues

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How May Space Assembly Enable Capabilities Not Currently Possible?

In-space assembly may . . .

- **enable space telescope designs that are not limited by launch vehicle fairing size and mass constraints.**
  - Examples: > 15 meter apertures and long-baseline interferometers
  - ~15 meters is the reported maximum telescope aperture that fits in the large fairing of a future SLS Block 2
- **enable 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
- **enable the use of new materials in space**
  - Example: ultra-low weight optics and structures, that cannot be adequately tested at 1 g or safely survive launch environment in an integrated state.
- **apply increasingly capable space robotic systems**
- **employ on-site astronauts at the cislunar Gateway analogous to servicing HST**

How Might In-Space Assembly and Servicing Reduce Cost and Risk?

Potential cost savings made possible by in-space assembly (iSA):

- **Eliminates engineering design work and I&T 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
- **Leverages existing, widely available, and less-costly medium-lift launch vehicles**
- **Moves architecture away from "every new telescope is a new point design"**
  - Greater commonality with preceding systems reduces development costs
  - Development may approach "assembly line" model, thus reducing "standing army" costs
- **Reduces requirements for system "ruggedization" to survive launch environment**
- **Reduces need for new and unique ground test facilities**
  - JWST required expensive new ground facilities to be built
- **Reduces need for hardware redundancy and potentially provides that *launch* failure need not be equivalent to *mission* failure**
- **Servicing allows instruments to be swapped out without having to design and build a new observatory: *Lesson #1 from HST***

Important to emphasize, however . . . .

The case for space assembly of large observatories (~4 – 15-meter apertures) being less expensive than autonomous deployment has to date *not* been made.

- Potential cost savings may very likely be offset with new sets of unknown challenges.
- Assessing potential cost savings is a priority activity for the NASA HQ Astrophysics Division-supported FASST studies described later.

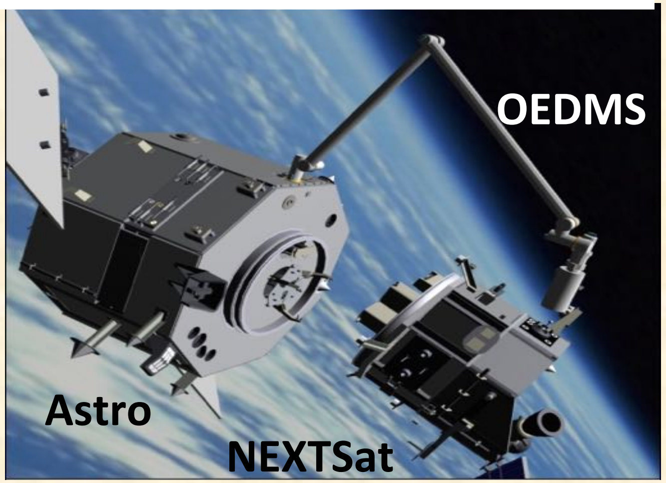
And, now, a few words about some of the capabilities that might be available over the next two decades to allow lower-cost assembly in space of very large observatories, beginning with the growing capabilities in space robotics . . .

Thumbnails of Work in this Field: In-Space Servicing and Assembly

Capabilities being developed to service and eventually assemble are accelerating with government and commercial involvement.

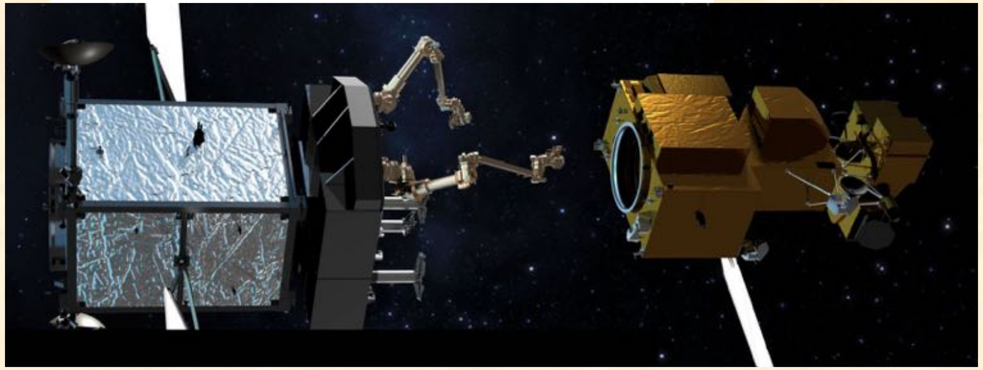
NASA – Astronaut-Enabled Servicing

DARPA - Orbital Express



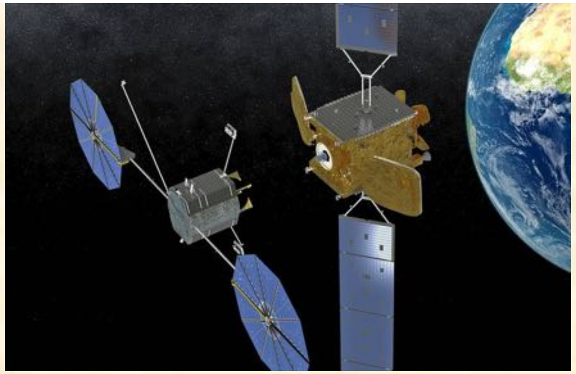
DARPA - Robotic Servicing of Geosynchronous Satellites

NASA - Restore-L



ISS Robotics

Orbital ATK - Mission Extension Vehicle



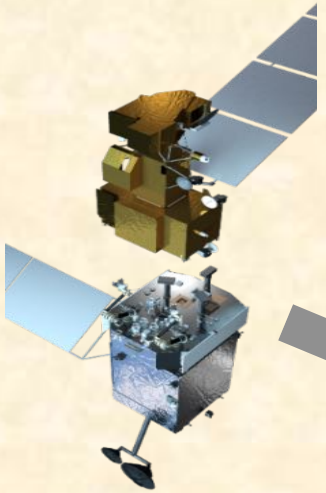
The Restore-L Mission (GSFC's Satellite Servicing Projects Division)

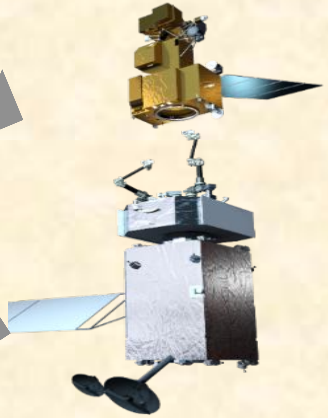
Restore-L Advancement

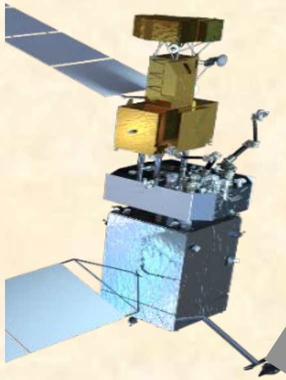
Technologies	Capabilities
Relative Navigation Sensors and Algorithms	Remote Inspection
Advanced Avionics	Legacy Rendezvous
Servicing Robotics	Legacy Capture
Servicing Tools	Legacy Refueling
Fluid Transfer	Client Relocation
Mission Autonomy Manager	
Berthing System	
Vision System	

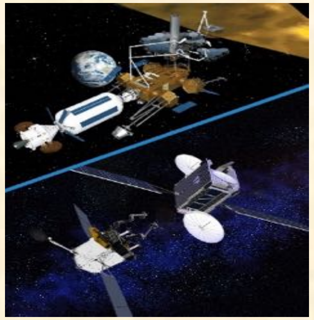
Other SSPD Projects

Technologies	Capabilities
Cryogen Transfer	Repair
Cooperative Servicing Aids	Replenish
Xenon Transfer	Replace
Modular Components	Assemble



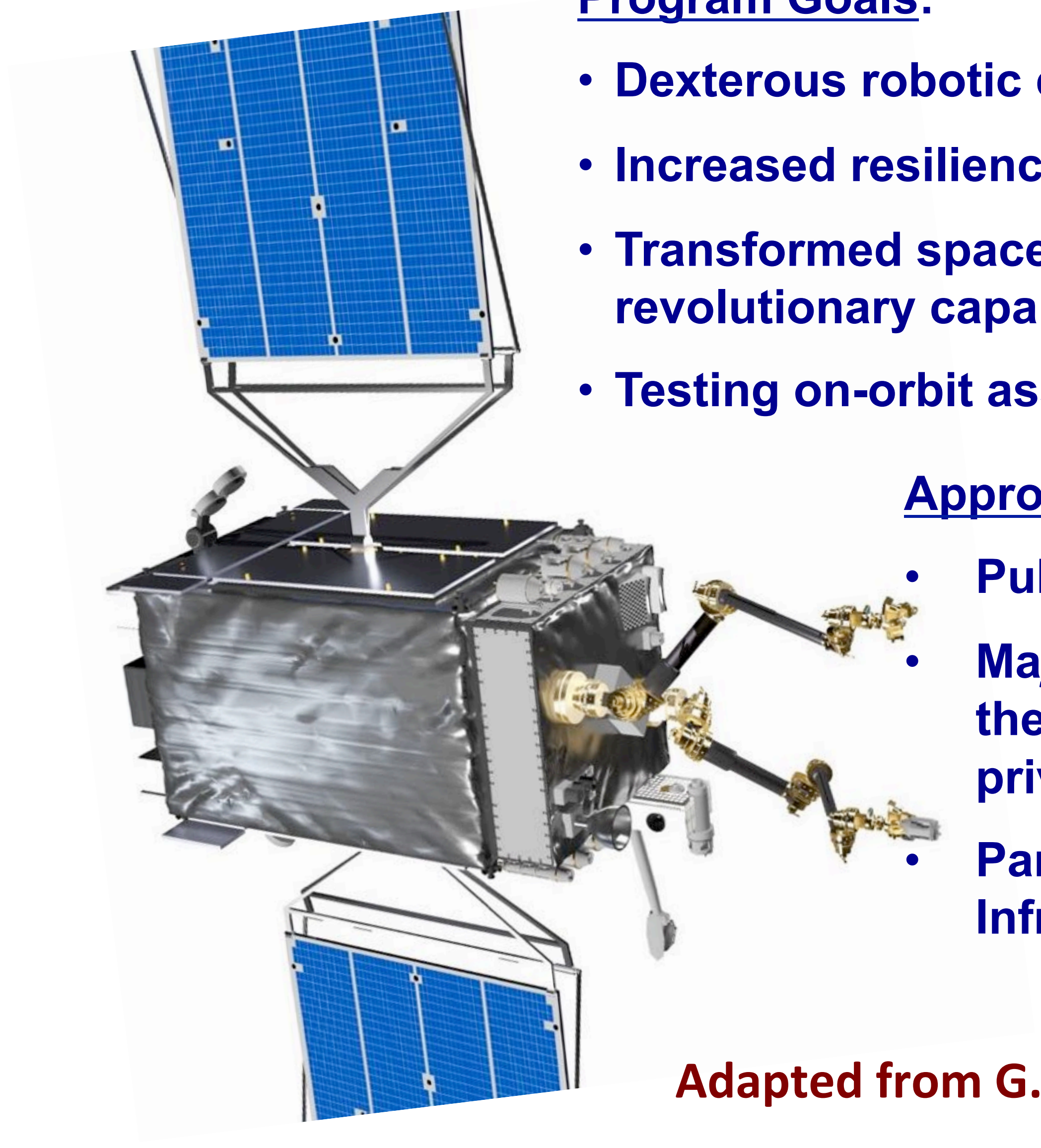






Adapted from B. Reed, RHGMS 2018

Robotic Servicing of Geosynchronous Satellites (RSGS)



Program Goals:

- Dexterous robotic capability in GEO
- Increased resilience for current infrastructure
- Transformed space architecture, revolutionary capabilities
- Testing on-orbit assembly techniques

Approach:

- Public-private-partnership
- Major investments by both the US government and private industry
- Partners: SSL and Space Infrastructure Services (SIS)

EXAMPLE BASELINE MISSION SET

Anomaly Correction

Install Upgrade Modules

Adapted from G. Roesler (FISO seminar; May 2, 2018)

SSL Dragonfly: robots on board!

Artist's conception: SSL

Enables larger and more powerful satellites that cannot be launched fully assembled

- packaged in pieces within a standard launch vehicle fairing
- The first step in changing the GEO infrastructure paradigm

On-orbit robotic assembly from efficiently stowed state

- Lower satellite mass while enabling higher satellite performance
- Commercial and government applications

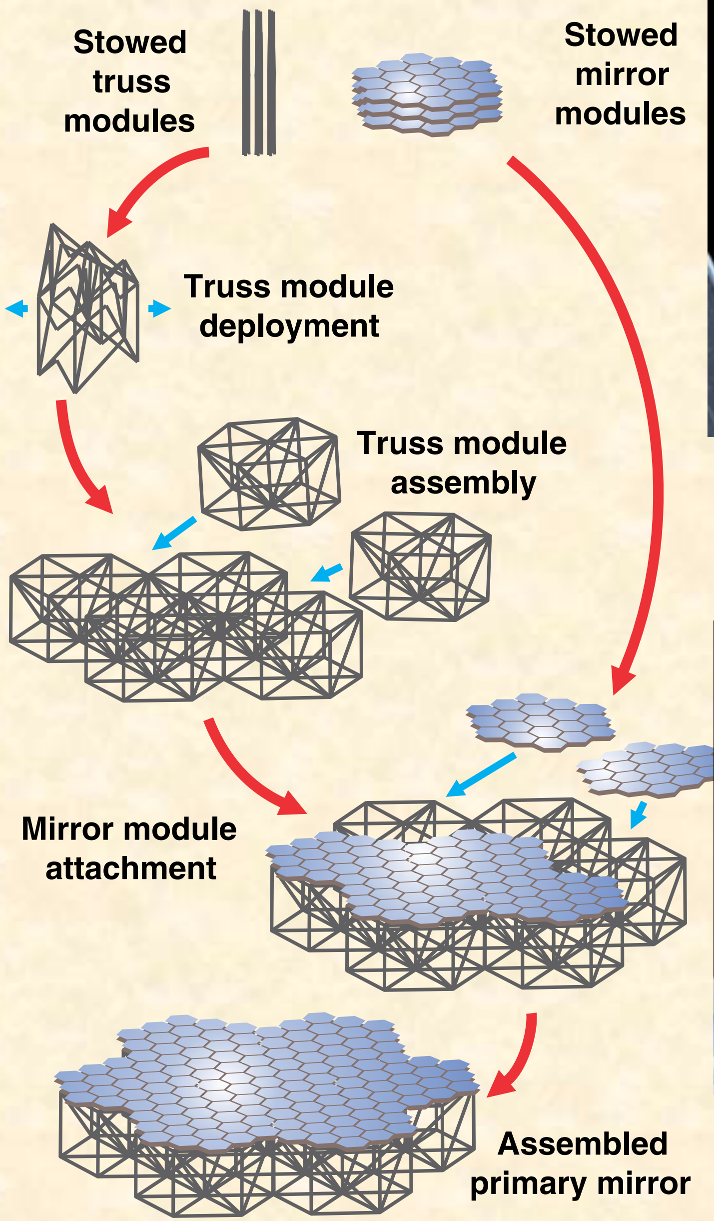
- **Robotic arm replaces traditional deployment mechanism**
- **Less cost, less weight, more reflectors**

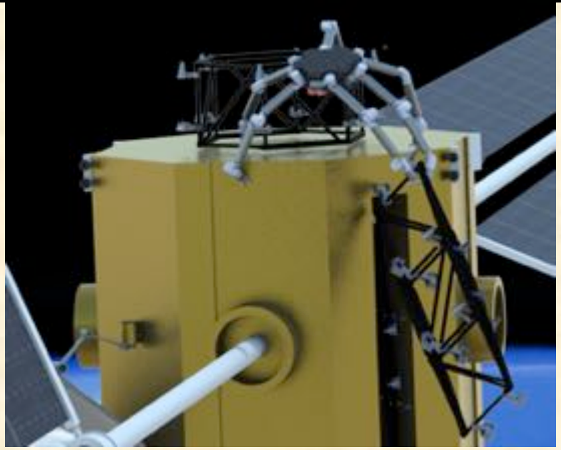
- **Future applications:**
  - On-orbit upgrade
  - Assembly
  - Repair

DARPA Seedling/NASA Tipping Point Project

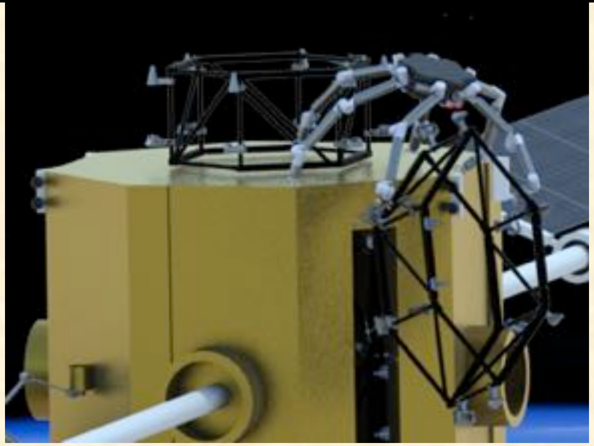
Adapted from G. Roesler (FISO seminar; May 2, 2018) and A. Tadros (RHGMS 2018)

A Concept for Robotic Large-Aperture Assembly (JPL/Caltech)

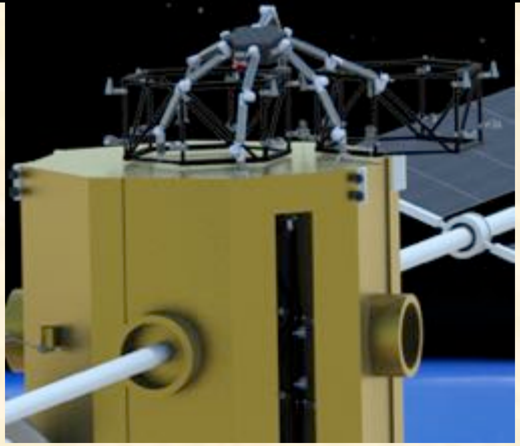




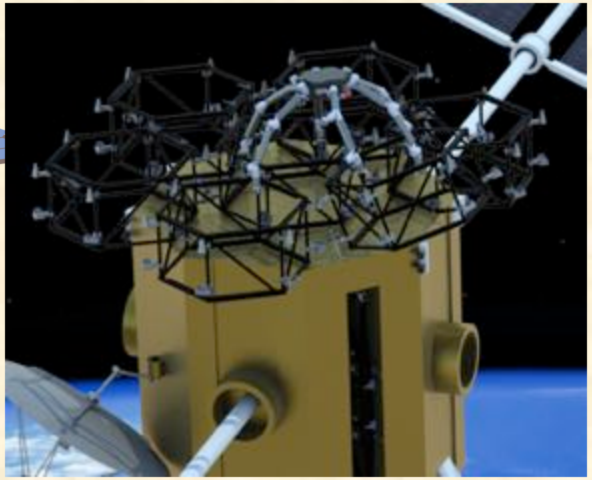
1. Extract Deployable Truss Module (DTM) from spacecraft



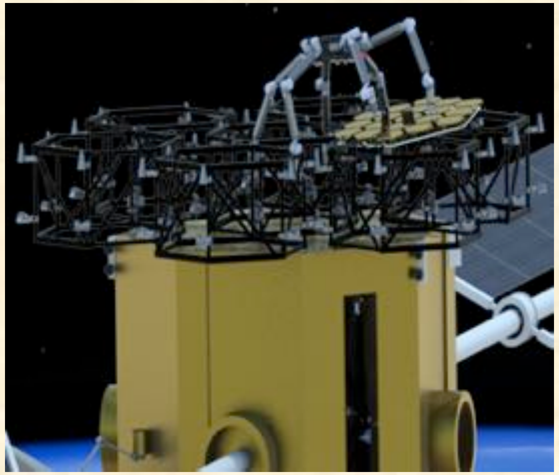
2. Deploy DTM



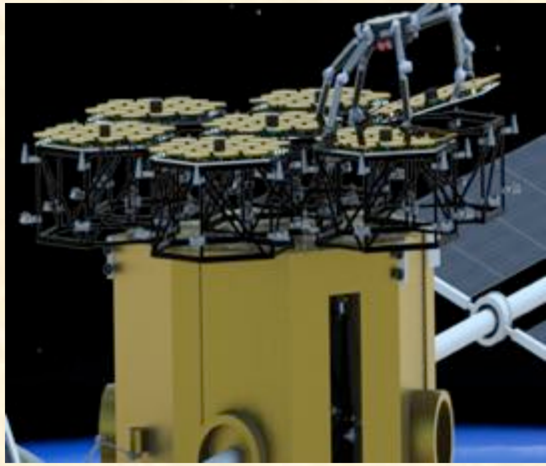
3. Assemble DTM



4. Repeat and finish backplane



5. Assemble Mirror Module

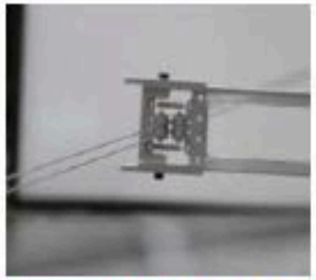


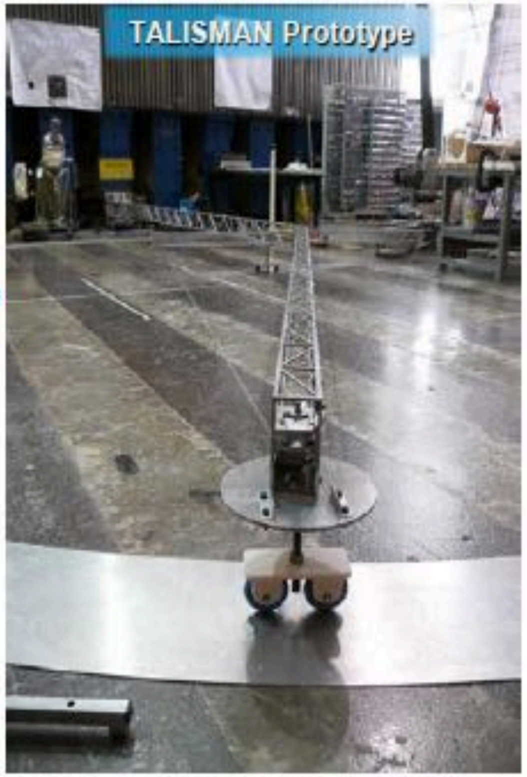
6. Repeat and finish primary mirror

Space Structures and Robotic Assembly (NASA LaRC)

Assembly Operations

- Long reach & dexterous manipulation
- Joining – Intelligent Precision Jigging Robot (IPJR)
- Joining – Electron Beam (E-Beam) Welding
- Joining – SBIR Technologies

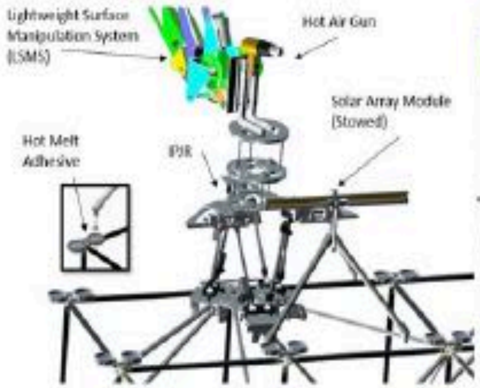

Spreader Constrained Lift Off

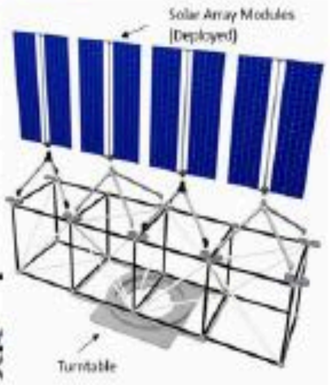



Hinge Joint


Gravity Off-Loading System


Motor/Gear-Box





In Addition to Robotics, Astronauts May Also Be On-Site

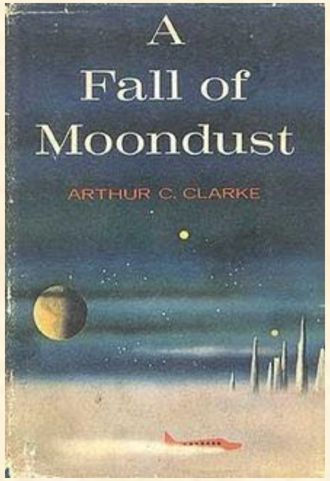
One of the ways to cope with [pressure on the federal discretionary budget]—not to solve it—is to look for synergies between exploration and science.

So for example, let's look at the "Deep Space Gateway," a space station near the moon, which NASA has proposed.

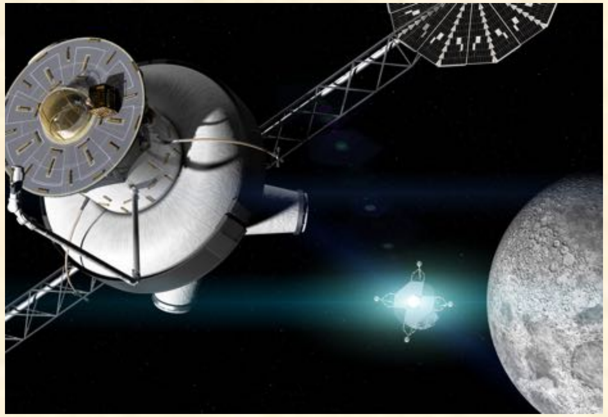
What kinds of astrophysics or lunar science might be done using that?

--- Scott Pace, Executive Secretary, National Space Council, November 6, 2017

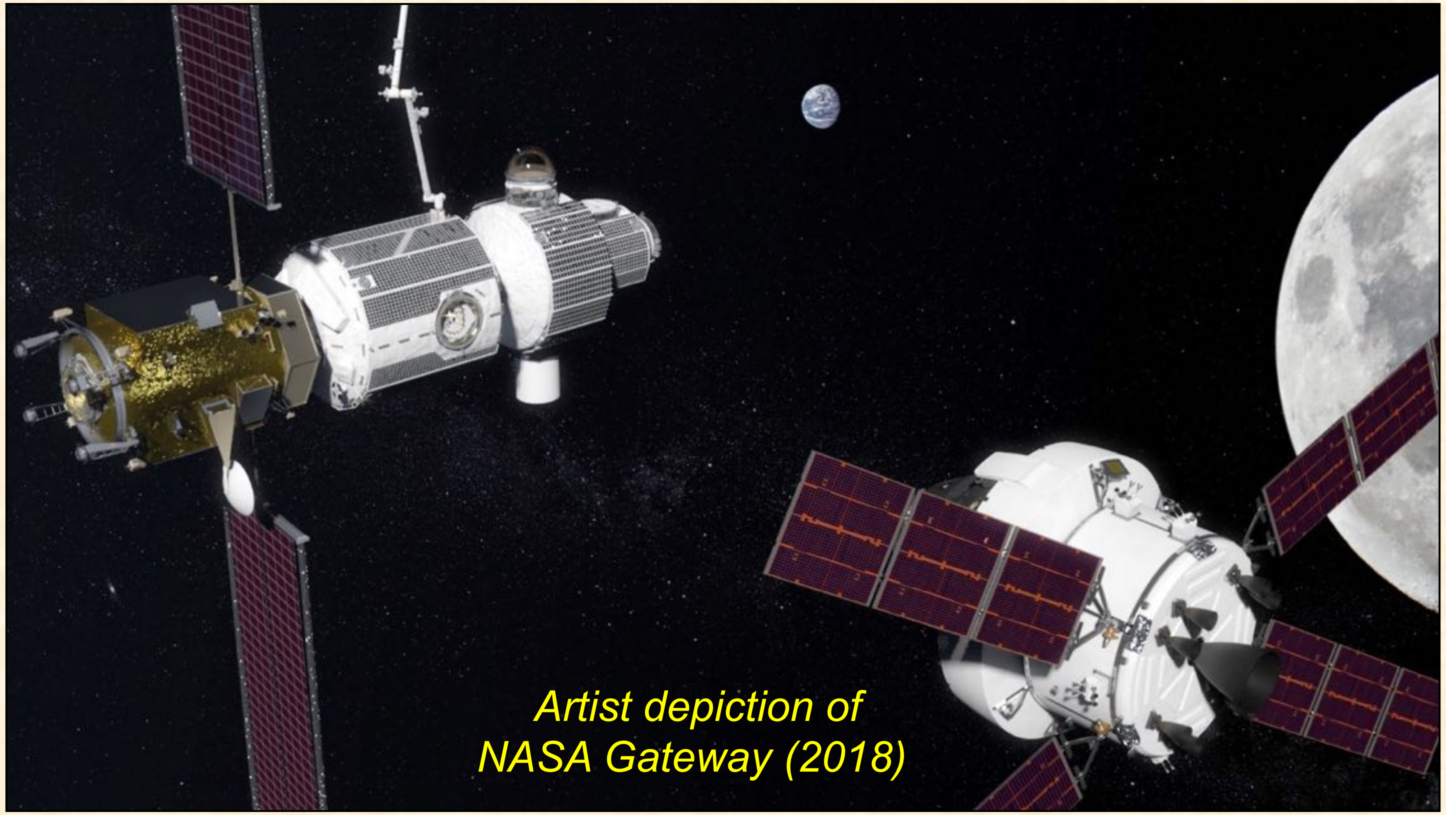
Cis-lunar Gateways: from science fiction to early designs



Arthur C. Clarke
1961



JF&A and Thronson
2007

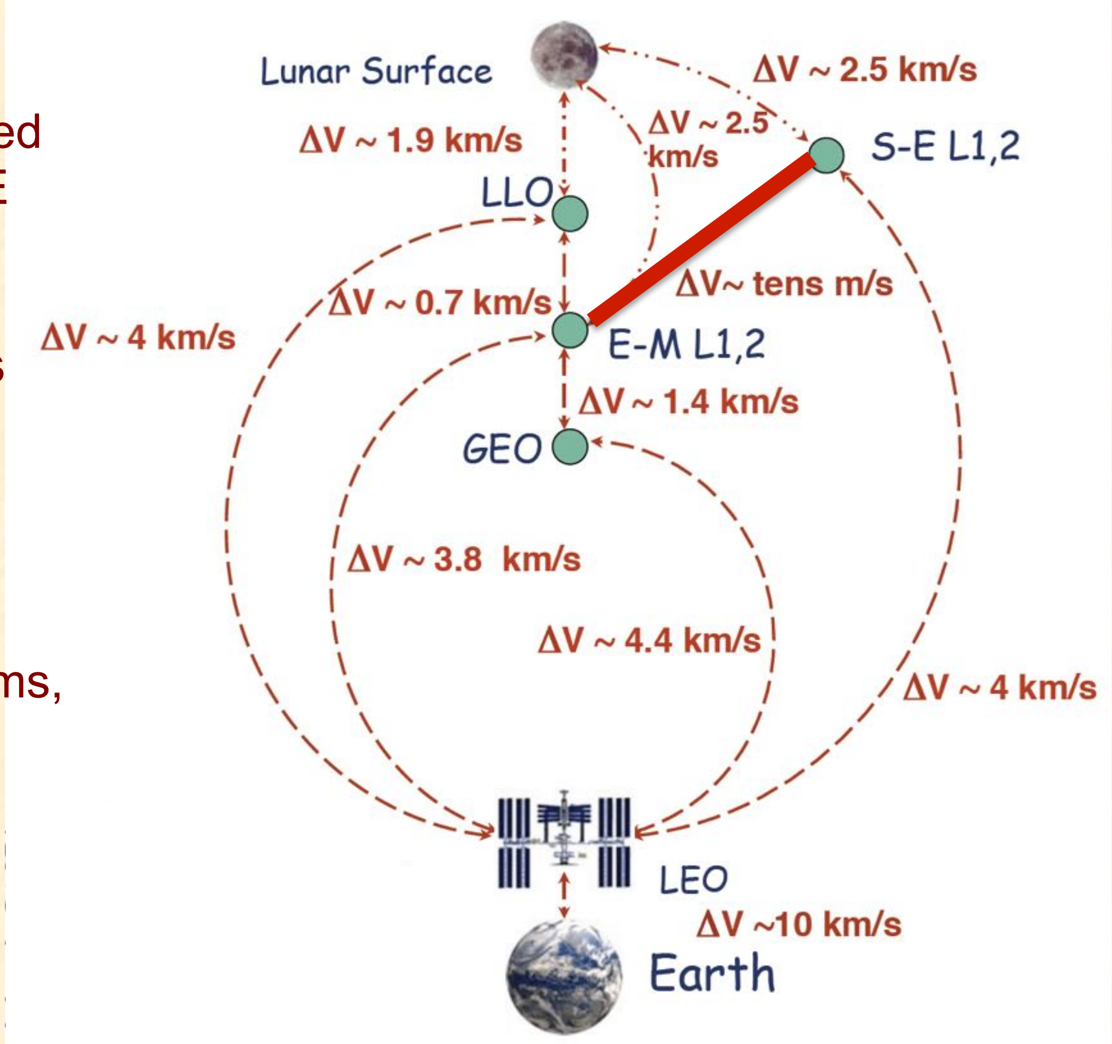


Artist depiction of NASA Gateway (2018)

Why a habitation and operations site in cis-lunar space?

Next major human exploration "stepping stone" offers major capabilities useful to space assembly

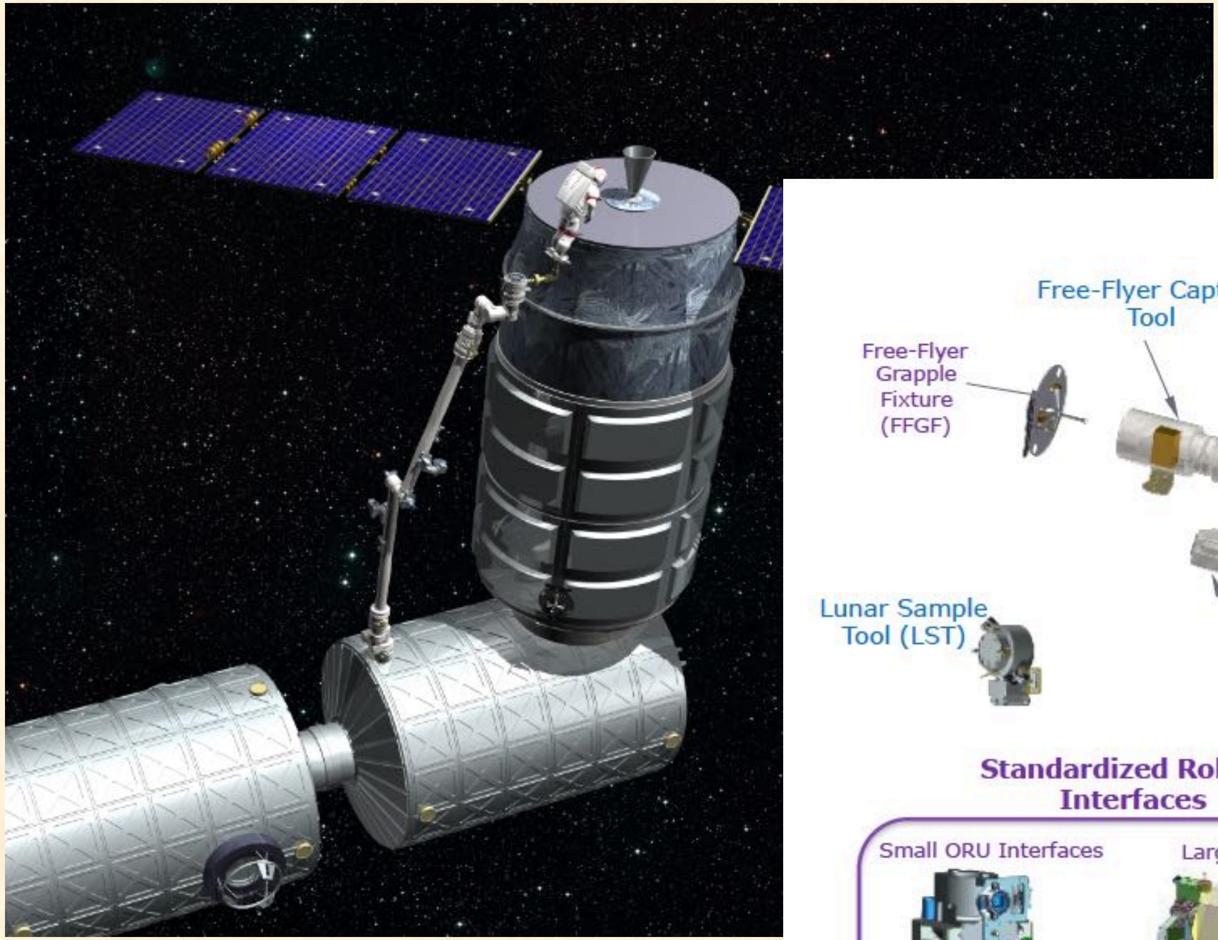
- **Likely venue is readily accessible to Sun-Earth L2**
  - SE L2: thermally stable; Earth, Moon, Sun easily blocked
  - Δv ~ 10s of m/s: low propulsion to go (EML1,2 <---> SE L2) for servicing
- **Expected to offer both astronaut and tele-robotics capabilities**
- **Expected to be equipped with important infrastructure**
  - High-data rate communication, versatile imaging systems, robotic arms, astronaut support
- **Analogous with Shuttle adapted to enable HST upgrade**
  - Public recognition of value to science of human space flight

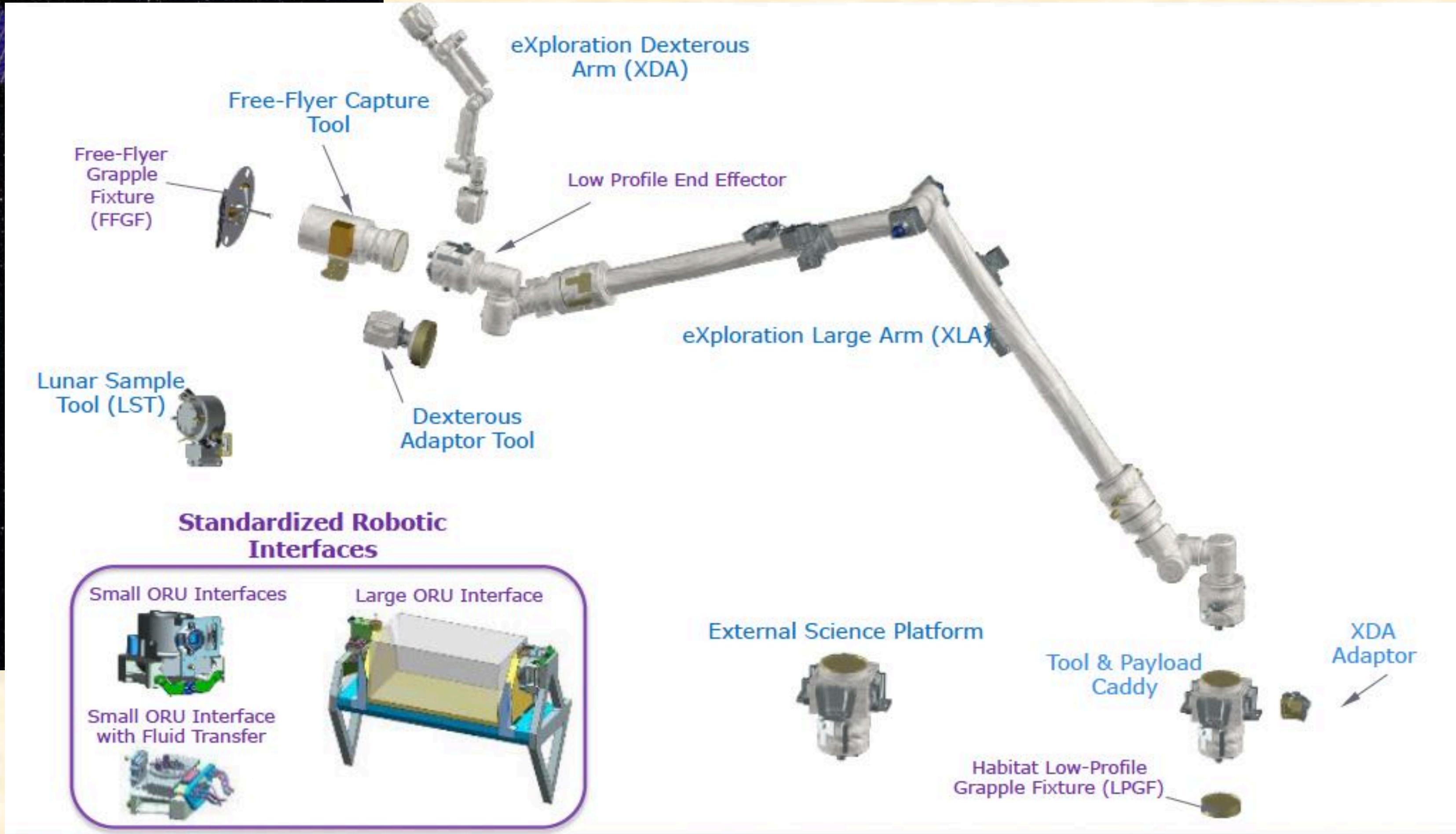


Sun-Earth-Moon transfer estimates adapted from NASA's Decade Planning Team (2000)

Deep Space Exploration Robotics: Canadarm for the Next Decade

A habitation and operations site in cislunar space will require a highly capable robotic arm.

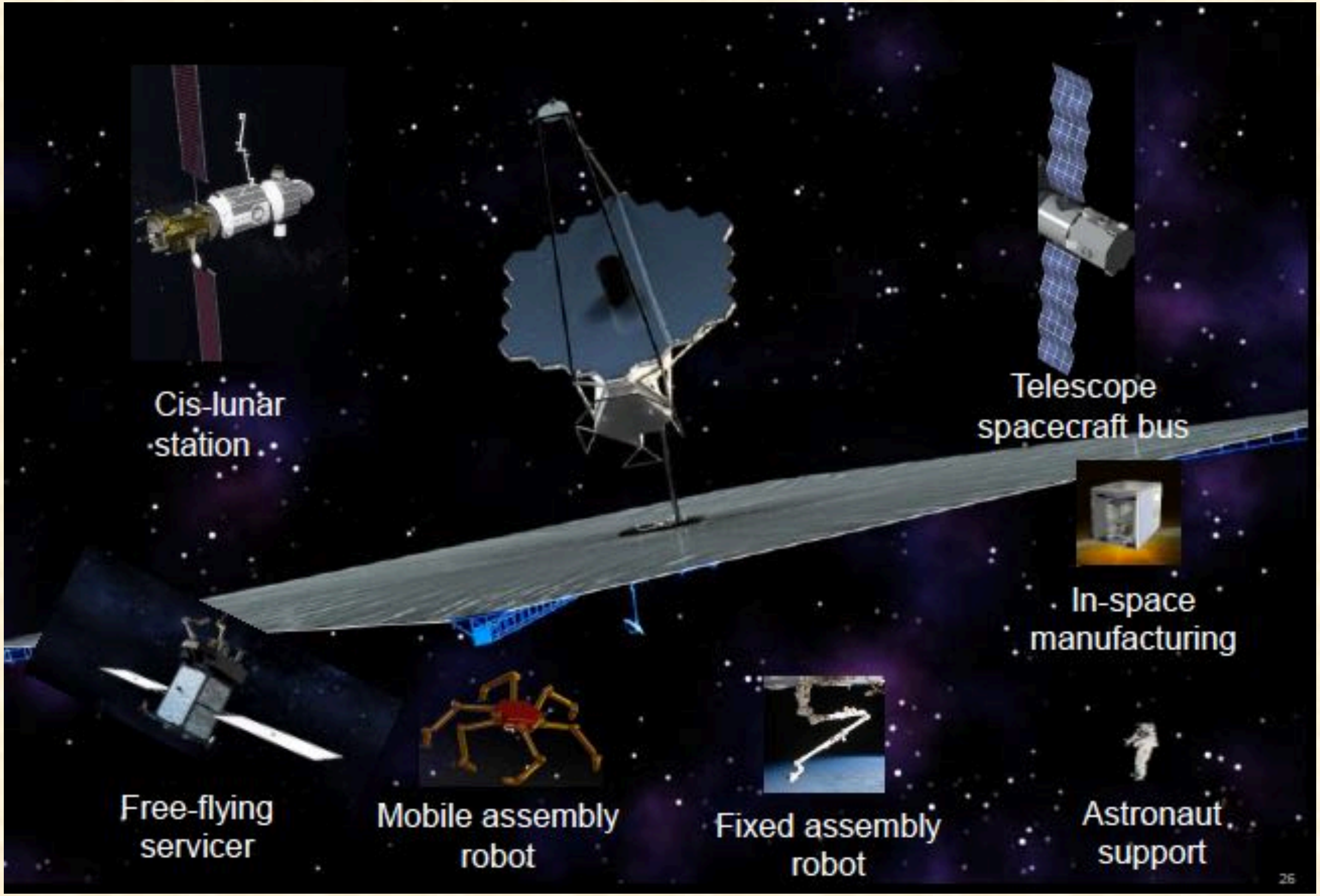




Images courtesy MDA (Paul Fulford) and Daniel Rey (CSA)

Adapted from FISO Seminar, 30 May 2018

A Large "Solution Space" for Observatory Servicing and Assembly



In-Space Assembled Telescope (iSAT) Study

Nicholas Siegler (Co-Chair)
Chief Technologist, Exoplanet Exploration Program Office, NASA JPL
Rudranaranyan Mukherjee (Co-Chair)
Robotics Technologist, NASA JPL
Harley Thronson (Co-Chair)
Physics of the Cosmos/Cosmic Origins Program Offices, NASA GSFC

Objective: ***When is it advantageous to assemble telescopes in space rather than to build them on the Earth and deploy them autonomously from individual launch vehicles?***

Deliverables:

A report submitted to NASA HQ Astrophysics and the Decadal Survey by May 2019 that assesses

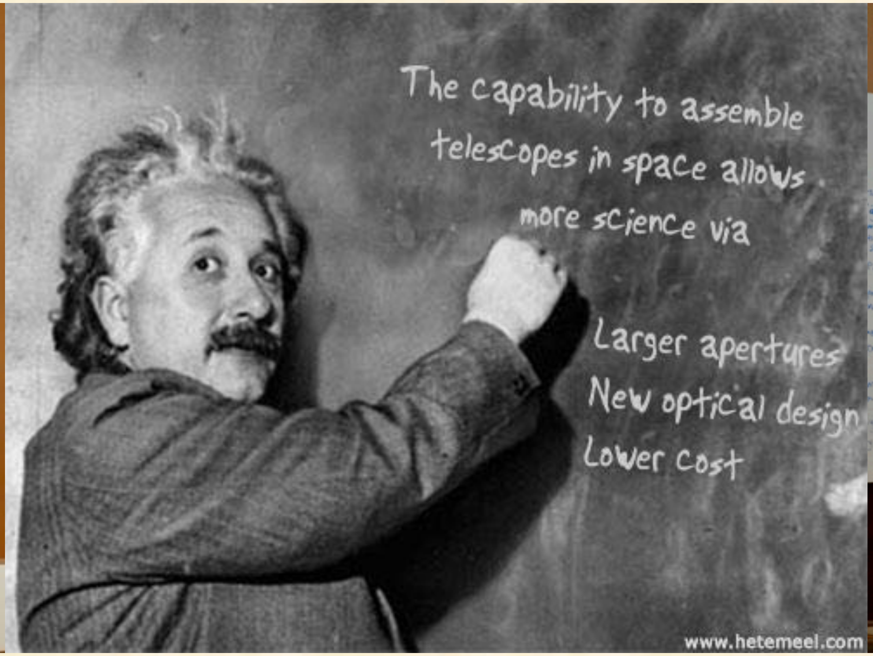
1. the telescope aperture at which in-space assembly is necessary (*an enabling capability*)
2. the telescope aperture at which in-space assembly is cheaper or lower risk with respect to traditional launch vehicle deployment (*an enhancing capability*)
3. the important factors that impact the answers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

Info tomorrow on recent workshops and trade studies:
Servicing and Assembly: Enabling the Most Ambitious Future Space Observatories
(Paper 10698-75)
Ron Polidan *et alia*, Thursday, June 14, 4:30 – 4:50 pm

Questions?

Selected Images From FASST-Organized iSA Trade Study (5 – 7 June at Caltech)

David Miller (MIT)



Early Adopter

John Grunsfeld (GSFC)

References and Additional Reading

Future Assembly/Servicing Study Team (FASST): https://exoplanets.nasa.gov/exep/technology/in-space-assembly/

Future In-Space Operations (FISO) Seminar Archives: http://fiso.spiritastro.net/archivelist.htm

Goddard Memorial Symposium (RHGMS) 2018 Presentations: http://astronautical.org/events/goddard/

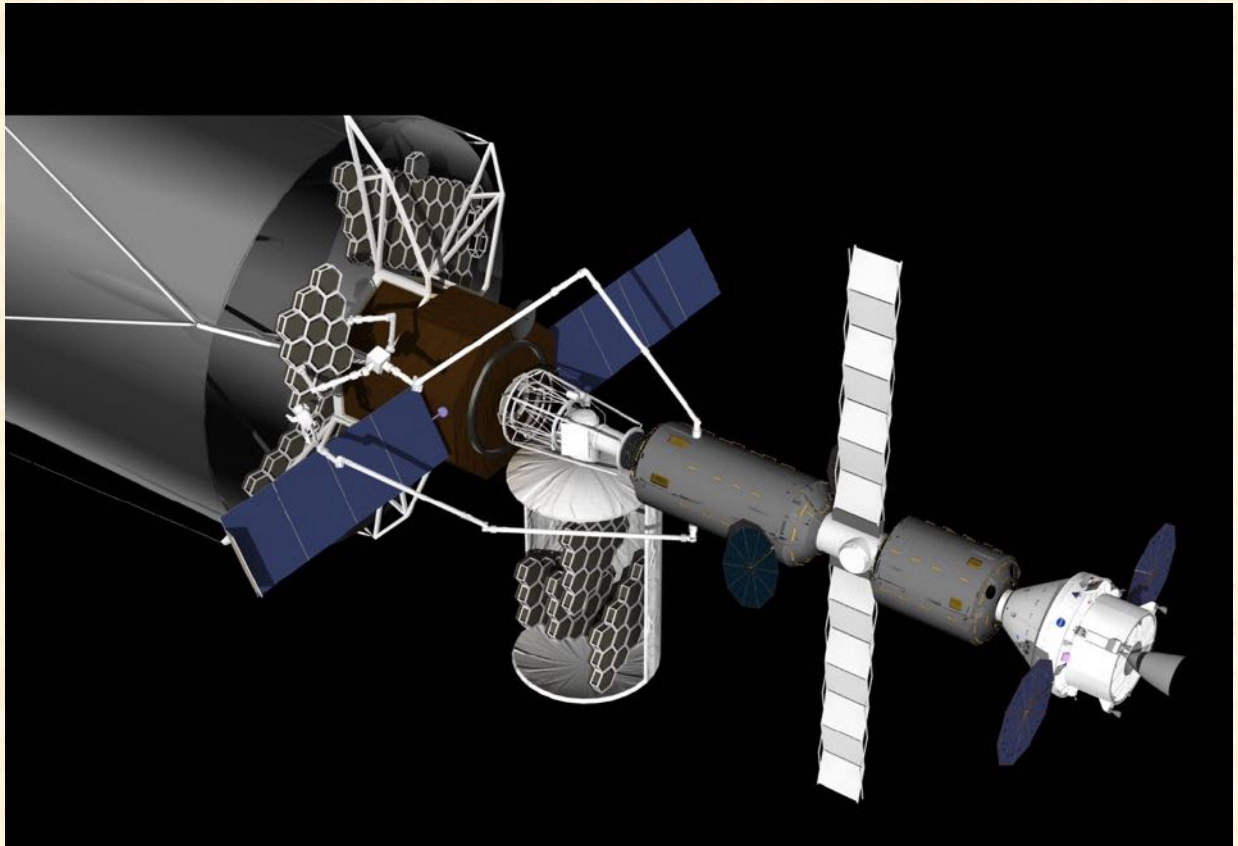
Backup/Additional Information

Potential Capability Needs of the Gateway

Proximity operations:
Docked during assembly?
Not docked during servicing?

Autonomous and dexterous external robotic arms capable of assembling and servicing

Berthing points for unpressurized cargo containers



NASA GSFC Concept for Gateway-based Telescope Assembly (2015)

Telerobotic operations from both Earth and the Gateway

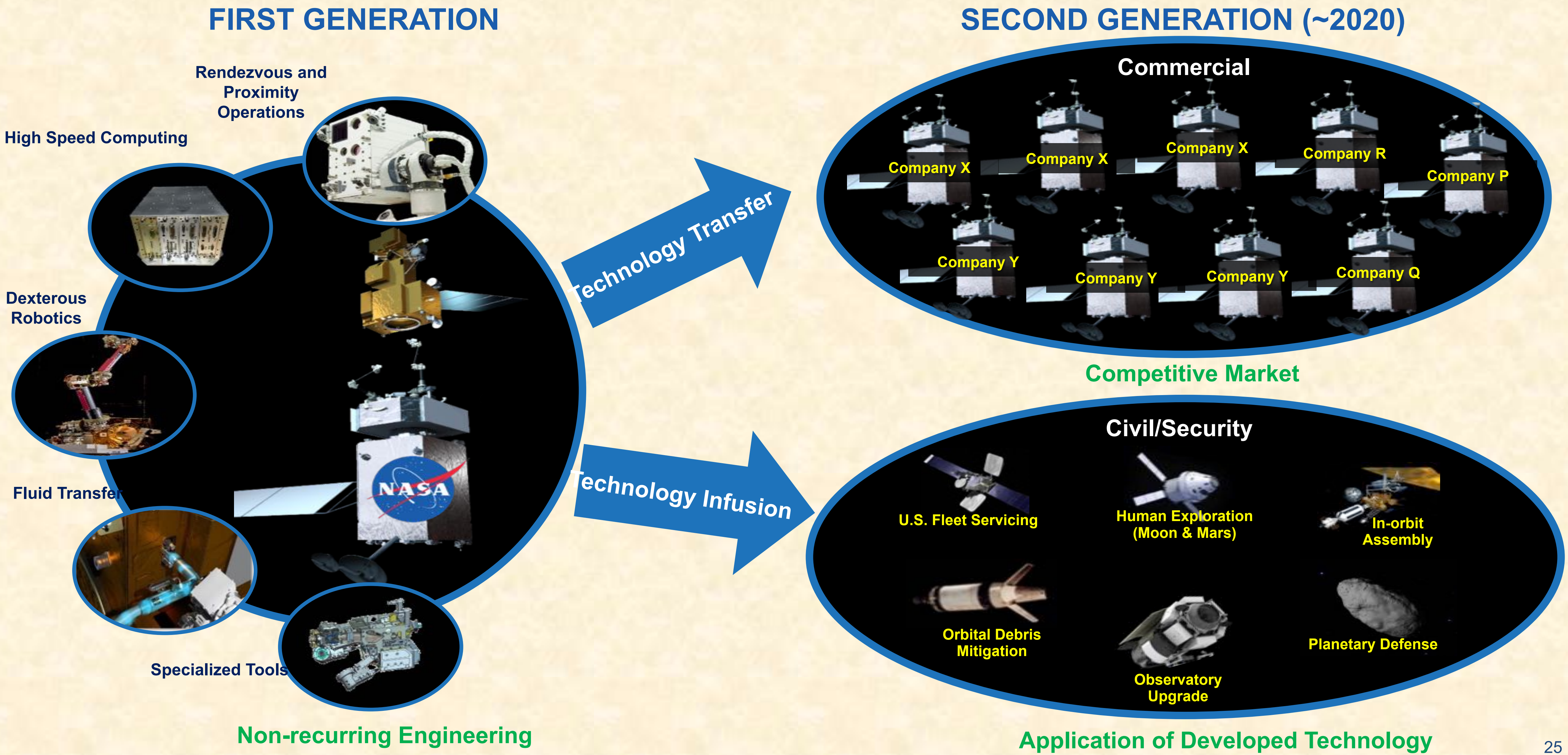
Astronaut EVAs

Defined power, propulsion, attitude control

Quiescent environment

Photogrammetry capabilities

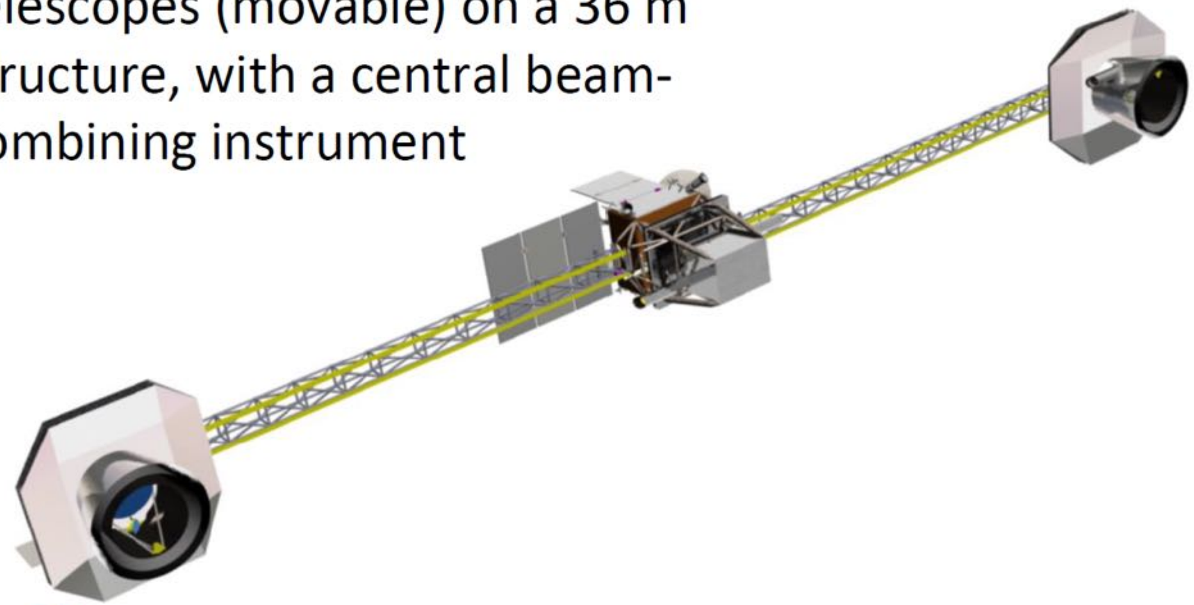
NASA Technology Transfer Enables a Robust Servicing Industry



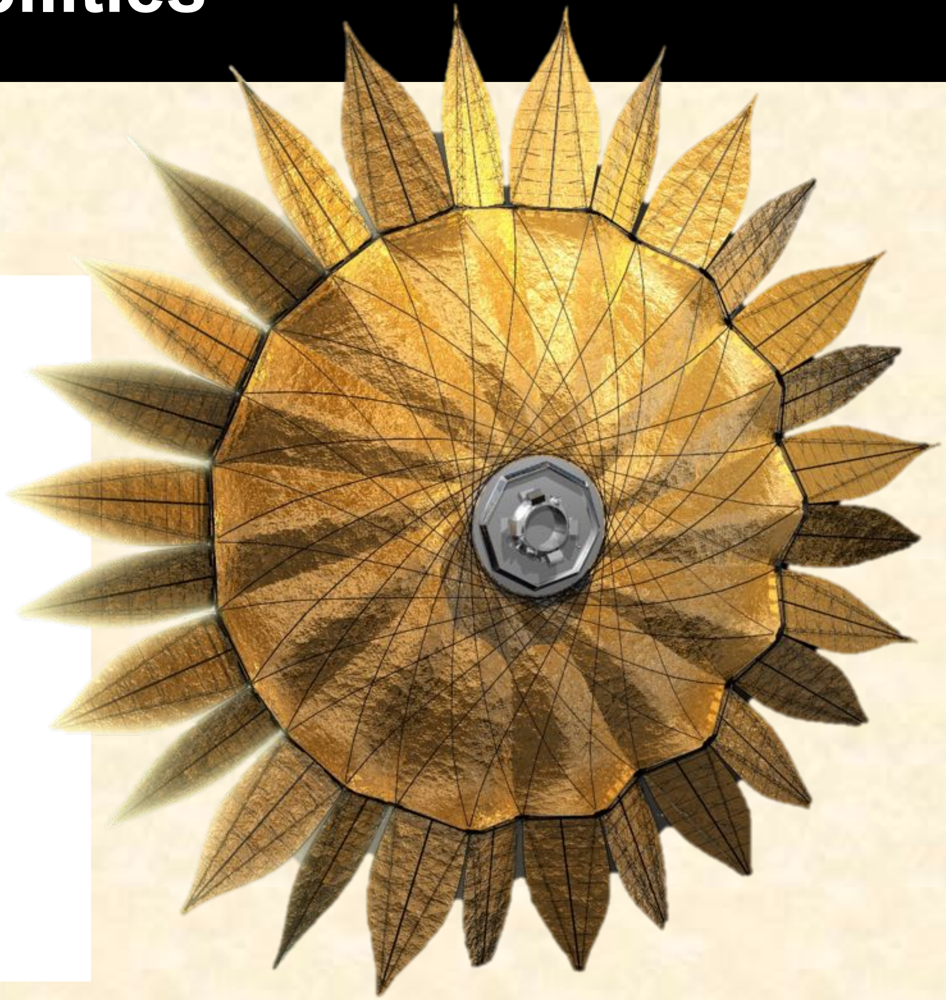
Other Spacecraft Assembly Possibilities

Interferometers

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



SPIRIT, David Leisawitz (NASA GSFC)



Starshades

Starshade deployed to block light from central star, allowing orbiting exoplanet to be observed.

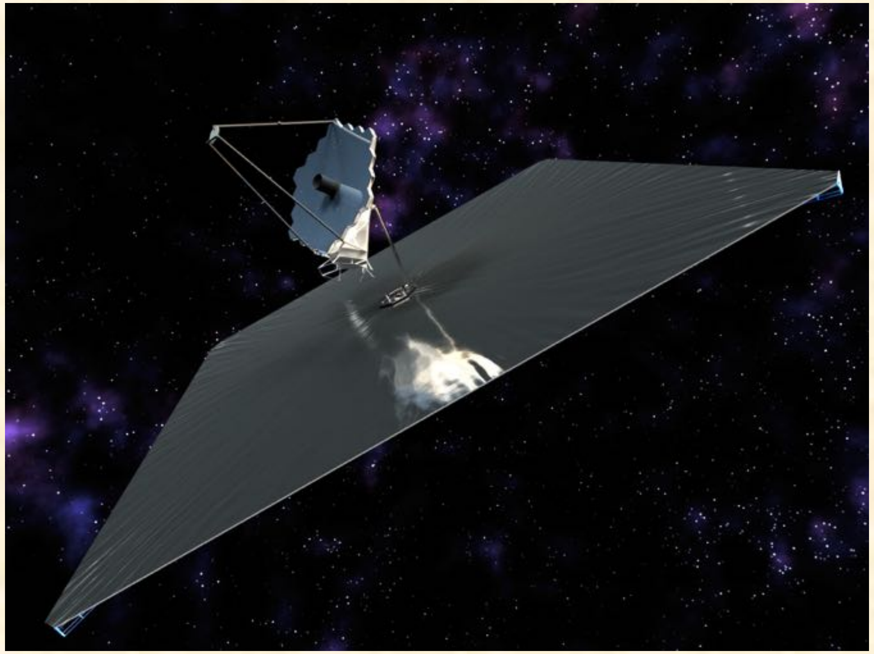
NASA/JPL/Caltech

Summary: Assembly of Extremely Large Telescopes in Space

- **Expansion of humans and their capabilities beyond LEO: robots and the Gateway**
- **Progressive expansion of human/robotic capabilities**
- **Feed forward of technologies**
- **Breakthrough science: the very early Universe, *Are we alone?***

HEAVY LIFT, LOW-COST MEDIUM LIFT
DEVELOPMENT IN ROBOTICS
HABITATS & AIRLOCKS
EVA & MOBILITY
TOOL & MANIPULATORS
ON-BOARD METROLOGY
SEGMENTED MIRRORS
STANDARD INTERFACES
LOW-THRUST PROPULSION

INPUT CAPABILITIES



DEEP-SPACE HUMAN OPERATIONS
HUMAN/ROBOTIC INTERACTIONS
MODULAR ASSEMBLY
SCALABLE ARCHITECTURES
LOW-THRUST DELIVERY
SPACE OBSERVATORIES
BREAKTHROUGH SCIENCE
NATIONAL SECURITY

OUTCOMES/ FEED FORWARD

RSGS Evolution: expanded capabilities, lower costs

LOGISTICS

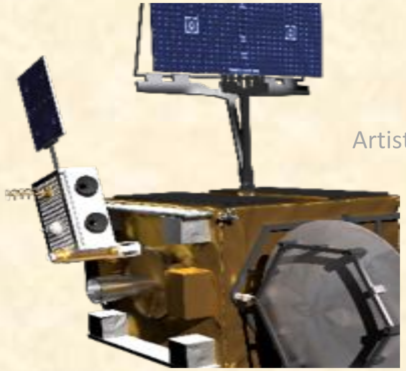
CONSTRUCTION

First robotic capabil
in GEO

Artist's Concept

Artist's Concept

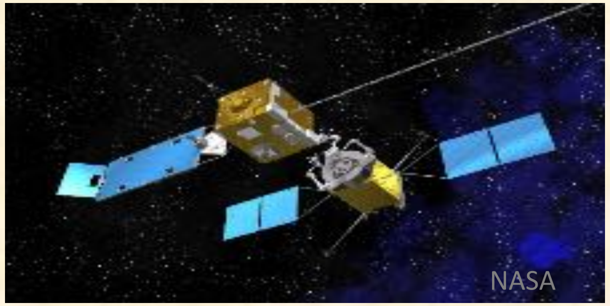
POD



Artist's Concept

OAC Capability

First steps in GEO logistics



Fully automated space logistics

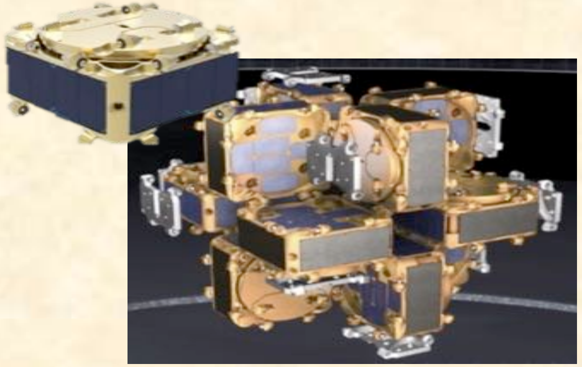
REPAIR ◆ *REPOSITION* ◆ *INSPECT* ◆ *AUGMENT*

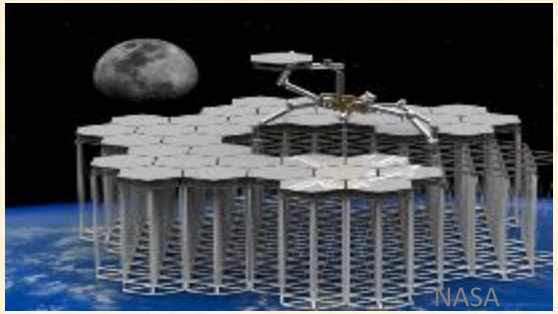
Technology development and investment

Expanded coverage, new tools, experiments

Modular spacecraft with on-orbit replaceable units

Large apertures, structures, and bases





Adapted from Roesler (FISO seminar; May 2, 2018)