Segmented or Monolithic Primary Mirror Considerations for Habitable Worlds Observatory

Lee Feinberg
JWST Telescope Manager and Optics Lead / HWO TAG Co-Chair
NASA Goddard Space Flight Center

National Academy of Sciences Committee on Astronomy and Astrophysics
13 October 2023

Thank you to Michael McElwain, Mike Menzel, Aki Roberge, Breann Sitarski, Chris Stark, Manuel Quijada, and Phil Stahl (all NASA) for material and discussions

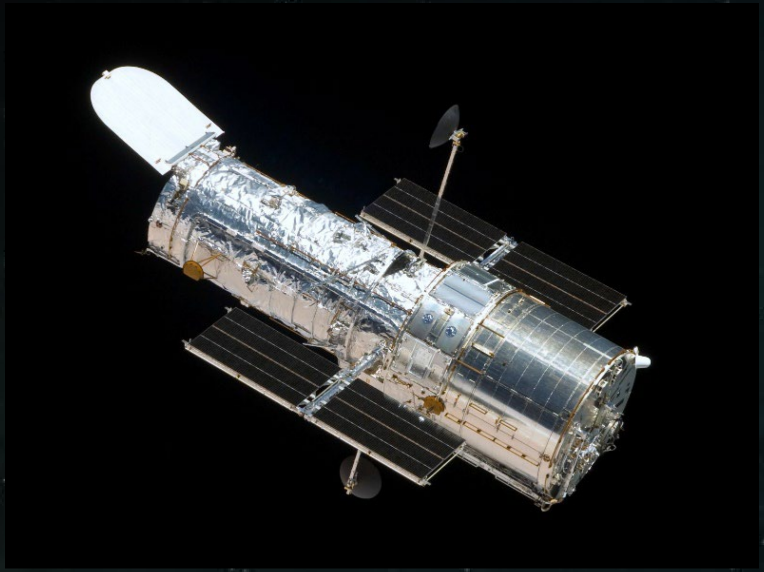
Introduction

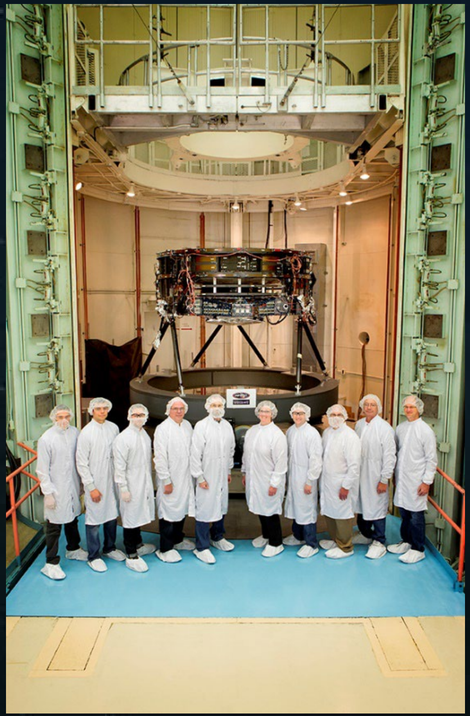
- Addressing segmented vs. monolith for HWO thoroughly would require details that are beyond what can be presented in a short public presentation.
- This presentation will focus on key considerations at a level that can be discussed in this forum.
- This presentation is based on input (and review) from many experts but ultimately is my own assessment.
- For space telescopes, the "devil is in the details". The details cover the entire observatory and there were many lessons learned from JWST and RST that are not well appreciated and difficult to summarize in a short presentation.
- This is not just a mirror issue but encompasses the space observatory system

KEY DISCRIMINATORS

	ULE or Zerodur Monolith	Thick Borosilicate Monolith	Segmented ULE or Zerodur
Compatible with both large fairings in devpt (both New Glenn and Starship)	↓	↓	↑
Low CTE (ultra thermal stability)	↑	↓	↑
High stiffness (insensitive to dynamics, lurches from the back)	↓	↑	↑
Compatible with enhanced LiF FUV coating (to 100nm)	↓	↑	↑
Can work with 10^10 contrast, off axis	↑	↓	↑
Allows for flexibility on aperture size	↓	↓	↑
Stepping stone to future larger telescopes	↓	↓	↑

History of Large (>1m) UVOIR Space Telescopes





Hubble Space Telescope

11,600 kg
Diffraction limited at 0.5 μm (post correction)
2.4 m Corning ULE Glass mirror
293K ± .1K
Space Shuttle

James Webb Space Telescope

6310 kg
Diffraction limited at 0.9 μm (reqt 2 μm)
6.5m semi-rigid Be segmented mirror
30-55K ± .15K (passive)
Ariane 5

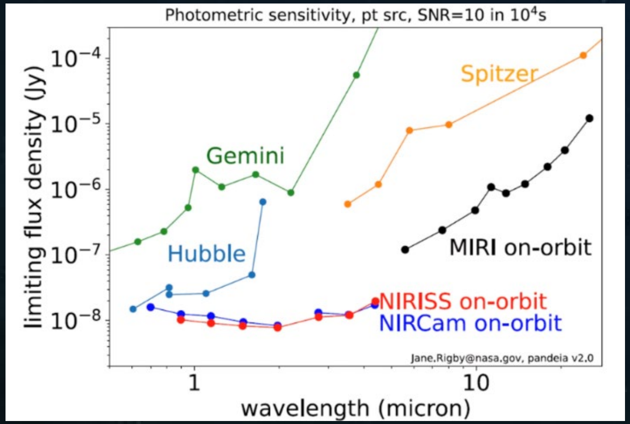
Roman Space Telescope

Mass Allowable: 10,000 kg
Diffraction limited at ~1.2 μm
2.4m Corning Ultra Low Expansion (ULE Glass) mirror
Mirror temp 265K ± 0.001K (active control)
Falcon 9H

JWST's Science Performance is Exceptional

- JWST has higher spatial resolution and is order(s) of magnitude more sensitive than previous space telescopes.
- While the science requirements were very ambitious, the measured science performance on-orbit is even *better* than expected across the board – spectacular performance.
- Image quality **2x as sharp as requirements** and more stable
  - ~65nm rms or diffraction limited at ~0.9µm, compared to a requirement of 150nm rms).
  - Wavefront stability is approximately 14nm RMS over two weeks vs. 50nm RMS EOL requirement
  - Pointing and guiding are 7x better than EOL requirements (<1mas image motion, compared to a top level requirement of 7mas EOL).
- Throughput of the telescope and instruments is better than requirements, almost across the spectrum.

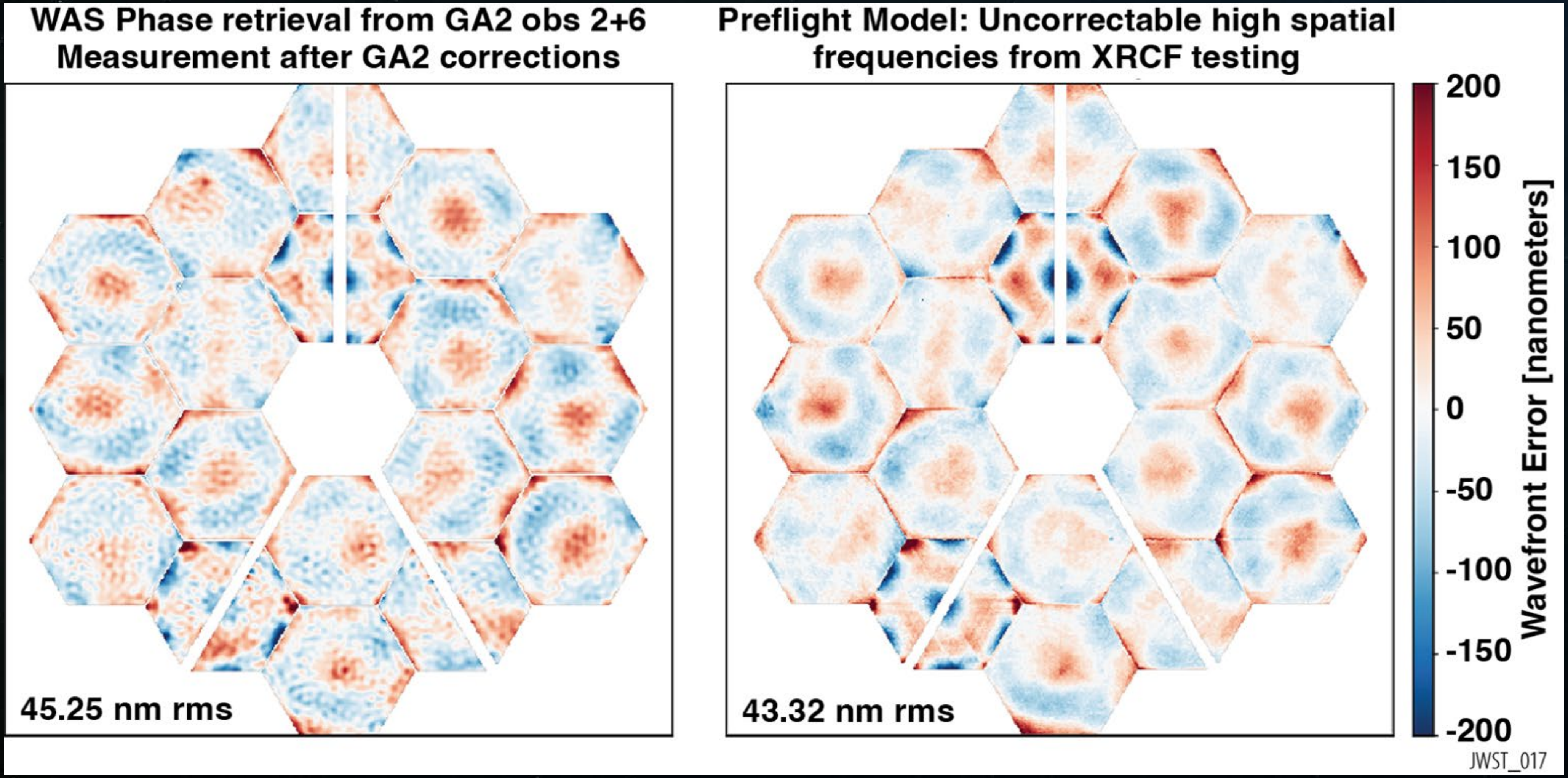
Webb's First Deep Field



Cosmic Cliffs in the Carina Nebula

Rigby, McElwain, Perrin, et al. 2023 PASP

JWST Mirror Segments Performed as Predicted in Space demonstrating that Semi-rigid Segmented Mirrors can be modeled and built



NB: WFE values reported for the primary mirror segments only.

McElwain, Feinberg, Perrin, et al. 2023 PASP

Habitable Worlds Observatory (HWO)

Observatory Drivers (to be reviewed by START/TAG):

- OTE Aperture ~6 m inner diameter
- 0.3 mas line of sight (LOS) stability
- Diffraction limited image quality at 0.5 μm
- Operating temperature of -30°C to 20°C
- Enhanced UV performance, goal of 100 nm cutoff (Lyman UV lines for H2 and CO)
- Slew times < 60 min for 90°
- Thermal control ~ mK
- Compatibility with future launchers (Blue Origin New Glenn, NASA SLS, Space X Starship)

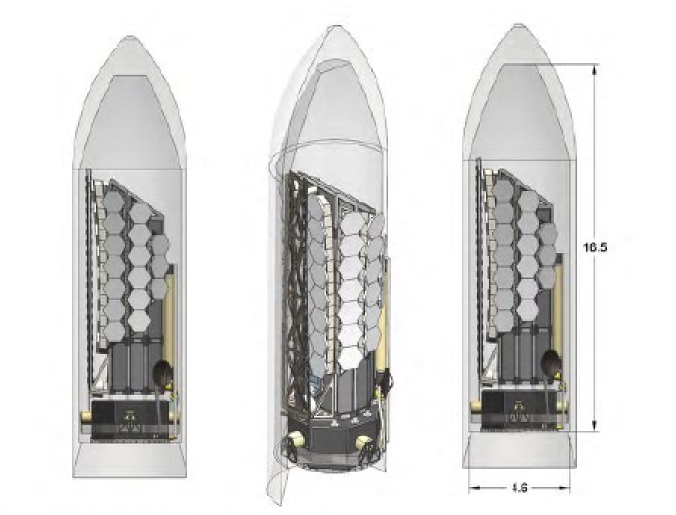
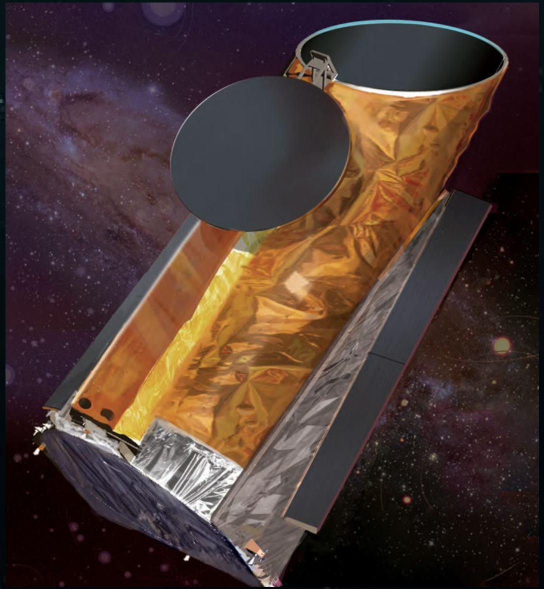


Figure 10-8. *LUVOIR-B in a "conventional" 5-m fairing*

LUVOIR-B:
- 8m outer diameter (6.7m inner diameter)
- Segmented mirror
- Could fit in 5m fairing
- ULE as baseline mirror

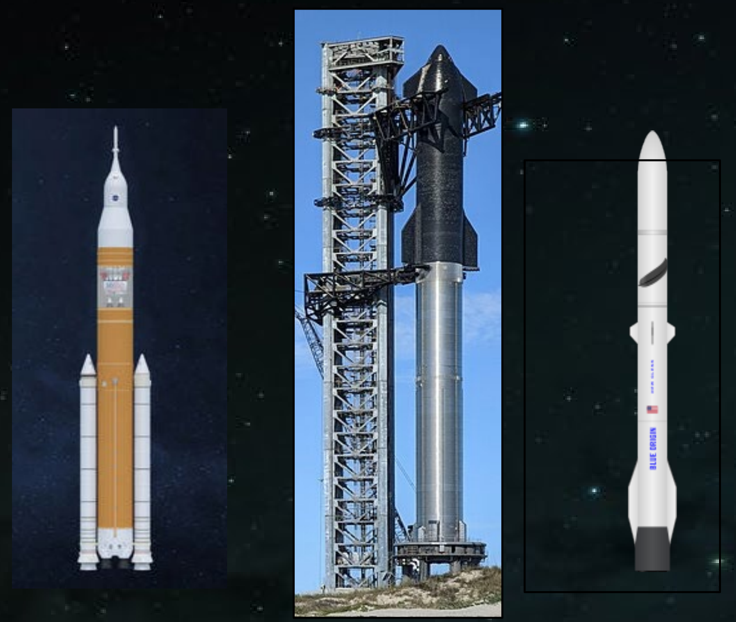
HabEx:
- 4m outer & inner diameter
- Monolithic mirror
- Zerodur mirror
- Picometer stability and starshade



Habitable Worlds Observatory (HWO)

- HWO is a .5um diffraction limited telescope optimized for both high contrast (10^{10}) Exo-earth studies and transformative astrophysics including FUV spectroscopy (likely goal of 100nm-2.5um)
  - Operational temperature (HabEx and LUVOIR designs brackets -30°C to 20°C and we expect somewhere in that range) – colder temperature shifts thermal emission farther into NIR. Cold mirrors require special consideration in mounting/flexures/strain/polymers.
  - Aperture size (roughly 6 m inner diameter, TBR, largest lever on yield to address Eta_Earth uncertainty)
  - Enhanced FUV coatings needed to achieve 100nm cutoff
  - Launch expected in 2040's, so need a rocket to be available at that time
  - Expect baseline to include a coronagraph with ultrastable observatory
    - Builds on the Roman Coronagraph experience and both LUVOIR and Habex studies
- Key enabling technological challenges are:
  - Coronagraphs to achieve 10^{10} raw contrast over roughly 20% bandpass (few x 10^{11} after post-processing)
  - Ultrastable observatory – dynamic, thermal, relaxation/lurch over temporal bandpasses defined by active controls

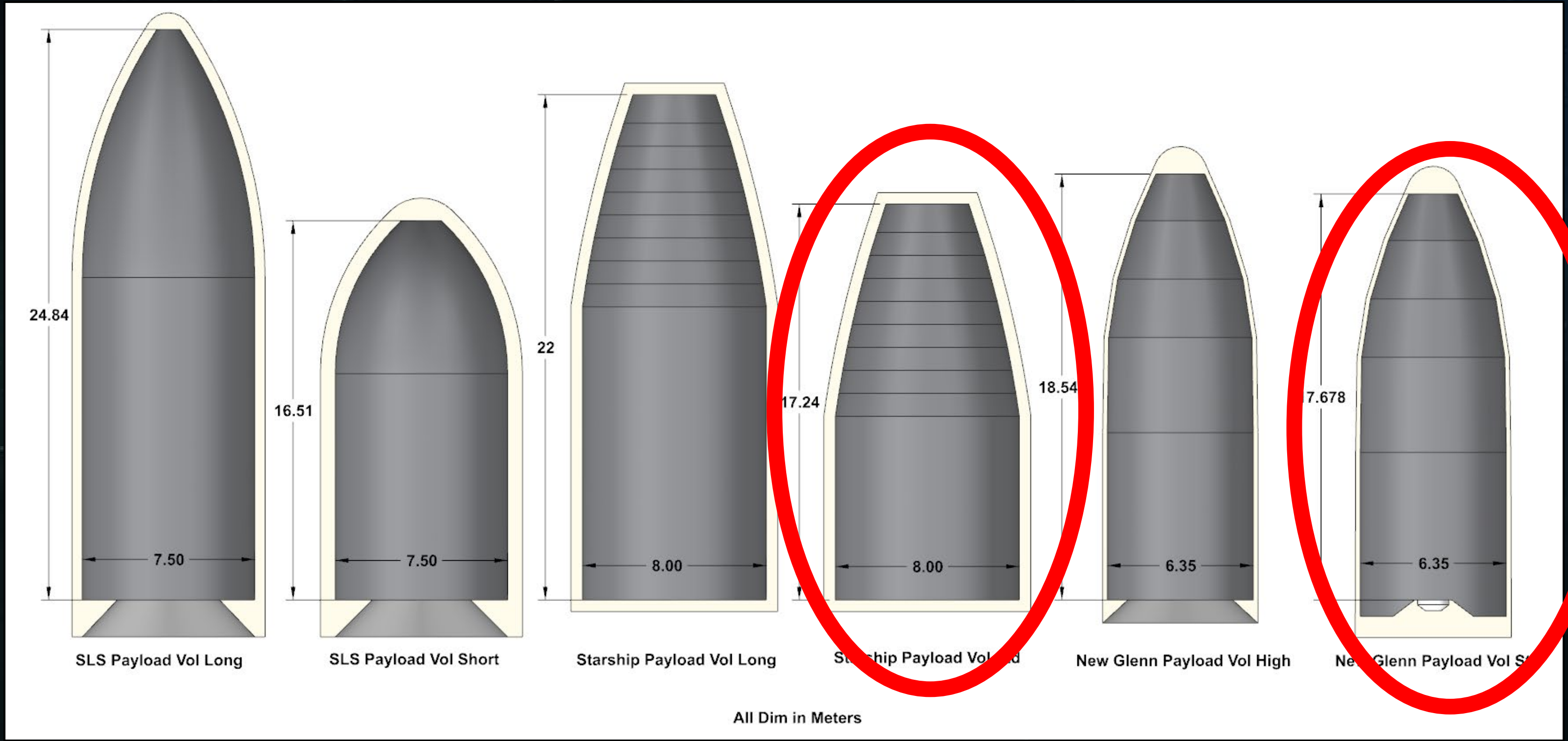
Launcher Mass and Volume Capabilities



NASA
Space Launch System

Space-X
Starship

Blue Origin
New Glenn



Roman Space Telescope started being compatible with 3 rockets. Only 1 was ready when Falcon 9H chosen.

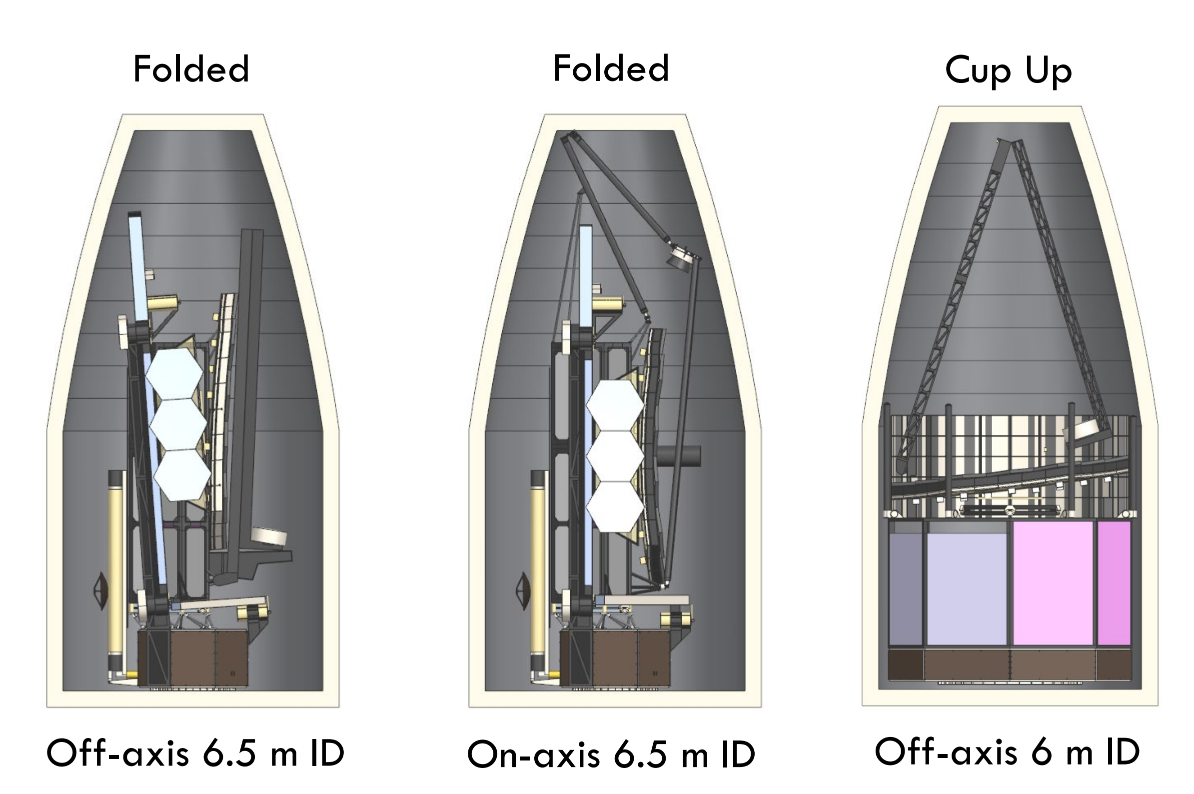
Fitting in both the New Glenn and Starship fairings in development mitigates risk.

Key issue is that rocked is needed in 20+ years.

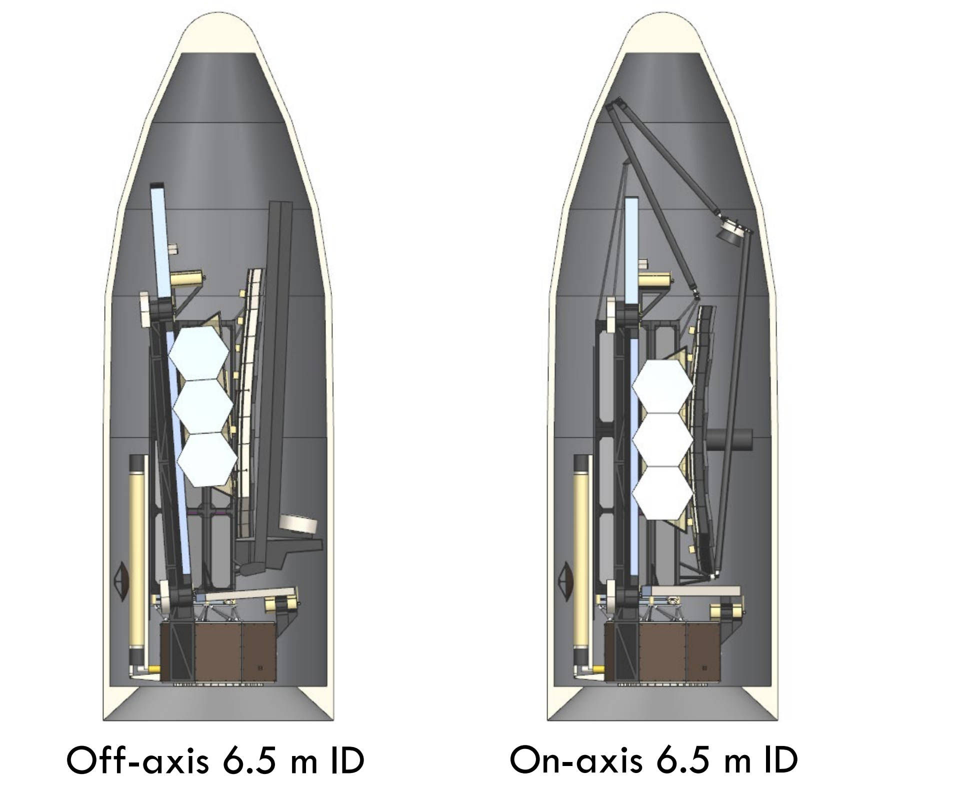
Launcher	Mass to L2 (kg)	Notes
Space-X Starship	100,000	Starship will require re-fueling in low earth orbit (and a fuel depot filled with multiple launches). Refueling adds risks like contamination, environment, needs to be economical to be viable in 2040s.
NASA Space Launch Systems (SLS)	44,300	Not currently building a large fairing.
Blue Origin New Glenn	15,000	First launch planned for 2024. More mass capability TBD.

Example notional 6-m concepts (Off-Axis) with Fairings in Development

Space X Starship Standard



Blue Origin New Glenn

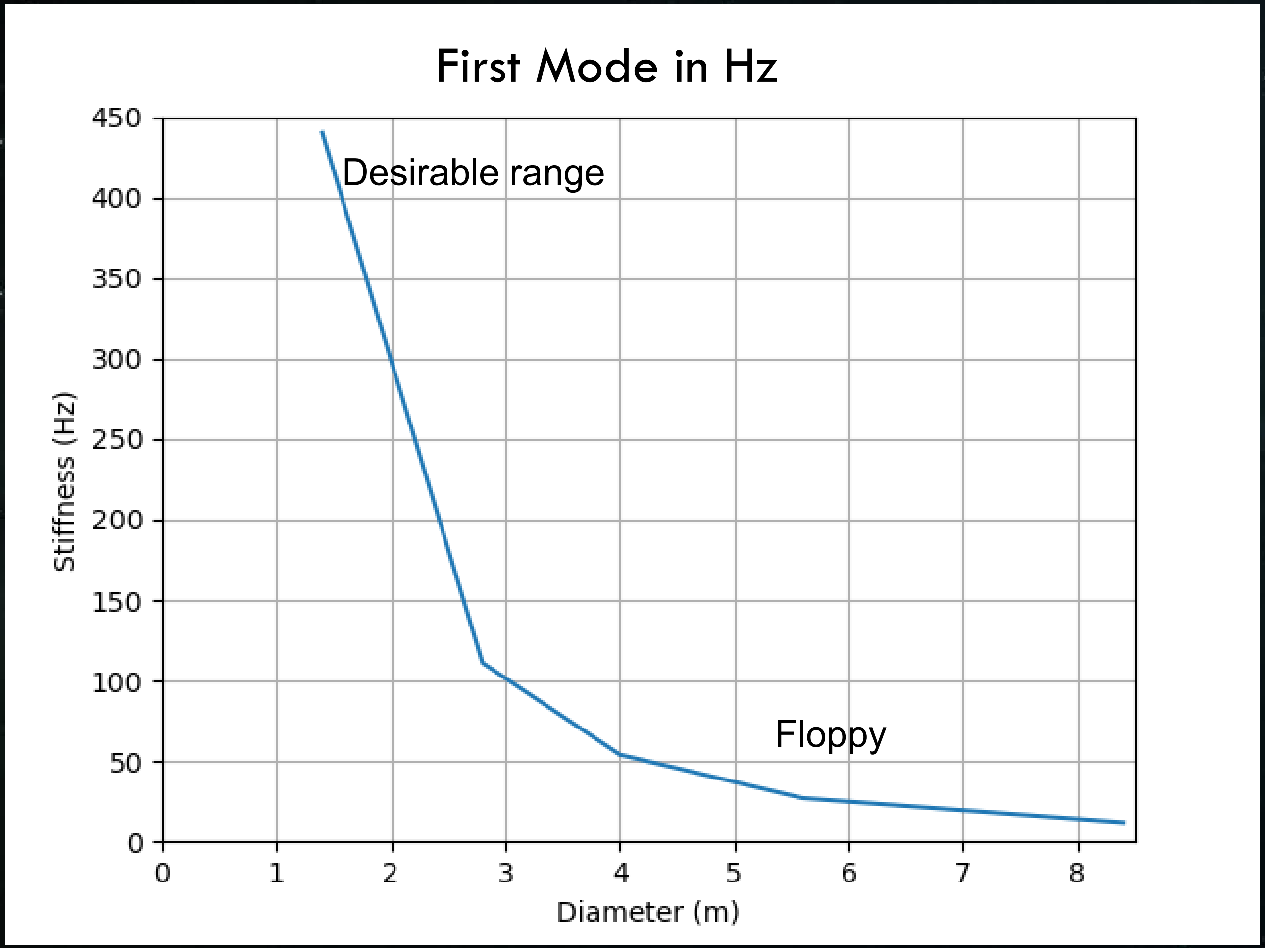


- Segmented telescopes >6.5m fit in either New Glenn (folded) or Starship (folded or cup up)
- A 6.5m off axis monolith only fits in starship

Coating Complexity

- Coatings over large areas are inherently challenging – goal here is high reflectivity and uniformity for both coronagraphy and FUV
  - Complexity of chamber scales exponentially with diameter.
  - High-reflectance Enhanced FUV Al+LiF coatings protected with the atomic layer deposition (ALD) process have been produced ≤ 6” (0.15 m) optics; ≥ 1m-class substrates require larger reactors that do not currently exist.
- There are key reflectance uniformity requirements (within a single segment) that are harder to meet for larger substrates
  - Investment will be needed to develop large enough chambers to meet the expected HWO uniformity requirements.
  - Segment-to-segment variation of ~3% is tolerable for high-contrast imaging with a segmented aperture (J. Krist, JPL).
  - Larger chambers require exquisite contamination (including humidity) control.

Mirror Stiffness Scales Non-Linearly with Diameter



- A stiffer mirror is highly desirable to prevent mirror bending form dynamic inputs or from strain from back
- Example based on 15 kg/m^2 areal density, depends on mirror construction so notional.
- Can make a thicker stiffer mirror but mirror manufacturing for ULE and Zerodur limit thickness and thus stiffness.
- Borosilicate can be thicker depending on mass but would exceed New Glenn

MONOLITH CONSIDERATIONS

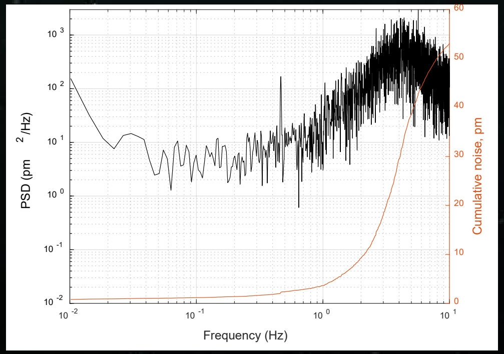
- Most studied solution for space ultrastability is the HabEx approach of using a large Zerodur mirror
  - Limited fabrication heritage in the US and minimal space heritage overall, provides thermal stability but limited dynamic stability due to thickness limitation.
- A high stiffness solution would be a large casted Borosilicate mirror
  - Borosilicate is high CTE near room temperature (roughly 1000x higher than ULE** and Zerodur at room temp implying needing 1000x better thermal control than RST which is state of the art)
    - Use of laser guide star has been proposed, but adds system complexities and risks
    - “Devil is in the details” operations, costs, verification
  - A stiff borosilicate mirror would only be compatible with SpaceX Starship (with refueling) due to mass and size and would not be scalable for the future
  - Achieving the many requirements of the observatory (UV quality, mounting, surviving launch, temperature environmental would be challenging and hard to demonstrate)

** J.H. Burge, T. Peper, and S.F. Jacobs, "Thermal Expansion of Borosilicate Glass, Zerodur, Zerodur M, and Unceramized Zerodur at Low Temperatures," Appl. Opt. 38, 7161-7162 (1999) - see Figure 3.

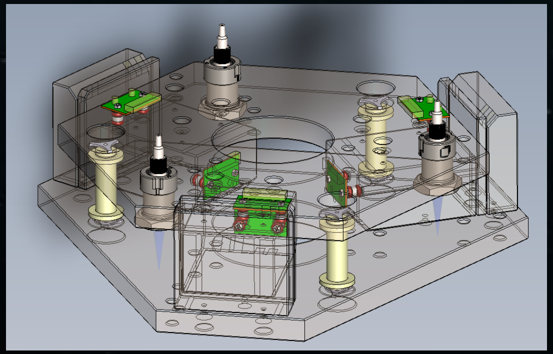
Segmented Considerations

- The mirror itself can be very stiff due to smaller size (scales non-linearly), backplane can be made stiff via depth
- The mount architecture, coarse actuator, wavefront sensing and control, error budgeting, alignment, gravity approach, metrology of segments, system level verification of telescope using the gravity sag, leverages JWST experience
  - JWST AMSD mirror was ULE and taken to TRL5, a mount design was also done
- Zerodur and ULE are both options
  - Zerodur has same ITAR and machining issues, ULE has a lot of heritage (eg, RST)
- Require edge sensors or metrology to measure segment to segment deviations (needs funding but progress being made)

Edge Sensor Demonstration
Ball Aerospace 1 DOF sensing and control
< 3 pm RMS from 0.01-1 Hz

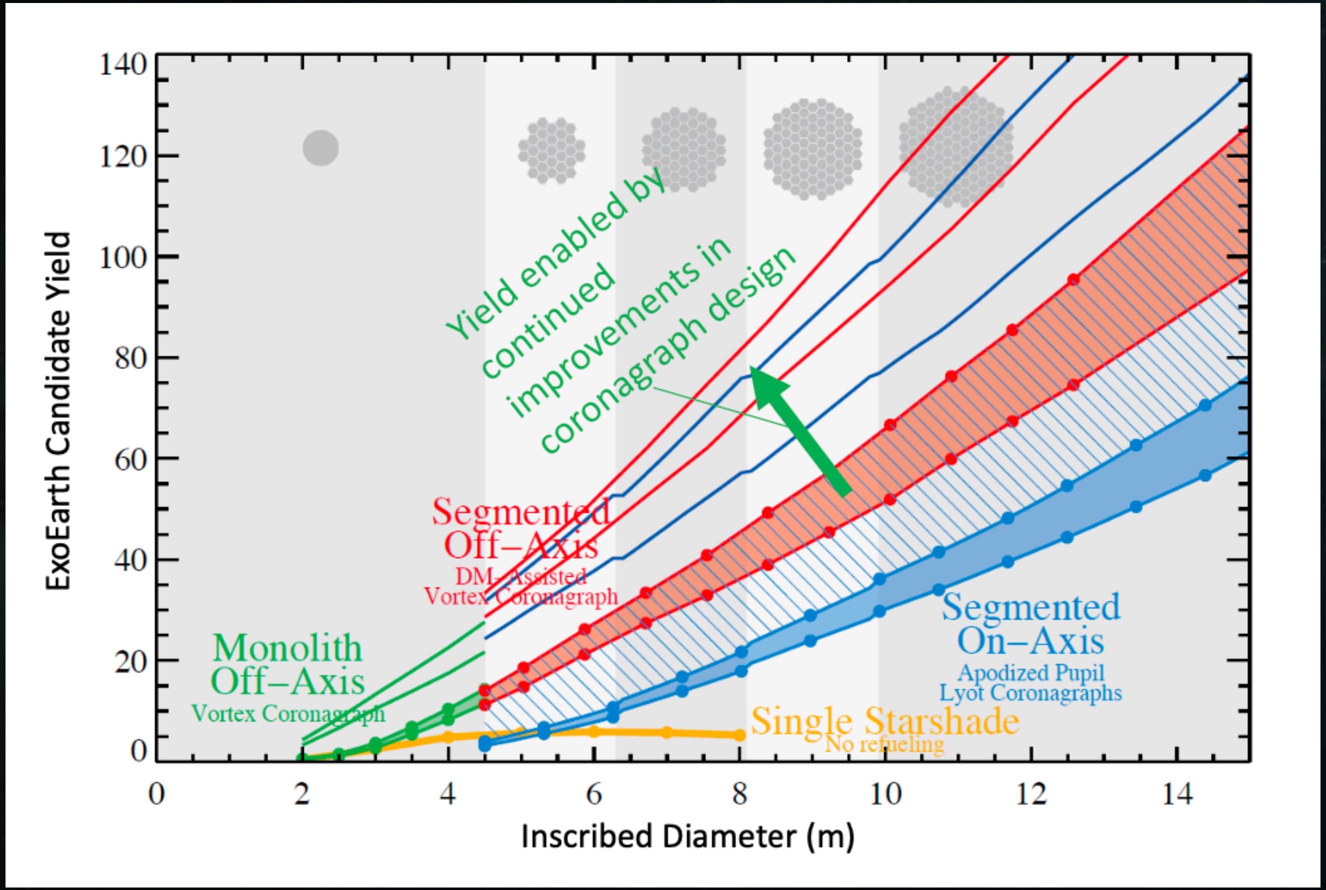


Segment Demonstration
Ball Aerospace 3 DOF sensing and control



High TRL substrate
L3 Harris Lightweight ULE mirror

Coronagraphs Can Accommodate Segmentation and Off Axis gives better yields



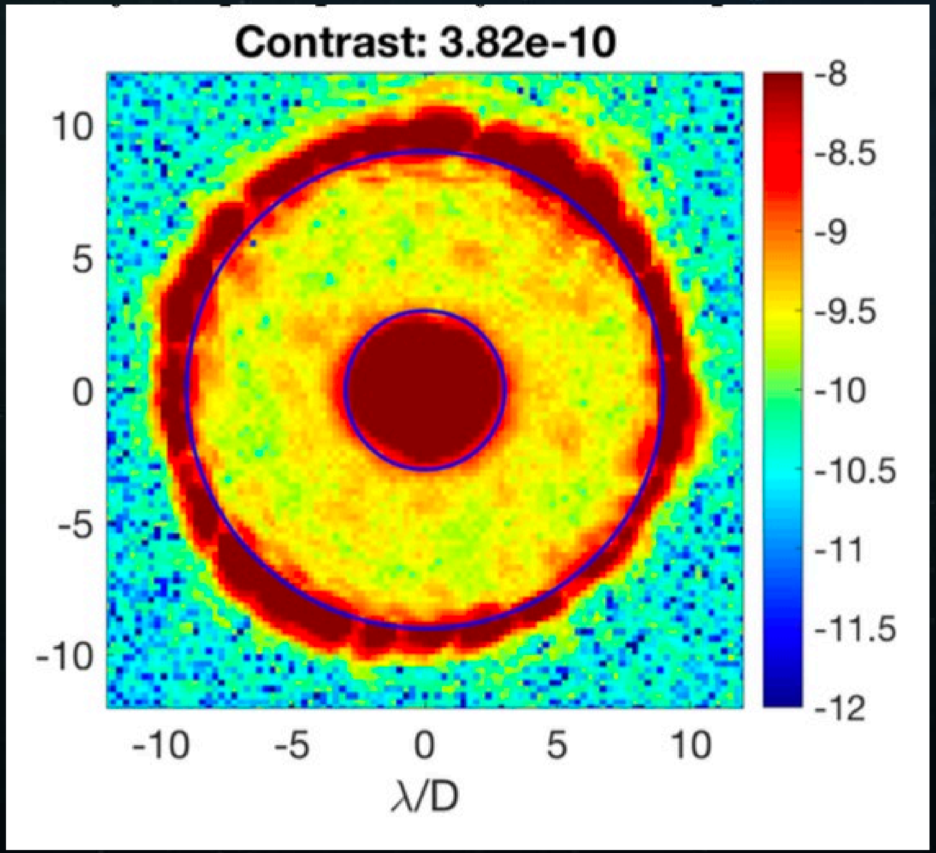
Belikov, Sirbu, Jewell, et al. 2021 SPIE

- Theoretical performance assessments found that the "performance of optimal coronagraphs does not strongly depend on aperture obstructions or segmentation."
- Yield does vary significantly with aperture size, which is a parameter that can help with margin and uncertainty in Eta_Earth

Coronagraphy with Monoliths or Segmented

- Segmentation can be compensated by coronagraph design with modest throughput reductions (Zimmerman et al., 2006, Nickson et al. 2022).
  - Need small gaps (6-8mm) which are feasible
- Demonstrations in the JPL High Contrast Imaging Testbeds focused on achieving high contrast over a broad bandpass for unobscured monoliths ($4x10^{-10}$ in a 10% spectral bandwidth).
  - Segmented demonstrations have only recently been prioritized but progress is being made (e.g., $4.7x10^{-9}$ contrast over 10% bandwidth, Riggs et al. 2022).
- Roman Space Telescope CGI instrument which works with struts and obscuration recently demonstrated $1.6x10^{-9}$ contrast at the instrument level and provides significant risk mitigation.
- Post processing with PSF calibration techniques potentially relax contrast requirements substantially (Guyon et al., 2022).

Unobscured monolith with 10% spectral bandwidth



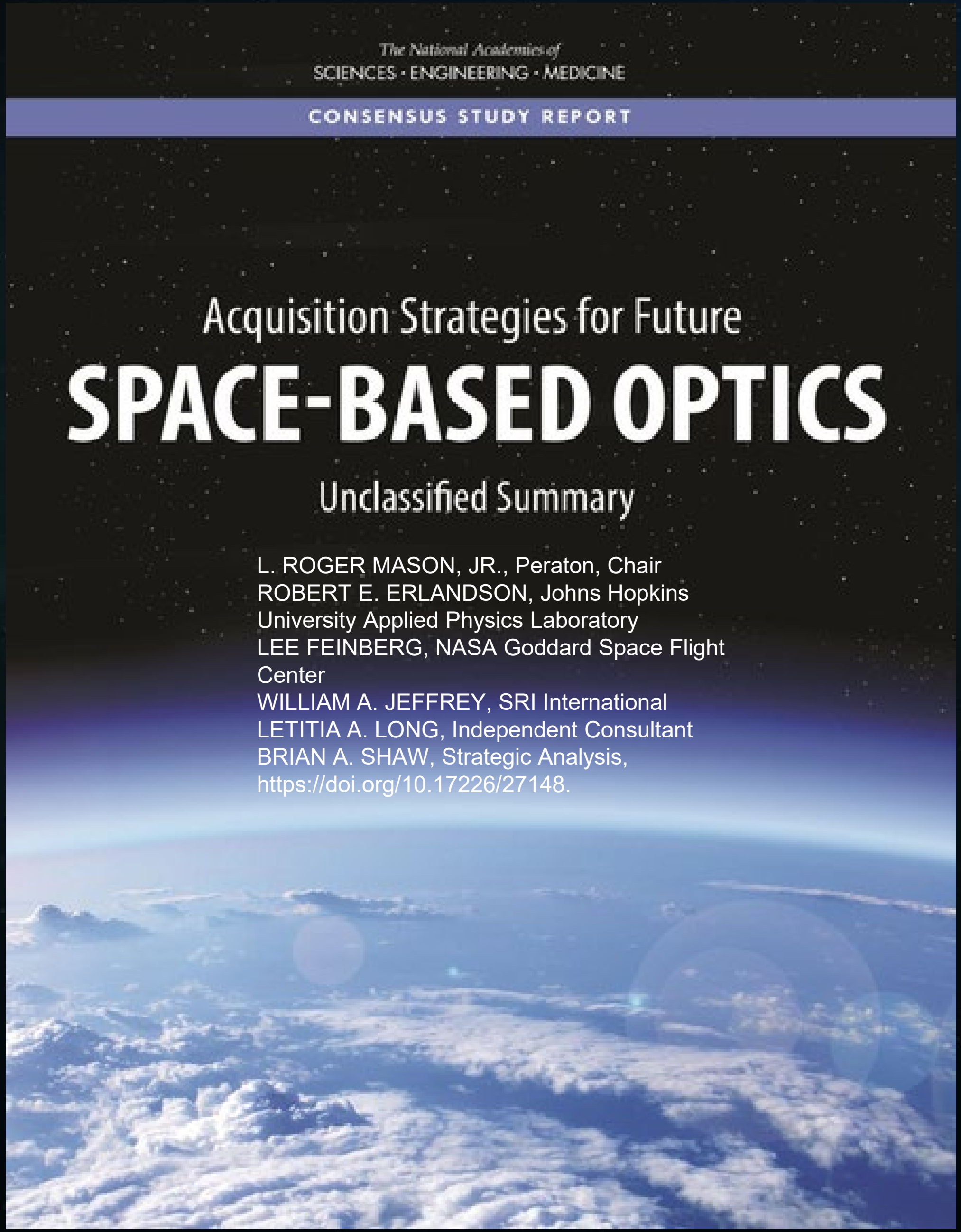
Seo, Patterson, Balasubramanian, et al. 2019 SPIE

Other factors

- Shipping JWST was a major challenge – JWST fit in a 5m fairing, substantial infrastructure for fairings of this size.
  - A folded architecture provides more options, monoliths may need to be shipped
- A large monolith that is picometer stable would likely be the single most expensive optic ever built
- A large monolith could have less parts, but that’s hard to assess in a way that consider details like launch loads. Moreover, this is not a major cost driver overall (instruments were the single largest cost on JWST)
- In general, monoliths are more at risk for damage on the ground or in space due to very unlikely micrometeoroids
- Fitting on vibration tables, acoustic chambers, and vacuum chambers favors a system that can fold up
- Aerospace companies that make flight mirrors (e.g., L3 Harris) are *not* facilitized for 6 m monoliths and facility costs could be quite large.

OTHER REFERENCES

- This CAA presentation was aimed at providing information at a summary level on the considerations of implementing a monolith or segmented primary mirror for the Habitable Worlds Observatory.
- A complete picture of the space telescope technological landscape is beyond the scope of this public assessment.
- This report and follow-on letters are another possible source
- Prioritization of funding requires holistically looking at the landscape and assessing risk



Final Thoughts

- There are limited funds to develop the critical technologies for HWO, funding backups and alternatives needs to be done based on holistic risk analysis
- Segmented solution provides a flexible, heritage based path with less uncertainty and path to future
  - Needs early dedicated funding

	ULE or Zerodur Monolith	Thick Borosilicate Monolith	Segmented ULE or Zerodur
Compatible with both large fairings in devpt (both New Glenn and Starship)	↓	↓	↑
Low CTE (ultra thermal stability)	↑	↓	↑
High stiffness (insensitive to dynamics, lurches from the back)	↓	↑	↑
Compatible with enhanced LiF FUV coating (to 100nm)	↓	↑	↑
Can work with 10^10 contrast, off axis	↑	↓	↑
Allows for flexibility on aperture size	↓	↓	↑
Stepping stone to future larger telescopes	↓	↓	↑

Thank You!

Backup

KEY RISKS AND MITIGATION

- The launch vehicle risk will not be retired soon. Even if a rocket works, it has to be operational in 20+ years implying some level of economic viability
  - Segmented approach compatible with multiple options best mitigates this risk.
- Eta Earth is a key science risk that can be best mitigated with flexibility on aperture size
- Contrast is a risk for both approaches, but more for segmented at this point
  - Mitigated by testbed work, post processing, modeling.
  - Significant technology overlap in what is needed in both segmented and monolith.
- Stability is a risk for both approaches
  - Overlap in what is needed for both approaches (e.g., build a 1-2 meter stable mirror).
- A real risk is studying too many architectures and spreading the limited number of resources too thin. Each implementation has to be studied for multiple parameters at the system level. See the initial list of design parameters that are likely to be studied.
- Cost and schedule risk is a major consideration overall.
  - Cost and schedule estimates are more reliable where there is a basis of estimate grounded in heritage rather an entirely new architecture which has large unknowns.

Aperture Size Is a Key Lever

Aperture size is the biggest lever for yield (number of Exoearths):

$$Y \propto D^{1.97}$$

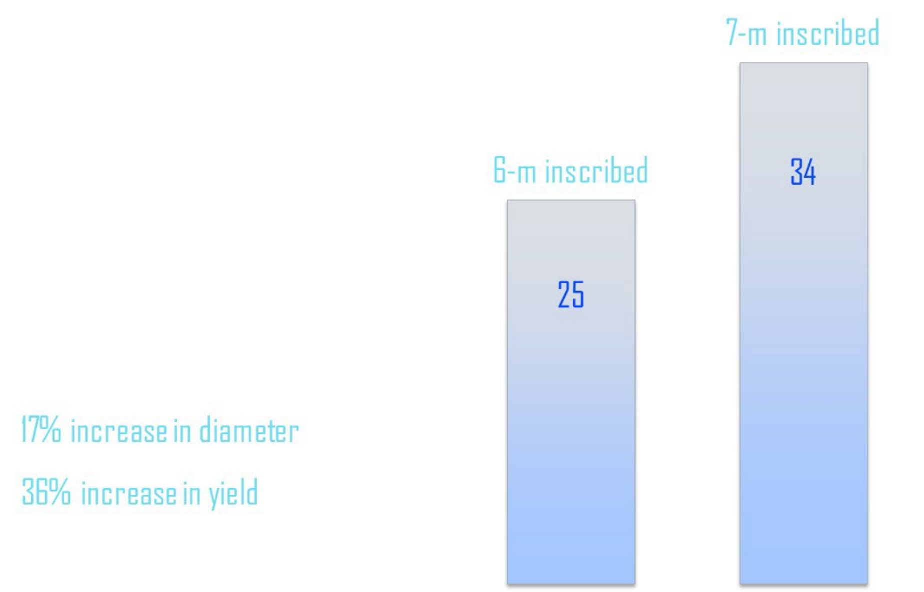
D = inscribed telescope diameter

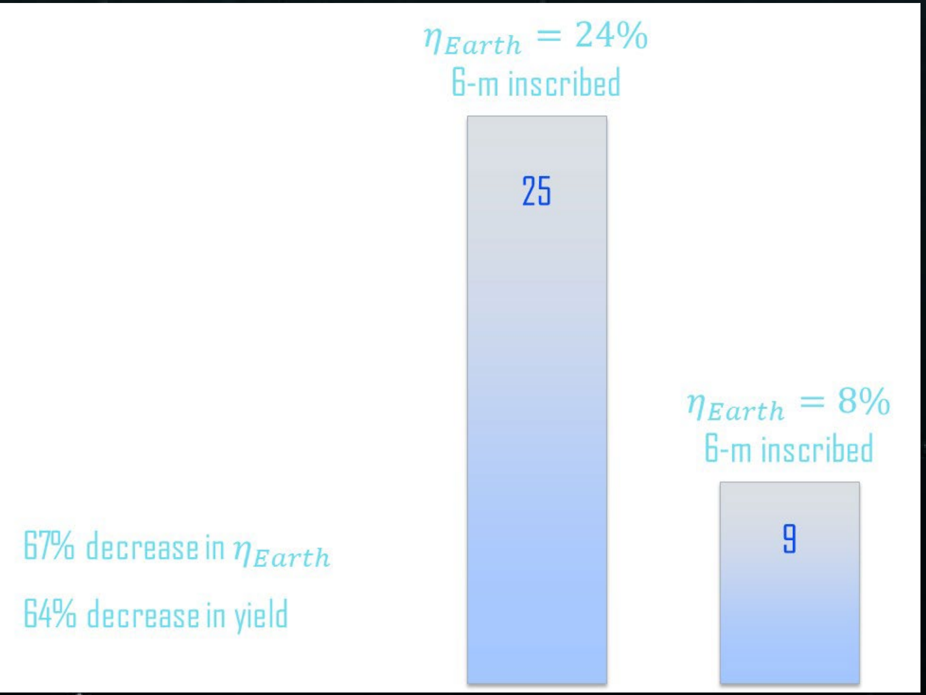
$$Y \propto (\eta_{Earth})^{0.96}$$

η_{Earth} = occurrence rate of habitable planet candidates

ExoPAG SAG13 value $(0.24^{+0.46}_{-0.16})$

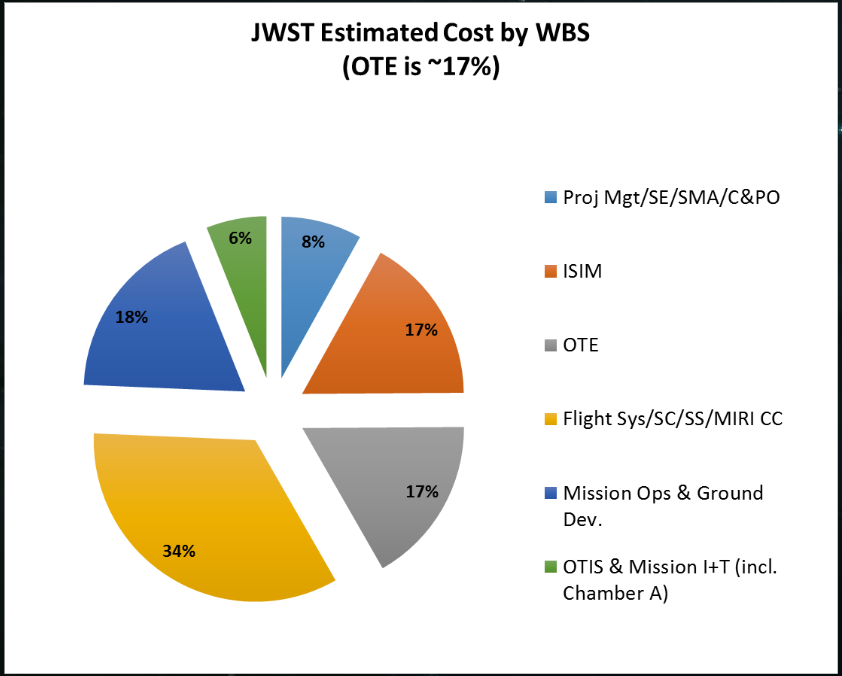
From Stark et al, 2014, 2015 and Roberge





JWST Cost

From experience on JWST, no single WBS drove costs. As can be seen below, the costs are spread across all of the WBS elements suggesting there is no single metric that can alone be correlated to costs.



From 2016, OTE completed in 2017 and ultimately was <15% of total cost, PM was <10% of total cost.

Science instruments were one of the largest costs in the end.

From "Breaking the Cost Curve", Feinberg et al, SPIE Proceedings

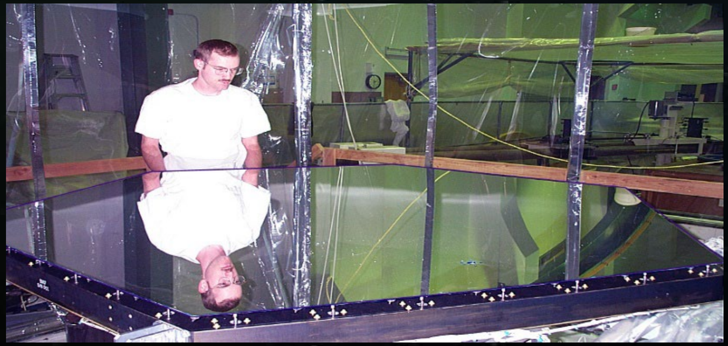
Includes full cost (contractor and government) for each WBS, does not include non-US contributions (launch vehicle and contributed instruments)

Flight systems includes Cooler, Sunshield

Acronyms:
SE=Systems Engineering
SMA= Safety/Mission Assurance
PO=Public Outreach
SC=Spacecraft
SS=Sunshield
CC=Cryo Cooler
OTE=Optical Telescope Element
ISIM=Integrated Science Instrument Module
OTIS= OTE+ISIM
I+T = Integration and Testing
WBS=Work Breakdown Structure

In the late 90's, early 00's, NASA did Fund Multiple high authority mirrors for Next Generation Space Telescopes

- 2 meters in diameter
- 2 mm thick facesheet
- 166 actuators



- NGST Mirror System Demonstrator and Advanced Mirror System Demonstrator made high authority mirrors – this approach was one of the selling points of the new "faster, better, cheaper" paradigm
- After funding several mirrors, JWST chose semi-rigid mirrors that only move in 6 degrees of freedom with radius of curvature (RoC) actuation (though it is expected RoC actuation will not be needed for HWO)
- None of these mirrors met specifications (or even came close)
- Facesheet stiffness, difficulty in scaling, actuator complexity were all factors…