SEGMENTED OR MONOLITHIC PRIMARY MIRROR CONSIDERATIONS FOR HABITABLE WORLDS OBSERVATORY

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National Academy of Sciences Committee on Astronomy and Astrophysics
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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.

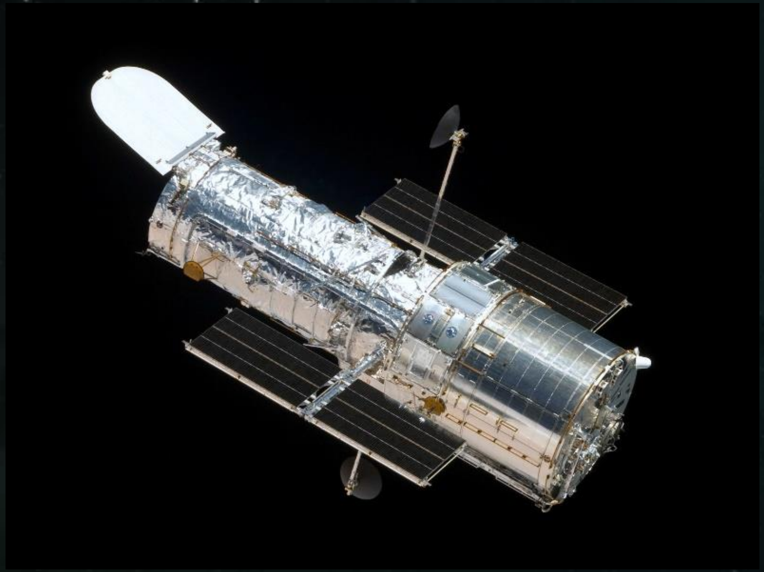
This presentation is based on input (and review) from many experts but ultimately is my own assessment.

This is not just a mirror issue but encompasses the space observatory system.

Bottom Line Up Front

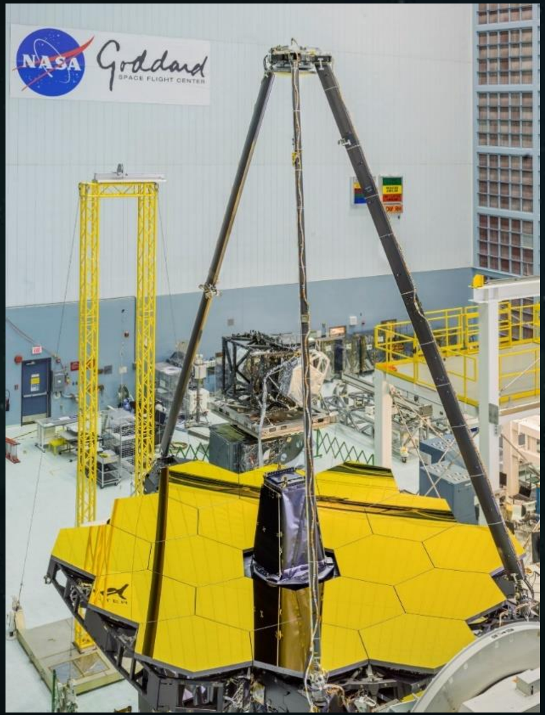
- An architecture that allows flexibility in future launch vehicle choice without major descopes greatly reduces risk.
- When assessing risks and costs, indirect factors such as launch vehicles, manufacturing, facilitization, and transportation are critical.
- Small segment gaps do not have a large impact on coronagraph performance though more testing is needed.
- Building a picometer stable telescope (over a control cycle) requires high stiffness, low coefficient of thermal expansion (CTE), and active controls.
  - JWST semi-rigid mirror approach is demonstrated in space
- Based on work to date, it is only feasible to meet HWO's stringent mirror coating goals with smaller optical elements.
- Building on JWST heritage and looking toward the future of space telescopes beyond HWO is a long-term strategy and a programmatic choice

History of Large (>1m) UVOIR Space Telescopes



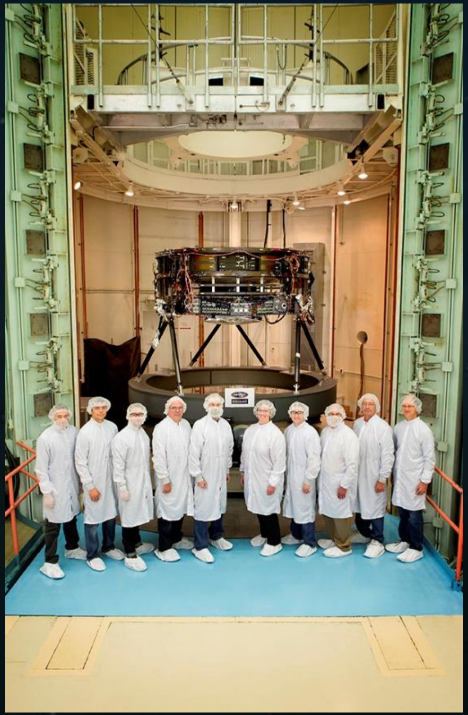
Hubble Space Telescope

- 11,600 kg
- Diffraction limited at 0.5 µm (post-correction), FUV quality mirror
- 2.4 m Corning ULE Glass mirror
- 293K
- 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

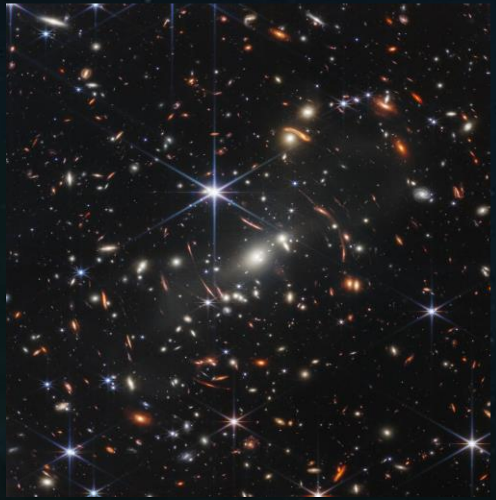
- Mass Allowable: 10,000 kg
- Diffraction limited at ~1.2 µm
- 2.4m Corning Ultra Low Expansion (ULE Glass) mirror
- Mirror temp 265K ± 0.001K (active control)
- Falcon 9H

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.

Webb's First Deep Field



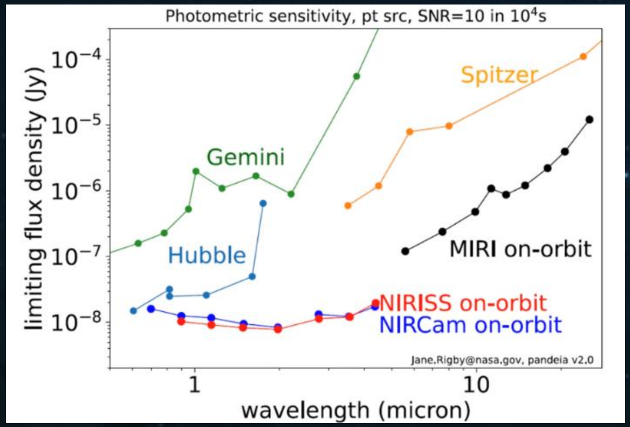


Image quality 2x as sharp as requirements and more stable.

- ~65nm RMS (or diffraction limited at ~0.9µm) vs. 150nm requirement
- Wavefront stability is approximately 14nm RMS over two weeks vs. 50nm RMS end-of-life (EOL) requirement
- Pointing and guiding are 7x better than EOL requirements (<1mas image motion vs. 7mas EOL top-level requirement).

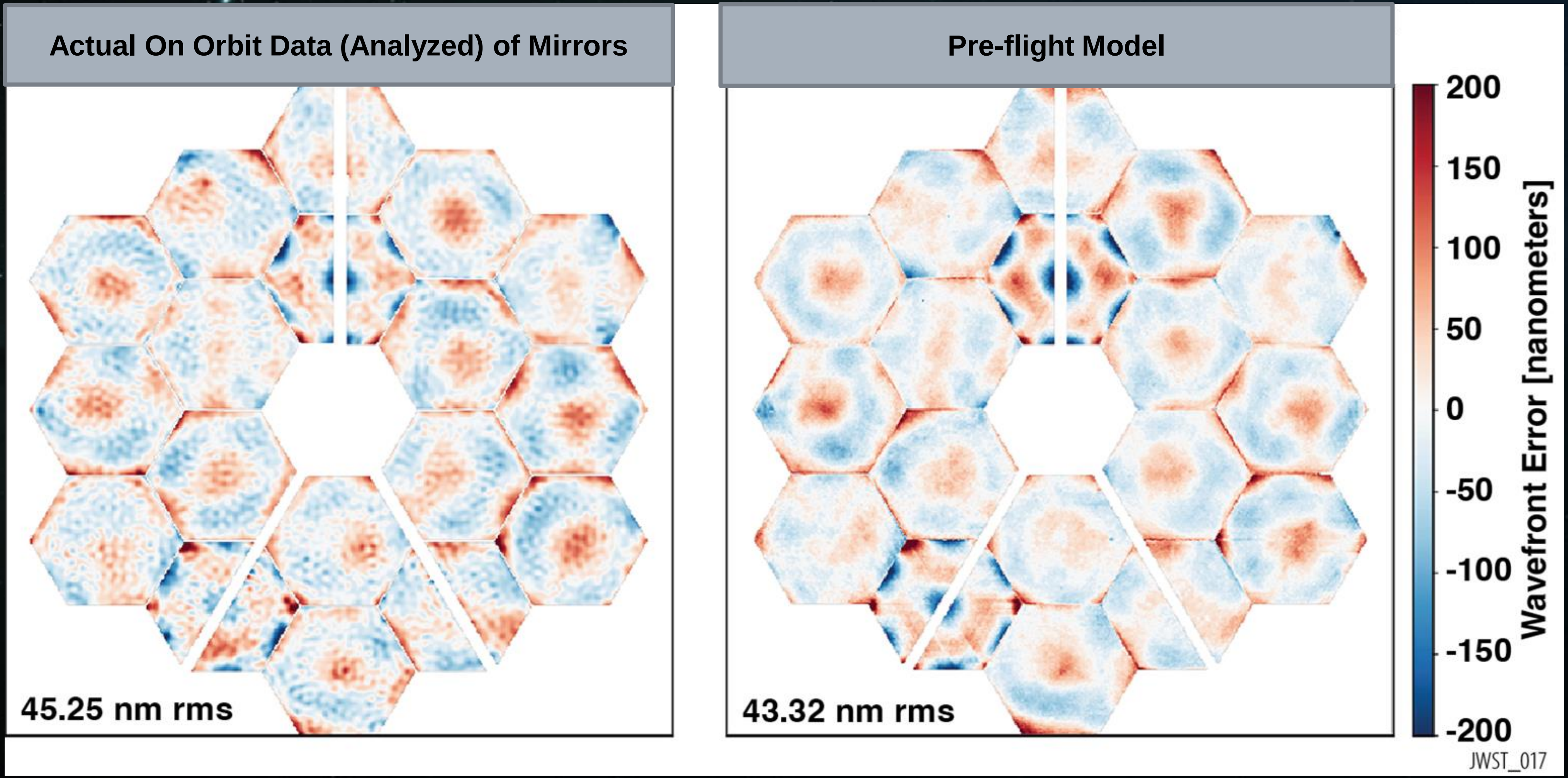
Throughput of the telescope and instruments is better than requirements, almost across the spectrum.

Cosmic Cliffs in the Carina Nebula

Rigby, McElwain, Perrin, et al. 2023 PASP

JWST Mirror Segments Performed as Predicted

Demonstrates segmented mirrors can be modeled and built to levels needed by HWO



WFE values reported for the primary mirror segments only.

McElwain, Feinberg, Perrin, et al. 2023 PASP

HABITABLE WORLDS OBSERVATORY (HWO)

Based on Astro2020 recommendations, HWO is a 0.5um diffraction limited telescope optimized for both high contrast (10^{10}) Exo-earth studies and general astrophysics including FUV spectroscopy

- OTE Aperture ~6 m inner diameter (TBR)
- 0.3 mas line of sight (LOS) stability
- Diffraction limited image quality at 0.5 µm
- Operating temperature of -30°C to 20°C (TBR)
- Enhanced UV performance, goal of 100 nm cutoff (Lyman UV lines for H2 and CO)
- Slew times < 60 min for 90°
- Expect coronagraph building on Roman Space Telescope CGI, likely to be starshade compatible

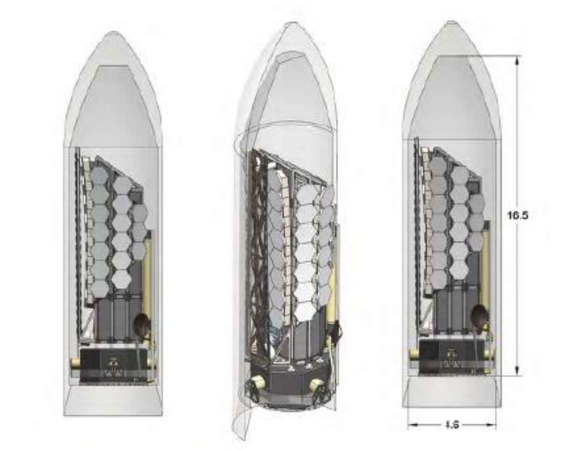
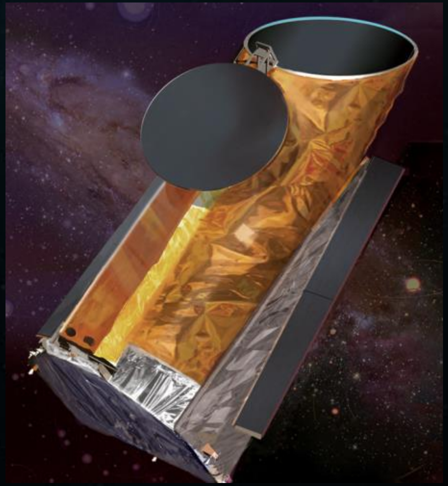


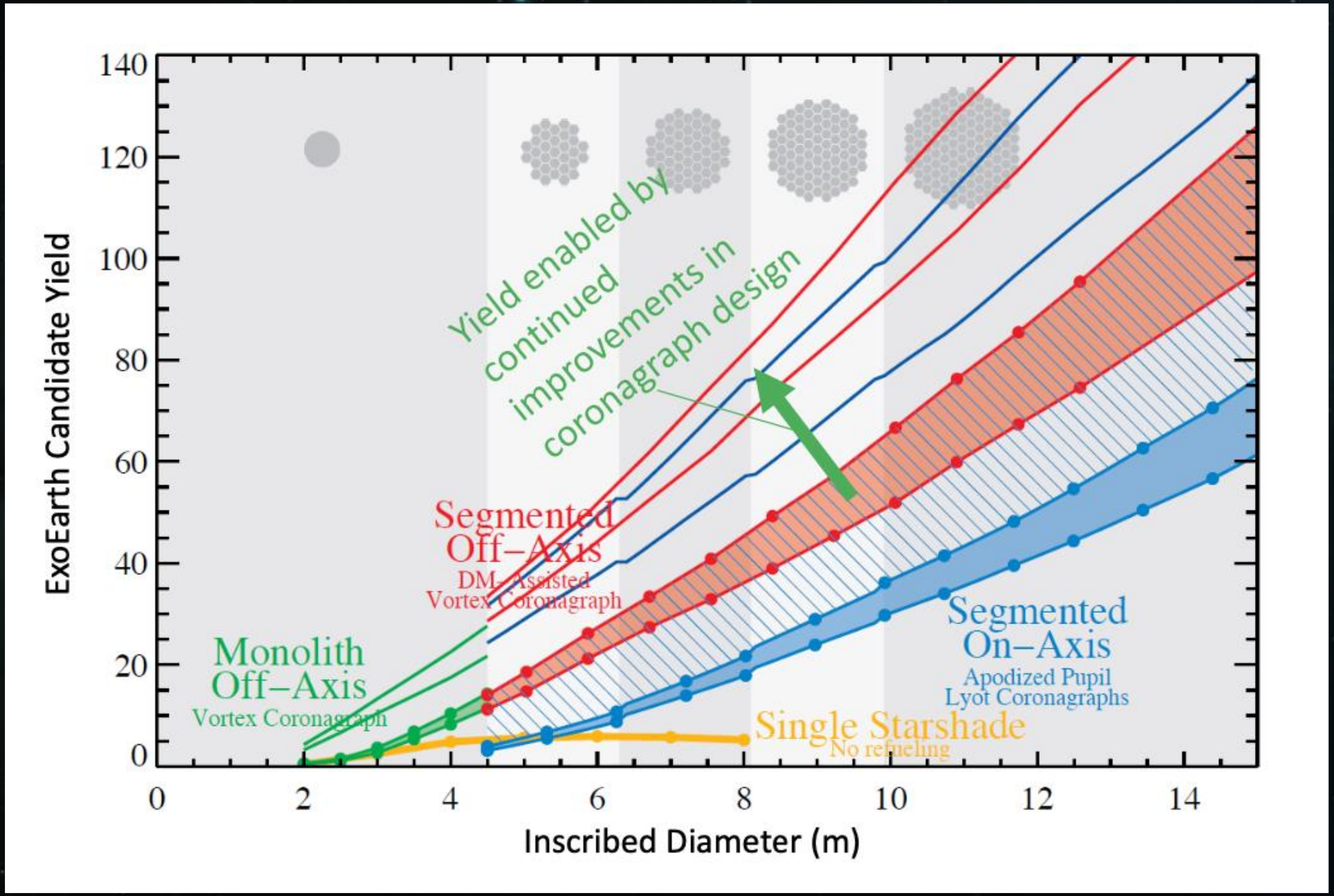
Figure 10-8. *LUVOIR-B in a "conventional" 5-m fairing*

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



Coronagraphs Can Accommodate Segmentation and Off-Axis Provides Better Yields



Belikov, Sirbu, Jewell, et al. 2021 SPIE

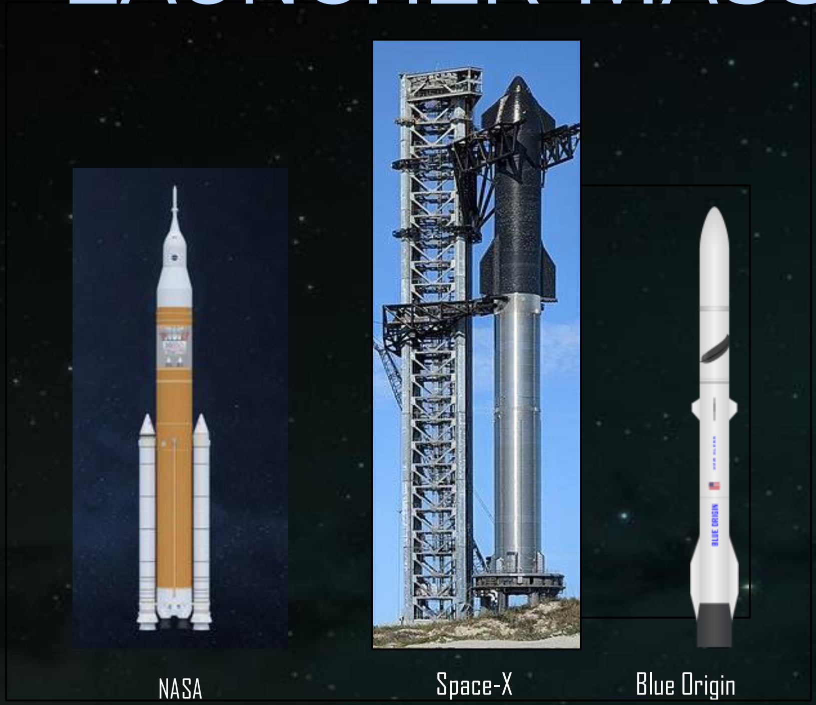
Theoretical analysis found that the "performance of optimal coronagraphs does not strongly depend on aperture obstructions or segmentation."

Yield varies significantly with aperture size, making it the strongest level arm to obtain margin or address uncertainty in Eta_Earth

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
- Lab results support this to 10^{-9} level, more testing is needed to confirm at 10^{-10} level (Riggs et al., 2022)

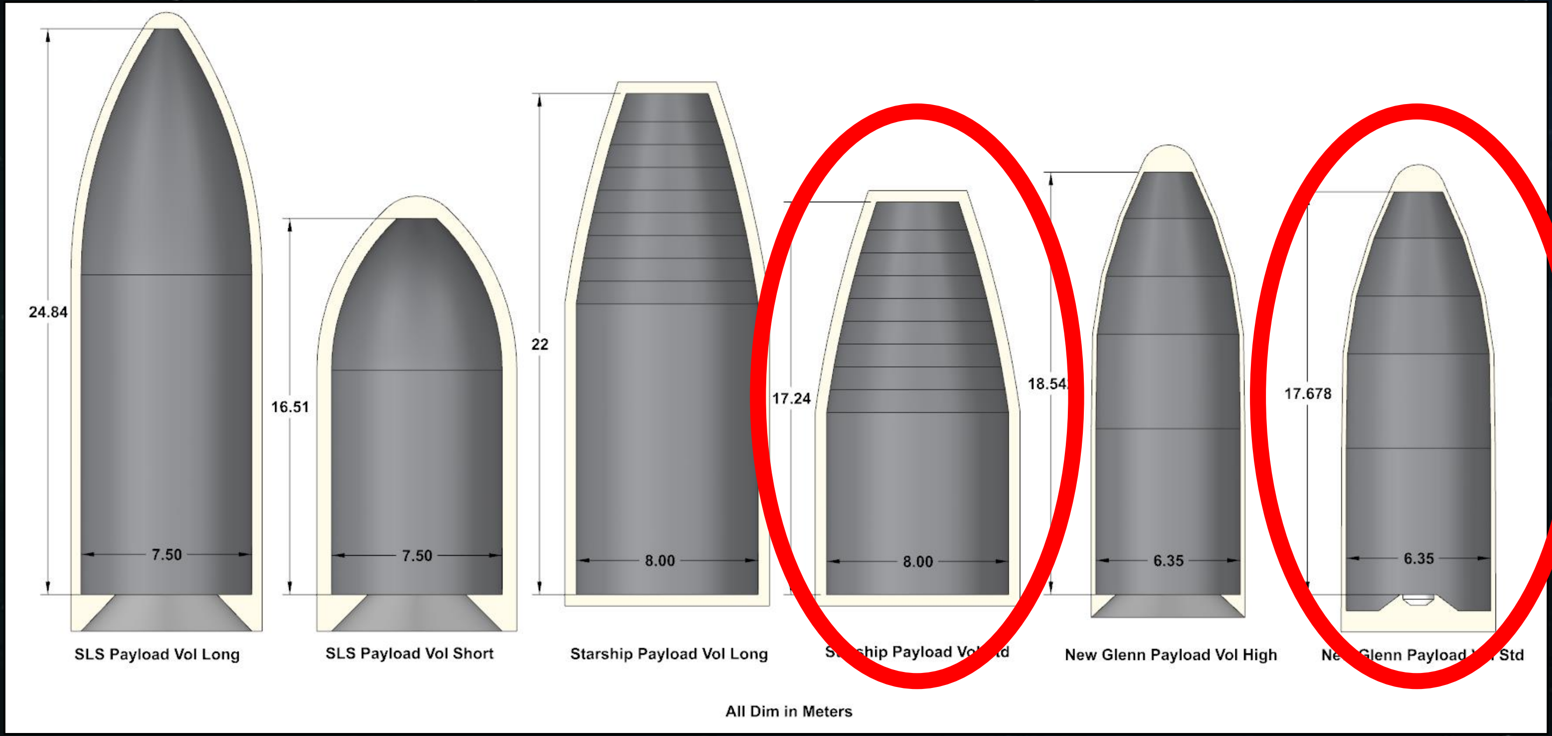
Launcher Mass and Volume Capabilities



NASA
Space Launch System

Space-X
Starship

Blue Origin
New Glenn



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

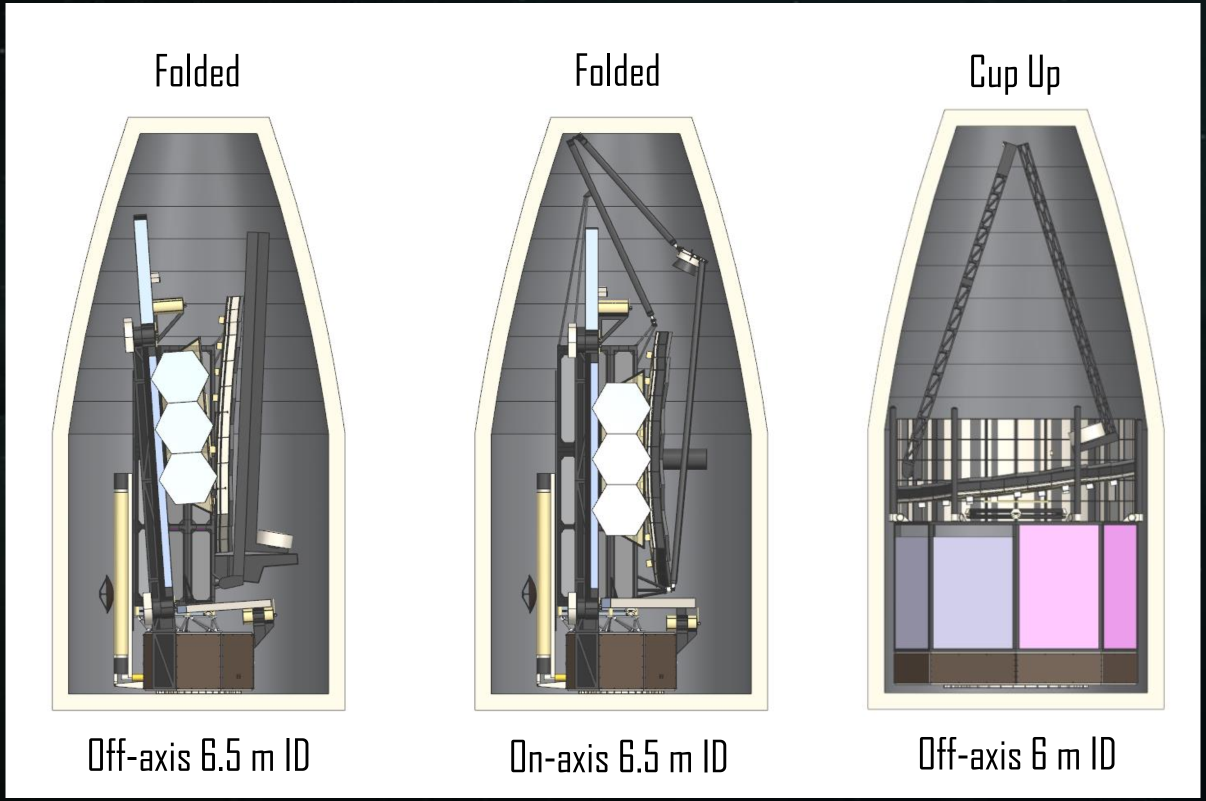
Fitting in both the New Glenn and Starship fairings in development mitigates risk.

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

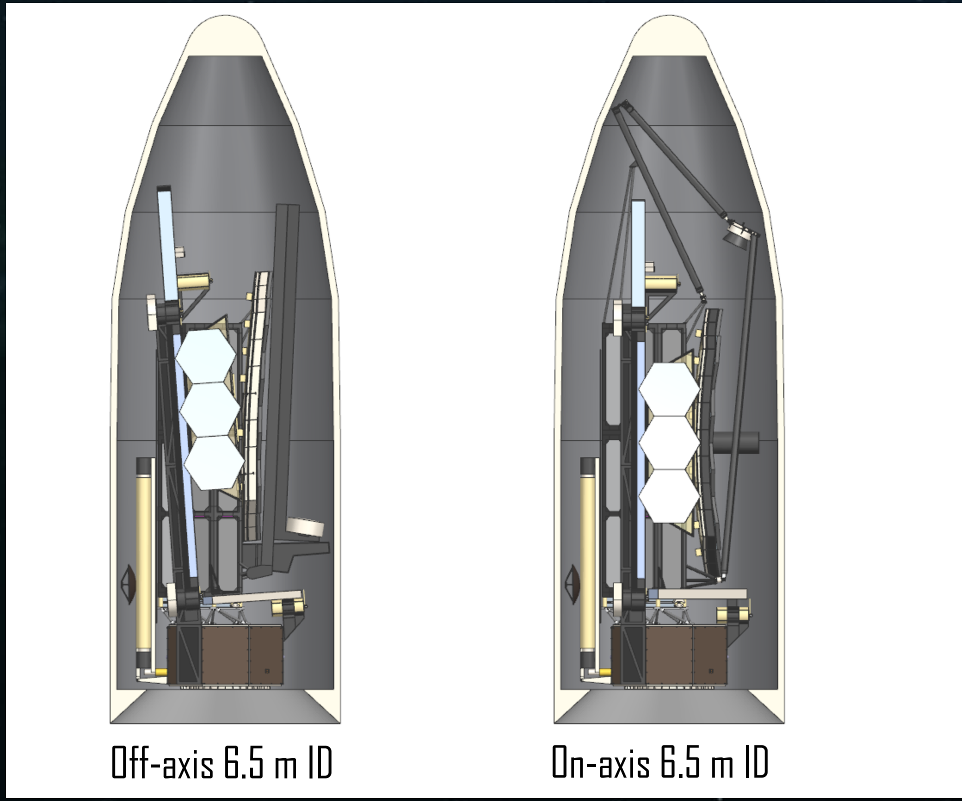
Launcher	Mass to L2 (kg)	Notes
Space-X Starship	100,000	To go beyond LEO, Starship will require re-fueling (and a fuel depot filled with multiple launches). Refueling adds risks like contamination, environment, needs to be economical to be viable in 2040s.
NASA Space Launch Systems (SLS)	44,300	Not currently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

NOTIONAL 6-M CONCEPTS (OFF-AXIS) WITH FAIRINGS IN DEVELOPMENT

Space X Starship Standard



Blue Origin New Glenn



- Starship can fit any 6m off axis option (monolith, segmented, cup up, folded) with margin.
- New Glenn can launch a folded, segmented off axis telescope (mass and volume constrained).

Coating Complexity

Coatings over large areas are inherently challenging – goal is high reflectivity and uniformity for both coronagraphy and FUV.

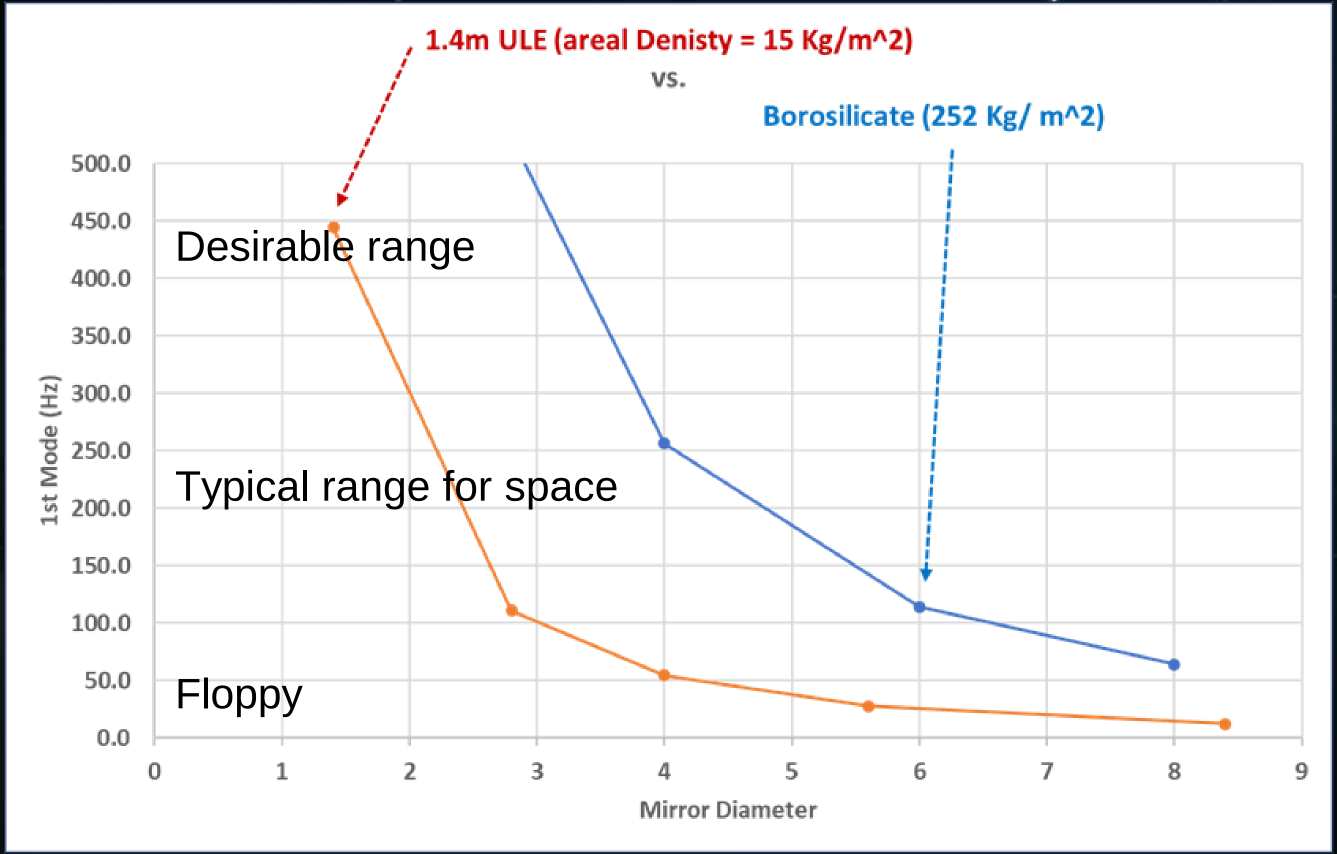
Especially desirable is FUV Enhanced LiF, which extends to 100nm.

- High-reflectance Enhanced FUV Al+LiF coatings protected with the atomic layer deposition process have been produced for ≤ 6” (0.15 m) optics; ≥ 1m-class substrates require larger reactors that are extremely challenging and don’t currently exist.
- Complexity of chamber scales exponentially with diameter.

Reflectance uniformity requirements 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) – 1% is achievable, possibly better
- Larger chambers require exquisite contamination (including humidity) control.

Mirror Stiffness Scales Non-Linearly with Diameter



Source is SAO Mirror Modeling Team

A stiffer mirror is highly desirable to prevent mirror bending from dynamic inputs or from strain from back or during polishing.

Example based on 15 kg/m^2 areal density, depends on mirror construction so notional (type of Areal Density needed for New Glenn)

Can make a thicker stiffer mirror but mirror manufacturing for ULE and Zerodur limit thickness and thus stiffness.

Borosilicate (like GMT) may require actuators that add instability and other complexities (was tried early on JWST) and exceeds New Glenn mass capability.

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 low stiffness due to thickness limitation, made in Germany, ITAR implications.

A medium-high stiffness solution would be a deep large casted Borosilicate mirror

- Borosilicate is high CTE near room temperature (roughly 1000x** higher than ULE and Zerodur at room temp implying need for much better thermal control than state of the art). Note: other details like thermal conductivity and mass matter too.
- May well need to be high authority which creates significant challenges (actuators, stability)
- Use of space-based laser guide star may be possible, but adds system complexities and risks, need many, limits flexibility and not clear how well it can work (many unknowns)

A deep borosilicate mirror would only be compatible with SpaceX Starship (with refueling) due to mass and size and would not be scalable for the future

Would also have to address 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 can be very stiff due to smaller size (scales non-linearly), backplane can be made stiff via depth.

Many components, analyses, models, and approaches leverage JWST experience

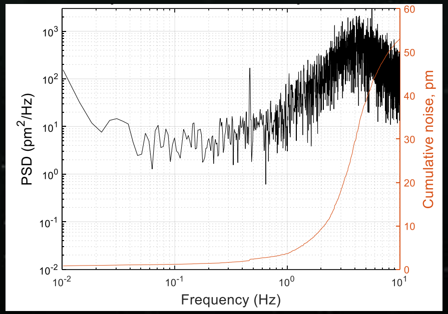
- For example, mount architecture, coarse actuator, wavefront sensing and control, error budgeting, alignment, gravity approach, metrology of segments, system level verification of telescope using the gravity sag
- JWST AMSD mirror was ULE and matured to TRL5; a mount design was also done

Zerodur and ULE are both options

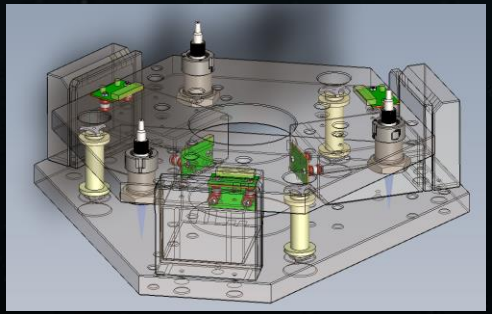
- Zerodur has same ITAR and machining issues, ULE has a lot of heritage (e.g., RST)

Requires edge sensors or metrology to measure segment-to-segment deviations

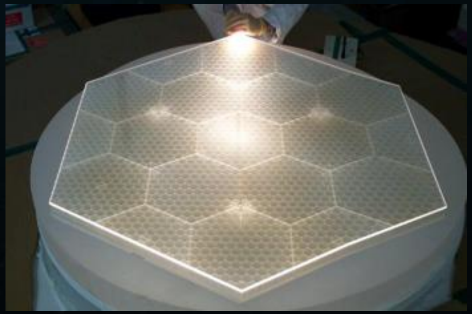
More piece parts to polish, test, and integrate.



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



Example High TRL substrate
- L3 Harris
- Lightweight ULE mirror

Other Practical 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

In general, monoliths are more at risk for damage on the ground due to handling or in space due to very rare high energy micrometeoroids

- Extremely difficult and expensive to have finished spares – large risk

Fitting on vibration tables, acoustic chambers, and vacuum chambers favors a system that can fold up

Aerospace companies that make flight and UV quality mirrors (e.g., L3 Harris) are *not* facilitized for 6 m monoliths. Facilitization is expensive early money.

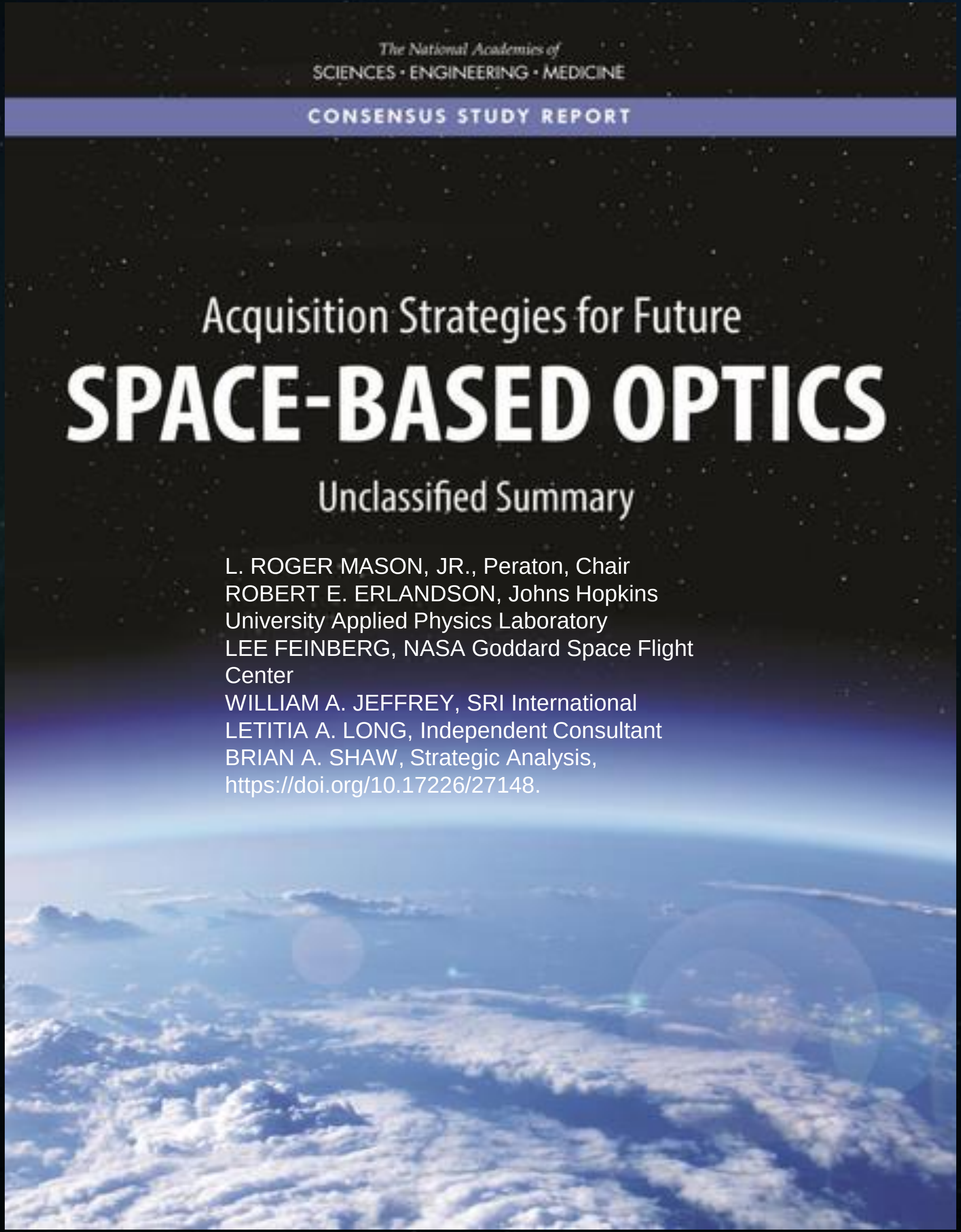
OTHER REFERENCES

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.



SUMMARY – KEY DISCRIMINATORS

	ULE or Zerodur Monolith	Thick Borosilicate Monolith	Segmented ULE or Zerodur
Compatible with both large fairings in development (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 (w/ultra stability), off axis	↑	↓	↑
Allows for flexibility on aperture size	↓	↓	↑
Stepping-stone to future larger telescopes	↓	↓	↑

Backup

Coronagraphy with Monoliths or Segmented

Segmentation can be compensated by coronagraph design with modest throughput reductions (Zimmerman et al., 2006, Nickson et al. 2022).

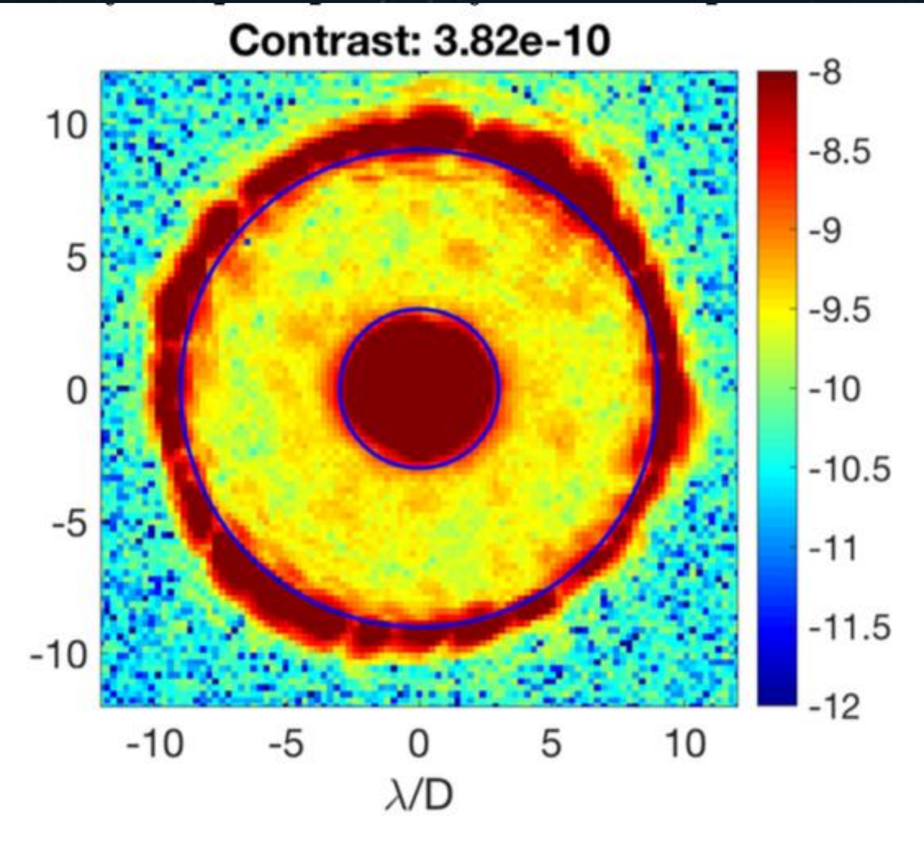
- Need small gaps (6-8mm) which are feasible
- Lab results support this to 10^{-9} level, more testing is needed to confirm this at 10^{-10} level (Riggs et al, 2022)

Demonstrations in the JPL High Contrast Imaging Testbeds focused on achieving high contrast over a broad bandpass for unobscured apertures (4×10^{-10} in a 10% spectral bandwidth).

- Segmented demonstrations have only recently been prioritized but progress is being made (e.g., 4.7×10^{-9} contrast over 10% bandwidth averaged from 3-10 l/D, Riggs et al. 2022).
- Alternative approach PAPLC has demonstrated 4.2×10^{-8} contrast over 9% bandwidth averaged from 2-13 l/D in air (Por et al, SPIE 2023).

Roman Space Telescope CGI instrument which works with struts and obscuration recently demonstrated 1.6×10^{-9} contrast at the instrument level and provides significant risk mitigation.

Unobscured monolith
with 10% spectral bandwidth



Seo, Patterson, Balasubramanian, et al. 2019 SPIE

Post processing with PSF calibration techniques potentially relax contrast requirements substantially (Guyon et al., 2022).