



UVO to Far-IR Mirror Technology Development: Year 2 Status

H. Philip Stahl
Marshall Space Flight Center

Initiated in FY22, UVO-FIR Mirror System & Telescope Technology Development is a 3-year NASA Astrophysics Division Internal Scientist Funding Model (ISFM) directed work package to develop/mature ‘cross-cutting’ technologies that address two Tier-1 gaps identified by the 2022 Astrophysics Biennial Technology Report and their sub-gaps identified by the 2022 Exoplanet Exploration Program Technology Gap List:

- Coronagraph Stability
 - Ultra-stable Telescope
 - Integrated Modeling of Telescope/Coronagraph System
 - Thermal Sensing and Control
- Mirror Technologies for High Angular Resolution (UV/Vis/Near IR)
 - Mirror Substrate and Structure
 - Gravity Sag Off-Loader
 - Coefficient of Thermal Expansion (CTE) Characterization

After award, responding to ‘Integrated Modeling of Telescope/Coronagraph System’ sub-gap, we add four more tasks:

- Modeling of the AMTD 1.5-m ULE® Mirror’s Thermal Performance (reported 2023)
- Ultra-Stable Passive Opto-Mechanical Secondary Mirror Support Structure Design
- Modeling of the Impact of Near Angle Scatter on Coronagraph Performance
- Coronagraph Contrast Error Budget

Additionally, the MSFC UVO/FIR Mirror/Telescope Team provides services to the community, including cryo-testing, and analysis.

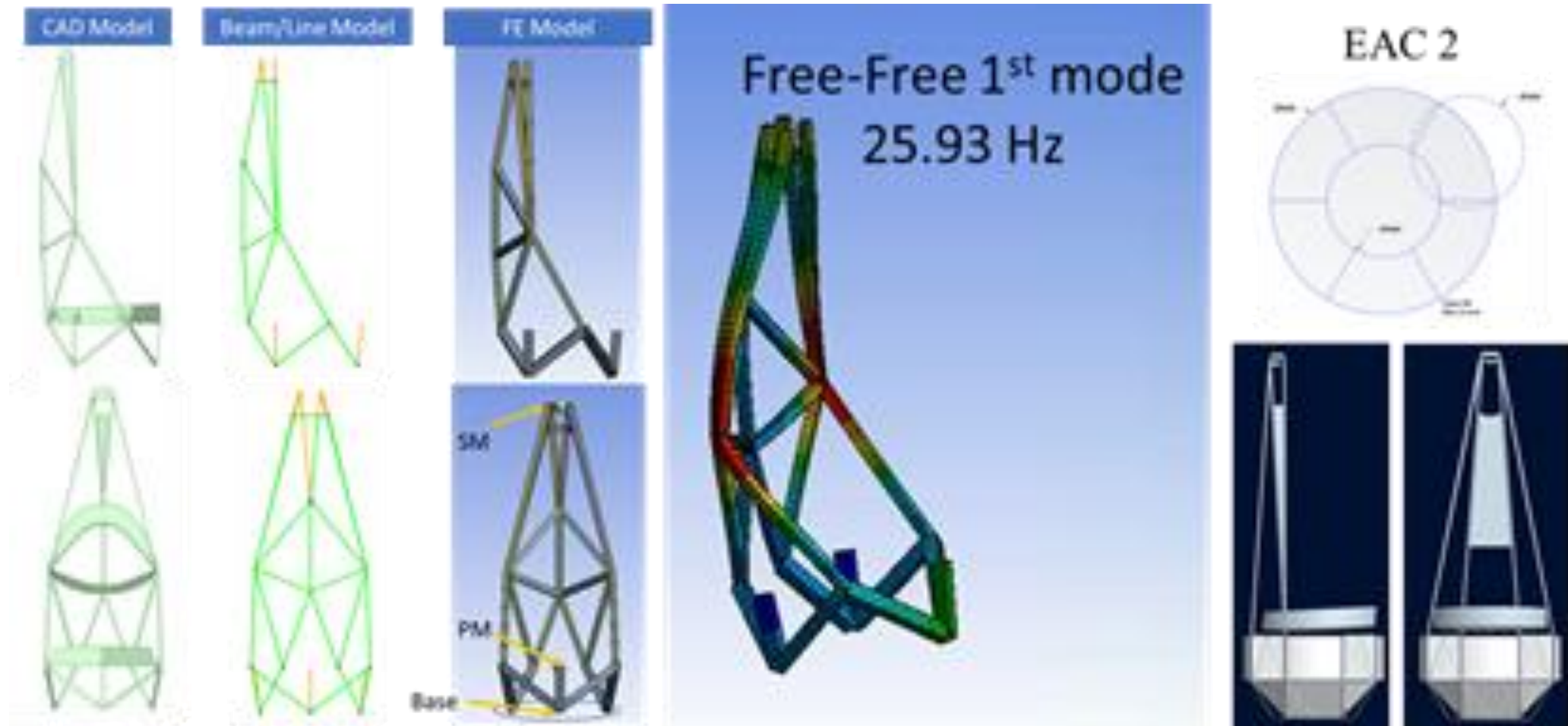
And MSFC’s UVO/FIR Team provides subject matter expertise to multiple Habitable Worlds Observatory (HWO) GOMAP Working Groups, Sub-Working Groups, and Exploratory Analytical Case (EAC) Studies.



Ultra-Stable Telescope: Mechanical

Secondary Mirror Support Structure

MSFC ISFM Team used its Structural Optimization Tool to design a Secondary Mirror Support Structure for JPL's 6mST concept with can be applied to EAC-2.



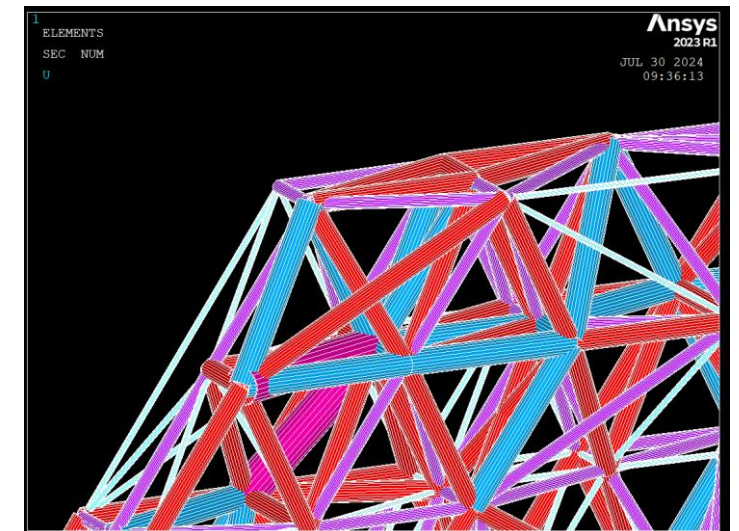
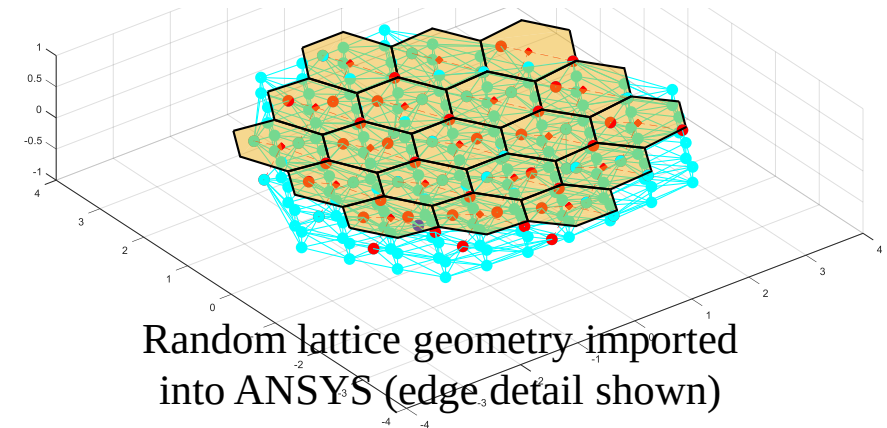
EAC Primary Mirror Backplane Optimization



Applied Optimization Tools to HWO PM Backplane

- Engineering Analysis Configuration-1 (EAC-1)
 - Optimize existing backplane Finite Element Model by changing truss element diameter & thickness
- Engineering Analysis Configuration-2 (EAC-2)
 - Optimize backplane truss topology as well as truss elements
 - Optimize secondary mirror metering structure
- Design optimization goals
 - Minimize structure mass for desired 1st-mode resonance frequency
 - Incorporate keep-out regions
- Development Status
 - ANSYS integration with MatLab complete (bottom right figure)
 - 19-segment backplane w/curvature generated (top right figure)
 - Optimization algorithm working as expected (no major bugs)

Example EAC-1 backplane created by MatLab (pre-optimization)



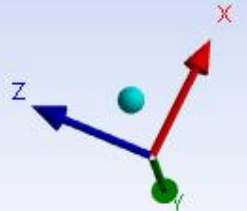
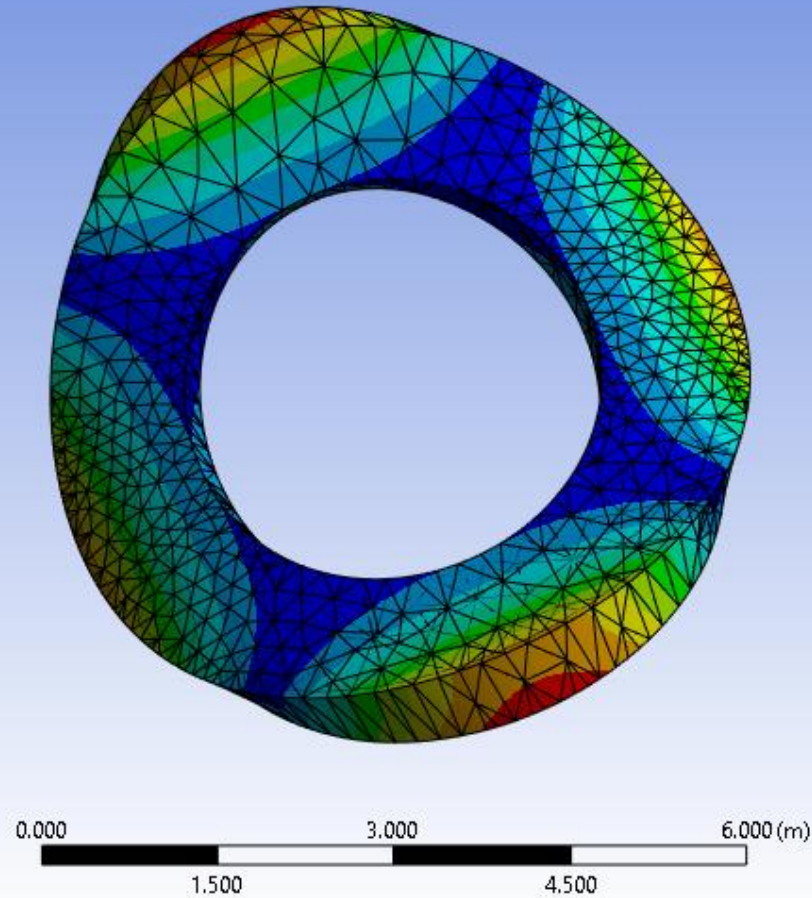
Modal Analysis of Pre-mature Backplane



Ansys
2023 R2

B: Modal

Total Deformation
Type: Total Deformation
Frequency: 14.288 Hz
Unit: m
7/31/2024 1:52 PM





For More Information:

Bridging the gap between finite element modeling and wavefront analysis for streamlined optical system design

Paper 13129-13

Jaganathan Ranganathan
NASA Marshall Space Flight Ctr.

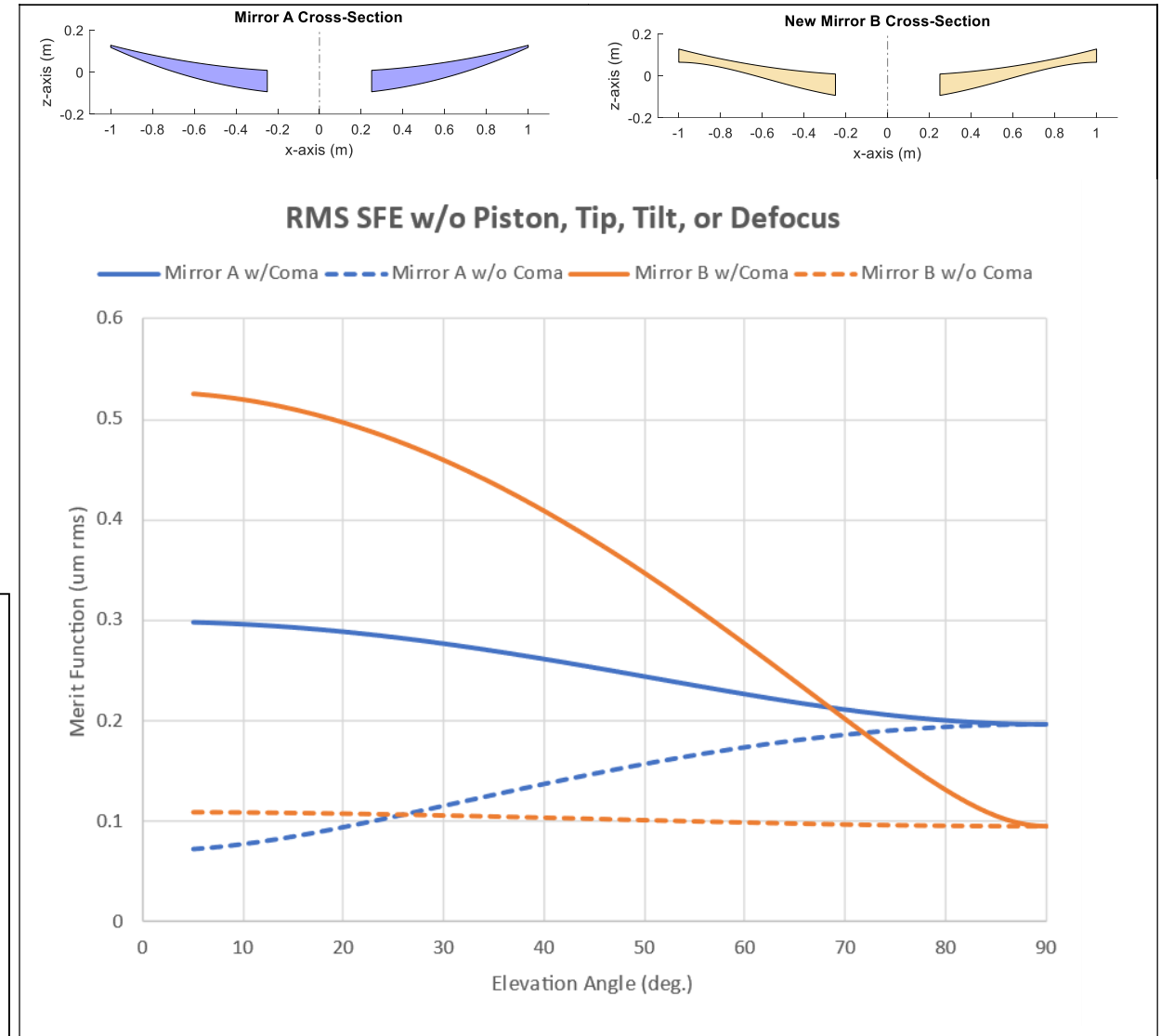
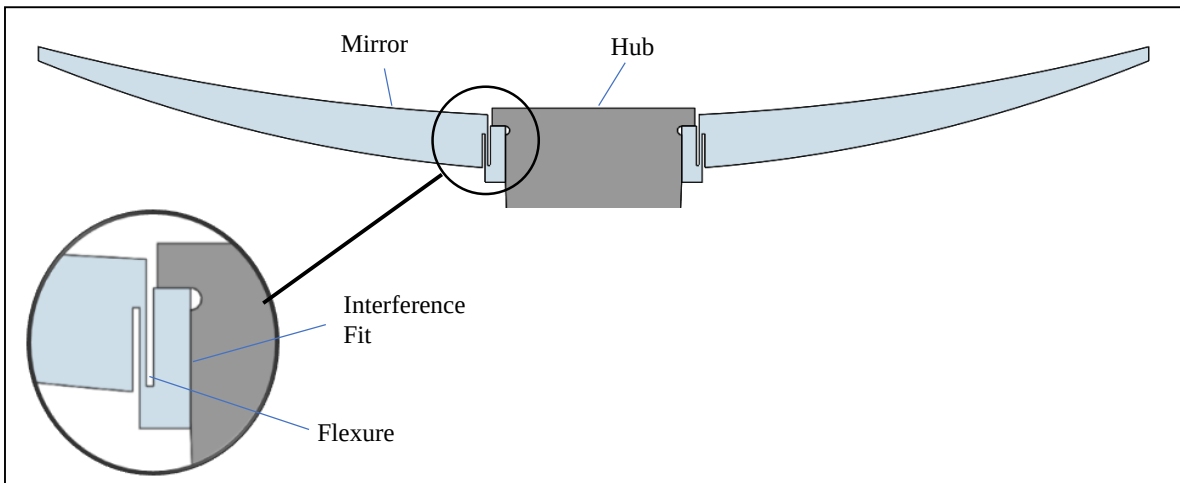


Tailored Stiffness

Balloon Mission Primary Mirrors

To maintain diffraction limited performance, balloon missions need to minimize G-sag as a function of elevation angle.

Developed a ‘shaped’ substrate center mounted mirror that minimizes all aberrations except coma – which can be corrected via SM alignment.





Arnold Mirror Modeler (AMM)

EAC-2 Primary Mirror Trades



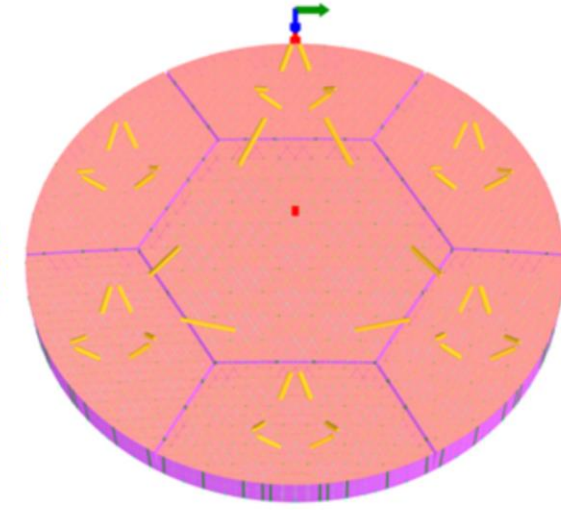
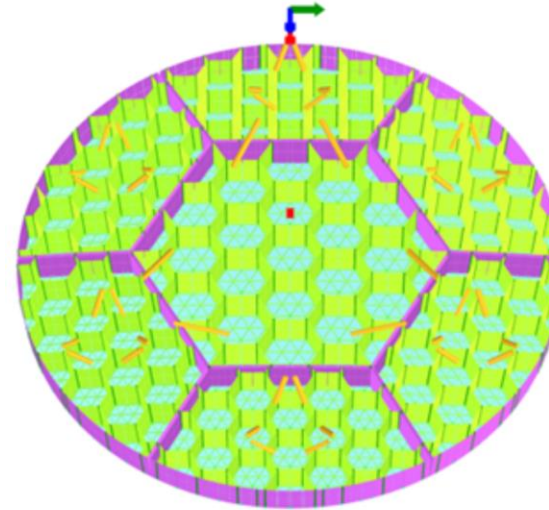
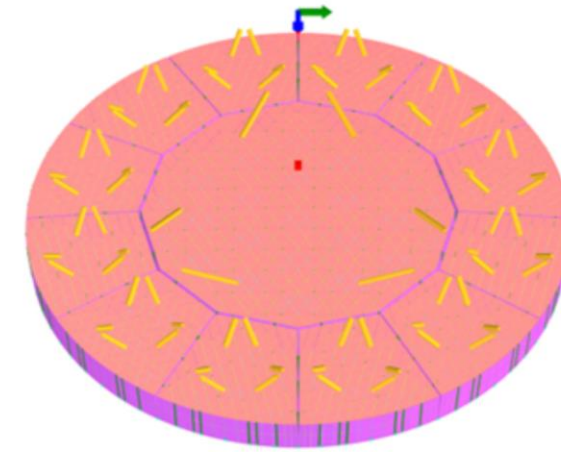
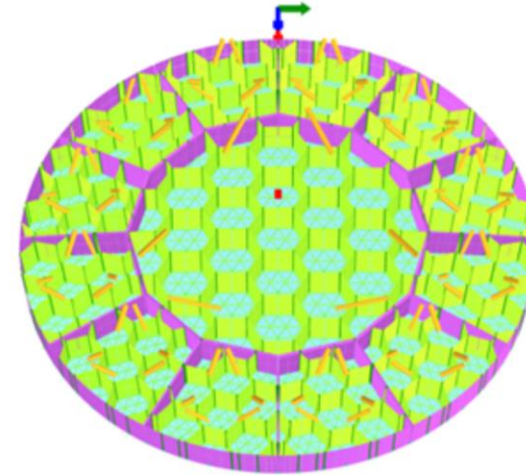
Used MSFC's AMM to develop EAC-2 primary mirror design concepts – substrates & mounts

Multiple parameters were traded to arrive at a 3.5-m diameter mirror design:

- three face/back-sheet thicknesses;
- three core wall thicknesses; and
- three different core cell sizes.

Total mass ranged from 672 to 1272 kg.

First mode frequency ranged from 190 to 222 Hz.



For More Information:

Stiffness comparison of a monolithic vs. segmented mirror

Paper 13129-14

Brent Knight

NASA Marshall Space Flight Ctr.



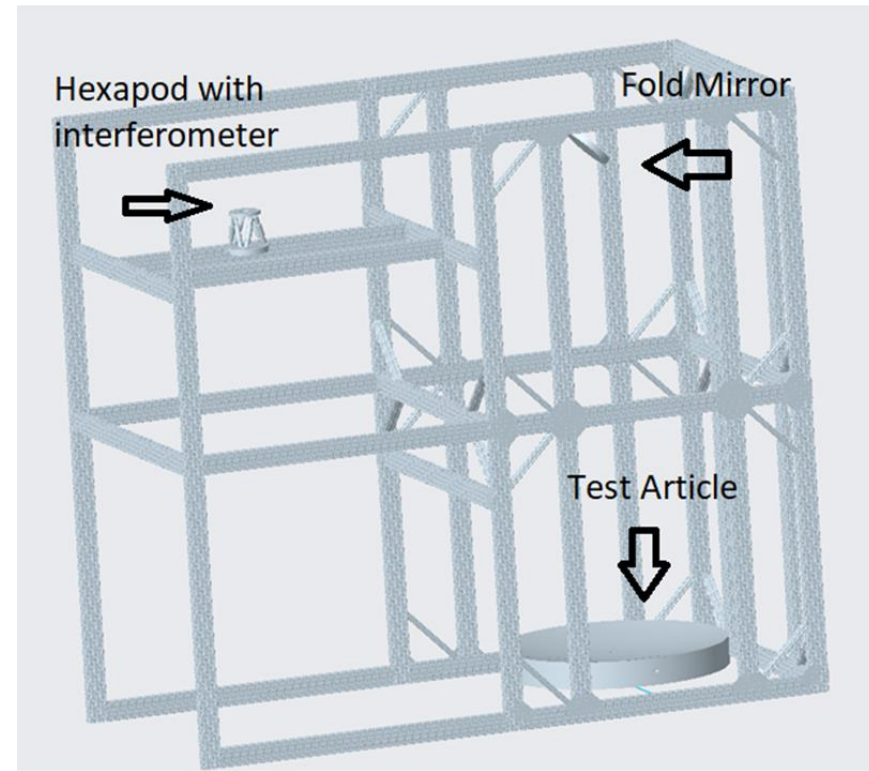
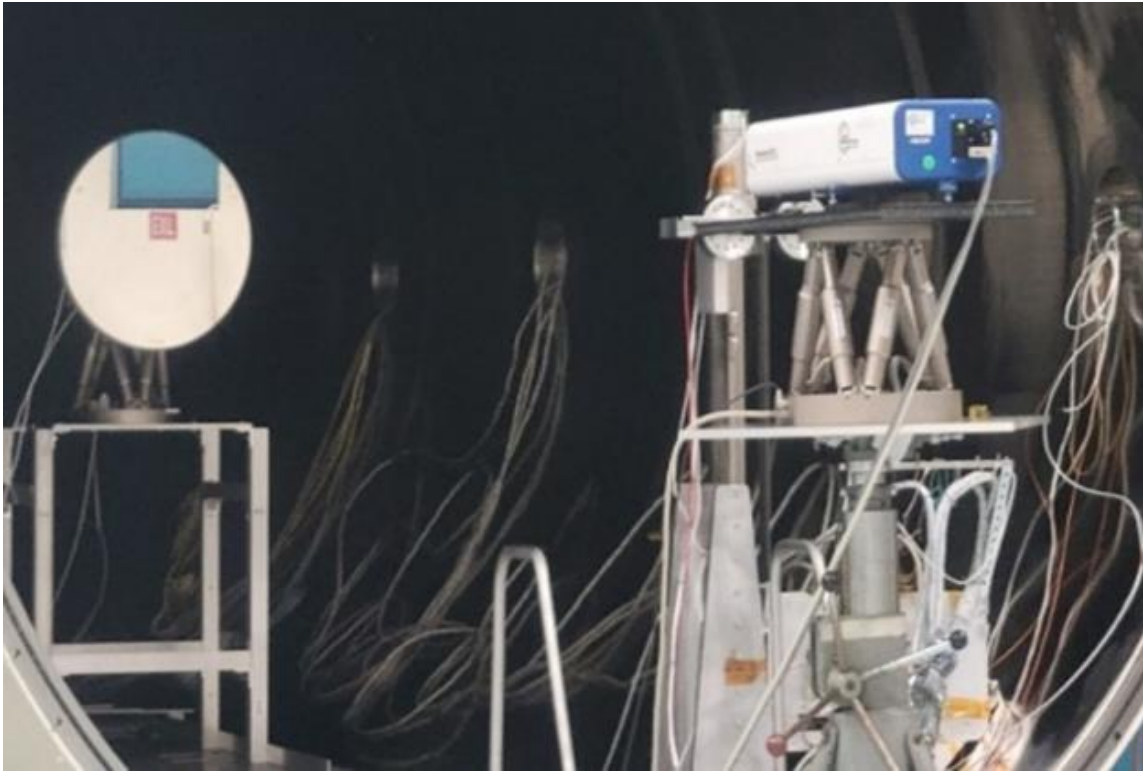
Absolute Gravity Sag Characterization

Horizontal Rotation versus Vertical Flip Test



MSFC Center for Mirror System Characterization, Qualification and Acceptance Testing can:

- Characterize a mirror's gravity sag via either a horizontal rotation test or vertical flip test.
- Rotation test can be performed in Vacuum and at Cryogenic Temperatures.

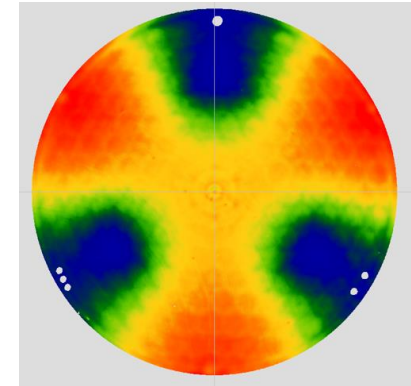


G-Sag Estimate: Rotation vs Flip Test

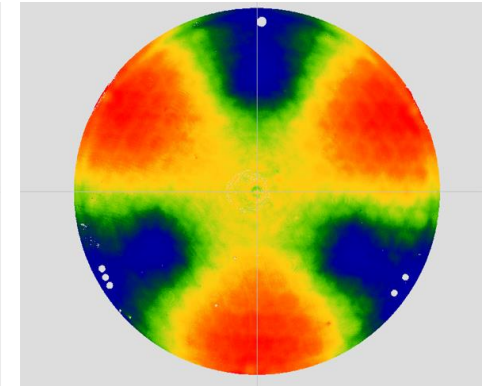
Rotation Test is 'blind' to rotationally symmetric errors such as spherical aberration.

G-Sag is consistent with 3-point Mount.

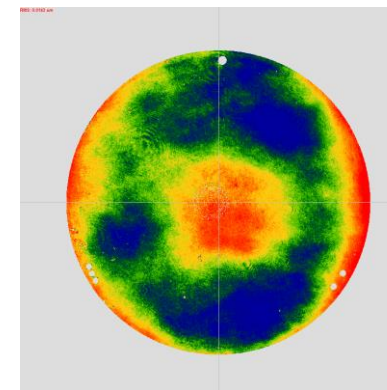
Both tests performed in 'air', thus Δ has turbulence.



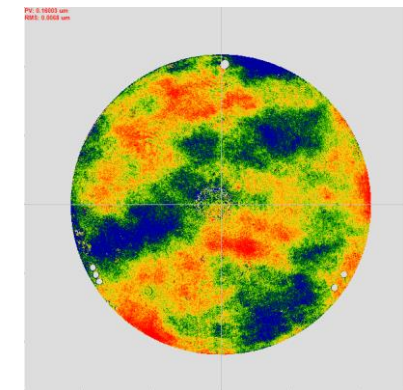
Rotation Test
75 nm RMS



Face-up/Face-down Test
74 nm RMS



Difference
14 nm RMS



Diff (w/o) spherical
7 nm RMS

For More Information:

A comparison of G-release measurement methods

Paper 13134-14

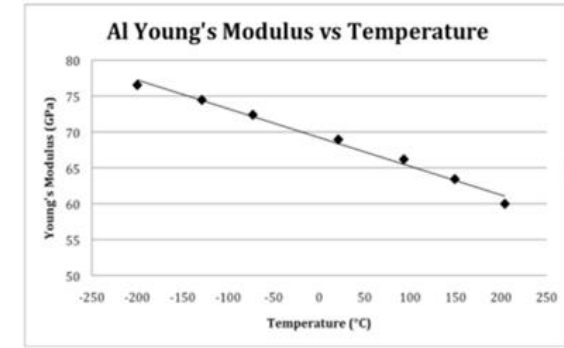
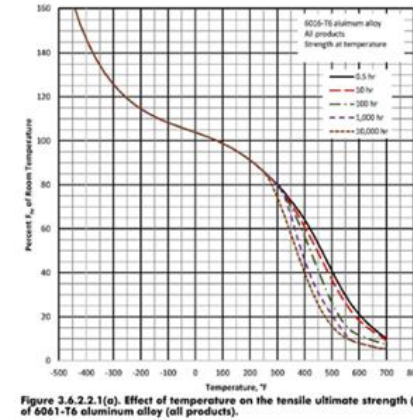
Stephen Cheney
NASA Marshall Space Flight Ctr.

Cryogenic Gravity Sag

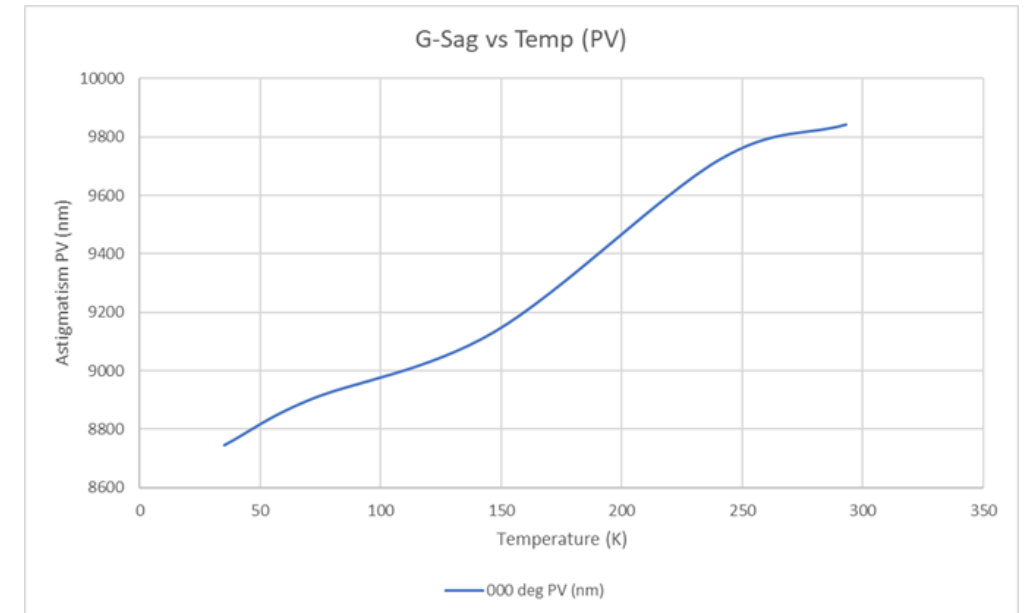
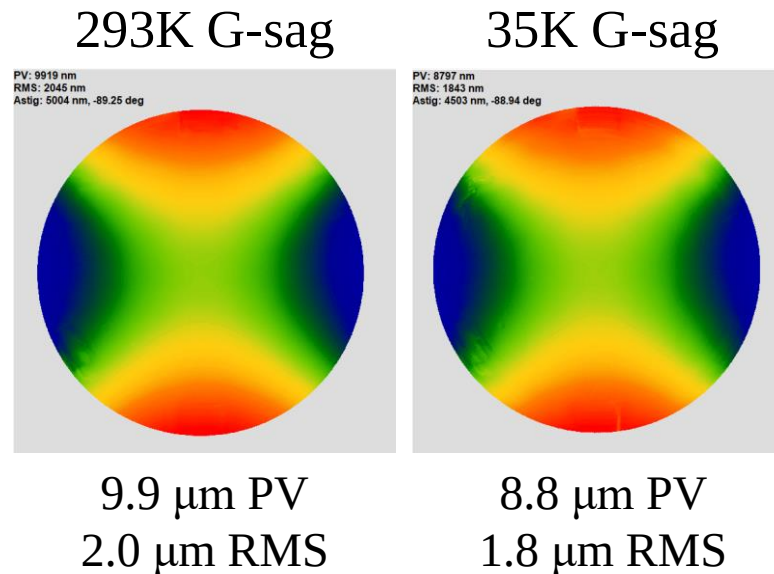
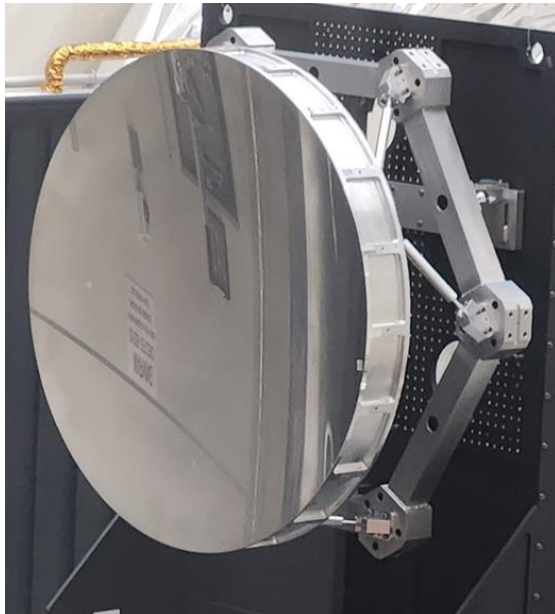
Material elastic modulus changes with temperature, therefore, so will a mirror's gravity sag.

1.2-m AL mirror G-Sag was measured (via 3-rotation test at 0, 120 and 240 deg) from ambient to 35K

G-Sag decreased by $\sim 1 \mu\text{m}$ (from 9.8 to 8.8 μm) from 293K to 35K



Hopkins, D.C., et. al. "Extreme Thermal Transient Stress Analysis with Pre-Stress in a Metal Matrix Composite Power Package." Additional Conferences (Device Packaging, HITEC, HITEN, & CICMT). 2012. 000361-000372. 10.4071/HITEC-2012-THA25.



For More Information:

Characterizing gravity sag at cryogenic temperatures

Paper 13134-41

Tomasz Lis

NASA Marshall Space Flight Ctr.



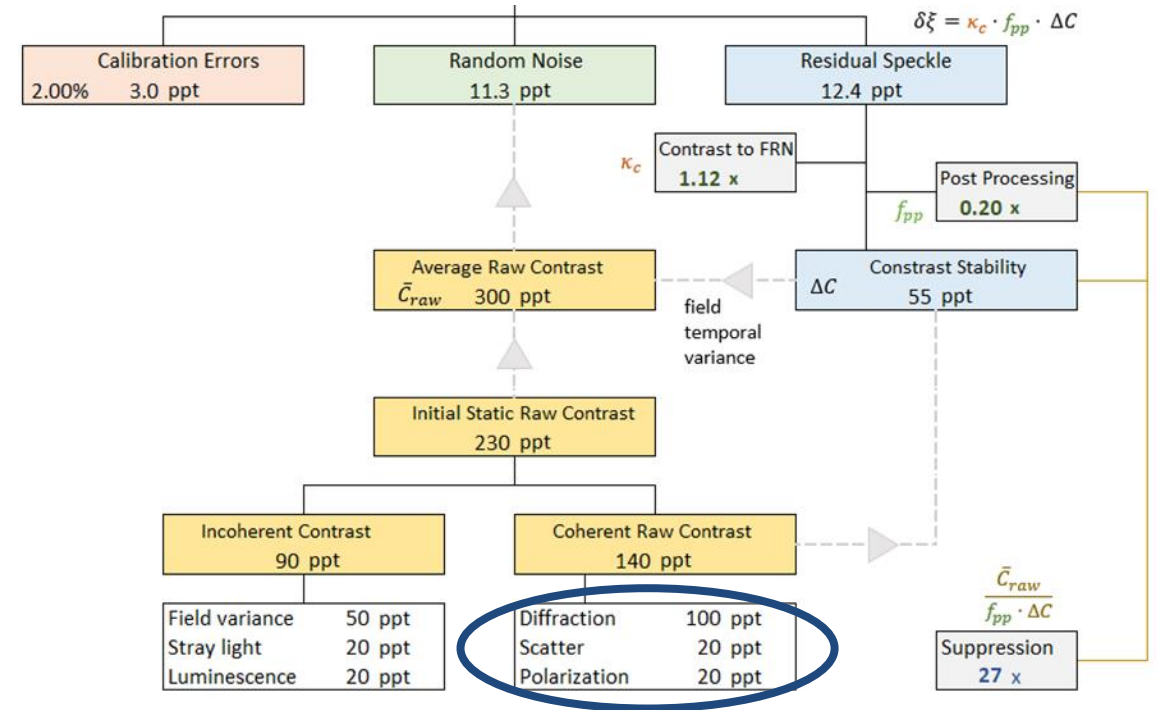
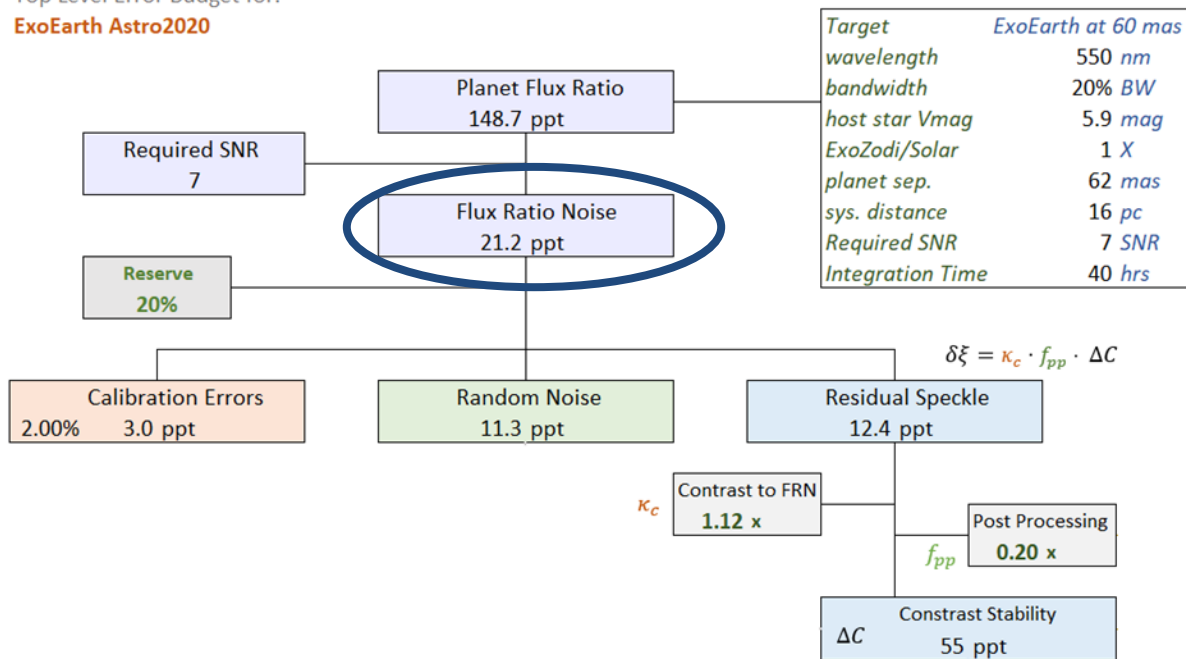
Near-Angle Scatter Study

Error Budget

Error Budget to detect an Earth-like planet around a Sun-like star with a SNR = 7 requires a flux ratio noise of ~ 20 ppt.

‘Post-correction’ scattered light allocation is 20 ppt.

Top Level Error Budget for:
ExoEarth Astro2020



Bijan Nemati and H. Philip Stahl, “Leveraging the Roman Coronagraph Approach for the HWO Error Budget”, SPIE Proc. 13092, (June 2024).

SPIE Proceedings 13134, Optical Manufacturing and Testing, 2024

Long Spatial Frequency Surface Structure



Solving the grating equation for maximum allowed change in PV surface PSD amplitude to have a scattered light flux ratio of 10^{-11}

$$a = \sim \left(\frac{\lambda}{2} \right) \times 10^{-6}$$

PV Surface Amplitude Stability as function of Wavelength for Temporal Scatter from Star to be 10% of exo-Earth Flux (i.e. 10^{-11})			
Wavelength	300 nm	600 nm	1800 nm
PV Surface Amplitude	0.15 pm	0.3pm	0.9 pm
Surface Spatial Period at 60 mas	1 m	2 m	6 m

This result is consistent with published wavefront stability analysis

These errors are correctable via a DM, but the ability of a DM to correct wavefront instability to sub-picometer precision is limited by sense and control resolution.

An expression was developed that specifies mirror statistical surface rough for a given specified near-angle scatter throughput (τ_{NAS})

If we assume the surface roughness is Gaussian:

$$\sigma[\text{\AA}] = \frac{1}{4\pi} \left[\frac{\lambda^2}{\ell} \cdot 10^4 \right] \left[\frac{\tau_{NAS}}{\pi \Omega_{\text{core}}} \right]^{1/2}$$

10^4 is scale factor from μm to $\text{\AA}$, because λ and ℓ are in units of μm .

where:

- λ and ℓ are in units of μm
- $\lambda/D = 0.1 \mu\text{rad}$ (for $\lambda = 600 \text{ nm}$, $D = 6\text{m}$)
- $\Omega_{\text{Core}} = \pi \theta_{\text{Core}}^2 = \pi (\lambda/D)^2 \sim (0.0\pi) \text{ pico-Steradians}$

Microstructure RMS Roughness Specification

EACs have ~ 14 optical surfaces before focal plane occulting mask.

Allocating $\tau_{NAS} = 0.5\text{E-}12$ to each surface, the specification becomes

Surface RMS Microstructure [$\text{\AA}$] to have NAS Throughput $< 0.5\text{E-}12$				
	Wavelength (λ) [μm]			
Correlation Length (ℓ) [μm]	0.300	0.680	1.000	1.800
10	16.2	83.2	180.0	583.2
100	1.6	8.3	18.0	58.3
1000	0.2	0.8	1.8	5.8
10000	0.0	0.1	0.2	0.6

Note: $\sigma \sim \sqrt{\tau_{NAS}}$.

Thus, if τ_{NAS} changes by 10X, roughness changes by $\sim 3\text{X}$

Specification is driven by shortest coronagraph wavelength.

Microstructure RMS Slope Specification

Another potential Key Performance Metric is RMS Slope

$$RMS\ Slope = \sqrt{2} \frac{\sigma}{\ell}$$

Slope is potentially more intuitive, provides an angular spread.

Table 2: Surface RMS Slope [μ rad] to have NAS Throughput $< 0.5E-12$				
	Wavelength (λ) [μ m]			
Correlation Length (ℓ) [μ m]	0.300	0.680	1.000	1.800
10	229.1	1177.1	2545.6	8247.7
100	2.3	11.8	25.5	82.5
1000	0.0	0.1	0.3	0.8
10000	0.0	0.0	0.0	0.0

Contamination Cleanliness Level Specification



Using the CL to BRDF and BRDF to NAS Throughput, a surface contamination specification can be defined for a given allocation.

Assuming a TOTAL Raw Contrast allocation for Contamination of 5 ppt AND that there are 10 optical surfaces before the Coronagraph Focal Plane Mask, then the Raw Contrast allocation per surface is 0.5 ppt.

For a 6-m diameter telescope, the BRDF per surface that contributes 0.5 ppt:

$$\text{BRDF}_0 = \frac{\tau_{\text{NAS}}}{\Omega_{\text{core}}} = \frac{0.5E-12}{\pi E-14} = 16 \text{ [1/sr]}$$

Per Pfisterer, Harvey, & Breckinridge Fig 4: this defines a per surface spec of < CL-500. Webb was specified to be < CL-600.

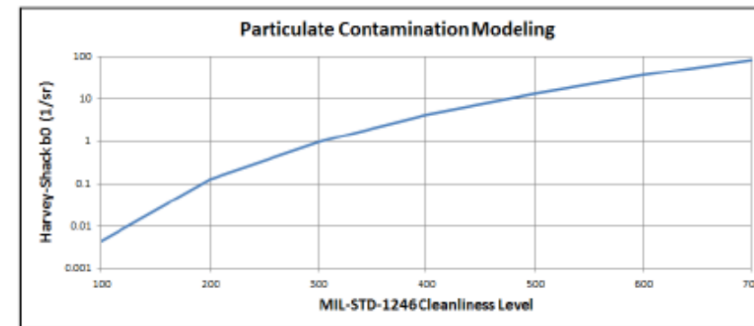


Figure 4 Derived relationship between Harvey-Shack b₀ parameter and MIL-STD-1246 cleanliness level.

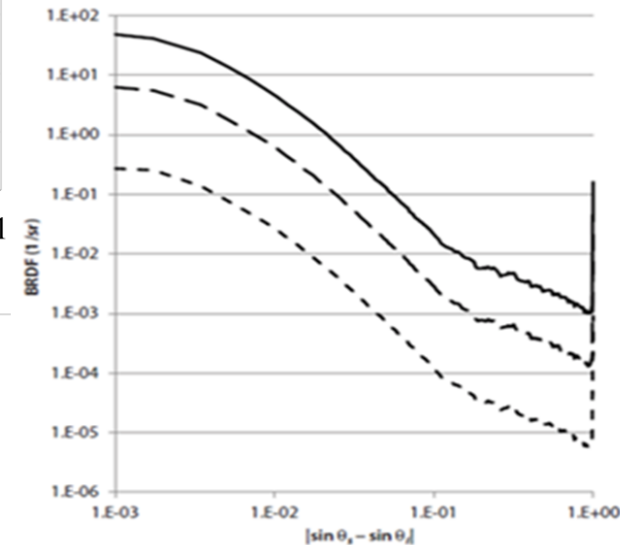
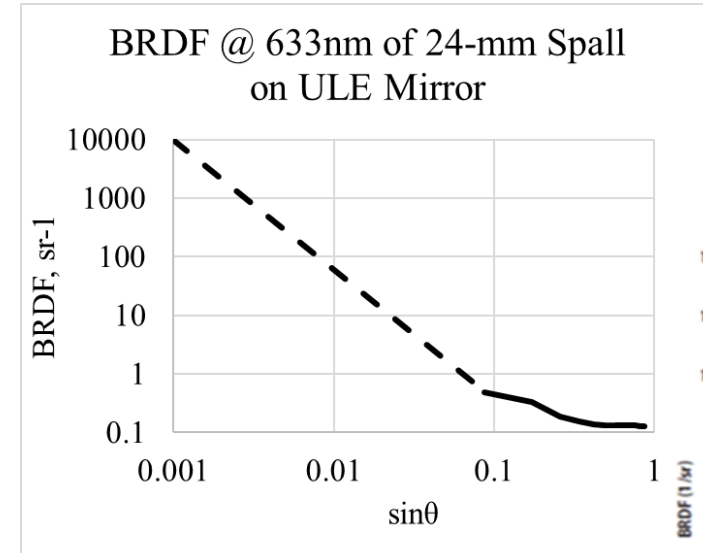
Richard N. Pfisterer, James E. Harvey, James B. Breckinridge, "The role of narrow-angle forward surface scatter and particulate scatter in exoplanet exploration," Proc. SPIE 10698, Space Telescopes and Instrumentation 2018, 106985F (6 July 2018); <https://doi.org/10.1117/12.2314229>

Micrometeoroid Impact: Spall Scatter

The Webb Program Office has impacted glass samples with hypervelocity particles to study micrometeoroid impacts.

BRDF was measured for sample with ~5-mm central crater & ~24-mm spall with a scatterometer from 5 to 60 deg.

‘Extrapolating’ measured data with slope similar to CL BRDF curves (from Fest) gives a ‘peak’ BRDF estimate of $\sim 1\text{E}+3$.



Multiplying by area ratio of 24-mm spall to 6-m PM gives:

$$\text{BRDF} = \sim 2\text{E}-2$$

$$\tau_{NAS} = \sim (5\text{E}-10) \text{ BRDF} = \sim 10 \text{ ppt}$$

One 24-mm spall may contribute entire Raw Contrast micrometeoroid allocation.

Georgi Georgiev, Private Communication, 22 July 24

Fest, Eric, Stray Light Analysis and Control, Chapter 5 Scattering from Particulate Contaminants, SPIE Press, 2013, <https://doi.org/10.1117/3.1000980>

SPIE Proceedings 13129, Optical Modeling and Performance Predictions XIV, 2024

Micrometeoroid Impact: Diffraction Analysis



Assuming that a micrometeoroid impact has a ‘rect(x)’ profile with diameter (d), then its scattered wavefront has a ‘sinc()’ amplitude with angular spread λ/d .

$$\text{rect}(x/d) \langle \mathcal{F} \rangle d \cdot \text{sinc}(d \xi) = \frac{d \sin(d \xi)}{\pi \xi}$$

To calculate Dark Hole power at $2\lambda/D = 0.2 \mu\text{rad}$ (for $\lambda = 600 \text{ nm}$, $D = 6\text{m}$)

- Ratio Area of Impact to Primary Mirror
- Multiple Area Ratio times ‘peak’ $\sim d^2/\pi$ (because small angle $\text{Sin}(d \xi) = (d \xi)$)

Relative Power in Dark hole from Micrometeoroid Impact					
Impact Diameter [mm]	Input Power Ratio	Scatter Angular Spread [μrad]	Scatter Angular Spread [λ/D]	Peak Scatter Amplitude	Relative Power at $2\lambda/D$
24	1.6E-05	25.00	125	2E-04	3E-09
12	4.0E-06	50.00	250	5E-05	2E-10
6	1.0E-06	100.00	500	1E-05	1E-11
3	2.5E-07	200.00	1000	3E-06	7E-13

One 6-mm impact may contribute entire Raw Contrast micrometeoroid allocation.

For More Information:

Mirror surface roughness specification derived from
coronagraphy scatter error budget allocation

Paper 13129-4

H. Philip Stahl
NASA Marshall Space Flight Ctr.

Conclusions



The MSFC UVO-FIR Mirror System & Telescope Technology Development Team is developing / maturing ‘cross-cutting’ technologies that address two Tier-1 gaps identified by the 2022 Astrophysics Biennial Technology Report and their sub-gaps identified by the 2022 Exoplanet Exploration Program Technology Gap List.

During Year 2, significant progress has been made on:

- Absolute Gravity-Sag Characterization
- Tailored Stiffness Mirror Substrates
- Impact of Near-Angle Scatter on Coronagraphy
- Support of Habitable Worlds Observatory (HWO) Exploratory Analytical Concepts (EAC)



Thank You

Questions?