

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

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ABSTRACT

UVO to Far-IR (UVO-FIR) mirror technology development project is a multiyear effort initiated in Fiscal Year (FY) 2022 to mature the Technology Readiness Level (TRL) of critical technologies required to enable ultra-stable telescope of the Habitable Worlds Observatory (HWO) mission. 2023/24 accomplishments include: continued investigations into gravity sag by comparing rotation test vs flip test, quantifying gravity sag as a function of temperature and designing mount for mirror whose G-sag with elevation angle is only coma. Significant progress in developing a methodology for specify optical surface microstructure, contamination cleanliness level and allowable micrometeoroid impacts. Support of HWO. And, a parametric cost model for x-ray telescopes and a parametric volume cost model for normal incidence telescopes.

Keywords: Mirror System Technology Development

1. INTRODUCTION

Marshall Space Flight Center (MSFC) UVO/FIR Team matures mirror and telescope technologies needed to enable or enhance potential UV/Optical to Mid/Far-Infrared Flagship and Probe missions; and provides insight/oversight subject matter experts needed for the manufacture, test, and certification of mirror/telescope assemblies for these missions. Additionally, MSFC's Center for Mirror System Characterization and Acceptance Testing provides services to the community, including thermal-vacuum performance characterization and analysis. Other services to the community include managing SBIR Sub-Topic and awarded contracts; organizing the annual Mirror Technology Days in the Government Workshop; and maintaining the Stahl Telescope Cost Model and Arnold Mirror Modeler tools. As part of these activities, MSFC's senior engineers provide mentoring and training to MSFC's junior and early career engineers.

Initiated in FY22, UV/Optical to Mid/Far-Infrared (UVO/FIR) Mirror System & Telescope Technology ISFM (Internal Scientist Funding Model) Directed Work Package, is a three-year effort to develop/mature 'cross-cutting' technologies that address two Tier 1 Gaps identified by the 2022 Astrophysics Biannual Technology Report [1] and their Sub-Gaps identified by the 2022 Exoplanet Exploration Program Technology Gap List [2] needed to enable a potential Habitable Worlds Observatory (HWO):

- 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

There is significant overlap and synergy between these Gaps. Mirror substrate/structure stiffness and CTE homogeneity are critical for enabling an ultra-stable telescope. CTE homogeneity drives thermal sense and control specifications. And both require validated integrated models. Also mirror substrate/structure stiffness determines gravity sag amplitude.

The UVO/FIR Work Package was initially funded to mature three parallel over-lapping technology maturation tasks and service to community. The three were: 1) mirror substrate CTE homogeneity characterization, 2) absolute characterization of mirror gravity sag, and 3) mitigation of gravity sag via tailored stiffness mirror structures. Additionally, it was expected that other efforts will be added once the Great Observatory Maturation Process (GOMaP) begins.

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
- Ultra-Stable Passive Opto-Mechanical Secondary Mirror Support Structure Design (for JPL)
- Modeling of the Impact of Near Angle Scatter (from Telescope Mirrors) on Coronagraph Performance
- Preliminary Error Budget for Near Angle Scatter

In FY22/23 the team built and correlated a new ‘as-built’ analysis model of the 1.5-m ULE® AMTD-2 mirror, and extrapolated implications for achieving an ultra-stable wavefront for coronagraphy; implemented absolute gravity-sag characterization algorithms and demonstrated the ability to compensate G-sag via a computer generated hologram (CGH); used tailored stiffness to design a mirror for a balloon mission whose only significant gravity sag as a function of elevation angle is coma (which can be eliminated via adjusting the secondary mirror); investigated near-angle scatter from long spatial surface structure; and as a community service, MSFC’s Center for Mirror System Characterization and Acceptance Testing cryo-tested 7 different mirror technologies provided by industrial partners. [3]

2. PROGRESS AND ACCOMPLISHMENTS

In FY23/24 we continued our investigations into gravity sag by comparing results via rotation test versus vertical flip test, quantifying change in gravity sag as a function of temperature and designing center mount for the balloon mission primary mirror whose gravity sag with elevation angle is only coma. We made significant progress in the near-angle scatter study developing a methodology for specifying optical surface microstructure, contamination cleanliness level and allowable micrometeoroid impacts. We had planned to characterize the thermal performance of Schott’s 1.2-m Zerodur mirror but availability schedule conflicts have delayed the test until FY25 Q2. Finally, we supported the HWO GOMaP activity.

2.1 Absolute Gravity Sag Characterization

Gravity Sag characterization and mitigation is a key technology sub-gap of “Mirror Technologies for High Angular Resolution (UV/Vis/Near IR)” Tier 1 technology gap identified to enable HWO. For HWO to perform UV science (i.e. diffraction limited at < 500 nm). The ability to characterize large telescope mirror surface figures to < 4 nm RMS is enabling. Webb with its ultra-stiff beryllium mirrors had a G-sag uncertainty of approx 10 nm rms. Kepler’s 1.5-m ULE® mirror had an uncertainty of 13 to 18 nm rms. Roman’s 2.4-m ULE® mirror has a G-sag uncertainty of 15 to 24 nm rms (L3Harris Document F18902-0586-002, RST PMA Optical Horizontal Test Report).

The goal of this ISFM task is to demonstrate technologies and train the next generation of SMEs in processes to absolutely characterize gravity sag of large mirrors to provide insight/oversight support to HWO.

2.1.1 Comparison of G-Release Measurement Methods

REF: Stephen Cheney, “A comparison of G-release measurement methods”, Proc. SPIE 13134-14, 2024

To expand our experimental capabilities, we are adding a 30-cm window to the 3-m SLTF (Straylight Test Facility) vacuum chamber to enable cryo-vacuum G-sag rotation testing. And we built a vertical test tower using MSFC IRAD and ISFM funding. (Fig 1) The test tower enables ‘face-up/face-down’ G-sag test methodology as well as G-sag as a function of elevation angle testing of mirrors up to 2-m in diameter.

These capabilities are important for three reasons. First, air turbulence is the largest source of G-sag characterization uncertainty. Moving the rotation test into a vacuum environment removes this uncertainty and allows us to explore how small of an uncertainty can be achieved. Second, the rotation test is blind to rotationally symmetric errors, such as spherical aberration. These errors can be characterized via the face-up/face-down flip test; and, if spherical is the only term to be independently characterized, this can be done in air. Third, MSFC is supporting several potential balloon missions whose telescopes must perform over elevation angles from 10 to 65 deg. To achieve these mission’s desired diffraction limited performance, it is necessary to null-polish the primary mirror such that its ‘best’ figure is at an elevation angle of approx 40 degrees. This ‘balances’ the G-sag variation as a function of elevation angle. The MSFC vertical test tower’s off-axis design enables it to provide G-sag data of a 2-m primary mirror over a range of elevation angles.

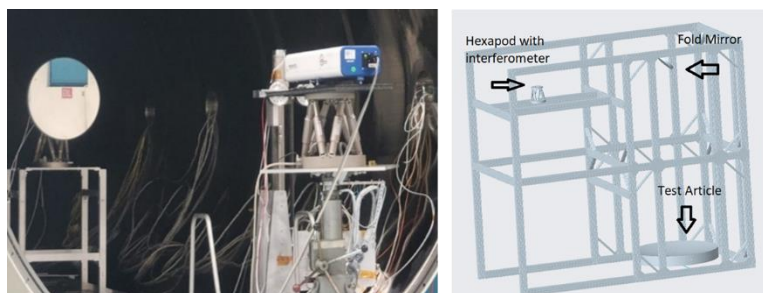


Fig 1: (left) 60-cm Mirror in SLTF for Rotation G-Sag Test; (right) Illustration of 2-m Vertical Test Tower.

Gravity Sag of 60-cm diameter 5-m radius ULE® mirror was characterized in SLTF via rotation test and in 2-m Vertical Test Tower via Flip Test. (Fig 2) As expected, because the rotation test is blind to rotationally symmetric errors, the largest difference between the two tests is spherical aberration (~ 12 nm rms via RSS subtraction). The 7-nm rms difference (after subtracting spherical) is dominated by air turbulence, because both tests were performed in air. The next step is to perform the rotation test in vacuum to eliminate air turbulence. Then repeat for mirrors with larger gravity sags.

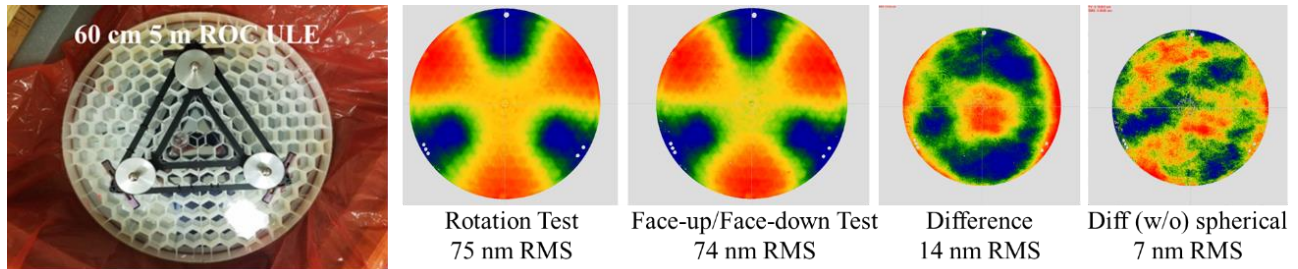


Fig 2: Comparison of Gravity Sag of 60-cm diameter 5-m radius ULE® mirror tested in SLTF via rotation test and in 2-m Vertical Test Tower via Flip Test. As expected, largest difference is spherical aberration. Largest error is air turbulence.

Correlating independent gravity sag estimates (horizontal and vertical) allows us to create an ‘as-built’ model of the mirror’s spatial stiffness. The process is added by changing the gravity vector. For example, the vertical test tower allows us to solve for mirror substrate stiffness as a function of elevation angle.

2.1.2 Cryogenic Gravity Sag

REF: Tomasz M. Lis, "Characterizing gravity sag at cryogenic temperatures", Proc. SPIE 13134, 2024

Given the precision to which gravity sag uncertainty knowledge is needed for a potential HWO mission, potential error sources which were unimportant for other missions, need to be considered. One such error source is change in gravity sag as a function of temperature. This potential error was considered for Webb but determined to be too small to be significant. But the L3Harris Technologies Report F18902-5708-001, Test Report for RST Cold Test of Primary Mirror Assembly offered an interesting observation.

“diagnostic tests led us to consider the change in the stiffness of the PM between 293 K and 263 K. This leads to a change in the gravity sag between the two temperatures. Though this change is small percentage-wise, it becomes significant in the 1g CGH test, when the weight of the PM is not offloaded. The observed amount of change of gravity sag between 263 K and 293 K (about 1.2%) was consistent with values from the manufacturer (Corning), although the values from Corning were not specific to the as-built mirror.”

The reason why G-sag changes as a function of temperature is because material elastic modulus changes with temperature.

To test our ability to characterize this phenomenon, we tested our 1.2-m aluminum mirror’s figure at three rotations (0, 120 and 240 degrees) from ambient (293K) to 35K and calculated its G-sag at each temperature. The mirror’s G-sag (which is almost entirely astigmatism) decreased by ~1 μm (from 9.8 to 8.8 μm) from 293K to 35K. This decrease is consistent with an increase of the mirror’s modulus (i.e. stiffness) with lower temperature. (Fig 3)

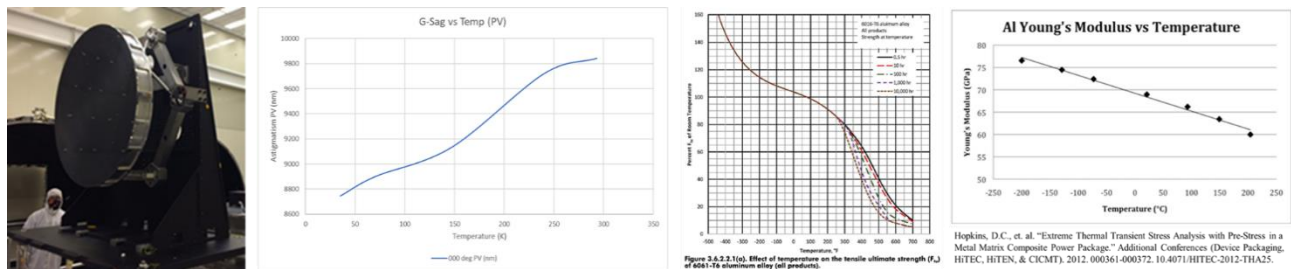


Fig 3: 1.2-m Aluminum Mirror’s G-Sag decreased with Temperature consistent with Modulus increase with Temperature.

2.1.3 CGH Test

Characterizing 100s of nm of G-sag with an uncertainty of 1 to 5 nm rms is good, but for larger (2-m to 6-m) HWO mirrors, G-sags of 10s to 100s of micrometer (larger than what can be resolved by an interferometer) need to be characterized to < 4 nm rms. One solution is to use model-based computer-generated hologram (CGH) to compensate for most of the error (just as CGHs are used to test aspheric mirrors with many 100s of micrometer of aspheric departure).

To demonstrate, CGHs of the 60-cm diameter 5-m radius ULE® mirror's measured G-sag were ordered. In an ambient air environment, the rotation method and CGH method agreed to ~ 10 nm. (Fig 4)

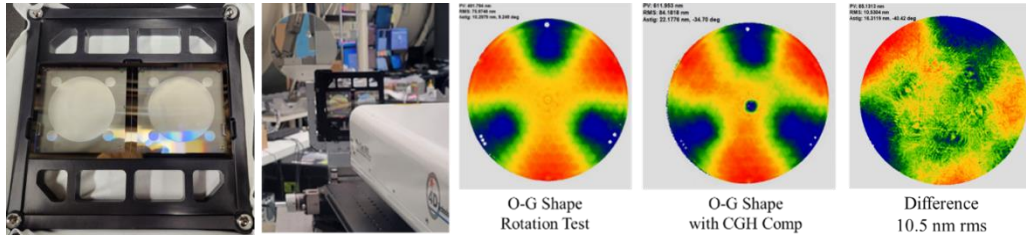


Fig 4: Measured G-Sag and Uncertainty for 4 Mirrors.

Finally, MSFC has taken delivery from Meadowlark a 4D Interferometer with an integrated programmable eCGH (1536 x 1536 pixel Liquid Crystal on Silicon SLM). (Fig 5) The plan is to predict G-sag for a given mirror, program that G-sag into the eCGH, then perform a rotation test. This could eliminate the need for individual CGHs.

2.2 Tailored Stiffness

Tailored stiffness design optimizes a mirror's stiffness to mass ratio via how mass is distributed in the substrate – asymmetric thickness variation of face/back-sheets or core, local reinforcement of core structure, etc. Mirror stiffness is important to HWO as well as potential Probes and Balloon missions. All potential HWO Exploratory Analytical Concept (EAC) telescopes require stiff primary mirror segments – to minimize G-Sag during manufacture and on-orbit G-Release Error; to survive launch; and, to act like rigid bodies on-orbit. EAC-1 has an additional constraint – mass. Its mirrors need to be as low mass as possible. Stiffness is also important for balloon missions – designing the primary mirror to minimize G-sag variation as a function of elevation angle enables diffraction limited performance over all elevation angles.

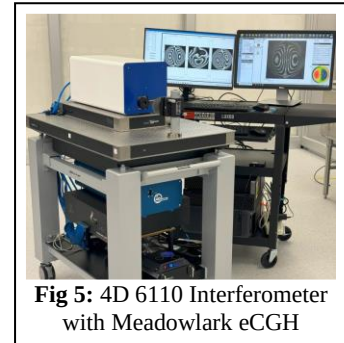


Fig 5: 4D 6110 Interferometer with Meadowlark eCGH

In FY23/24 we continued our tool development activities, including: increasing the number of parameters used for defining the cross-sectional thickness; increasing the number of annular Zernike terms supported; adding support for asymmetric thickness variation (enables optimization at elevations other than 90 degrees); and finding faster, more accurate optimization algorithms to decrease run-time. The tool creates an objective function (desired surface shape) that takes a set of geometry defining parameters as the input and outputs the resulting aberration coefficients. The optimization algorithm interprets how the aberration coefficients change by varying geometry parameters and selects those parameters that best meet the user defined goal.

For a potential balloon mission, we designed two candidate mirror substrates whose G-sag as a function of elevation angle is less than 1 μm rms. Fig 6 compares the performance of the two designs. Mirror A is optimized for minimal total deflection while mirror B is optimized for minimal spherical and higher aberrations – assuming that the PM to SM alignment is adjusted to remove piston, Tip/Tilt and Defocus. While Mirror B has more G-sag as a function of elevation angle than Mirror A, this error is mostly coma – which can be removed via a linear displacement of the secondary mirror relative to the primary mirror. Fig 6 shows that after compensating for coma, Mirror B's error is nearly independent of elevation angle. Next, we will investigate whether the secondary mirror support structure can be designed to passively provide this linear displacement as a function of elevation angle to compensate for coma.

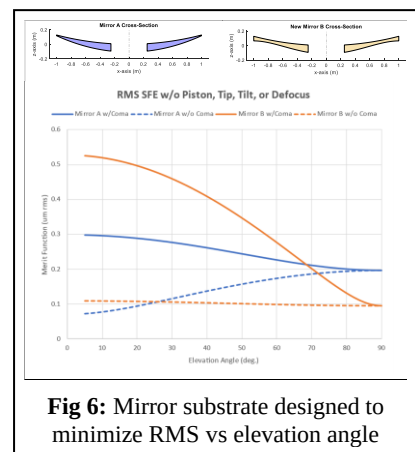


Fig 6: Mirror substrate designed to minimize RMS vs elevation angle

The elevation angle optimization was performed for the mirror rigidly held at its inner diameter. Thus, a center mount interface was designed to simulate a rigid mount (Fig 7).

2.3 Near Angle Scatter

Near Angle Scatter (NAS) of the host star's light from optical surfaces before the coronagraph's focal plane mask produces an E-field across the dark hole that is coherent. These E-fields sum and might be as large or larger than the coronagraph mask leakage E-field. NAS E-fields contribute to the dark hole noise floor via both shot noise and heterodyne amplification of the wavefront instability. There are multiple sources of near-angle scatter, including: long-scale surface structure, surface microstructure, contamination, and micrometeoroid impacts.

REF: Nemati & Stahl "Leveraging the Roman Coronagraph Approach for the HWO Error Budget", SPIE Proc.13092, Space Telescopes and Instrumentation 2024: Optical, Infrared, and Millimeter Wave, 2024

Leveraging the ROMAN error budget approach, we developed a potential raw contrast error budget for detecting an Earth-like planet around a Sun-like star that defined a 'post-correction' NAS allocation of 20 ppt (parts per trillion). (Fig 8)

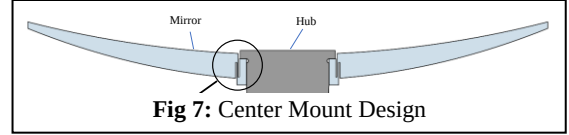


Fig 7: Center Mount Design

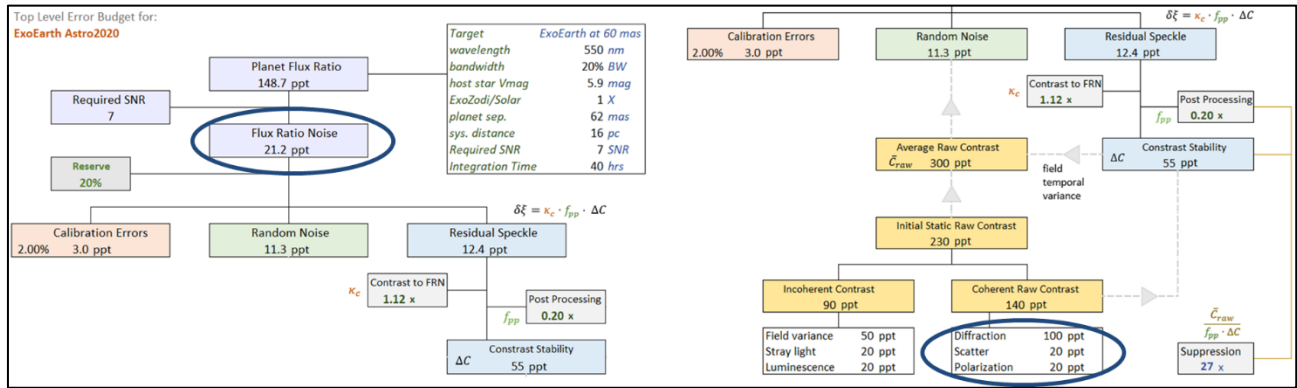


Fig 8: Scattered Light error budget allocation flows from flux ratio to detect exoplanet with SNR = 7 and 40 hr. integration time.

REF: H. Philip Stahl, "Assessment of near-angle scatter on exo-Earth coronagraphy," Proc. SPIE 12676, (4 October 2023); <https://doi.org/10.1117/12.2676543>

In 2023, we published a first-order single-surface analysis that derived 'placeholder' specifications for the primary mirror using Rayleigh-Rice vector scatter theory, generalized Harvey-Shack scalar scatter theory, and Greynolds approximation. For a 10 ppt throughput error budget allocation, the primary mirror specification was: static surface roughness < 1 nm rms, and dynamic 'post-correction' surface structure < 1 pm PV.

REF: Stahl, Smith, & Nemati, "Impact of near-angle scatter on Exo-Earth coronagraphy", SPIE Proc.13092, Space Telescopes and Instrumentation 2024: Optical, Infrared, and Millimeter Wave, 2024

Stahl, "Mirror surface contamination specification derived from coronagraphy scatter error budget", SPIE Proc.13129, Optical Modeling and Performance Predictions XIV, 2024

We derived an expression that specifies the surface statistics required to achieve a given coronagraph error budget NAS throughput allocation. We did this by deriving a direct connection between coronagraph contrast throughput and mirror surface BRDF. And applied this relationship to derive specifications for surface microstructure, contamination and allowed micrometeoroid impacts.

$$\tau_{NAS} = \frac{\Phi_{NAS}(u, v)}{\Phi_i} = BRDF \cdot \Omega_{Core} = BRDF \cdot \pi (\lambda/D)^2$$

where Ω_{Core} = Airy Disc solid angle = $\pi (\theta_{Core})^2 = \pi (\lambda/D)^2$.

The amount of NAS is determined entirely by the statistical properties of the optical surface microroughness and the operating wavelength. Surface properties include not only rms roughness, but also correlation length. (Table 1)

Table 1: Surface RMS Microstructure [$\text{\AA}$] to have NAS Throughput < 0.5 ppt				
	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
1,000	0.2	0.8	1.8	5.8
10,000	0.0	0.1	0.2	0.6

Note that the shortest coronagraph science wavelength drives the surface specification. And correlation length is important. Alternatively, the surface microstructure can be defined via a slope specification. (Table 2)

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

Table 2: Surface RMS Slope [μrad] to have NAS Throughput < 0.5 ppt				
	Wavelength (λ) [μm]			
Correlation Length (ℓ) [μm]	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
1,000	0.0	0.1	0.3	0.8
10,000	0.0	0.0	0.0	0.0

Applying the NAS Throughput to BRDF relationship, we determine that a primary mirror cleanliness level specification for the primary mirror of < CL-400 is needed to meet its error budget allocation. And we calculate that a single primary mirror micrometeoroid impact with a central pit of ~4-mm and spall of ~24-mm may contribute its entire allocation.

3. COMMUNITY SERVICE

In addition to maturation of specific technologies, the MSFC UVO/FIR Team provides service to the community via providing subject matter experts to projects, such as HWO; managing SBIR Sub-Topic and awarded contracts; organizing the annual Mirror Technology Days in the Government Workshop; and maintaining the Stahl Telescope Cost Model and Arnold Mirror Modeler tools. And the Center for Mirror System Characterization and Acceptance Testing provides thermal-vacuum performance characterization and analysis services.

3.1 Habitable Worlds Observatory

During Habitable Worlds Observatory (HWO) GOMAP, MSFC's UVO/FIR Team provided subject matter experts to multiple Working Groups, Sub-Working Groups, and Exploratory Analytical Case (EAC) Studies.

The opto-mechanical team is working to optimize the EAC-1 primary mirror support structure (Fig 9), EAC-2 secondary mirror support structure based on MSFC's design for the JPL 6mST concept (Fig 10) and EAC-2 primary mirror (Fig 11).

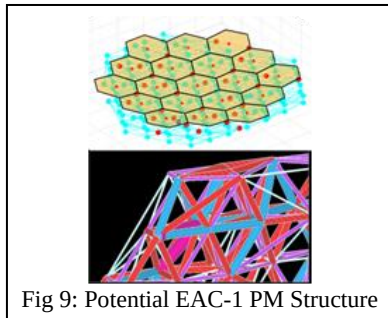


Fig 9: Potential EAC-1 PM Structure

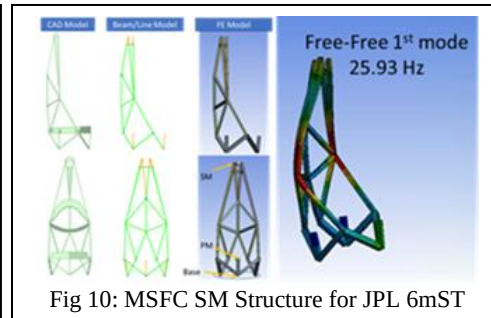


Fig 10: MSFC SM Structure for JPL 6mST

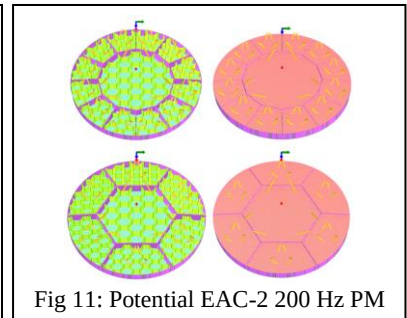


Fig 11: Potential EAC-2 200 Hz PM

The potential EAC-2 primary mirror was designed using MSFC Arnold Mirror Modeler (AMM). 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. The total mass of all variations ranged from 672 to 1272 kg. And the first mode frequency of all variations ranged from 190 to 222 Hz.

3.2 Arnold Mirror Modeler (AMM)

AMM is a tool (subject to ITAR export control restrictions) that rapidly creates input decks for ANSYS, ABAQUS and NASTRAN. It creates a complete analysis stream including: model (geometric structure, material properties, etc.), loads (static and dynamic), etc. AMM can model on-axis and off-axis mirrors; segmented and monolithic; flat back, shaped back, or meniscus; etc. AMM automatically reinforces the core structure for mounting structure.

3.3 Cost Modeling

3.3.1 Normal Incidence Optical Telescope Cost Model

REF: Stahl, “Variations of Parametric Cost Model for Ground & Space Telescopes”, SPIE Proc.13099, Modeling, Systems Engineering, and Project Management for Astronomy XI. 2024

Parametric cost models can be used by designers and managers to compare between major architectural cost drivers and allow high-level design trades; enable cost-benefit analysis for technology development investment; and provide a basis for estimating total project cost between related concepts. Previously, we developed two parametric first-article optical telescope assembly cost models – one based on aperture diameter and the other based on primary mirror segmentation – using a database with 47 total ground and space telescopes.

In FY23/24 we updated these models to FY23 current dollar

$$\begin{aligned} \text{Diameter Model:} \quad \text{OTA\$ (FY23)} &= \$25\text{M} \times 30^{(S/G)} \times D^{(1.7)} \times \lambda^{(-0.5)} \times T^{(-0.25)} \times e^{(-0.028) (Y-1960)} \\ \text{Segmentation Model:} \quad \text{OTA\$ (FY23)} &= \$25\text{M} \times 30^{(S/G)} \times N_{\text{seg}}^{(0.8)} \times D_{\text{seg}}^{(1.7)} \times \lambda^{(-0.5)} \times T^{(-0.25)} \times e^{(-0.028) (Y-1960)} \end{aligned}$$

and developed a new volume-based model.

$$\text{Volume Model:} \quad \text{OTA\$ (FY23)} = \$10.5\text{M} \times 23^{(S/G)} \times V^{(0.6)} \times \lambda^{(-0.25)} \times T^{(-0.2)} \times e^{(-0.014) (Y-1960)}$$

where volume is defined by the telescope diameter and primary to secondary separation.

The purpose of the volume model is to investigate potential cost impact of on-axis versus off-axis telescope configurations. And, the new volume cost model implies that, for a fixed F/# and diameter, an off-axis telescope may cost 50% more than an on-axis telescope – because the volume of the off-axis telescope is 2X longer than for on-axis. Also, the models continue to imply that segmented aperture telescopes costs as much as 30% more than monolithic primary mirror telescopes.

The three cost models have been exercised to predict the 50% and 85% most likely costs for the current Habitable World Observatory Exploration Analytical Cases. (Fig 12)

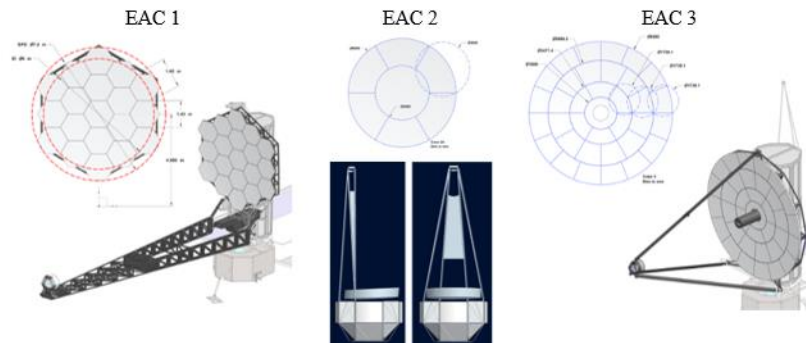


Fig 12: Current Habitable Worlds Observatory Exploratory Analytical Models

The diameter model’s 85% probable cost estimate for the 3 EACs ranged from \$1.5B to \$2.4B. The segmentation model’s 85% cost estimate ranged from \$1.9B to \$3.4B. And the volume model’s 85% cost estimate ranged from \$2.2B to \$3.0B. In general, EAC-2 always has the lowest cost because it has the smallest diameter mirror. As a reminder, these models provide an estimate of the 50% most likely cost. The standard error of these model’s fit to the data is in the 21% to 25% range, and their prediction uncertainty is 2X their standard error. Thus, to get an 85% most likely cost, multiple the 50% estimate by 1.5.

It is important to note that these cost models are for telescopes design and built via conventional engineering practice. These models DO NOT include the cost of the active control systems required to achieve picometer-level ultra-stable optical performance. Such a telescope has never been built. Therefore, there is nothing in the MSFC database that can inform the potential cost of a picometer active control system. Finally, the EAC cost estimates produced by these models are speculative. They need to be evaluated against actual engineering point designs and bottoms up cost estimates.

3.3.2 Grazing Incidence X-Ray Telescope Cost Model

REF Snyder, Stahl, Gaskin, & Perez, "Preliminary Parametric Cost Model for Space X-Ray Telescope", SPIE Proc.13099, Modeling, Systems Engineering, and Project Management for Astronomy XI. 2024

In FY23/24 MSFC created a preliminary parametric model that estimates the 50% most likely cost for space-based X-ray telescopes with grazing incidence optics.

$$XMA\$ (FY23) = \$0.35M \times A^{(-1.05)} \times P^{1.07}$$

where A is the angular resolution measured in arcsec half-power diameter (HPD) and P is the projected area of the mirror module measured in cm². This model explains 98% (adjusted R squared) of the cost variation of 6 space-based X-ray telescope assemblies that used or are currently using grazing incidence optics. To get the 85% likely cost, multiply by 1.3. The data base for this model is limited to fabrication techniques used on previous and current missions, such as direct polished glass full shell, replicated, and foil optics.

4. CONCLUSION

Marshall Space Flight Center (MSFC) UVO/FIR Team matures mirror and telescope technologies needed to enable or enhance potential UV/Optical to Mid/Far-Infrared Flagship and Probe missions; and provides insight/oversight subject matter experts needed for the manufacture, test, and certification of mirror/telescope assemblies for these missions. Additionally, MSFC's Center for Mirror System Characterization and Acceptance Testing provides services to the community, including thermal-vacuum performance characterization and analysis.

MSFC's current UVO to Far-IR (UVO-FIR) mirror technology development project is a multiyear effort initiated in Fiscal Year (FY) 2022 to mature the Technology Readiness Level (TRL) of critical technologies required to enable ultra-stable telescope of the Habitable Worlds Observatory (HWO) mission. 2023/24 accomplishments include: continued investigations into gravity sag by comparing rotation test vs flip test, quantifying gravity sag as a function of temperature and designing mount for mirror whose G-sag with elevation angle is only coma. Significant progress in developing a methodology for specify optical surface microstructure, contamination cleanliness level and allowable micrometeoroid impacts. Support of HWO. And, a parametric cost model for x-ray telescopes and a parametric volume cost model for normal incidence telescopes.

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