Advanced Mirror Technology Development (AMTD): Year Five Status

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ABSTRACT

The Advanced Mirror Technology Development (AMTD) project is in Phase 2 of a multiyear effort initiated in Fiscal Year (FY) 2012, to mature the Technology Readiness Level (TRL) of critical technologies required to enable 4-m-or-larger monolithic or segmented ultraviolet, optical, and infrared (UVOIR) space telescope primary-mirror assemblies for general astrophysics, ultra-high-contrast observations of exoplanets, and National Interest missions. Key accomplishments of 2016/17 include the completion of the Harris Corp ~150 Hz 1.5-meter Ultra-Low Expansion (ULE®) mirror substrate using stacked core method to demonstrate lateral stability of the stacked core technology, as well as the characterization and validation by test of the mechanical and thermal performance of the 1.2-meter Zerodur® mirror using the STOP model prediction and verification of CTE homogeneity.

Keywords: space telescopes, astrophysics, astronomy, HabEx, Zerodur®, LUVOIR,

1. INTRODUCTION

"Are we alone in the Universe?" is probably the most compelling science question of our generation. Per the 2010 *New Worlds, New Horizons* Decadal Report[1]: "One of the fastest growing and most exciting fields in astrophysics is the study of planets beyond our solar system. The ultimate goal is to image rocky planets that lie in the habitable zone of nearby stars." The Survey recommended, as its highest priority, medium-scale activity such as a "New Worlds Technology Development (NWTD) Program" to "lay the technical and scientific foundations for a future space imaging and spectroscopy mission." The National Research Council (NRC) report, *NASA Space Technology Roadmaps & Prioroties*[2], states that the second highest technical challenge for NASA regarding expanding our understanding of Earth and the universe in which we live is to "Develop a new generation of astronomical telescopes that enable discovery of habitable planets, facilitate advances in solar physics, and enable the study of faint structures around bright objects by developing high-contrast imaging and spectroscopic technologies to provide unprecedented sensitivity, field of view, and spectroscopy of faint objects." *NASA's Enduring Quests Daring Vision*[3] called for a LUVOIR surveyor mission to "enable ultra-high-contrast spectroscopic studies to directly measure oxygen, water vapor, and other molecules in the atmospheres of exoEarths," and "decode the galaxy assembly histories through detailed archeology of their present structure." As a result, NASA will study in detail a LUVOIR surveyor and a HabEx Imager concept for the 2020 Decadal Survey.[4,5] Additionally, AURA's *From Cosmic Birth to Living Earths*[6] details the potential revolutionary science that could be accomplished from "directly finding habitable planets showing signs of life."

AMTD's objective is to mature towards TRL6 technologies to enable large monolithic or segmented UVOIR space telescopes. Phase 1 advanced technology readiness of six key technologies required to make an integrated primary mirror assembly (PMA) for a large aperture UVOIR space telescope.

- *Large-Aperture, Low-Areal Density, High-Stiffness Mirror Substrates*
- *Support System*
- *Mid/High-Spatial Frequency Figure Error*
- *Segment Edges*
- *Segment-to-Segment Gap Phasing*
- *Integrated Model Validation*

Phase 2 is continuing the efforts in High-Stiffness Substrates, Support Systems, Segment-to-Segment Gap Phasing and Integrated Model Validation with three clearly defined milestones:

- *Fabricate a ⅓-scale model of 4-m class 400-mm thick deep-core ULE® mirror substrate* to demonstrate lateral scaling of the deep-core process. (Successfully Completed in 2016.)
- *Characterize two candidate primary mirrors* (the ⅓-scale mirror and a 1.2-m Extreme Lightweight Zerodur® Mirror owned by Schott) by measuring their modal performance and optical performance from 250 K to ambient. (Schott 1.2-m Zerodur® mirror successfully characterized in 2016; 1.5-m ULE® Harris mirror is schedule for characterization in 2017.)
- *Add capabilities and validate integrated design and modeling tools* to predict the mechanical and thermal behavior of the candidate mirrors, validate models, generate Pre-Phase-A point designs, and predict on-orbit optical performance. (Schott 1.2-m Zerodur® mirror mechanical and thermal performance models were successfully validated by test in 2016; 1.5-m ULE® Harris mirror models are schedule for validation by test in 2017; Additionally, NASA MSFC is using integrated design and modeling tools on the potential Habitable Exoplanet Imager mission.).

2. PROGRESS AND ACCOMPLISHMENTS

2.1 Large-Aperture, Low-Areal-Density, High-Stiffness Mirror Substrates

Need: Thicker, stiffer mirror substrates are required to achieve ultra-stable mechanical and thermal performance required for high-contrast imaging, either (4-m to 8-m) monolithic or (8-m to 16-m) segmented mirrors.

Accomplishment: During FY 2016/17, AMTD-2 advanced the TRL of this technology by fabricating a 450-Hz 1.5-m substrate and producing a 3.5-m radius of curvature spherical mirror with a protected aluminum coating.

High-Stiffness Mirror Substrates: Previously, AMTD-1 advanced TRL by successfully demonstrating the ability to make a 40-cm thick subscale mirror substrate via the stacked-core low-temperature fusion (LTF) process. This extended the previous SOA for deep-core substrates from <300 mm to >400 mm. This was done by making a 43-cm diameter 40-cm thick full-scale 'cut-out' of a 4-m mirror. In 2016, AMTD-2 achieved its major milestone for this technology when Harris Corp successfully low-temperature-fused (LTF) a 1.5-m diameter by 165 mm thick 5-layer ULE® mirror substrate with a 450 Hz first mode frequency. In 2016/17 Harris Corp low-temperature-slumped (LTS) the mirror substrate to a 3.5 meter radius of curvature then ground, polished, coated it with protective aluminum and integrated it into a flight-like mount (Figure 1). In 2017 the mechanical and thermal performance of this mirror assembly will be characterized at NASA MSFC.

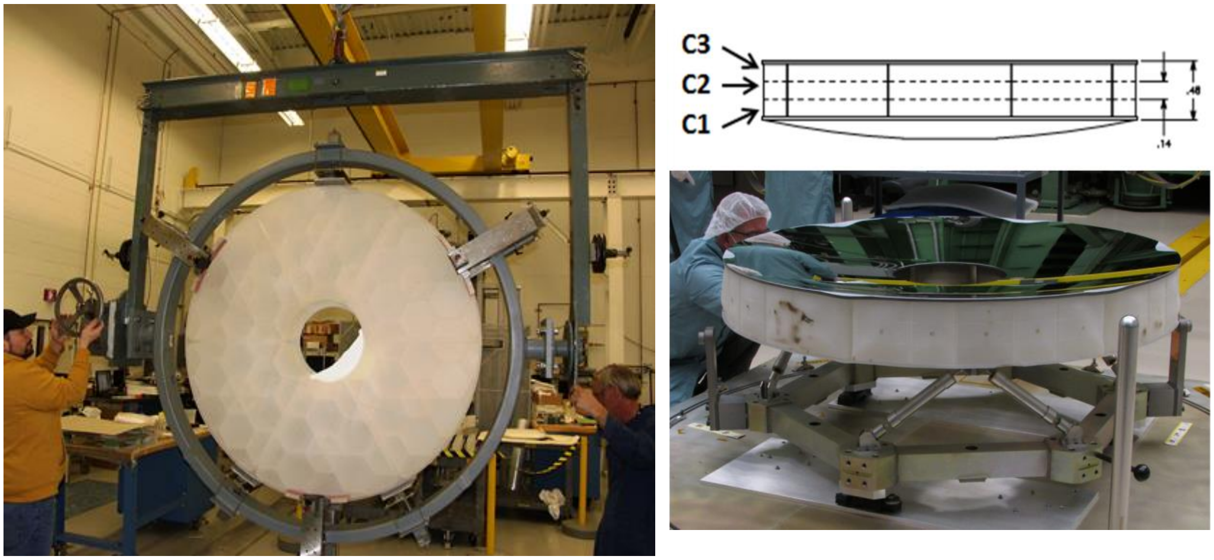


Figure 1: (left) Low-temperature-fused substrate; (top right) 5-layer design; (bottom right) completed mirror assembly.

During AMTD-1 when the 43-cm deep-core mirror was slumped from 5.0 to 2.5-meter radius of curvature, there was noticeable deformation in the core walls. To quantify the magnitude of this bending MSFC imaged the mirror's internal structure via x-ray tomography. A small amount of bending was expected because slumping places the concave surface in compression and stretches the convex surface; this places the core elements in shear stress. The measured deformation exceeded that expectation. Fortunately, analysis indicated that such core-wall bending had a limited effect on the mirror's strength.

In designing the 1.5-meter 1/3rd scale model of a 4-meter mirror, Harris Corp used proprietary modeling tools to predict the visco-elastic performance of the mirror (Figure 2). The spacing between the wedge-shaped core elements was specifically increased to prevent adjacent core-walls from touching. While the core walls never touched, they did get within <0.25 mm at four locations. (Figure 2). In 2017 MSFC plans to image the internal structure of the mirror via X-Ray computed tomography, use that data to create an as-built 3D model of the mirror to predict its mechanical and thermal performance, and characterize its performance.

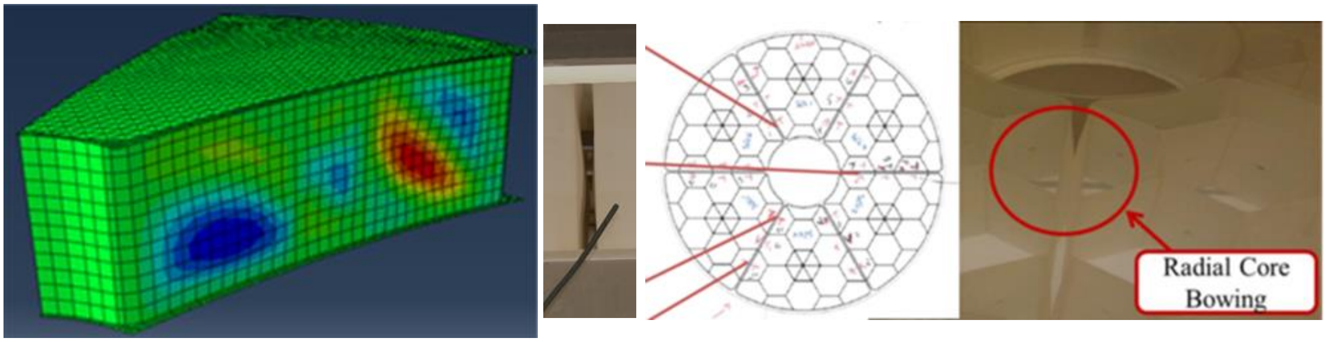


Figure 2: (left) predicted visco-elastic deformation used to design mirror substrate; (right 3 images) actual visco-elastic deformation; 4-locations with gaps of less than 0.25 mm.

Explaining core-wall bending is complicated. Previous to AMTD, the only mirrors fabricated via LTS replication were AMSD/MMSD. Neither of these mirrors exhibited core-wall bending. Preliminary analysis indicates that the effect depends upon the shear stress in the radial core-walls. The greater the amount of shear stress, the greater the amount of viscous flow of the glass during LTS replication and the greater the core-wall bending. Preliminary analysis indicates that this shear stress is proportional to the unsupported radial core wall length divided by the radius of curvature (independent of core thickness and independent of whether the core is composed of a single layer or multiple layers). The AMTD-1 2.5-m ROC 0.43-m diameter x 400-mm thick mirror had significantly larger core cells than the AMTD-2 3.5-m ROC 1.5-m diameter x 165-mm thick mirror; and thus, less bending. An AMTD-3 proposal to resolve this issue was submitted to the ROSES 2016 SAT.

<u>Arnold Mirror Modeler:</u> the Arnold Mirror Modeler was developed under AMTD to rapidly create and analyze detailed mirror designs. The AMM creates a complete analysis stream, including model, loads [static and dynamic], plots and a summary file of input variables and results suitable for optimization or trade studies. Values of all settings can be archived and recalled to continue or redo any configuration. In FY16/17 an updated AMM was released and is being used to perform point design trade studies for HabEx closed-back ULE® and open-back Zerodur® mirror systems.

2.2 Support Systems

Need: Large mirrors require large support systems to ensure they survive launch and deploy on-orbit, stress-free, and undistorted. Additionally, segmented mirrors require structure systems that establish and maintain the mirror's shape.

Accomplishment: During FY 2016/17, AMTD-2 progressed this technical area by continuing to develop mount capabilities in the Arnold Mirror Modeler and using it to perform trade studies of candidate mirror mount systems for HabEx. The emphasis of these trade studies is understanding and specifying dynamic primary mirror wavefront error.

Dynamic WFE is produced when a mirror is inertially accelerated by a mechanical disturbance, causing it to react (i.e. bend) against its mounts. A 'static' example is gravity sag. The acceleration of gravity causes a mirror to bend on its mount. Assuming that no resonant mode is excited, a mirror's dynamic WFE has the same shape as its gravity sag with an amplitude proportional to the disturbance's 'G-acceleration'. Assuming that the mirror substrate's first mode stiffness is higher than the mechanical disturbance frequencies, the biggest accelerations occur when the mechanical disturbance excites a mount resonance mode. AMTD-2 has studied dynamic WFE for various mirror substrates on both 3-point and 6-point mounts attached to the substrate at the edge, 80% and 50% radial points (Figure 3).

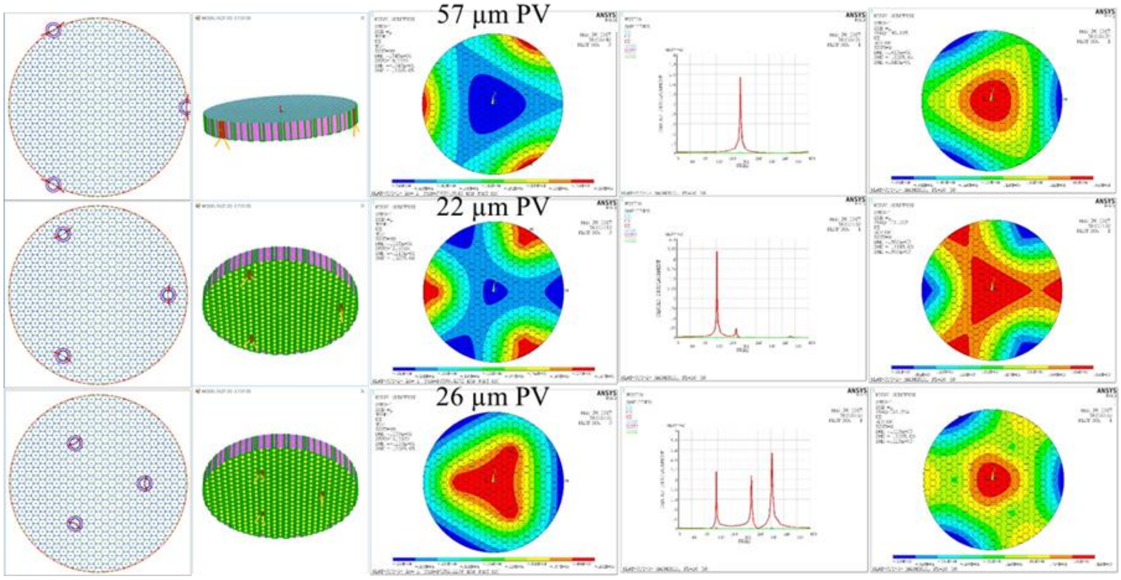


Figure 3 Static gravity sag and dynamic deformation of 180-Hz 4-m diameter closed-back mirror on 3-point mount attached at edge, 80% and 50% radial locations.

2.3 Mid/High-Spatial Frequency Error

Need: High-contrast imaging requires mirrors with very smooth surfaces (< 10 nm rms). While deformable mirrors can correct low-order errors, they cannot correct mid and high-spatial frequency errors. Such errors can arise from the fabrication process or CTE inhomogeneity and can introduce artifacts into the dark hole.

Accomplishment: During FY 2016/17, AMTD-2 advanced TRL in this area by characterizing the thermal performance of the 1.2-m Extreme Lightweighted Zerodur® Mirror (ELZM) owned by Schott. This test accomplished half of this task's major milestone. Anticipated testing of the 1.5-m ULE® mirror in 2017 will complete this milestone. Previously, AMTD-1 had demonstrated the ability of the Harris Corp's ion polishing process to produce a 5.4-nm rms surface.

Thermal Characterization: In 2016/17 NASA MSFC enhanced its 23m x 7m thermal vacuum test chamber by adding a pressure tight enclosure that allows test equipment to be placed at the center of curvature of short radius of curvature mirrors (Figure 4 left). This new capability enabled testing of the Schott 1.2-m ELZM mirror from ambient to 250K. No thermal deformation induced high-spatial quilting associated with the lightweight was measured. The test did measure 9.4 nm rms of mid-spatial error associated with coefficient of thermal expansion (CTE) inhomogeneity (Figure 4 right).

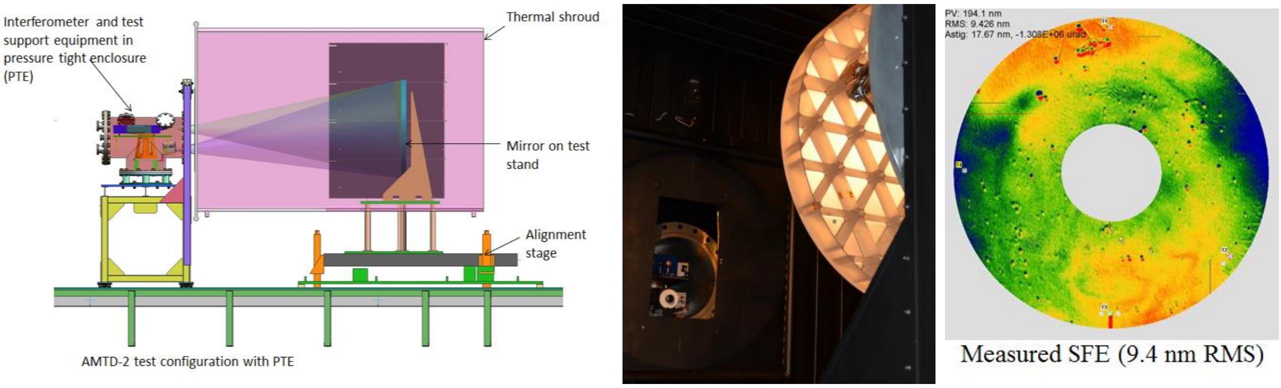


Figure 4: (left) Short radius of curvature mirror test setup with pressure tight enclosure. (center) Schott ELZM Mirror in test setup. (right) Measured thermal surface figure change from 250K to ambient.

2.4 Segment-to-Segment Gap Phasing

Need: To avoid speckle noise which can interfere with exoplanet observation, internal coronagraphs require an ultra-stable wavefront.

Accomplishment: During FY 2016/17, AMTD-2 progressed this technical area by continuing the systems engineering effort to understand the interaction between optical telescope wavefront stability and coronagraph contrast leakage.

<u>Contrast Leakage WFE Tolerances:</u> In our previous studies, we evaluated the contrast leakage over specific regions of interest (ROI). These studies showed a correlation between numbers of segment rings and noise in a dark-hole ROI. These studies also provided preliminary tolerance values for the allowed amounts of different wavefront errors. Because of the asymmetric nature of the ROI, the tolerance results were misleading. Therefore, in FY2016/17 we implemented a new method that decomposes contrast leakage into average radial (photometric noise) and azimuthal (systematic noise) components as defined by Shaklan.[7] The new method confirms our previous conclusions that segment-to-segment co-phasing (piston and tip/tilt) errors must be stable in the 10 to 20 picometer PV range. The new method was used to evaluate the contrast leakage in annular ROI for 50 random trials global Seidel and Zernike aberration produced by rigid body motion of the primary and/or secondary mirror assemblies. The maximum allowance for static aberration and contrast leakage for aberration exhibiting sinusoidal variation was also studied. Table 1 lists the maximum amount of random WFE that a 4th order radial coronagraph can tolerate while keeping the photometric noise less than 10-10 and the systematic noise less then 5x10-11 over an annular ROI from 1.5 to 2.5 λ/D.

Table 1: PV Aberration Amplitude Tolerance for Contrast Leakage over an annular ROI from 1.5 to 2.5 λ/D

Aberration (Random)	WFE (pm) for 1×10^{-10} of Photometric Noise	WFE (pm) for 5×10^{-11} of Systematic Noise
Tip/Tilt	9,600	35,000
Seidel Power	1,100	22,000
Zernike Astigmatism	6,800	49,000
Zernike Trefoil	6,800	44,000
Zernike Hexafoil	9,600	78,000
Seidel Spherical	300	11,000
Seidel Coma	6,800	840

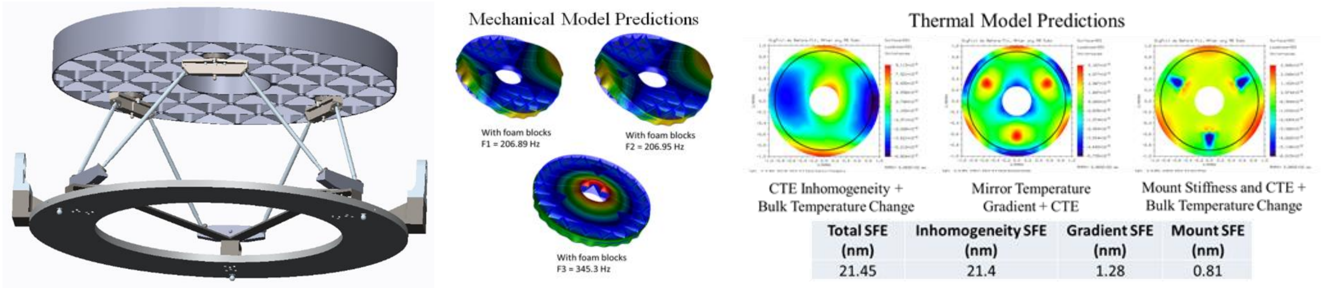
Photometric noise (radial average) is more sensitive to rotationally symmetric aberrations such as Seidel spherical than Seidel power. It is equally apparent that systematic noise is more sensitive to rotationally asymmetric aberrations, such as Seidel coma, than to rotationally symmetric aberrations like Zernike astigmatism.

2.5 Integrated Model Validation

Need: On-orbit performance is driven by mechanical stability (both thermal and dynamic). As future systems become larger, compliance cannot be fully tested; performance verification will rely on results from a combination of sub-scale tests and high-fidelity models. It is necessary to generate and validate as-built models of representative prototype components to predict on-orbit performance for transmitted wavefront, point spread function (PSF), pointing stability, jitter, thermal stability, vibro-acoustic, and launch loads.

Accomplishment: During FY 2016/17, AMTD-2 accomplished a defined major milestone by applying its developed integrated design and modeling tools to conduct point design trade studies for the HabEx primary mirror, including on-orbit performance predictions. Additionally during FY2016/17, AMTD-2 accomplished half of another major milestone by using its integrated modeling tools to predict the mechanical and thermal behavior of the Schott 1.2-m ELZM mirror assembly then validating those predictions by test. AMTD-2 expects to complete this major milestone in 2017 through validating by test its performance predictions for the 1.5-m ULE® mirror assembly.

Mechanical and thermal models were made of the Schott 1.2-m ELZM mirror. The mechanical model predicted a gravity sag deformation of 125 nm rms and a first free-free resonant bending mode of 207 Hz. The thermal model predicted a 21 nm rms total surface figure error (SFE) consisting of contributions from its athermal mount, through thickness thermal gradient and bulk CTE homogeneity. The largest contributor of this error is from an assumed CTE homogeneity of 10 ppb (based on Schott catalog data). (Figure 5)



Total SFE (nm)	Inhomogeneity SFE (nm)	Gradient SFE (nm)	Mount SFE (nm)
21.45	21.4	1.28	0.81

Figure 5: (left) Schott 1.2-m ELZM assembly; (center) Predicted 1st mode frequency; (right) Predicted thermal surface error.

The models were validated by test in the MSFC XRCF. First mode frequency was measured via tap test on foam blocks to be 196 Hz (5% agreement). Gravity sag was measured by rotation test to be 142 nm rms; with a 31 nm rms difference between predicted and measured. (Figure 6) This difference could be caused by a 2-mm error between the model and the 'as-built' mount pad locations.

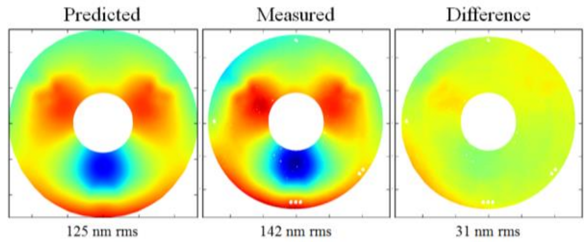
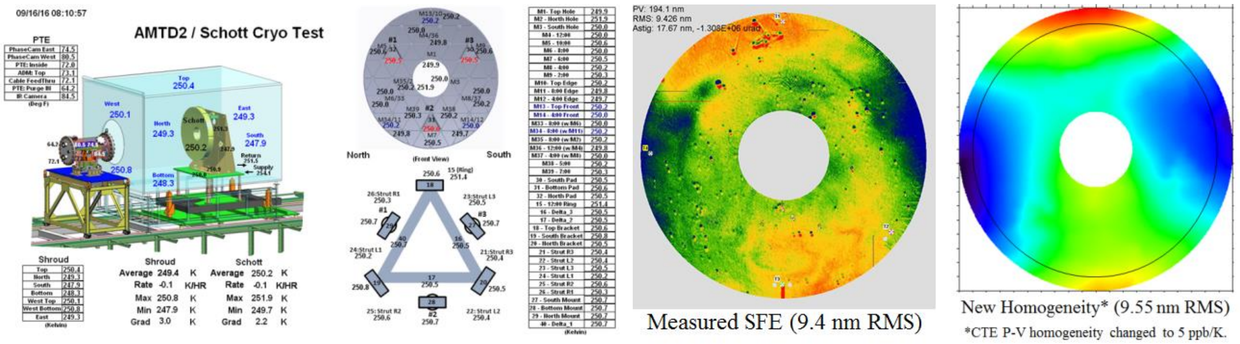


Figure 6: ELZM Gravity Sag Predicted versus Measured.

Thermal model predictions are validated by measuring how the mirror shape deforms from 294K to 250K. To facilitate the thermal model, the mirror assembly was fully instrumented with thermal sensors to measure its bulk temperature and thermal gradients. Using the Schott catalog specification of 10 ppb CTE homogeneity the predicted thermal SFE is 21 nm rms. But, the measured SFE is 9.4 nm rms. After consulting with Schott, we were informed that the 1.2-m ELZM mirror has a CTE homogeneity of 5 ppb. With this new CTE specification, the predicted SFE is 9.55 nm rms. (Figure 7)



PTE

PhaseCam East	74.5
PhaseCam West	80.5
PTE: Inside	72.0
ADM: Top	73.1
Cable FeedThru	72.1
PTE: Purge IR	64.2
IR Camera	84.5

(Deg F)

Shroud

Top	250.4
North	249.3
South	247.9
Bottom	248.3
West Top	250.1
West Bottom	250.8
East	249.3

(Kelvin)

Shroud			Schott		
Average	249.4	K	Average	250.2	K
Rate	-0.1	K/HR	Rate	-0.1	K/HR
Max	250.8	K	Max	251.9	K
Min	247.9	K	Min	249.7	K
Grad	3.0	K	Grad	2.2	K

M1 - Top Hole	249.9
M2 - North Hole	251.9
M3 - South Hole	250.0
M4 - 12:00	250.0
M5 - 10:00	250.6
M6 - 8:00	250.0
M7 - 6:00	250.5
M8 - 4:00	250.2
M9 - 2:00	250.3
M10 - Top Edge	250.2
M11 - 8:00 Edge	249.8
M12 - 4:00 Edge	249.7
M13 - Top Front	250.2
M14 - 4:00 Front	250.0
M33 - 8:00 (w M6)	250.0
M34 - 8:00 (w M11)	250.2
M35 - 8:00 (w M2)	250.2
M36 - 12:00 (w M4)	249.8
M37 - 4:00 (w M8)	250.0
M38 - 5:00	250.2
M39 - 7:00	250.3
30 - South Pad	250.5
31 - Bottom Pad	250.6
32 - North Pad	250.5
15 - 12:00 Ring	251.4
16 - Delta_3	250.5
17 - Delta_2	250.5
18 - Top Bracket	250.6
19 - South Bracket	250.8
20 - North Bracket	250.5
21 - Strut R3	250.4
22 - Strut L2	250.4
23 - Strut L3	250.5
24 - Strut L1	250.2
25 - Strut R2	250.6
26 - Strut R1	250.3
27 - South Mount	250.7
28 - Bottom Mount	250.7
29 - North Mount	250.7
40 - Delta_1	250.7

(Kelvin)

Measured SFE (9.4 nm RMS)

New Homogeneity* (9.55 nm RMS)

*CTE P-V homogeneity changed to 5 ppb/K.

Figure 7: (left) Test thermal sensors; (center) Measured SFE; (right) Predicted SFE with corrected CTE Homogeneity.

3. CONCLUSION

The Advances Mirror Technology Development (AMTD) project is a multi-year effort to mature towards TRL-6 technologies needed to enable 4 to 8 meter UVIOR space telescope primary mirror assemblies for both general astrophysics and ultra-high contrast observations of exoplanets. To provide the science community with option, we are pursuing multiple technology paths including both monolithic and segmented space mirrors. AMTD continues to make measureable progress against defined milestone metrics.

ACKNOWLEDGEMENTS

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