Overview and Accomplishments of Advanced Mirror Technology Development Phase 2 (AMTD-2) project

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ABSTRACT

The Advance Mirror Technology Development (AMTD) project is in Phase 2 of a multiyear effort, initiated in FY12, to mature by at least a half TRL step critical technologies required to enable 4 meter or larger UVOIR space telescope primary mirror assemblies for both general astrophysics and ultra-high contrast observations of exoplanets. AMTD Phase 1 completed all of its goals and accomplished all of its milestones. AMTD Phase 2 started in 2014. Key accomplishments include deriving primary mirror engineering specifications from science requirements; developing integrated modeling tools and using those tools to perform parametric design trades; and demonstrating new mirror technologies via sub-scale fabrication and test. AMTD-1 demonstrated the stacked core technique by making a 43-cm diameter 400 mm thick 'biscuit-cut' of a 4-m class mirror. AMTD-2 is demonstrating lateral scalability of the stacked core method by making a 1.5 meter 1/3rd scale model of a 4-m class mirror

Keywords: Space Telescope Mirrors, Mirror Technology Development

1. INTRODUCTION

Measurements at ultraviolet, optical and infrared (UVOIR) wavelengths provide robust, often unique, diagnostics for investigating astronomical environments and objects. UVOIR observations are responsible for much of our current astrophysics knowledge and will produce as-yet unimagined paradigm-shifting discoveries. A new, larger UVOIR telescope is needed to help answer fundamental scientific questions, such as: Does life exist on nearby Earth-like exoplanets? How do galaxies assemble their stellar populations? How do galaxies and the intergalactic medium interact? And, how did planets and smaller bodies in our own solar system form and evolve?

According to the 2010 Decadal Survey *New Worlds, New Horizons in Astronomy and Astrophysics*[1], an advanced large-aperture UVOIR telescope is required to enable the next generation of compelling astrophysics and exo-planet science. It also noted that present technology is not mature enough to affordably build and launch UVOIR telescopes that are diffraction-limited at visible (or shorter) wavelengths, with apertures larger than 4 m. Per the NRC 2012 report *NASA Space Technology Roadmaps & Prioroties*[2], the second highest technical challenge for NASA regarding expanding our understanding of Earth and the universe in which we live is "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 2014 Astrophysics Plan *Enduring Quests Daring Visions*[3] recommends building an 8 to 16-meter Large UV/Optical/Infrared (LUVOIR) Surveyor mission with sufficient sensitivity and angular resolution to "dramatically enhance detection of Earth-sized planets to statistically significant numbers, and allow in-depth spectroscopic characterization. AURA's 2015 report *Cosmic Birth to Living Earths*[4] states that "a 12 meter class space telescope with sufficient stability and appropriate instrumentation can find and characterize dozens of Earth-like planets and make transformational advances in astrophysics".

Finally, according to the NASA Office of Chief Technologist *Science Instruments, Observatory and Sensor Systems Technology Assessment Roadmap*[5], technology to enable a future UVOIR or high-contrast exo-planet mission needs to be at TRL 6 by 2018, so a viable flight mission can be proposed to the 2020 Decadal Review.

2. ADVANCED MIRROR TECHNOLOGY DEVELOPMENT (AMTD)

AMTD is a NASA Strategic Astrophysics Technology project. Begun in 2011, we are currently in Phase 2. Our objective is to mature towards TRL-6 critical technologies to produce 4-meter or larger flight-qualified UVOIR mirrors needed to enable future missions. Just as JWST's architecture was constrained by the Ariane 5 mass and volume capacity, future mission architectures will depend on future launch vehicle capacities. To provide the science community with options, we are pursuing technology for monolithic, segmented or sparse aperture telescopes. AMTD uses a science-driven systems engineering approach. We mature technologies required to enable the highest priority science AND result in a high-performance low-cost low-risk system. Our outstanding team from academia (STScI and Univ of Arizona), industry (Harris, Corning, Schott and Teledyne), and government (GSFC, JPL and MSFC) has extensive expertise in astrophysics and exoplanet characterization, and the design/manufacture of monolithic and segmented space telescopes.[6-7] One of our key accomplishments is that we have derived engineering specifications for advanced normal-incidence monolithic and segmented mirror systems needed to enable both general astrophysics and ultra-high contrast observations of exoplanets missions as a function of potential launch vehicle and its inherent mass and volume constraints.[8-10] To assist in architecture trade studies, the Engineering team develops Structural, Thermal and Optical Performance (STOP) models of candidate mirror assembly systems including substrates, structures, and mechanisms. These models are validated by test of full- and subscale components in relevant thermo-vacuum environments. Specific analyses include: maximum mirror substrate size, first fundamental mode frequency (i.e., stiffness) and mass required to fabricate without quilting, survive launch, and achieve stable pointing and maximize mechanical and thermal stability.[11-13]

2.1 AMTD Phase 1

Phase 1 defined and initiated a program to mature by at least a 0.5 TRL step 6 key technologies required to fabricate monolithic and segmented UVOIR space mirrors. AMTD-1 completed all its stated goals; two of which are being further developed in Phase 2. AMTD's key Phase 1 accomplishment was proving the ability to make a 400-mm deep mirror, at the 0.5-m scale, that is traceable to a UVOIR 4-m mirror with <6 nm rms surface figure and a 60 kg/m^2 areal density.[14-15]

Phase 1 technical milestone accomplishments include:

- *Large-Aperture, Low Areal Density, High-Stiffness Mirror Substrates:* We successfully demonstrated (on a 43 cm diameter cut-out of a 4 meter mirror) a new fabrication process (stacked core low-temperature fusion) which extends the previous state of the art for deep core mirrors from less than 300 mm to greater than 400 mm. This advance leads to stiffer 4 to 8 meter class monolithic primary mirror substrates at lower cost and risk.[14-15]
- *Support System:* We generated point designs for 4- to 8-m mirror substrates which minimize internal mirror stress using a new opto-mechanical design and modeling tool.[11-12]
- *Mid/High Spatial Frequency Figure Error:* We successfully demonstrated ability to produce a zero-gravity optical surface of < 6 nm rms at a 2C operating temperature.[14-15]
- *Segment Edges:* We successfully demonstrated an achromatic edge apodization process to minimize segment edge diffraction and straylight on high-contrast imaging PSF.[16]
- *Segment to Segment Gap Phasing:* We investigated utility of correlated magnetic interfaces to reduce segment to segment co-phasing error. But determined that it cannot achieve the extreme (< 10 pm rms on 600 second timescales) engineering tolerances needed to meet ultra-high contrast exoplanet imaging requirements. Additionally, we successfully demonstrated the fine stage of a two-stage actuator that can be used to align a monolithic mirror or co-phase a segmented mirror.[6]
- *Integrated Model Validation:* We developed a new opto-mechanical design and modeling tool which creates point designs of monolithic and segmented primary mirrors > 10X faster than commercial tools and facilitates transfer of a high-resolution mesh to various mechanical and thermal analysis tools. We conducted trade studies for 4-m and 8-m mirror systems; created and validated models to predict gravity sag and 2C thermal gradients; defined and started implemented a systems analysis framework that combines simulation results from multiple engineering disciplines to predict on-orbit optical performance.[11-13]

Finally in the last year we had 4 student interns; and, Jessica Gersh-Range received her PhD from Cornell University and published two papers in the SPIE Journal of Astronomical Telescope and Instrument Systems.[17-18]

2.2 AMTD Phase 2

Phase 2 is the next step towards our goal of sufficiently maturing technology required to enable a viable Pre-Phase-A design for a large-aperture UVOIR telescope. Based on our Phase 1 success – of demonstrating, at the 0.5-m scale, the ability to make very stiff UVOIR traceable ULE® mirrors (<6 nm rms surface on a 60-kg/m^2 400-mm deep-core substrate with appropriate flexure strength) using the stack-core low-temperature-fusion/low-temperature-slumping (LTF/LTS) process – the Cosmic Origins (COR) Program Office Technology Management Board found that: "larger aperture (≥4-m dia), low-areal-density, high-stiffness mirror substrate development is currently at TRL3"; and if successfully completed, AMTD "will elevate the flat-to-flat stacked-core ULE® mirror substrate technology to TRL4".

In consultation with the COR Program Office, we are focusing our Phase 2 efforts on three clearly defined goals:

- Fabricate a ⅓-scale model of 4-m class 400-mm thick deep-core ULE® mirror. The purpose of this mirror is to demonstrate lateral scaling of the deep-core process to a larger mirror.
- 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.
- Continue to add capabilities and validate our integrated design and modeling tools to predict the mechanical and thermal behavior of the candidate mirrors; validate our models; generate Pre-Phase-A point designs; and predict on-orbit optical performance.

3. ACCOMPLISHMENTS

In the last year, as we completed Phase 1 and started Phase 2, we advanced the TRL in four technologies. Additionally, we continued our effort to derive engineering specifications for primary mirrors from science requirements.

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

Need: To achieve the ultra-stable mechanical and thermal performance required for high-contrast imaging, both (4 to 8 meter) monolithic and (8 to 16 meter) segmented primary mirrors require larger, thicker, and stiffer substrates.

Accomplishment: In FY 2014/15, MSFC performed X-Ray tomographic 3D measurements of the 43 cm deep core mirror (Figure 1) to quantify the visco-elastic geometric deformations produced during the LTF process.

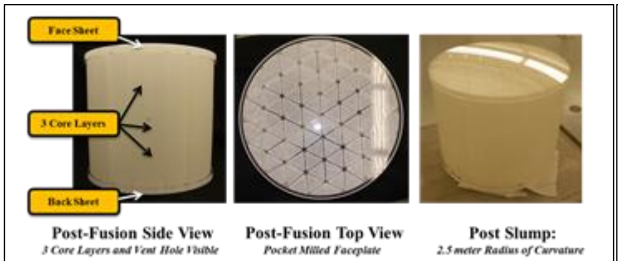


Fig. 1: 43 cm Deep core mirror

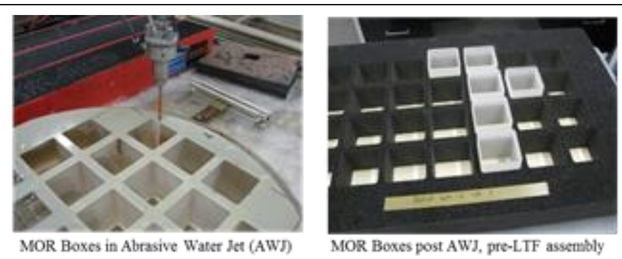


Fig. 2: MOR test-articles

Previously, in FY 2013/14, Harris tested the core-to-core Low Temperature Fusion (LTF) bond strength using 12 Modulus of Rupture (MOR) test articles (Figure 2). The Weibull 99% survival value was 50% above the most conservative design allowable value for margin of safety calculations at the core-to-plate LTF bond. The data on the 50 samples ranged from 60% to 250% above this design allowable value. In FY 2014/15, Harris performed an A-Basis test of the core-to-core LTF bond strength using 60 MOR samples: 30 samples were assembled with nominal alignment and 30 samples were deliberately misaligned. The A-basis Weibull 99% Confidence strength allowable based on 49 of the samples was found to be 17.5MPa which is approximately 50% higher than the strength of core-to-plate LTF bonds.

In FY 2014/15, Harris completed the design of the 1.5-m diameter, 200 mm thick mirror (Figure 3), to be fabricated via the deep core technology. Using the X-ray tomography data, A-Basis strength data and a non-linear visco-elastic design tool, Harris started by designing a 4-m class mirror that could be manufactured via the deep core 'stack & seal' process; then, they scaled the mirror to 1.5-m diameter. The primary purpose of this mirror is to demonstrate lateral scalability of the fabrication process. Currently, Harris is polishing the faceplates. The 18 core elements will be fabricated in September.

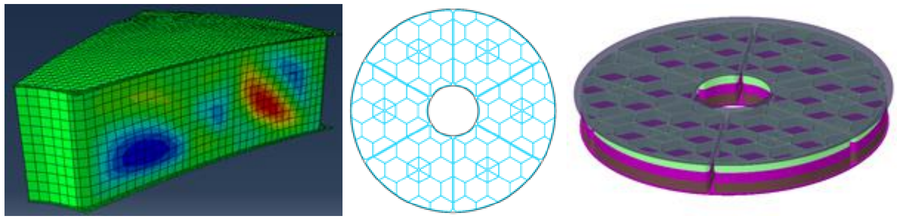


Fig. 3: Final design for 1.5m mirror.

Additionally, we continue to develop our modeling tool in Visual Basic for ANSYS Finite Element Modeling (FEM). This tool allows rapid creation and analysis of detailed mirror designs. In FY14/15, we added architectures for monolithic and segmented mirrors (including Sofia-style and hub and petal mirrors).[20-21] And, we continue to perform Pre-Phase-A trade studies. Figure 4 shows an analysis of how mass scales as a function of mirror diameter when a 400 mm thick mirror substrate is designed to have either a 100 Hz or 200 Hz first mode.

CRITERIA	2 meter		4 meter		6 meter		8 meter	
	kg	hz	kg	hz	kg	hz	kg	hz
100 hertz	88	100	911	106	14908	106	(2)	(2)
200 hertz	130	231	5727	204	(1)	(1)	(2)	(2)

(1) Doubling facesheet thickness (24010 kg) still only increased f=109 hz.
(2) Upper limits of feasible design (32,312 kg) only produced f=66 hz. at 8 meter OD

Fig. 4: Trade Study of Mass versus Diameter as a function of Stiffness.

3.2 Support System

Need: Large mirrors require large support systems to survive launch and deploy on-orbit stress-free and undistorted.

Accomplishment: We continue to develop our modeling tool in Visual Basic for ANSYS Finite Element Modeling (FEM). In FY 2014/15 we have added the ability to automatically integrate the suspension system support locations to the stiffest substrate locations. And, if necessary, strengthen the interface point and adjust the pad sizes to minimize stress. This tool allows rapid creation and analysis of detailed mirror designs for Pre-Phase-A trade studies. For example, Figure 5 shows a trade study of the launch load stress distribution associated with different support systems for a 4-m class mirror. Also, we continue to employ undergraduate interns to support these efforts.

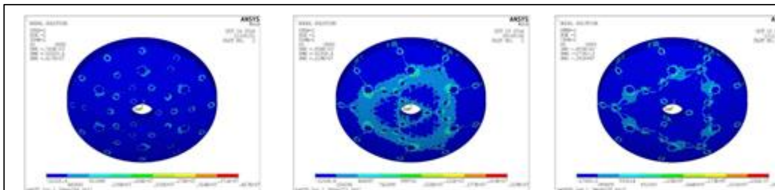


Fig. 5: Different support types demonstrated by mirror modeler.

3.3 Mid/High-Spatial Frequency Figure Error

Need: High contrast imaging requires a high-quality point spread function which requires a very smooth mirror (~7 nm rms). While a deformable mirror can correct low-spatial errors, it cannot correct mid/high spatial errors. And, because the on-orbit operational temperature is different from the fabrication temperature, thermal stress, even for a low CTE material such as Ultra-Low Expansion (ULE®) glass, might cause deformations which can impact UVOIR performance.

Accomplishment: In Phase 1 we successfully demonstrated ability to produce a zero-gravity optical surface of < 6 nm rms at a 2C operating temperature[14-15] by ion-polishing the 43 cm deep-core mirror to 5.4 nm rms. And, any figure error change from ambient to 2C was below our 4 nm rms noise floor. In Phase 2 we plan to characterize optical performance from 250 K to ambient of the ⅓-scale ULE© mirror and the 1.2-m Extreme Lightweight Zerodur© Mirror owned by Schott.

3.4 Segment Edges

Need: For a segmented primary mirror, the quality of segment edges impacts PSF for high-contrast imaging applications, contributes to stray light noise, and affects the total collecting aperture. Diffraction from secondary mirror obscuration and support structure also impacts performance.

Accomplishment: In Phase 1, AMTD partner STScI successfully demonstrated an achromatic apodization process to minimize segment edge diffraction.[16] No further development of this technology is planned in Phase 2.

3.5 Segment-to-Segment Gap Phasing

Need: To achieve diffraction-limited performance at a wavelength of 500 nm, the figure error of the primary mirror surface needs to be less than 10 nm root-mean-square (rms). For a segmented mirror, it is necessary to co-phase the mirror segments to less than 5 nm rms. And, to avoid speckle noise which can interfere with exo-planet observation, internal coronagraphs require segment to segment dynamic co-phasing error < 10 pm rms between WFSC updates.

Accomplishment: In FY14/15 we investigated the co-phasing specification for a segmented primary mirror to achieve the required science.[22] Some of our findings are coronagraph leakage is 10X more sensitive to random segment piston error than to random segment tip/tilt error; coronagraph leakage is smaller for fewer (< 4 segments per diameter) or many segments (> 32 segments per diameter); and the required stability period depends on the host star's brightness. Figure 6 shows the contrast leakage as a function of mirror segments for 1 nm rms tilt error. Reducing the tilt error by 10X (to 0.1 nm rms) reduces the contrast leakage by 100X. Figure 7 shows the time required to update the WFSC control loop for a 10-m aperture telescope as a function of host star magnitude. Setting a required telescope stability specification is a critical systems engineering task that will drive the final mission architecture. Larger aperture telescope collect more photons which shortens the time for which the telescope must remain stable. But, larger telescopes are also inherently less stiff. At the same time, the science requires a minimum inner working angle of approximately 40 mas. For an 8-m telescope this IWA is at 2λ/D while for a 12-m telescope it is at 3λ/D. And, the stability tolerances to achieve the required contrast leakage relaxes with the angular distance from the central PSF core.

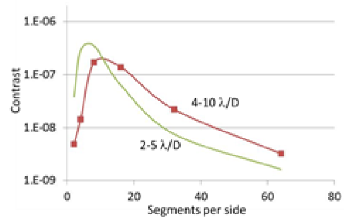


Fig. 6: Contrast Leakage for 1 nm rms random segment tilt as function of # of segments.

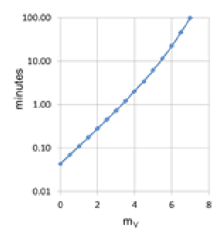
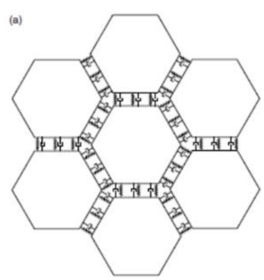


Fig. 7: WFE stability time for 10-m telescope as function of host star magnitude.

In anticipation of the contrast leakage effect of segment rigid-body motion in a segmented aperture, AMTD funded Jessica Gersh-Range to investigate mitigation strategies. In FY 2014/15, she published her PhD research[17-18] which indicates that connecting segments along their edges with damped spring interfaces provides potentially significant performance advantages for very large mirrors (Figure 8). With no edgewise connection, the segments behave independently. With as few as 3 damped spring interfaces, the segments start to act as a monolith, provided that the interface connection to the segment is strong enough that the bending stiffness along the segment edge is comparable to the bending stiffness of the monolithic mirror. If the interface strength is too weak, the segments will behave independently. Adjusting the spring stiffness tunes the assembly's first mode frequency. Initially, the frequency increases proportional to the square root of the interface stiffness, then asymptotically approaches the performance of a monolithic. By adjusting stiffness and damping, a segmented mirror will stabilize faster after a force impulse than a monolith. A segmented mirror with low to intermediate interface stiffness does not propagate disturbance waves. And, a segmented mirror with high damping reduces the propagating wave amplitude quickly. Please note that this study did not evaluate the propagation of disturbances through the backplane and into the mirror.



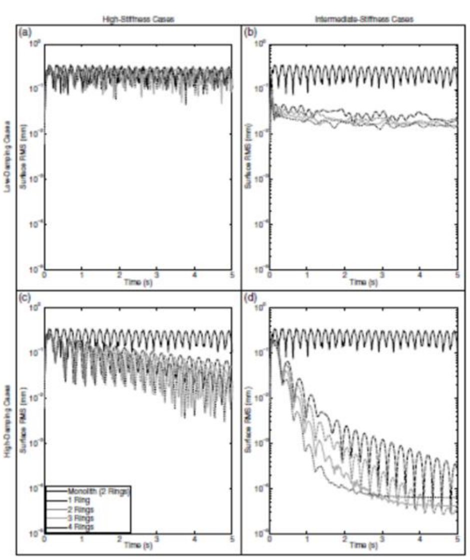


Fig. 8: Segmented mirror with edgewise interfaces and dynamic motion as function of stiffness and damping.

3.6 Integrated Model Validation

Need: On-orbit performance is determined by mechanical and thermal stability. As future systems become larger, compliance cannot be 100 percent tested on the ground before launch; performance verification will rely on results from a combination of sub-scale tests and high fidelity models. Therefore, 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, pointing stability, jitter, and thermal stability, as well as vibro-acoustics and launch loads.

Accomplishment: In FY14/15, we continue to develop our suite of integrated modeling tools and use these tools to conduct performance trade studies. In FY15/16 we will generate mechanical and thermal performance predictions that can be validated by characterizing the performance for the 1.5 meter ULE® mirror to be manufacture by AMTD Partner Exelis and a 1.2 meter Zerodur® mirror owned by Schott North American. Currently, we are preparing to validate these model predictions by test in the XRCF.

AMTD has developed a new methodology for understanding how a primary mirror responds to a dynamic thermal environment that we are calling Thermal Modulation Transfer Function.[23] Figure 9 provides a high level overview of this methodology. Any thermal environment can be decomposed into a set of periodic thermal oscillations. These oscillations cause wavefront figure errors on the primary mirror with a thermal time constant determined by the mirror's thermal properties (e.g. mass and conductivity). The amplitude of these figure errors depends on the mirror's CTE and the amplitude and period of the input thermal oscillation. For the AMTD 4-m point design, the primary mirror wavefront error can be kept below the required 10 pm rms with a thermal environment that is actively controlled with an accuracy of 50 mK and a control period of less than 140 seconds. This tool can be used to determine thermal boundary and control conditions for passive and active telescope thermal control.

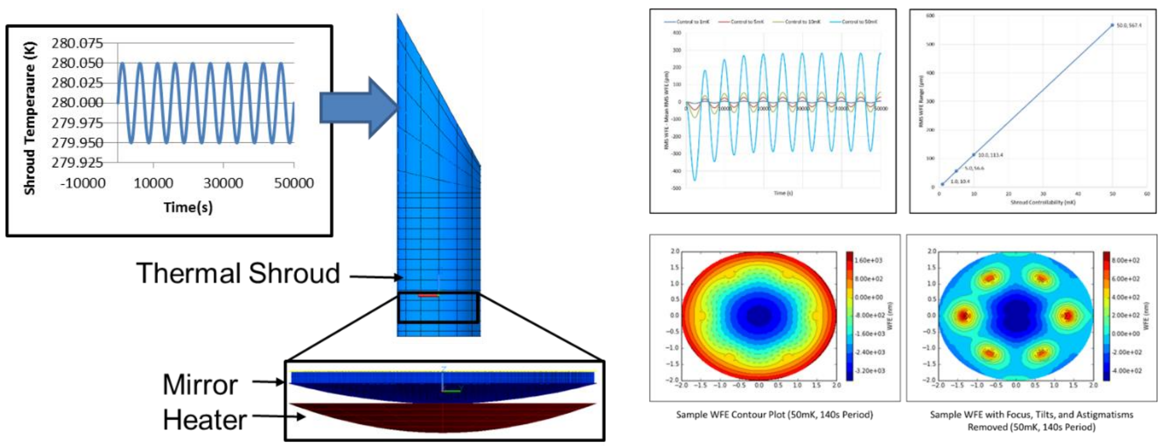


Fig. 9: Thermal Modulation Transfer Function for Space Telescopes

AMTD is developing a similar (although more conventional) methodology for understanding how a primary mirror responds to a dynamic mechanical environment.[24] Figure 10 provides a high level overview of this methodology. Any mechanical disturbance environment can be decomposed into a set of periodic oscillations. These oscillations cause wavefront figure errors on the primary mirror with a thermal time constant determined by the mirror's mechanical properties (e.g. mass, stiffness, dampening, etc.). The amplitude of these figure errors depends on the mirror's frequency response. Using this analysis it is possible to determine the telescope boundary conditions, i.e. passive mechanical isolation and active vibration control, needed to keep the telescope wavefront error below 10 pm rms.

Finally, modeling methodology has no value unless it produces measurable predictions which can be validated. AMTD plans to make modal and thermal deformation performance predictions for the 1.5 meter ULE® mirror to be manufacture by AMTD Partner Exelis and a 1.2 meter Zerodur® mirror owned by Schott North American and validate these predictions by test in the XRCF. Because the mirror's radius of curvatures are too short for the current XRCF test configuration, we are building a pressure tight vessel to place the interferometer and IR camera inside of the XRCF. The interferometer measured surface shape while the camera monitors the mirror's surface temperature. We also plan to do traditional and full aperture interferometric modal characterization.

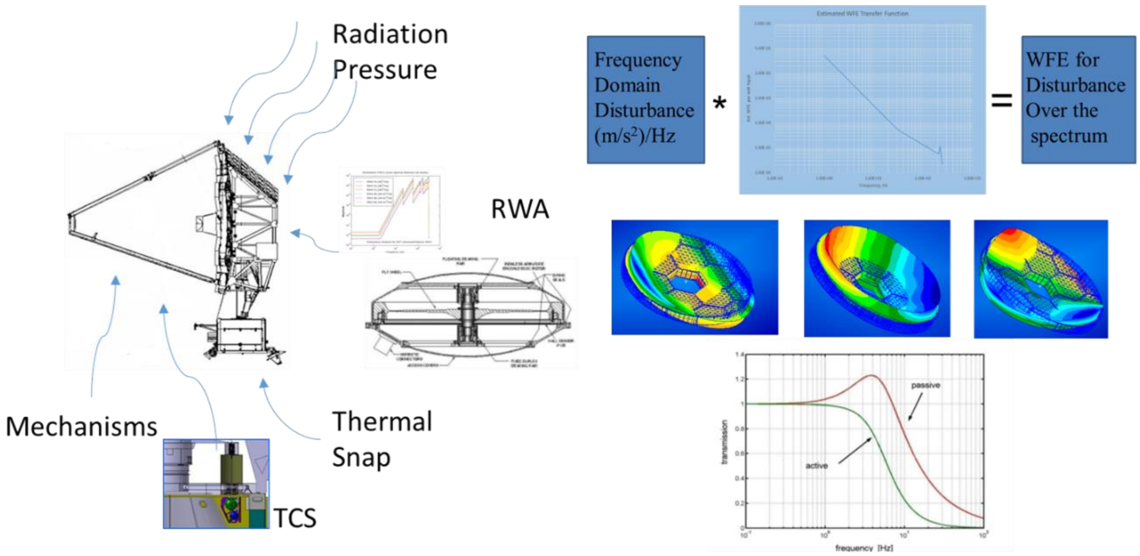


Fig. 10: Mechanical Frequency Response Analysis for Space Telescopes

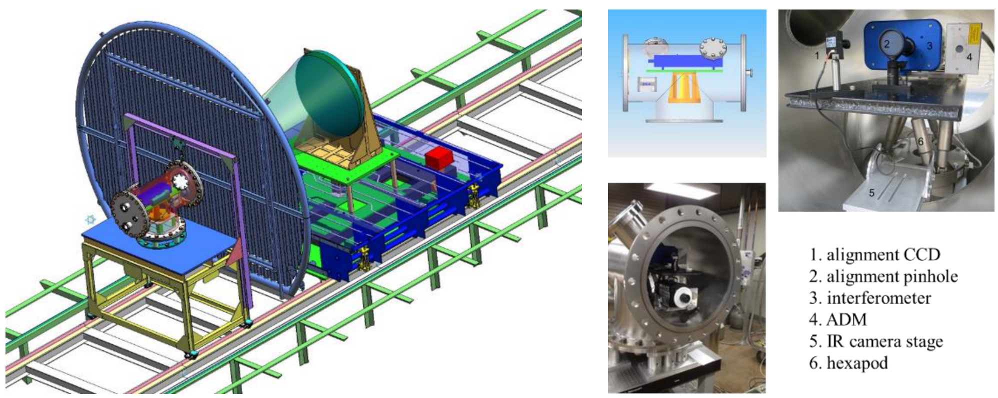


Fig. 11: Test Setup in XRCF using Interferometer and IR Camera in a Pressure Tight Vessel

4. CONCLUSIONS

The Advance Mirror Technology Development (AMTD) project is a multi-year effort initiated in FY12 to mature, by at least a half TRL step, six critical technologies required to enable 4 to 8 meter UVOIR space telescope primary mirror assemblies for both general astrophysics and ultra-high contrast observations of exoplanets.

- *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*

Our objective is to mature these technologies towards TRL-6 by 2018 so that the 2020 Decadal Review can consider a viable large-aperture UVOIR astronomy mission.

AMTD uses a science-driven systems engineering approach. We mature technologies required to enable the highest priority science AND result in a high-performance low-cost low-risk system. To provide the science community with options, we are pursuing multiple technology paths including both monolithic and segmented space mirrors. We do this by assembling an outstanding team from academia, industry, and government with extensive expertise in astrophysics and exoplanet characterization, and in the design/manufacture of monolithic and segmented space telescopes; by deriving engineering specifications for advanced normal-incidence mirror systems needed to make the required science measurements; and by defining and prioritizing the most important technical problems to be solved.

Phase 1 has completed all of its goals and milestones. Phase 2 is continuing to develop three of the key technologies.

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