Advanced Mirror Technology Development (AMTD) Project: Overview and Year 4 Accomplishments

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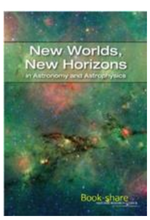
AMTD is a funded NASA Strategic Astrophysics Technology (SAT) project

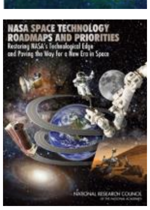
SPIE Conference on Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation, 2016

Future UVOIR Space Telescopes require Mirror Technology



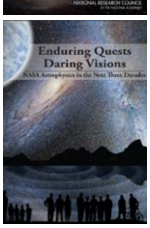
Astro2010 Decadal Study recommended technology development (page 7-17) for a potential future:

- Exoplanet Mission (New-Worlds Explorer)
- UVOIR Space Telescope (4 meter or larger)



2012 NASA Space Technology Roadmaps & Priorities: Top Technical Challenge C2 recommended:

- New Astronomical Telescopes that enable discovery of habitable planets, facilitate advances in solar physics, and enable the study of faint structures around bright objects …



2014 Enduring Quests Daring Visions recommended:

- 8 to 16-m LUVOIR Surveyor with sensitivity and angular resolution to “dramatically enhance detection of Earth-sized planets to statistically significant numbers, and allow in-depth spectroscopic characterization.”

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Objective

AMTD's objective is to mature to TRL-6 the critical technologies needed to produce 4-m or larger flight-qualified UVOIR mirrors by 2018 so that a viable mission can be considered by the 2020 Decadal Review.

AMTD is not developing technology for a specific mission.

Potential high-contrast imaging & spectroscopy architectures:

single aperture monolithic mirror telescope,
single aperture segmented mirror telescope,
sparse aperture, and
interferometers.

Multiple Technology Paths

Just as JWST's architecture was driven by launch vehicle, future mission's architectures (mono, segment or interferometric) will depend on capacities of future launch vehicles (and budget).

Since we cannot predict future, we must prepare for all futures.

To provide the science community with options, we are pursuing multiple technology paths for both monolithic and segmented aperture telescopes.

All potential UVOIR mission architectures (monolithic, segmented or interferometric) share similar mirror needs:

Very Smooth Surfaces	< 10 nm rms
Thermal Stability	Low CTE Material
Mechanical Stability	High Stiffness Mirror Substrates

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Technical Approach/Methodology

To accomplish our objective, we:

- Use a science-driven systems engineering approach.
- Mature technologies required to enable highest priority science AND result in a high-performance low-cost low-risk system.

Mature Technology Simultaneous because all are required to make a primary mirror assembly (PMA); AND, it is the PMA's on-orbit performance which determines science return.

PMA stiffness depends on substrate and support stiffness.

Ability to cost-effectively eliminate mid/high spatial figure errors and polishing edges depends on substrate stiffness.

On-orbit thermal and mechanical performance depends on substrate stiffness, the coefficient of thermal expansion (CTE) and thermal mass.

Segment-to-segment phasing depends on substrate & structure stiffness.

Phase 1 & 2

Goals, Objectives & Tasks

Goals

To accomplish Objective, must mature 6 linked technologies:

Large-Aperture, Low Areal Density, High Stiffness Mirrors: 4 to 8 m monolithic & 8 to 16 m segmented primary mirrors require larger, thicker, stiffer substrates.

Support System: Large-aperture mirrors require large support systems to ensure that they survive launch & deploy on orbit in a stress-free & undistorted shape.

Mid/High Spatial Frequency Figure Error: A very smooth mirror is critical for producing a high-quality point spread function (PSF) for high-contrast imaging.

Segment Edges: Edges impact PSF for high-contrast imaging applications, contributes to stray light noise, and affects the total collecting aperture.

Segment-to-Segment Gap Phasing: Segment phasing is critical for producing a high-quality temporally stable PSF.

Integrated Model Validation: On-orbit performance is determined by mechanical & thermal stability. Future systems require validated models.

Phase 1: Goals, Progress & Accomplishments

Key
- **Done**
- **Stopped**
- **In-Process**
- Not Started Yet

Systems Engineering:

- **derive from science requirements monolithic mirror specifications**
- **derive from science requirements segmented mirror specifications**

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

- **make a subsection mirror via a process traceable to 500 mm deep mirrors**

Support System:

- **produce pre-Phase-A point designs for candidate primary mirror architectures;**
- **demonstrate specific actuation and vibration isolation mechanisms**

Mid/High Spatial Frequency Figure Error:

- **'null' polish a 1.5-m AMSD mirror & subscale deep core mirror to a < 6 nm rms zero-g figure at the 2°C operational temperature**.

Segment Edges:

- **demonstrate an achromatic edge apodization mask**

Segment to Segment Gap Phasing:

- **develop models for segmented primary mirror performance; and**
- **test prototype passive & active mechanisms to control gaps to ~ 1 nm rms**.

Integrated Model Validation:

- **validate thermal model by testing the AMSD and deep core mirrors at 2°C**
- **validate mechanical models by static load test.**

Phase 1: Key Accomplishments

- Derived from Science Requirements, Specifications for Primary Mirror Wavefront Error and Stability
  - Surface < 10 nm rms (low ~5 nm, mid ~5 nm, high ~3 nm)
  - Stability < 10 picometers rms per 10 minutes
- Demonstrated, at the 0.5-m scale, the ability to make mechanically stiff, i.e. stable, UVOIR traceable mirrors:
  - <6 nm rms surface
  - 60-kg/m2
  - 400-mm deep-core substrate

using the stack-core low-temperature-fusion/low-temperature-slumping (LTF/LTS) process.

- Developed Tools for Integrated Modeling & Verification

Phase 2: Tasks

Refine engineering specifications for a future monolithic or segmented space telescope based on science needs & implementation constraints.

Mature 4 inter-linked critical technologies.

Large-Aperture, Low Areal Density, High Stiffness Mirrors
Fabricate a 1/3rd scale model of a 4-m class 400 mm thick deep-core ULE© mirror – to demo lateral scaling.

***Support System* – continue Phase A design studies**

Mid/High Spatial Frequency Figure Error
Test 1/3rd scale ULE© & 1.2 m Zerodur Schott mirror at 280K

***Integrated Model Validation* – continue developing and validating tools**

Key
Done
Stopped
In-Process
Not Started Yet

Phase 2: Tasks

Monolithic Mirror Substrate Technology

- Fabricate and test A-Basis allowable required for mirror
- Design 1/3-scale model of a 4-m x 400-mm class ~150Hz ULE® mirror
- Design support structure for Zerodur 1.2m mirror

Mirror Preparation

- Fabricate & polish 1/3-scale model ULE mirror & support structure
- Fabricate support structure & Polish Zerodur mirror

Thermal Characterization

- "Qualify" (i.e., test) two candidate lightweight primary mirrors (1.35m or 1.5m Harris & 1.2m Zerodur Schott) in X-Ray & Cryogenic Facility at MSFC
  - Characterize their optical performance from 250K to ambient

Expose to representative vibration and acoustic launch environments & conduct modal test of both mirrors

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

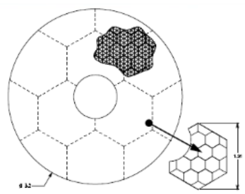
Large Stable Mirror Substrates

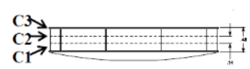
Future large-aperture space telescopes (regardless of monolithic or segmented) need ultra-stable mechanical and thermal performance for high-contrast imaging.

This requires larger, thicker, and stiffer substrates.

Phase 1 demonstrated stacked core low-temperature fusion process to cost effectively make mirrors thicker than 300 mm by making a 40 cm ‘cut-out’ of a 4-m mirror.

Phase 2 designing a 1.5 m subscale of a 4-m mirror to demonstrate lateral scalability of stacked core process.



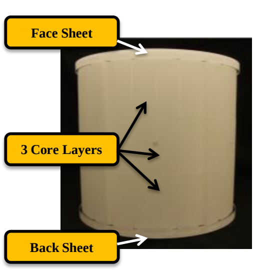


4m PM Conceptual Layout

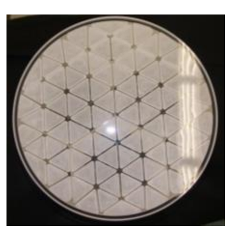
43 cm Deep Core Mirror

Harris successfully demonstrated 5-layer ‘stack & fuse’ technique which fuses 3 core structural element layers to front & back faceplates.

Made 43 cm ‘cut-out’ of a 4 m dia, > 0.4 m deep, 60 kg/m^2 mirror substrate.



Post-Fusion Side View
3 Core Layers and Vent Hole Visible



Post-Fusion Top View
Pocket Milled Faceplate

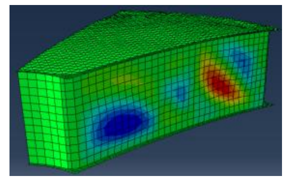
Post Slump:
2.5 meter Radius of Curvature

This technology advance leads to stiffer 2 to 4 to 8 meter class substrates at lower cost and risk for monolithic or segmented mirrors.

Matthews, Gary, et al, *Development of stacked core technology for the fabrication of deep lightweight UV quality space mirrors*, SPIE Conference on Optical Manufacturing and Testing X, 2013.

Phase 2: Demonstrates Lateral Scaling

Demonstrate lateral scaling of 'stacked-core' to larger diameter
- Approximately 1/3rd scale model of a 4 meter mirror
  - 1.5m class diameter and about 200mm thick
  - (2) ULE® face plates
  - (3) ULE® glass boules
  - On-axis



Non-linear visco-elastic tools and methods used to design 4-m class mirror, then scaled to 1.5-m

Fused 1.5-m mirror substrate.


Courtesy of Harris Corp

Support Systems

Support System

Technical Challenge:

- Large-aperture mirrors require large support systems to survive launch & deploy on orbit in a stress-free and undistorted shape.

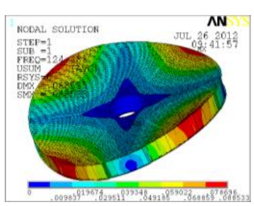
Accomplishments:

- Developed a new modeler tool for ANSYS which can produce 400,000-element models in minutes.
- Tool facilitates transfer of high-resolution mesh to mechanical & thermal analysis tools.
- Used our new tool to compare pre-Phase-A point designs for 4-meter and 8-meter monolithic primary mirror substrates and supports.

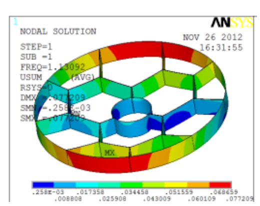
Design Tools and Point Designs

AMTD has developed a powerful tool which quickly creates monolithic or segmented mirror designs; and analyzes their static & dynamic mechanical and thermal performance.

Point Designs: AMTD has used these tools to generate Pre-Phase-A point designs for 4 & 8-m mirror substrates.



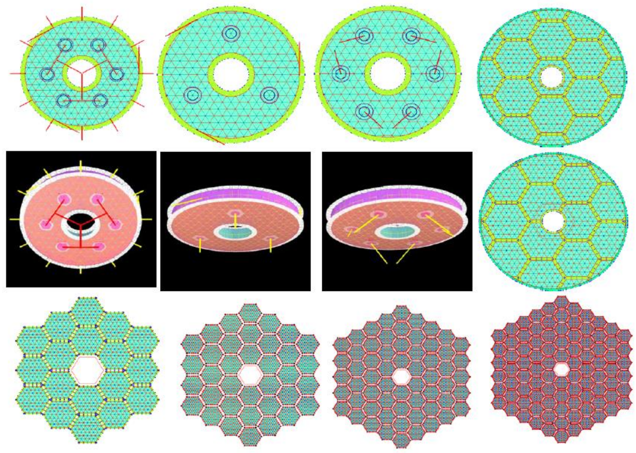
Free-Free 1st Mode: 4 m dia 40 cm thick substrate



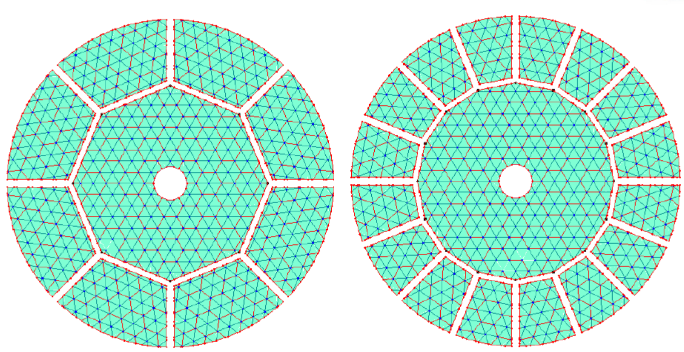
Internal Stress: 4 m dia with 6 support pads

Support System: AMTD has used these tools to generate Pre-Phase-A point designs for 4-m mirror substrate with a launch support system.

TYPES OF MODELS GENERATED



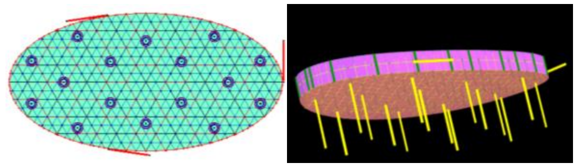
COMBINING PETALS WITH MONOLITH



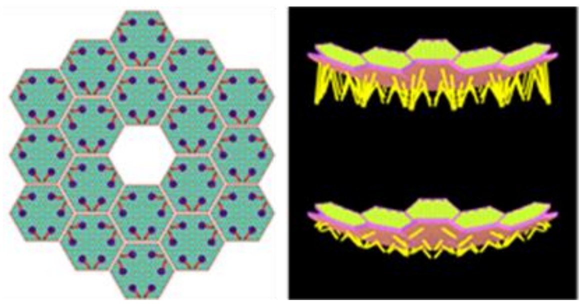
One option for limited shroud diameter is to have as large a central monolith as possible, with deployable petals. This provides a better diffraction pattern than uniform segment patterns, as well as more mission flexibility.

Custom Support Systems

Elliptical Mirrors and Support Systems for Off-Axis Telescopes



Segmented Support Systems for Flat or Curved Backplanes.



Point Design Trade Studies

Trade assuming constant 40 cm thickness & core cell size.

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

Trade assuming constant face/back-sheet & core wall thicknesses

4-meter Mirror Point Designs			
Thickness [m]	0.45	0.6	0.75
Mass [kg]	2200	2560	2860
First Mode [Hz]	180	215	245

Integrated Modeling & Design Tools

Wavefront Stability

Coronagraphy requires a stable Wavefront Error (WFE)

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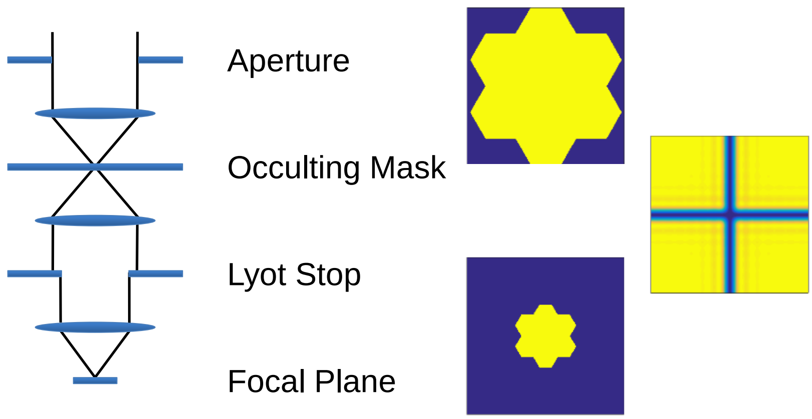
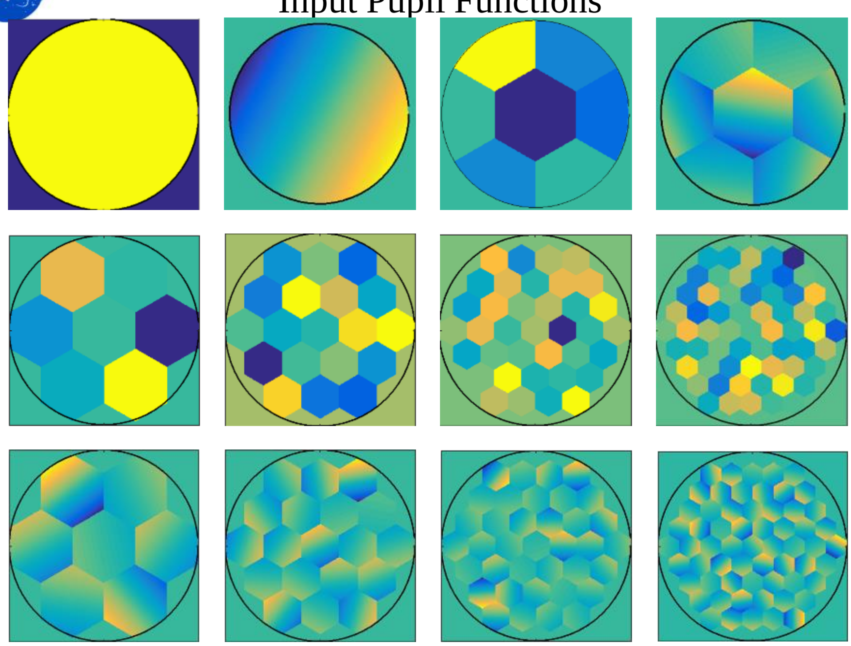
Integrated Model

Using Matlab, we created an integrated model of a segmented aperture telescope and a single stage internal linear band-limited coronagraph: $\{1\text{-sinc}^2(x) \times \text{sinc}^2(y)\}$.



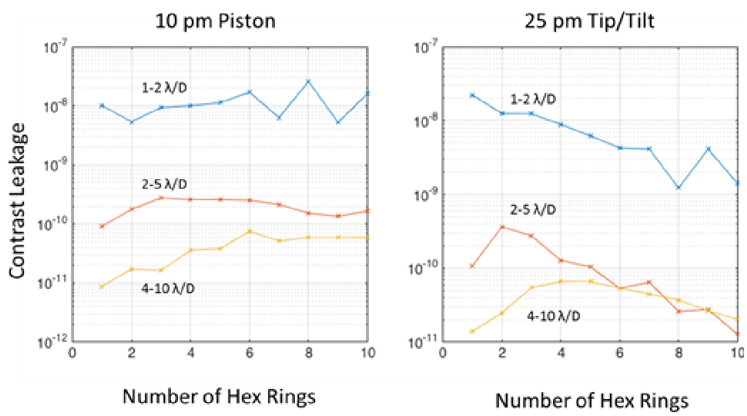
Input Pupil Functions



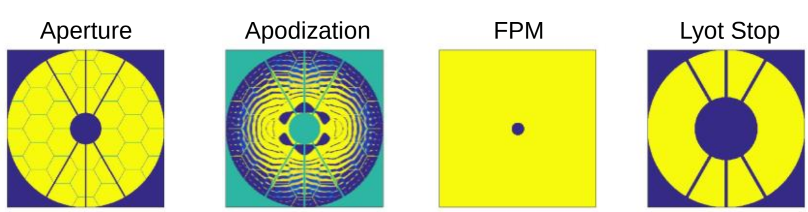
Contrast vs. Number of Segments

Coronagraph is 2.5X more sensitive to Piston than Tip/Tilt.

Contrast leakage at λ/D depends on number of Segment Rings.



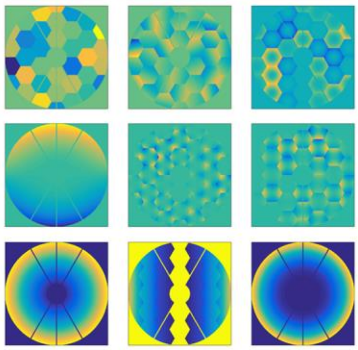
Analysis of Random Segment Errors on Performance of Apodized Pupil Lyot Coronagraph for JWST Aperture

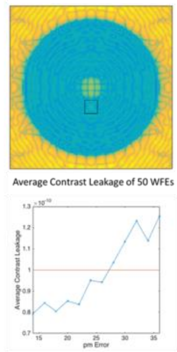


N'Diaye, et. al., "Apodized Pupil Lyot Coronagraphs for Arbitrary Apertures", Astro-PH, 2016

Contrast Leakage for Segmented Aperture

Contrast Leakage as function of Segment and Global (Secondary Mirror misalignment & Backplane bending) Errors.





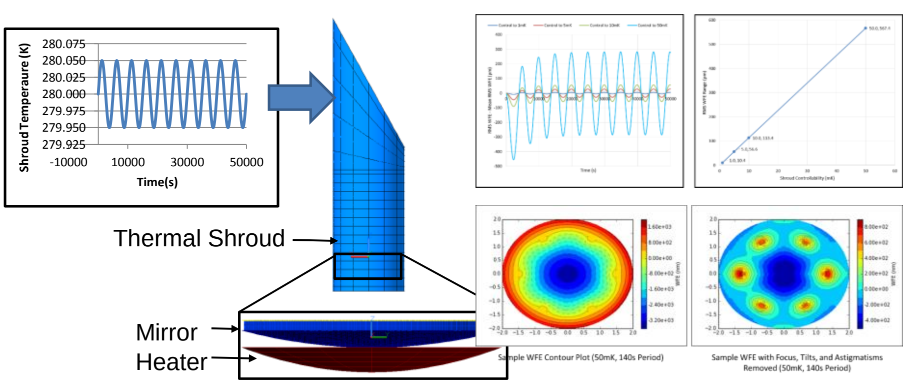
Calculated Average Contrast inside 4 to 6 λ/D ROI as a function of 50 random error realizations.

Error Limit is when Average Contrast equals 10^{-10}.

Table 2: Misalignment Error Amplitude for 10^{10} Average Contrast Leakage of Apodized Coronagraph									
Segment Errors					Secondary Mirror			Backplane	
Piston	Tip/Tilt	Power	Astig	Trefoil	Power	Coma	Sphere	X-Bend	Y-Bend
10 pm	20 pm	30 pm	35 pm	65 pm	3000 pm	5800 pm	500 pm	500 pm	120 pm

Thermal Stability Study

- Understand how primary mirror responds to dynamic external thermal environment.
- Specify how to control telescope thermal environment to keep primary mirror stable to better than 10 pm per 10 minutes



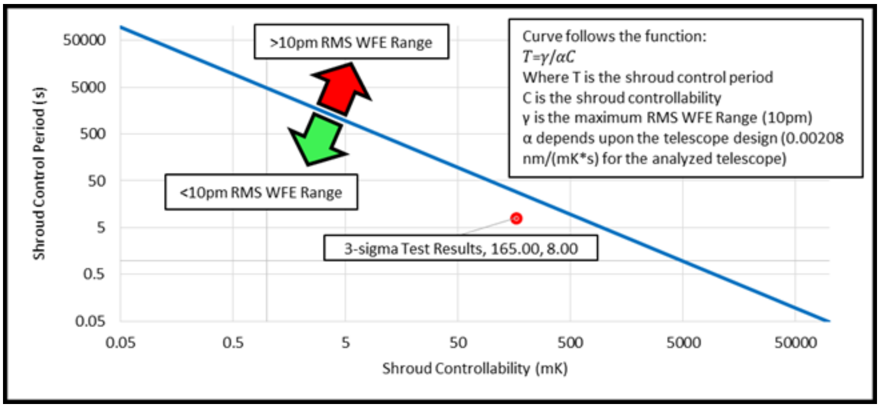
Sample WFE Contour Plot (50mK, 140s Period)

Sample WFE with Focus, Tilts, and Astigmatisms Removed (50mK, 140s Period)

Thermal Stability

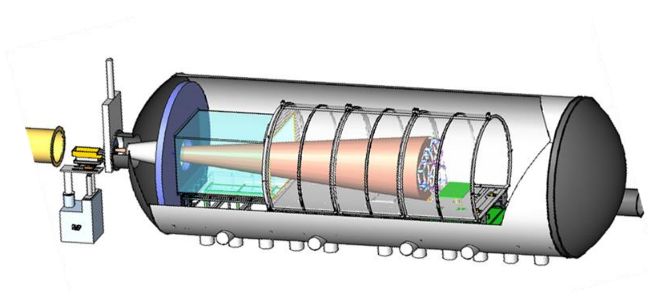
Wavefront error can meet the desired stability when the primary mirror is inside a thermally controlled environment with appropriate period and controllability performance.

Performance trade varies as a function of specific mirror design.



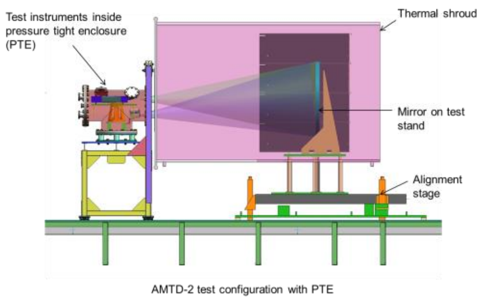
Integrated Models Validated by Test

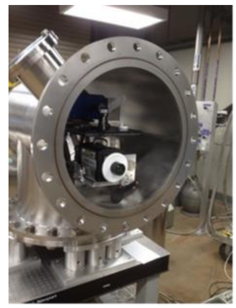
Thermal and Mechanical Performance will be Predicted by Model and Validated by Test in the XRCF.



Pressure Tight Enclosure for Center of Curvature Test

Added a PTE to enable testing of short radius of curvature mirrors in the XRCF.





Conclusions

AMTD uses a science-driven systems engineering approach to define & execute a long-term strategy to mature technologies necessary to enable future large aperture space telescopes.

Because we cannot predict the future, we are pursuing multiple technology paths including monolithic & segmented mirrors.

Demonstrated capability of 'stack & seal' process:

- Make 40-cm deep mirrors
- Lateral scalability to 1.5-m diameter
- Validated Non-Linear Visco-Elastic Modeling

Continuing development and improvement of Arnold Mirror Modeler for rapid design of mirror substrates and support systems to enable point design trade studies.

Developing integrated modeling methods to derive engineering specifications from science requirements.

Plan to Validate by Test the Integrated Model Predictions.