Advanced mirror technology development (AMTD) project status

Mirror Technology Days in the Government 2014
Albuquerque
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H. Philip Stahl

Programmatic Summary

To date, AMTD Phase 1 has accomplished all of its technical tasks on-schedule and on-budget.

AMTD was awarded a Phase 2 contract.

We are now performing Phase 2 tasks along with those tasks continued from Phase 1.

Technical Challenge

Most future space telescope missions require mirror technology.

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 must pursue multiple technology paths.

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

Objectives and Goals

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.

This technology must enable missions capable of both general astrophysics & ultra-high contrast observations of exoplanets.

Mature 6 inter-linked critical technologies.

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

TRL Assessment

Technology Readiness Assessment

Technology	Metric	Before AMTD-1	Current	After AMTD-2
Large-Aperture, Low Areal Density, High Stiffness Substrate	1.5-m Seg	TRL6 (AMSD/MMSD)[note 1]	-	TRL6 (1.5mDC&1.2mZerodur)[note 2]
	4-m Mono	TRL2 (subscale 2.4 m HST) TRL5 (8 m Ground)	TRL3 (43 cm Deep Core) -	TRL4 (1.5m Deep Core) -
Support System	Segment	TRL3 (JWST is not UVOIR)	-	TRL3 (8-m Point Design)
	Monolithic	TRL6 (subscale 1.4 m Kepler) TRL5 (8 m Ground)	TRL6 (4-m Point Design) TRL5 (8-m Point Design)	TRL6 (4-m Point Design) TRL5 (8-m Point Design)
Mid/High Spatial Frequency Error	< 4nm rms	TRL5 (HST, 8 m Ground)	TRL6 (43 cm @ 250K)	TRL6 (1.5m & 1.2m at 250K)
Segment Edges	Polished	TRL6 (2 mm demonstrated)	X	X
	Apodize	TRL2	TRL3 (BNL demo)	X
Segment-to-Segment Gap Phasing	Alignment	TRL3 (JWST is not UVOIR)	TRL3.5 (2 stage Actuator)	X
	Stability	TRL0 (<10 pm rms stability)	X	X
Integrated Model Validation	Structural	TRL4/5 (JWST & SVMV)	TRL4/5 (43 cm Gravity)	TRL5 (1.5 m Modal & Gravity)
	Thermal	TRL4/5 (JWST & SVMV)	TRL4/5 (43 cm Thermal)	TRL5 (1.5 m Thermal)
	Optical	TRL4/5 (JWST & SVMV)	-	TRL4/5 (GSFC Tool)

NOTE 1: AMSD/MMSD Exelis mirror was manufactured from ULE©. Other AMSD mirrors were manufactured from Be & Fused Silica.

NOTE 2: AMTD-2 achieving TRL6 for Segmented requires unfunded Strength, Vibration & Acoustic Test of 1.5 m Deep Core & 1.2 m Zerodur

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.

Philosophy

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

We are deliberately pursuing multiple design paths to enable either a future monolithic or segmented space telescope

- Gives science community options
- Future mission architectures depend on future launch vehicles, AND
- We cannot predict future launch vehicle capacities

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 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**

AMTD-1 Tasks

Three AMTD-1 technologies are not continued into AMTD-2:

Mid/High Spatial Frequency Figure Error

AMTD-1 demonstrated the ability to achieve a < 6 nm rms surface figure on a facesheet that is representative of and scaleable to a 4 meter or larger primary mirror. The ability to deterministically polish ULE© glass mirrors to < 6 nm rms is at TRL-6.

Segment Edges

AMTD-1 demonstrated a technology to mitigate edge diffraction.

Several SBIR contracts have demonstrated ability to polish mirrors to 2 mm of the edge. JWST demonstrated 5-7 mm edges.

Thus, until requirement to do better, further development is not warranted.

Segment-to-Segment Gap Phasing

AMTD-1 demonstrated the fine stage of a two-stage actuator for controlling mirror segments. There is no plan to continue this in Phase 2

9 Publications from Year 1

Stahl, H. Philip, *Overview and Recent Accomplishments of the Advanced Mirror Technology Development (AMTD) for large aperture UVOIR space telescopes project*, SPIE Conference on UV/Optical/IR Space Telescopes and Instrumentation, 2013.

Stahl, H. Philip, W. Scott Smith, Marc Postman, *Engineering specifications for a 4 meter class UVOIR space telescope derived from science requirements*, SPIE Conference on UV/Optical/IR Space Telescopes and Instrumentation, 2013.

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.

Matthews, Gary, et al, *Processing of a stacked core mirror for UV applications*, SPIE Conference on Material Technologies and Applications to Optics, Structures, Components, and Sub-Systems, 2013.

Eng, Ron, et. al., *Cryogenic optical performance of a lightweighted mirror assembly for future space astronomical telescopes: correlation of optical test results and thermal optical model*, SPIE Conference on Material Technologies and Applications to Optics, Structures, Components, and Sub-Systems, 2013.

Sivaramakrishnan, Anand, Alexandra Greenbaum, G. Lawrence Carr, and Randy J. Smith, *Calibrating apodizer fabrication techniques for high contrast coronagraphs on segmented and monolithic space telescopes*, SPIE Conference on UV/Optical/IR Space Telescopes and Instrumentation, 2013.

Arnold, William et al, *Next generation lightweight mirror modeling software*, SPIE Conference on Optomechanical Engineering, 2013.

Arnold, William et al, *Integration of Mirror design with Suspension System using NASA's new mirror modeling software*, SPIE Conference on Optomechanical Engineering, 2013.

Gersh-Range, Jessica A., William R. Arnold, Mason A. Peck, and H. Philip Stahl, *A parametric finite-element model for evaluating segmented mirrors with discrete edgewise connectivity*, SPIE Proceedings 8125, 2011, DOI:10.1117/12.893469

Engineering Specifications

Engineering Specifications Accomplishment

Derived from Science Requirements, 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.

Table 2.1: Science Flow-down Requirements for a Large UVOIR Space Telescope

Science Question	Science Requirements	Measurements Needed	Requirements
Is there life elsewhere in Galaxy?	Detect at least 10 Earth-like Planets in HZ with 95% confidence.	High contrast (ΔMag > 25 mag) SNR=10 broadband (R = 5) imaging with IWA ~40 mas for ~100 stars out to ~20 parsecs.	≥ 8 meter aperture Stable 10^{-10} starlight suppression ~0.1 nm stable WFE per 2 hr ~1.3 to 1.6 mas pointing stability
	Detect presence of habitability and bio-signatures in the spectra of Earth-like HZ planets	High contrast (ΔMag > 25 mag) SNR=10 low-resolution (R=70-100) spectroscopy with an IWA ~40 mas; spectral range 0.3 – 2.5 microns; Exposure times <500 hrs	
What are star formation histories of galaxies?	Determine ages (~1 Gyr) and metallicities (~0.2 dex) of stellar populations over a broad range of galactic environments.	Color magnitude diagrams of solar analog stars (Vmag~35 at 10 Mpc) in spiral, lenticular & elliptical galaxies using broadband imaging	≥ 8 meter aperture Symmetric PSF 500 nm diffraction limit 1.3 to 1.6 mas pointing stability
What are kinematic properties of Dark Matter	Determine mean mass density profile of high M/L dwarf Spheroidal Galaxies	0.1 mas resolution for proper motion of ~200 stars per galaxy accurate to ~20 μas/yr at 50 kpc	
How do galaxies & IGM interact and affect galaxy evolution?	Map properties & kinematics of intergalactic medium over contiguous sky regions at high spatial sampling to ~10 Mpc.	SNR = 20 high resolution UV spectroscopy (R = 20,000) of quasars down to FUV mag = 24, survey wide areas in < 2 weeks	≥ 4 meter aperture 500 nm diffraction limit Sensitivity down to 100 nm wavelength
How do stars & planets interact with interstellar medium?	Measure UV Ly-alpha absorption due to Hydrogen "walls" from our heliosphere and astrospheres of nearby stars	High dynamic range, very high spectral resolution (R = 100,000) UV spectroscopy with SNR = 100 for V = 14 mag stars	
How did outer solar system planets form & evolve?	UV spectroscopy of full disks of solar system bodies beyond 3 AU from Earth	SNR = 20 - 50 at spectral resolution of R ~10,000 in FUV for 20 AB mag	

Table 3.1: Science Requirement to Technology Need Flow Down

Science	Mission	Constraint	Capability	Technology Challenge
Sensitivity	Aperture	EELV 5 m Fairing, 6.5 mt to SEL2	4 m Monolith	4 m, 200 Hz, 60 kg/m² 4 m support system
			8 m Segmented	2 m, 200 Hz, 15 kg/m² 8 m deployed support
		HLLV-Medium 10 m Fairing, 40 mt to SEL2	8 m Monolith	8 m, <100Hz, 200kg/m² 8 m, 10 mt support
			16 m Segmented	2-4m, 200Hz, 50kg/m2 16 m deployed support
		HLLV-Heavy 10 m Fairing, 60 mt to SEL2	8 m Monolith	8m, <100Hz, 480kg/m2 8 m, 20 mt support
			16 m Segmented	2-4m, 200Hz, 120kg/m² 16 m deployed support
	2 hr Exposure	Thermal 280K ± 0.5K 0.1K per 10min	< 5 nm rms per K	low CTE material
			> 20 hr thermal time constant	thermal mass
		Dynamics TBD micro-g	< 5 nm rms figure	passive isolation active isolation
	Reflectance	Substrate Size	> 98% 100-2500 nm	Beyond Scope
High Contrast	Diffraction Limit	Monolithic	< 10 nm rms figure	mid/high spatial error
		Segmented	< 5 nm rms figure	fabrication & test
			< 2 mm edges	edge fabrication & test
			< 1 nm rms phasing	passive edge constraint active align & control

Telescope Performance Requirements

Telescope Specifications depend upon the Science Instrument.

Telescope Specifications have been defined for 3 cases:

- 4 meter Telescope with an Internal Masking Coronagraph
- 8 meter Telescope with an Internal Masking Coronagraph
- 8 meter Telescope with an External Occulter

WFE Specification is before correction by a Deformable Mirror

WFE/EE Stability and MSF WFE are the stressing specifications

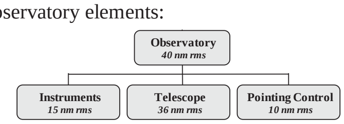
Specifications have not been defined for a Visible Nulling Coronagraph or phase type coronagraph.

8m Telescope Requirements for Coronagraph

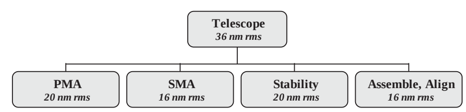
On-axis Monolithic 8-m Telescope with 3λ/D Coronagraph			
Performance Parameter	Specification	Source	Comments
Maximum total system rms WFE	38 nm	Diffraction limit (80% Strehl ratio at 500 nm)	
Encircled Energy Fraction (EEF)	80% within 16 mas at 500 nm	HST spec, modified to larger aperture and slightly bluer wavelength	Vary < 5% across 4 arcmin FOV
EEF stability	<2%	JWST	
WFE stability over 20 minutes	~1.5 nm	λ/500 at 760 nm	
PM rms surface error	5 - 10 nm	HST / ATLAST studies	
Pointing stability (jitter)	~2 mas	Guyon, scaled from HST	~ 0.5 mas floor determined by stellar angular diameter.
Mid-frequency WFE	< 20 nm	HST	

Primary Mirror Total Surface Figure Requirement

Primary Mirror requirements are derived by flowing System Level diffraction limited and pointing stability requirements to major observatory elements:



Then flowing Telescope Requirements to major Sub-Systems



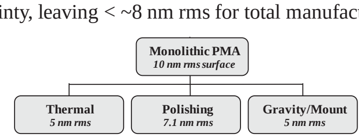
Primary Mirror Total Surface Figure Requirement

Regardless whether monolithic or segmented,

PM must have < 10 nm rms surface.

And, if segmented, it must have a 'phased' wavefront which as same performance as a monolithic aperture.

PM Specification depends on thermal behavior & mounting uncertainty, leaving < ~8 nm rms for total manufactured SFE.



Next question is how to partition the PM SFE error.

Primary Mirror Spatial Frequency Specification

Manufacturing processes typically range from -2.0 to -2.5 (in special cases to -3.0). Different slopes result in different allocations of PM spatial frequency surface figure error.

Spatial Frequency Band Limited Primary Mirror Surface Specification			
PSD Slope	- 2.0	- 2.25	- 2.5
Total Surface Error	8.0 nm rms	8.0 nm rms	8.0 nm rms
Figure/Low Spatial (1 to 4 cycles per diameter)	5.2 nm rms	5.5 nm rms	5.8 nm rms
Mid Spatial (4 to 60 cycles per diameter)	5.8 nm rms	5.6 nm rms	5.4 nm rms
High Spatial (60 cycles per diameter to 10 mm)	1.4 nm rms	1.0 nm rms	0.7 nm rms
Roughness (10 mm to < 0.001 mm)	0.6 nm rms	0.3 nm rms	0.2 nm rms

Phase 2

In AMTD-2 we will continue to refine the Science Derived Engineering Specifications.

Specific Analysis includes:

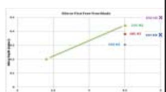
- Monolithic vs Segmented
- Segments Size – many small or few large
- Diffraction Effects on High Contrast Imaging
- Mid-Spatial Frequency Error Effects on High Contrast Imaging

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

Large Substrate: Technical Challenge

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

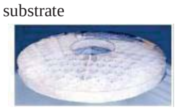
This requires larger, thicker, and stiffer substrates.



Current launch vehicle capacity limits requires low areal density.

State of the Art is

- ATT Mirror: 2.4 m, 3-layer, 0.3 m deep, 24 kg/m2 substrate
- AMSD ULE©: 1.4 m, 3 layer, 0.06m deep, 13 kg/m2 substrate
- Kepler: 1 m



Exelis 2.4 m ATT Mirror

Large Substrate: Achievements

Successfully demonstrated a new fabrication process (stacked core low-temperature fusion).

- New process offers significant cost and risk reduction over incumbent process. It is difficult (and expensive) to cut a deep-core substrate to exacting rib thickness requirements. Current SOA is ~300 mm on an expensive custom machine. But, < 130 mm deep cores can be done on commercial machines.

Extended state of the art for deep core mirrors from less than 300 mm to greater than 400 mm.

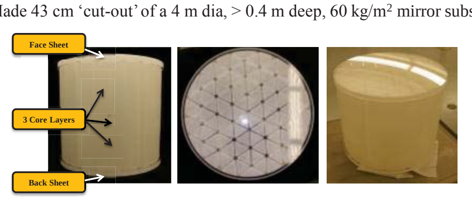
Successfully 're-slumped' a ULE© fused substrate.

- This is interesting because it allows generic substrates to be assembled and placed in inventory for re-slumping to a final radius of curvature.

43 cm Deep Core Mirror

Exelis 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.

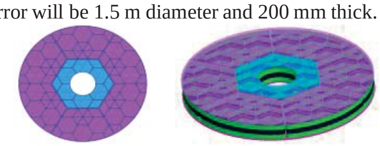
Matthews, Gary, et al, *Development of stacked core technology for the fabrication of deep lightweight UV quality space mirrors*, SPIE Conference on Optical Manufacturing and Testing X, 2013.

Phase 2

In Phase 2 we will build a 1/3rd scale model of a 4 meter mirror.

Mirror will demonstrate the ability to scale the 'stacked-core' construction approach to larger diameter.

The mirror will be 1.5 m diameter and 200 mm thick.



Subject to budget constraints, we plan to thermal test, modal test, and maybe vibe & acoustic test this mirror and a 1.2 meter lightweight Zerodur mirror owned by Schott.

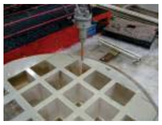
Strength Testing

AMTD-1: Exelis strength tested the core to core LTF bond strength on 12 Modulus of Rupture (MOR) test articles.

- Resulting Weibull 99% survival value was 15% above the most conservative design allowable. And, the data ranged from 30% to 200% above design allowable.

AMTD-2: Exelis is performing an A-Basis characterization of the core rib to core rib LTF bond strength.

- 60+ Modulus of Rupture Samples: 30+ samples for nominal alignment and 30+ samples for core mis-alignment


MOR Boxes in Abrasive Water Jet (AWJ)


MOR Boxes post AWJ, pre-LTF assembly

Mid/High Spatial Frequency Figure Error

Mid/High Spatial Frequency Figure Error

Technical Challenge:

- High-contrast imaging requires a very smooth mirror (< 10 nm rms)
- Mid/High spatial errors (zonal & quilting) can introduce artifacts
- DMs correct low-spatial errors, not mid/high spatial errors
- On-orbit thermal environment can stress mirror introducing error

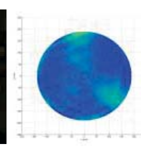
Achievements:

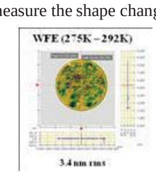
- AMTD partner Exelis designed facesheet to minimize mid/high spatial frequency quilting error from polishing pressure and thermal stress.
- Exelis ion polishing process produced 5.4 nm rms surface
- Thermal test showed no measurable cryo-deformation or quilting

Mid/High Spatial Frequency Error

Exelis polished 43 cm deep-core mirror to a zero-gravity figure of 5.5 nm rms using ion-beam figuring to eliminate quilting.

MSFC tested 43 cm mirror from 250 to 300K. Its thermal deformation was insignificant (smaller than 4 nm rms ability to measure the shape change)





Phase 2

In AMTD-2 we will characterize the thermal response of the:

1.5 m 1/3rd scale deep-core ULE© mirror, and

Schott's 1.2 meter Extreme-Lightweight Zerodur Mirror

this characterization data will be used to predict the need for 'null' polishing to correct low and mid-spatial frequency errors

Actual 'null polish ' is not recommended because capability is demonstrated

Integrated Model Validation

Integrated Model Validation

Technical Challenge:

- On-orbit performance is determined by mechanical & thermal stability
- As future systems become larger, compliance cannot be 100% tested
- Verification will rely on sub-scale tests & validated high fidelity models

Achievement:

- Developed new opto-mechanical tool to create high-fidelity models
- Created models to predict gravity sag & thermal gradients for the 43 cm mirror & validated them by interferometric and thermal imaging test

Deep Core Thermal Model

Thermal Model of 43 cm deep core mirror generated and validate by test.

43 cm deep core mirror tested from 250 to 300K

Test Instrumentation

4D Instantaneous Interferometer to measure surface Wavefront Error
InSb Micro-bolometer to measure front surface temperature gradient to 0.05C
12 Thermal Diodes.

Figure 8: 43-cm mirror test setup.

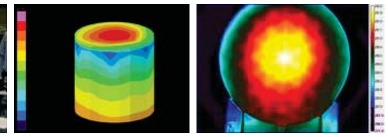


Figure 9: Predicted Thermal Model (left) vs. Measure Performance (right)

NOTE: This was first ever XRCF test using thermal imaging to monitor temperature

Phase 2

In AMTD-2 we will continue to refine tools to predict on-orbit system level optical performance using validated model inputs.

We will validate models via predicting and characterizing:

- thermal response
- static load deformation
- modal testing

of available mirrors

Within budgetary constraint:

- willing to add contributed mirrors to characterization testing
- try to perform vibe & acoustic model validate via test.

Segment Edges

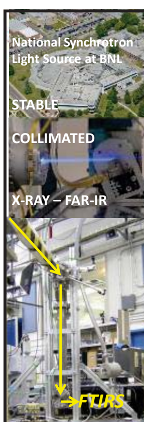
Segment Edges

Technical Challenge:

- Segmented primary mirror edge quality impacts PSF for high-contrast imaging applications and contributes to stray light noise.
- Diffraction from secondary mirror obscuration and support structure also impacts performance.

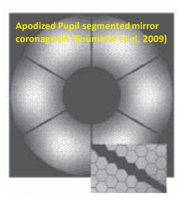
Achievement

- AMTD partner STScI successfully demonstrated an achromatic edge apodization process to minimize segment edge diffraction and straylight on high-contrast imaging PSF.

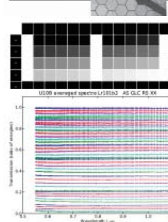


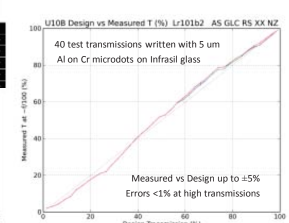
Primary mirror segment gap apodization in the optical

A. Sivaramakrishnan, G. L. Carr, R. Smith, X. X. Xi, & N. T. Zimmerman



Apodization mitigates segment gaps
  Achromatic apodization in collimated space
Tolerancing can be tight
  Gemini Planet Imager (1.1-2.4 um) – 0.5% accuracy req.
  UVOIR space coronagraphy - 0.55 – 1.1 um
Metal-on-glass dots look OK
Next
  Develop & confirm on reflective surfaces
  Reqs. on accuracy, reflectivity, absorption/, polarization?
  Use larger dots to reduce non-linearity





Use of the National Synchrotron Light Source, Brookhaven National Laboratory, was supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences, under Contract No. DE-AC02-98CH10886.

Support System

Support System

Technical Challenge:

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

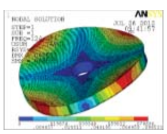
Accomplishments:

- 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.

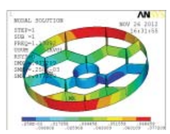
Design Tools and Point Designs

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.

Monolithic Substrate Point Designs

4-m designs are mass constrained to 720 kg for launch on EELV

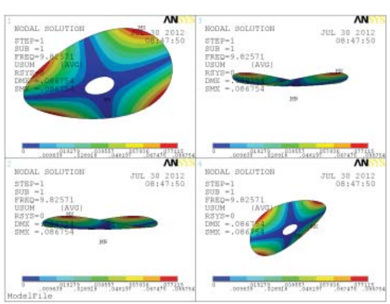
8-m designs are mass constrained to 22 mt for launch on SLS

Trade Study Concept #1: 4 m Solid

Design:

Diameter	4 meters
Thickness	26.5 mm
Mass	716 kg
First Mode	9.8 Hz

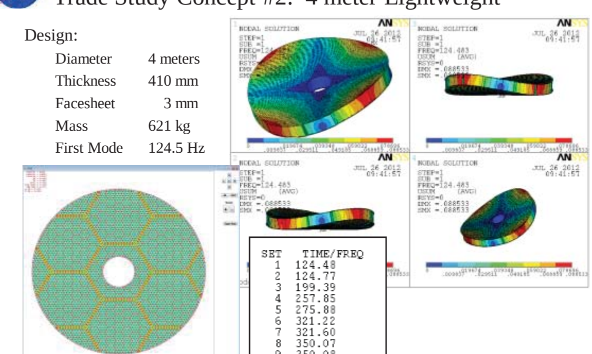
SET	TIME/FREQ
1	9.8257
2	9.8257
3	23.548
4	23.552
5	41.021
6	41.021
7	62.123
8	62.123
9	86.807
10	86.807



Trade Study Concept #2: 4 meter Lightweight

Design:

Diameter	4 meters
Thickness	410 mm
Facesheet	3 mm
Mass	621 kg
First Mode	124.5 Hz



SET	TIME/FREQ
1	124.48
2	124.77
3	199.39
4	257.85
5	275.88
6	321.22
7	321.60
8	350.07
9	350.08
10	350.33

THEIA PM design: 4m, 381mm thick, ~6mm pocktmilled faceplates, 600kg, first mode 140-160 Hz

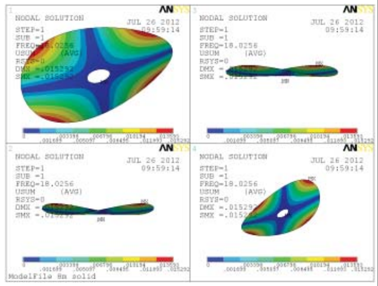
Trade Study Concept #3: 8 meter Solid 22 MT

Design:

Diameter	8 meter
Thickness	200 mm
Mass	21,800 kg
First Mode	18 Hz

Same as ATLAST Study

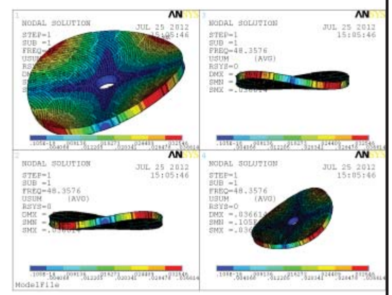
SET	TIME/FREQ
1	18.026
2	18.035
3	42.449
4	42.452
5	47.827
6	74.041
7	74.045
8	75.174
9	75.176
10	112.96



Trade Study Concept #4: 8 meter Lightweight

Design:

Diameter	8 meter
Thickness	510 mm
Facesheet	7 mm
Mass	3,640 kg
First Mode	48.4 Hz



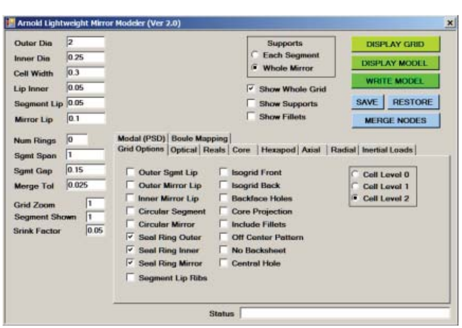
Exelis AMTD-1: 8m, 420mm thick, 2.5/2.0mm faceplates (front/back), 3,042 kg, first mode 33 Hz

Phase 2

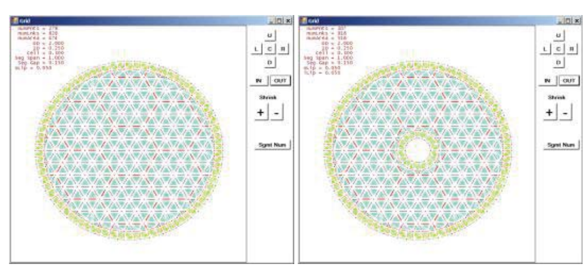
AMTD-2 will continue to use all our tools to generate and refine Pre-Phase A point designs for 4 meter mirrors on various potential launch vehicles.

Modeling Tool

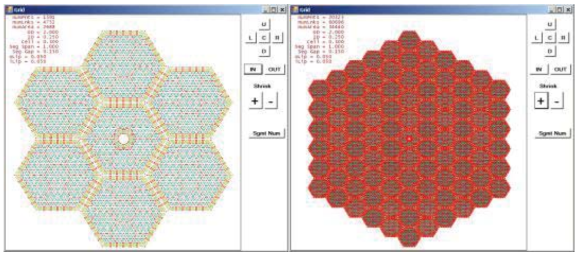
Program Control Window



Monolithic Mirrors

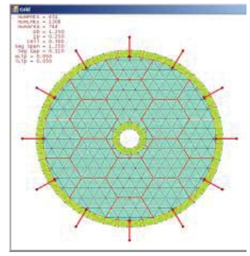


Segmented Mirrors

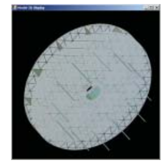


Support Systems

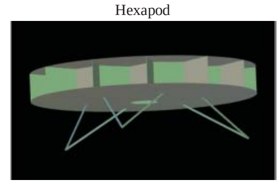
Radial



Axial

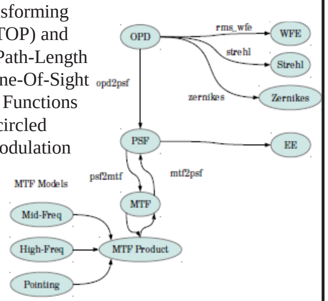


Hexapod



Fast Response Simulator for Telescopes (FaRSiTe)

- Suite of tools to compute optical response metrics from Integrated Modeling analysis results for spacecraft modeling
- MATLAB® based tool for transforming Structural-Thermal-Optical (STOP) and Jitter analysis results (Optical Path-Length Difference [OPD] maps and Line-Of-Sight [LOS] error) into Point Spread Functions and optical metrics: Strehl, Encircled Energy, Zernike modes, and Modulation Transfer Function.
- Incorporated direct integration to transform optical path difference to Point Spread Function (PSF) and between PSF to modulation transfer function



Carl Blaurock, Nightsky Systems, Inc. at GSFC

FaRSiTe: STOP

Structural-Thermal-Optical Performance (STOP)

- Degradation in optical response due to changes in thermal environment

Discipline models

- Thermal: thermal loads, heat transfer paths
- Structural: thermally induced strain
- Optical: change in line-of-sight (LOS) and wavefront error (WFE) as a function of mechanical strain
  - Rigid body motion of the optics (alignment error)
  - Bending of individual mirrors (figure error)

Outputs are OPD maps and LOS versus time

FaRSiTe: Jitter

Jitter

- Degradation in optical response due to excitation of flexible modes

Discipline models

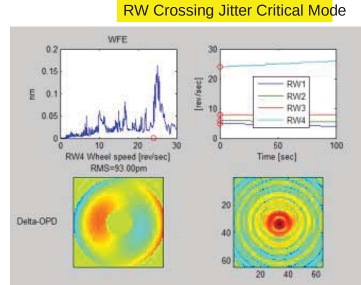
- Disturbances: Reaction Wheel Actuators, High Gain Antennae, Solar Arrays, cryocoolers
- Structural: Normal Modes responses
- Optical: change in LOS and WFE as a function of motions of optics
- Optionally: jitter mitigation technologies
  - Isolators (e.g. reaction wheel or payload isolators)
  - Fast Steering Mirrors
  - Tuned Mass Dampers

Outputs are LOS and spatial RMS WFE as a function of disturbance operating frequency

- Can be added to alignment/figure errors from STOP analysis for telescope performance modeling

WFIRST-AFTA Jitter

RW Crossing Jitter Critical Mode



* Courtesy GSFC/WFIRST-AFTA

Phase 2

AMTD-2 will continue to add capabilities to modeling tools:

We will investigate parametric optimization to find the best opto-mechanical design solution.

Segment to Segment Gap Phasing

Segment to Segment Gap Phasing

Technical Challenge:

- Diffraction limited performance requires co-phased segments.

Achievements:

- Demonstrated the 'fine' stage of a low mass two stage actuator which could be used co-phase segments.

Property	Performance
Mass	0.313 Kg
Axial stiffness	40.9 N/µm
Test Range	14.1µm
Resolution	6.6 nm (noise limited result) [expected is 0.8 nm]
Accuracy	1.1 µm

Segment to Segment Gap Phasing

Technical Challenge:

- 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.

Achievements:

- Investigated utility of Correlated magnetic interface to reduce vibration amplitude, but it provided only marginally improved dampening over conventional magnets.
- Given the inability to reduce dynamic vibration below the required level, we plan no further investigation of this approach.

Figure 6: Delrin Pendulum Test Setup

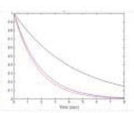


Figure 7: Oscillation Amplitude vs. Time for Unconstrained (black), Conventional Magnetic Interface (blue), and Correlated Magnetic Interface (red)

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.

Assembled outstanding team from academia, industry & government; experts in science & space telescope engineering.

Derived engineering specifications from science measurement needs & implementation constraints.

Maturing 6 critical technologies required to enable 4 to 8 meter UVOIR space telescope mirror assemblies for both general astrophysics & ultra-high contrast exoplanet imaging.

AMTD achieving all its goals & accomplishing all its milestones