Advanced mirror technology development (AMTD) project overview & status

Mirror Technology Days in the Government 2014
Albuquerque
18-20 Nov 2014

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AMTD Overview

The AMTD Team has multiple presentations and this presentation will try to avoid duplication.

Tech Days 2014 – Tues Nov 18				
#	Time	Presenter	Title	Org
			AMTD-II (OPEN)	
12	1320	Stahl	Overview & Status	NASA
13	1340	Stahl	Engineering Specifications	NASA
14	1400	Matthews	Exelis 1.5m Pathfinder Mirror status	Exelis
16	1440	Eng	AMTD-II test plan and preparation	NASA
17	1530	Arnold	Point Design Accomplishments & Status	NASA
Tech Days 2014 – Thurs Nov 20				
			Design Tools (ITAR)	
52	920	Brooks	Thermal induced wavefront error model of space telescope mirrors	NASA
53	940	Arnold	Mechanical Model Tool Accomplishments & Status	NASA

Programmatic Status

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.

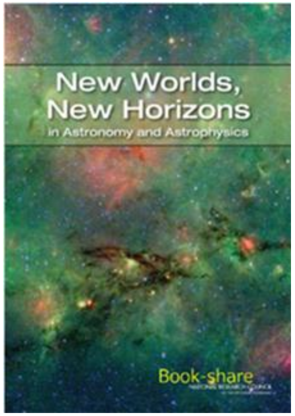
Problem

While many are aware of AMTD, I'm not sure how well its goals and objectives are understood. What is intuitively obvious to me is not necessarily obvious to others.

So, I'm going to re-introduce AMTD.

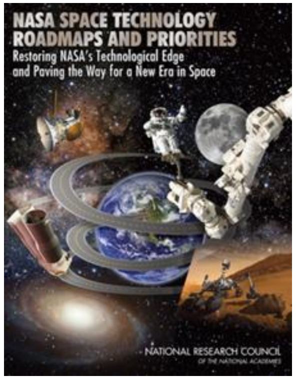
Introduction

Future UVOIR Space Telescopes require Mirror Technology



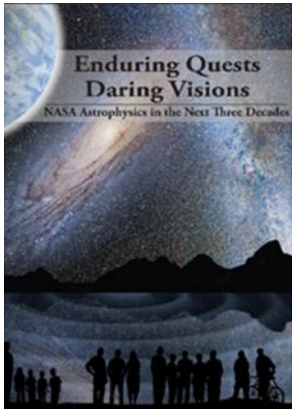
Astro2010 Decadal Study recommended technology development (page 7-17) for a potential future:

- 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:

- LUVOIR Surveyor with sensitivity to locate the bulk of planets in the solar neighborhood and reveal the details of their atmospheres.

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.

- Decadal 2010 called for technology development to enable a 4-m or larger UVOIR space telescope.
- General Astrophysics and Exoplanet Communities want the ability to perform high-contrast imaging and spectroscopy.
- This probably requires a telescope larger than 4 meters.

Architectures for high-contrast imaging & spectroscopy including:

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

Objective

Architecture for any potential future mission will be driven by:

- Science
- Launch Vehicle Capacity
- 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, for example:

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

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 science community with options, we must pursue multiple technology paths: monolithic AND segmented.

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

Approach

To accomplish our objective, we:

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

Outstanding team of academic, industry & government experts:

- UVOIR astrophysics and exoplanet characterization,
- design, fab & test of monolithic & segmented space telescopes

Integrate science & systems engineering to:

- derive engineering specifications from science measurement needs and implementation constraints (i.e. launch vehicles);
- identify technical challenges in meeting these specifications;
- iterate between science and engineering to mitigate challenges; and
- prioritize the challenges.

Systematically mature TRL of prioritized challenges using

- design tools to construct analytical models and
- prototypes/test beds to validate models in relevant environments.

Goals

To accomplish our 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.

Philosophy

These 6 technologies must be matured simultaneously because all are required to make a primary mirror assembly (PMA); AND, PMA’s on-orbit performance 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.

Key Point

It is not possible to design a telescope for a future mission.

It is only possible to identify concepts that may or may not work.

For example, acceptable outcomes of this study include:

- It is not possible (or maybe it is possible) to design a 4-m lightweight monolithic mirror which will survive launch on an EELV and meet the required on-orbit UVOIR optical performance.

  HPS: My initial bias was that it was not possible. And, the more we look at it, the more possible it may be. But, we are still a long way from saying yes.

- It is not possible (or maybe it is possible) to design a segmented aperture telescope of any size which can meet the required on-orbit UVOIR optical performance.

  HPS: My initial bias was that it was not possible. And, after looking at the dynamic stability requirements, we stopped work on segmented apertures.

Tasks

Phase 1 Tasks: Work Breakdown Structure

WBS 2.0 Science Advisory Team

Science team works with Engineering to:

- derive (and/or confirm) engineering specifications for advanced normal incidence mirrors which flow down from the astrophysical measurement needs and flow up from implementation constraints;
- collaborate with systems engineering to mitigate these challenges via architectural implementation trades; and
- prioritize which challenges should be solved first.

WBS 3.0 Systems Engineering

Systems Engineering working with Science:

- derives engineering mirror specifications to achieve on-orbit performance requirements;
- identifies technical challenges to meet specifications;
- prioritize technology development using a systems perspective to determine which technologies will yield the greatest on-orbit performance improvement; and
- defines metrics, evaluates TRL, and assesses advance.

Phase 1 Tasks: Work Breakdown Structure

WBS 3.0 Systems Engineering

Systems Engineering will

- develop thermal & mechanical models of candidate mirror systems including substrates, structures, and mechanisms;
- validate models 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, achieve stable pointing and maximum thermal time constant;
- segment edge dimensions and roll; and
- segment-to-segment gap dimensions, phasing and stability.

Systems Engineering Team:

- Developing Modeling Tool
- Developing 4 & 8-meter primary mirror substrate point designs
- Performing Trade Studies

Phase 1 Tasks: Work Breakdown Structure

WBS 4.0 Technology Development

4.1 Monolithic Mirror Technology
4.2 Segmented Mirror Technology
4.3 Model Verification and Validation

WBS 4.1 Monolithic Technologies

Required to manufacture, test, launch, and operate a 4 or 8-m monolithic mirror also 2-m class mirror segments.

4.1.1	Deep Core Mirror Substrate
4.1.2	Mirror Support Structure
4.1.3	Mid/High Spatial Frequency Surface Errors

WBS 4.2 Segmented Technologies

Required to assemble, align, phase, and operate a segmented mirror as an integrated unit to UVOIR tolerances.

4.2.1	Edge Control
4.2.2	Gap Phasing Control

Phase 1 Tasks: Work Breakdown Structure

WBS 4.3 Model Verification & Validation

Models are required to predict on-orbit performance for pointing stability, jitter, and thermal-elastic stability, as well as vibro-acoustics and launch loads. Performance data is required to verify and validate models.

4.3.1 Thermal Model Verification

4.3.2 Mechanical Model Verification

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

Accomplishments

Requirement Derivation:

From Science Needs to Technical Challenges

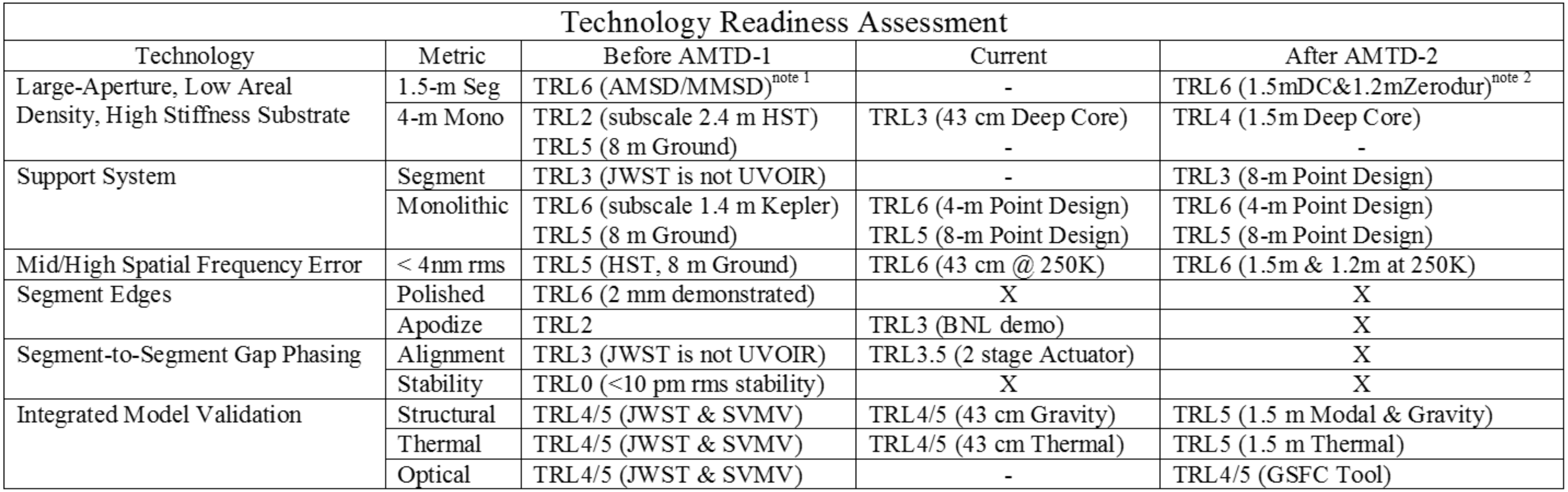
WBS 2.0 and WBS 3.0

Engineering Specifications Derived from Science Requirements is subject of next presentation

TRL Assessment

SAT Program request technology maturation to be assessed based on TRL advancement.

Before the AMTD-1 Proposal, we assessed the TRL for each of our Key Technologies.



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

TRL Assessment

We started an assessment process with the COR Office using their TRL Assessment Tool & an independent review team.

Scott Smith used the tool to assess TRL for a 4m lightweight monolithic mirror

For a Low Temperature Fused Substrate			
TRL	Pre-Phase 1	End Phase 1	End Phase 2
Low Temperature Fusion	3 2.4m x 135 mm 1 layer core	4 0.4 m x 400 mm 3 layer stack core	5 1.5 m x 200 mm 3 layer stack core
Low Temperature Slumping	3	3+	4
Polishing to < 6nm rms	4	5	5
Mechanical Modeling	5	5+	5+
Thermal Modeling	3	3+	4
Integrated Support	3	3+	4

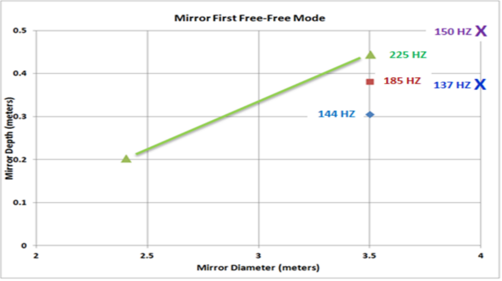
Feedback from the Review Team is that we need to think about gravity sag – (HPS: use existing solutions).

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.



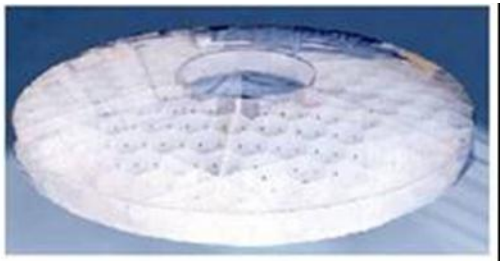
Current launch vehicle capacity limits requires low areal density.

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.

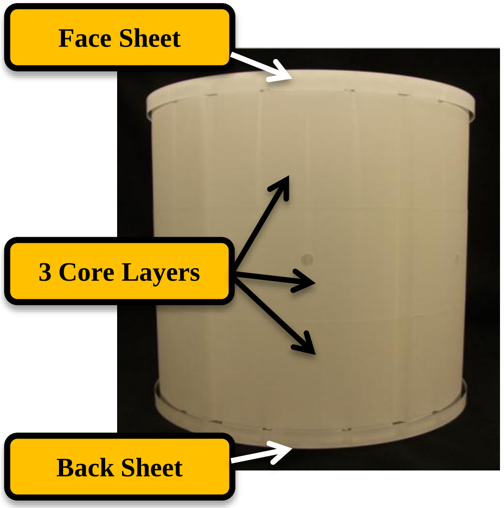
Successfully 're-slumped' a ULE© fused substrate.

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

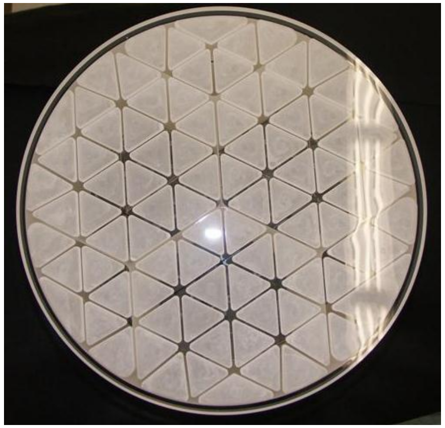
43 cm Deep Core Mirror

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.

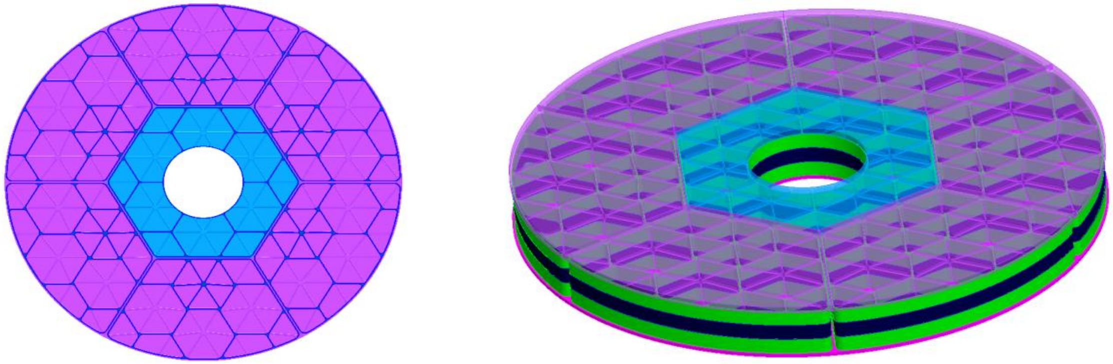
Matthews, Gary, et al, *Development of stacked core technology for the fabrication of deep lightweight UV quality space mirrors*, SPIE Conference on Optical Manufacturing and Testing X, 2013.

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.

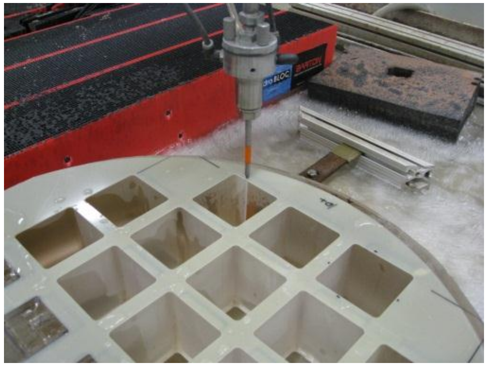
Strength Testing

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

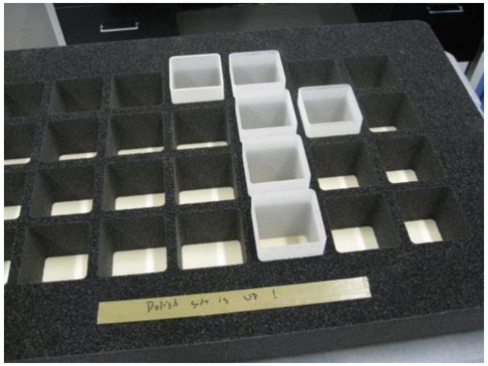
- Resulting Weibull 99% survival value was 15% above the most conservative design allowable. And, the data ranged from 30% to 200% above design allowable.

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:

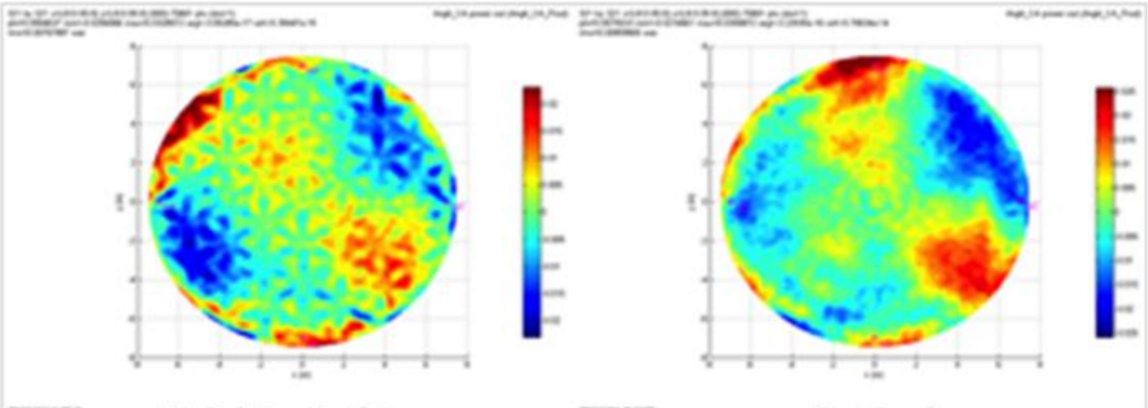
- High-contrast imaging requires a very smooth mirror (< 10 nm rms)
- Mid/High spatial errors (zonal & quilting) can introduce artifacts
- DMs correct low-spatial errors, not mid/high spatial errors
- On-orbit thermal environment can stress mirror introducing error

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

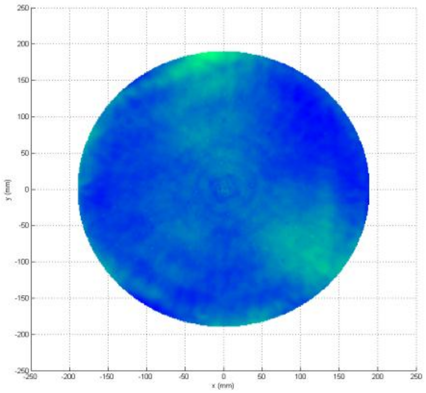
Exelis polished 43 cm deep-core mirror to a zero-gravity figure of 5.5 nm rms using ion-beam figuring to eliminate quilting.

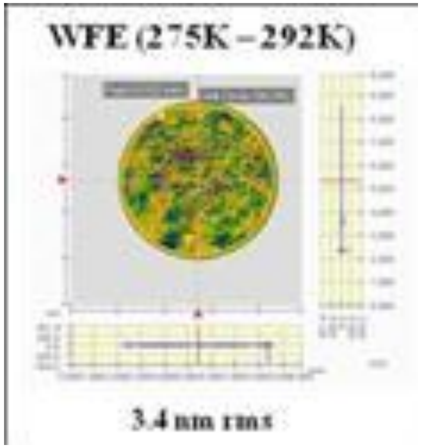


Polishing Quilting

Finished

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.

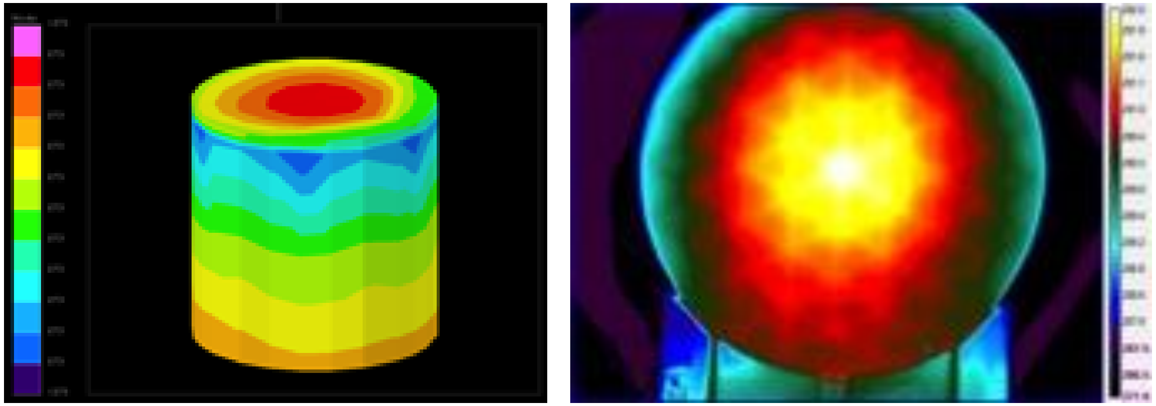


Figure 9: Predicted Thermal Model (left) vs. Measure Performance (right)

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:

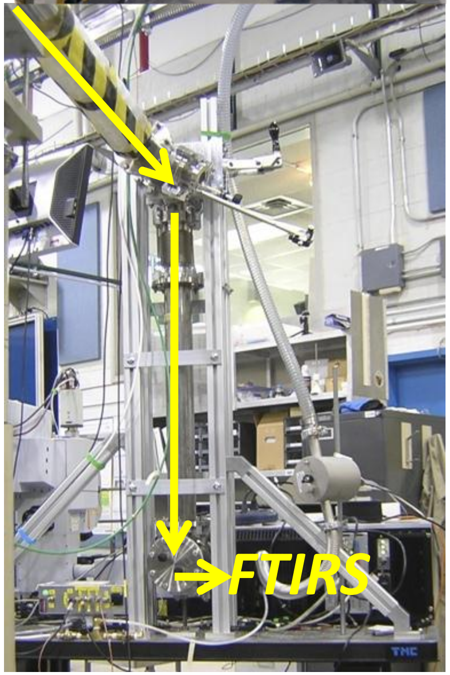
- Segmented primary mirror edge quality impacts PSF for high-contrast imaging applications and contributes to stray light noise.
- Diffraction from secondary mirror obscuration and support structure also impacts performance.

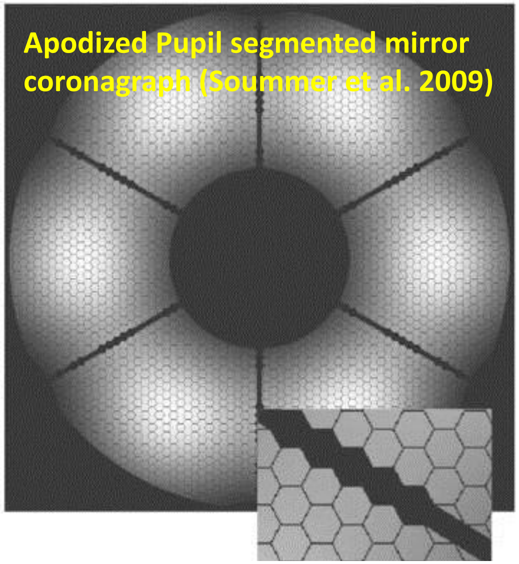
Achievement

- 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





Apodized Pupil segmented mirror coronagraph (Soummer et al. 2009)

Apodization mitigates segment gaps

- Achromatic apodization in collimated space

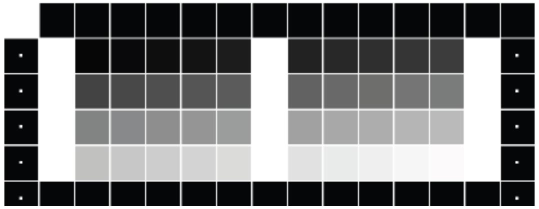
Tolerancing can be tight

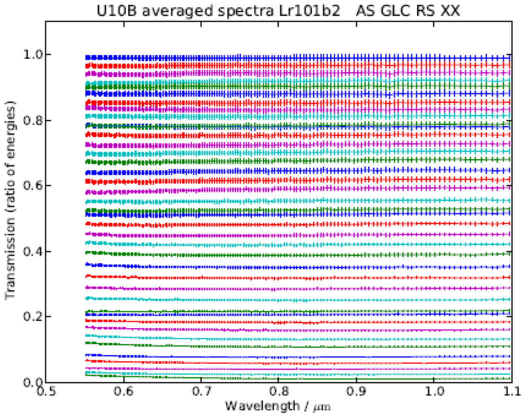
- Gemini Planet Imager (1.1-2.4 um) – 0.5% accuracy req.
- UVOIR space coronagraphy - 0.55 – 1.1 um

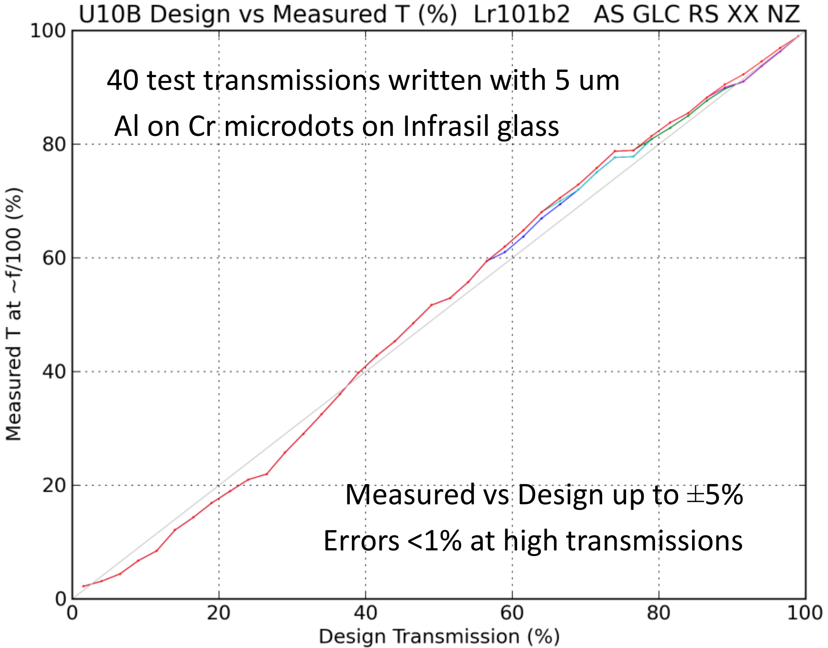
Metal-on-glass dots look OK

Next

- Develop & confirm on reflective surfaces
- Reqs. on accuracy, reflectivity, absorption/, polarization?
- Use larger dots to reduce non-linearity







40 test transmissions written with 5 um Al on Cr microdots on Infrasil glass

Measured vs Design up to ±5%

Errors <1% at high transmissions

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.

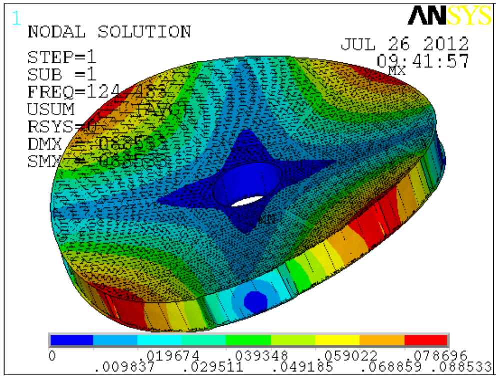
Accomplishments:

- 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.

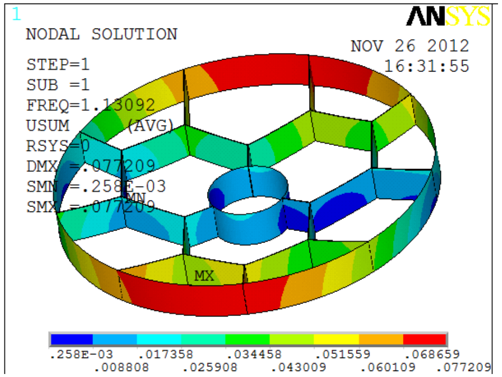
Design Tools and Point Designs

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

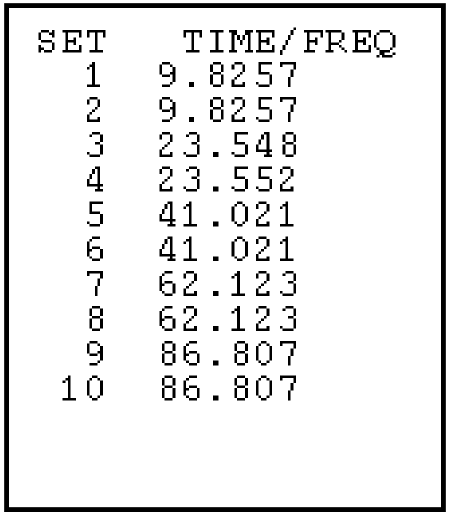
4-m designs are mass constrained to 720 kg for launch on EELV

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

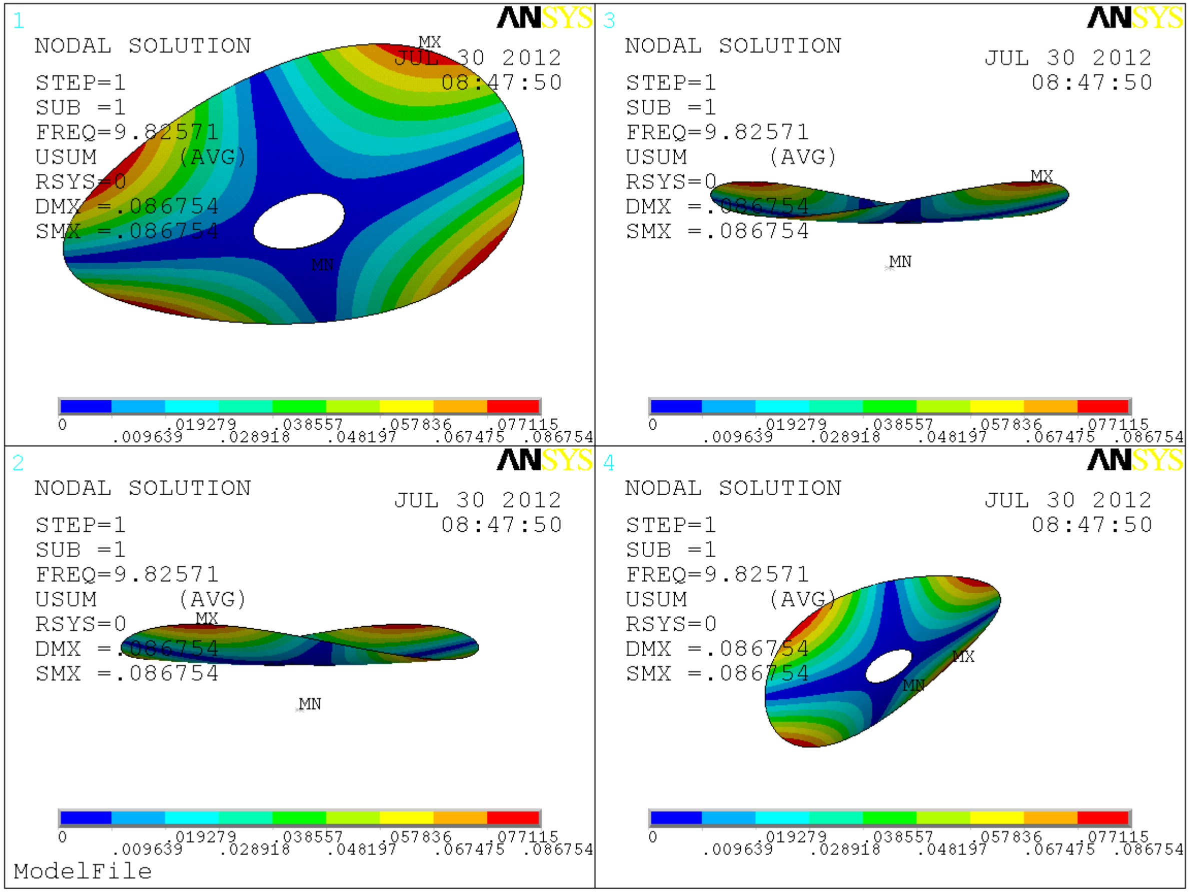
Trade Study Concept #1: 4 m Solid

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
```



```
1
NODAL SOLUTION
STEP=1
SUB =1
FREQ=9.82571
USUM       (AVG)
RSYS=0
DMX =.086754
SMX =.086754
JUL 30 2012
08:47:50
```

```
3
NODAL SOLUTION
STEP=1
SUB =1
FREQ=9.82571
USUM       (AVG)
RSYS=0
DMX =.086754
SMX =.086754
JUL 30 2012
08:47:50
```

```
2
NODAL SOLUTION
STEP=1
SUB =1
FREQ=9.82571
USUM       (AVG)
RSYS=0
DMX =.086754
SMX =.086754
JUL 30 2012
08:47:50
```

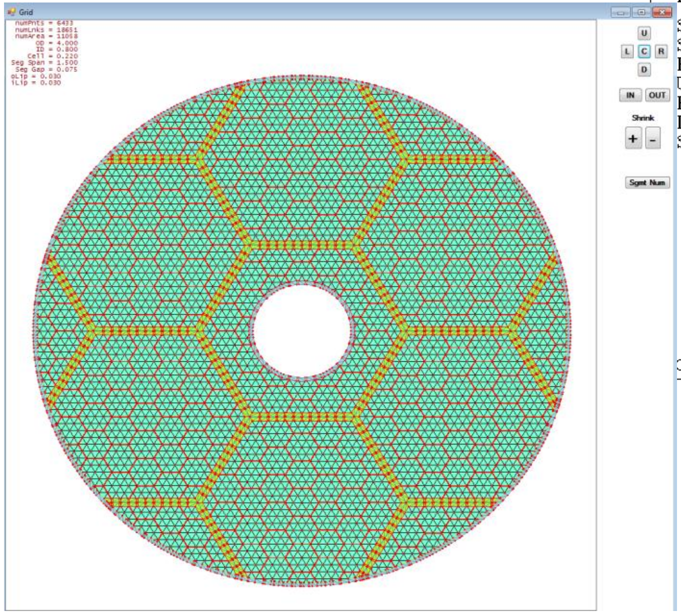
```
4
NODAL SOLUTION
STEP=1
SUB =1
FREQ=9.82571
USUM       (AVG)
RSYS=0
DMX =.086754
SMX =.086754
JUL 30 2012
08:47:50
```

ModelFile

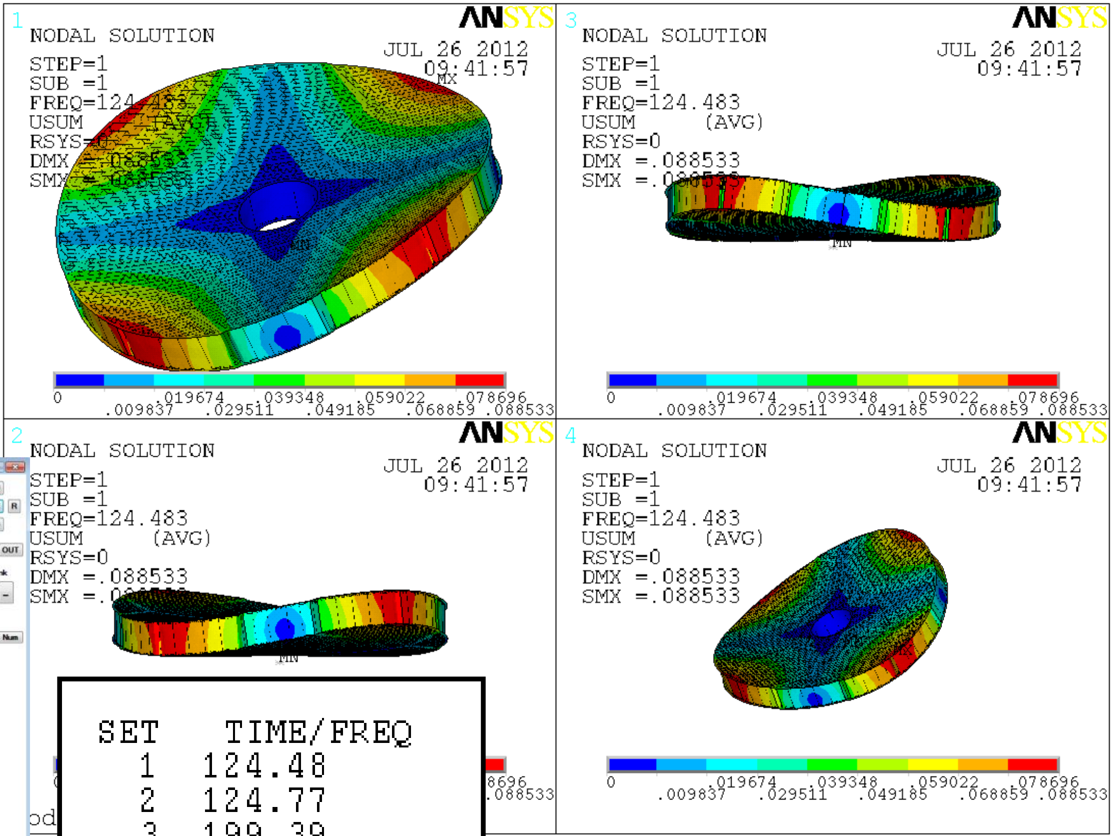
Trade Study Concept #2: 4 meter Lightweight

Design:

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



```
numPnts = 6433
numLnks = 18651
numArea = 11068
     OD = 4.000
     ID = 0.800
   Cell = 0.220
Seg Span = 1.500
 Seg Gap = 0.075
oLip = 0.030
iLip = 0.030
```



```
NODAL SOLUTION

STEP=1
SUB =1
FREQ=124.483
USUM      (AVG)
RSYS=0
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SMX =.088533
```

```
JUL 26 2012
09:41:57
```

```
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
```

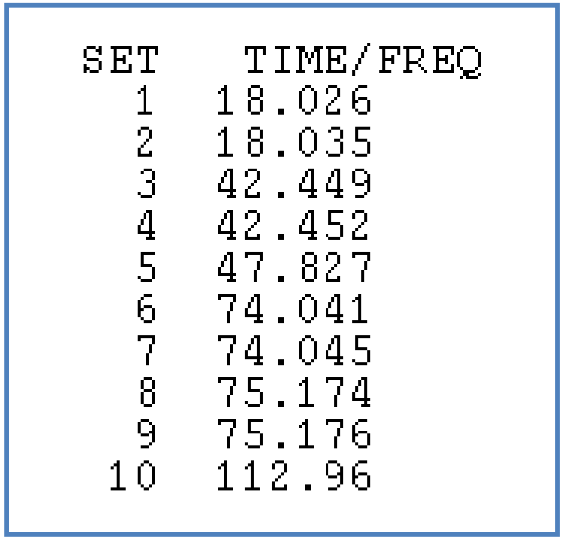
THEIA PM design: 4m, 381mm thick, ~6mm pocktmilled faceplates, 600kg, first mode 140-160 Hz

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
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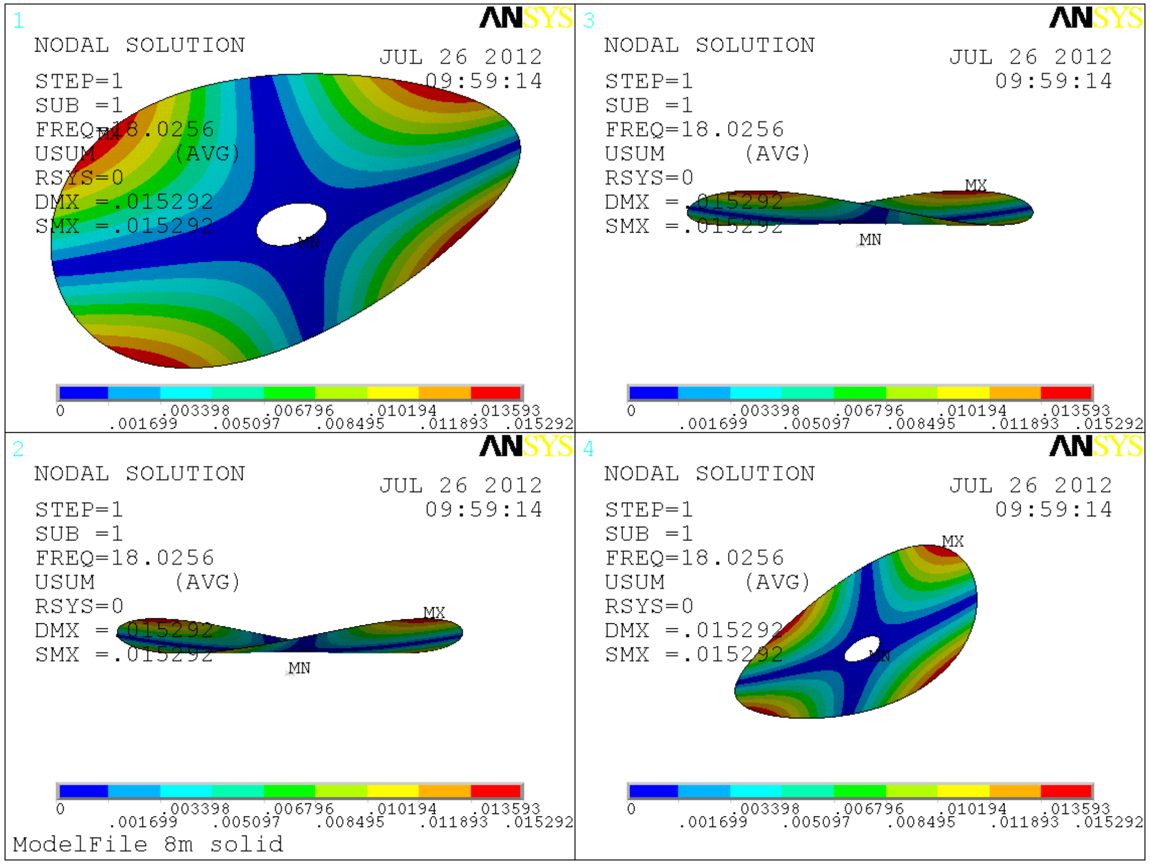
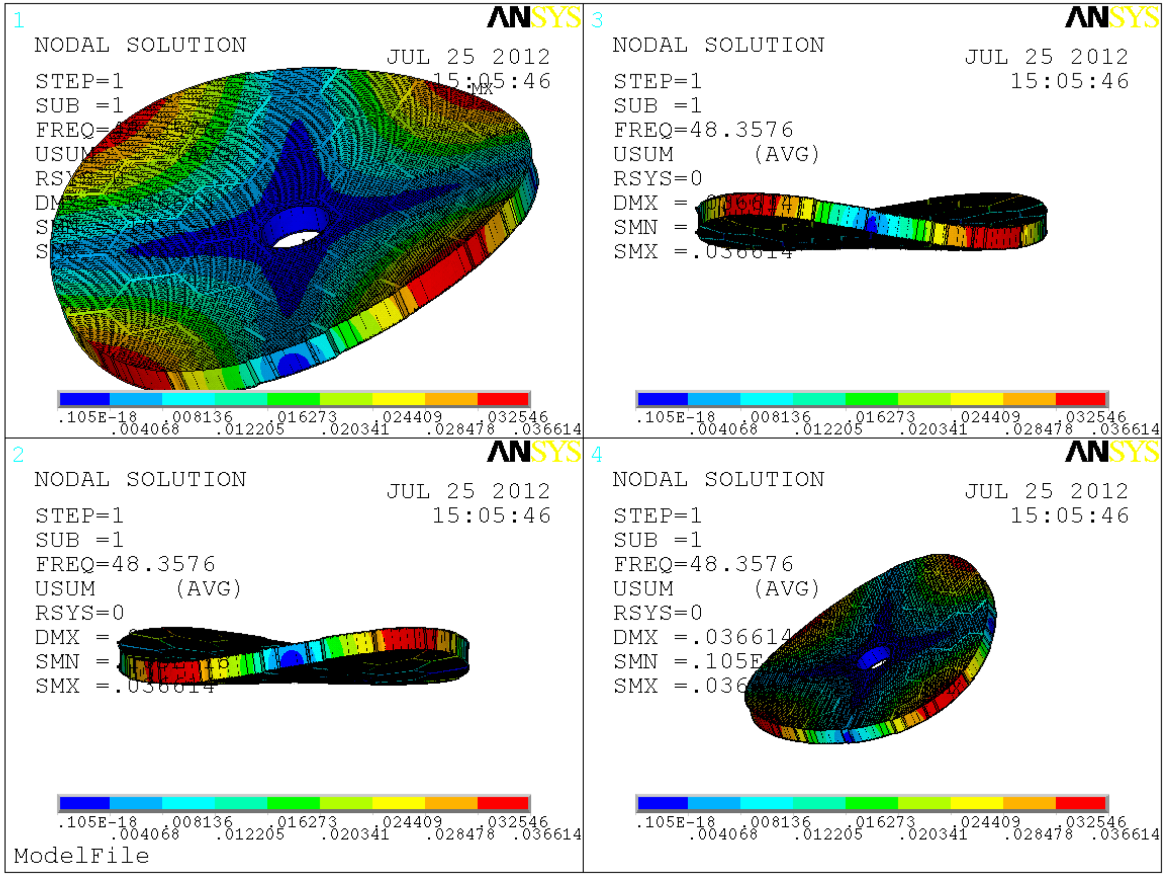
   2   18.035
   3   42.449
   4   42.452
   5   47.827
   6   74.041
   7   74.045
   8   75.174
   9   75.176
  10   112.96
```



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



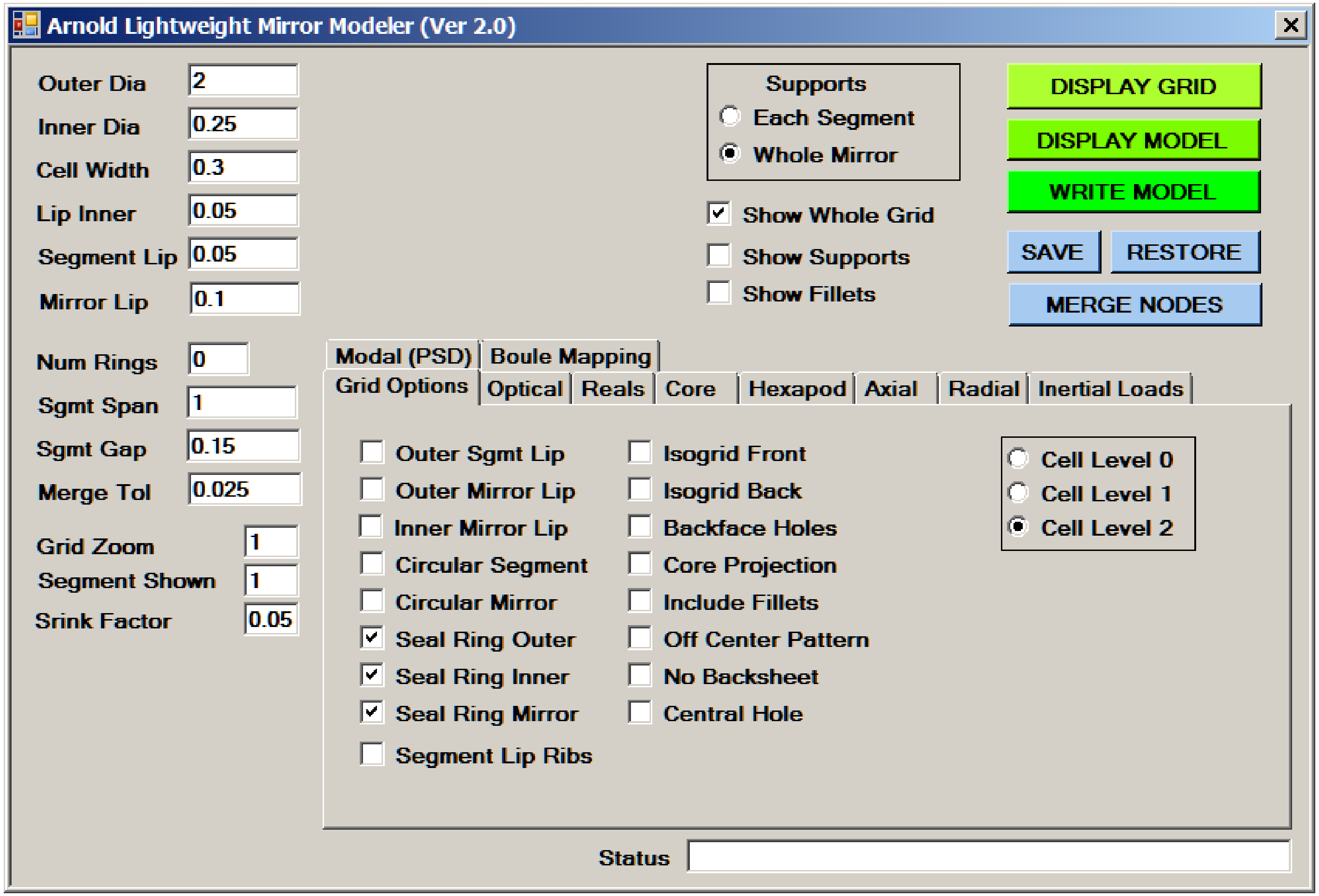
Exelis AMTD-1: 8m, 420mm thick, 2.5/2.0mm faceplates (front/back), 3,042 kg, first mode 33 Hz

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



Outer Dia 2
Inner Dia 0.25
Cell Width 0.3
Lip Inner 0.05
Segment Lip 0.05
Mirror Lip 0.1

Num Rings 0
Sgmt Span 1
Sgmt Gap 0.15
Merge Tol 0.025

Grid Zoom 1
Segment Shown 1
Srink Factor 0.05

Supports
○ Each Segment
● Whole Mirror

☑ Show Whole Grid
☐ Show Supports
☐ Show Fillets

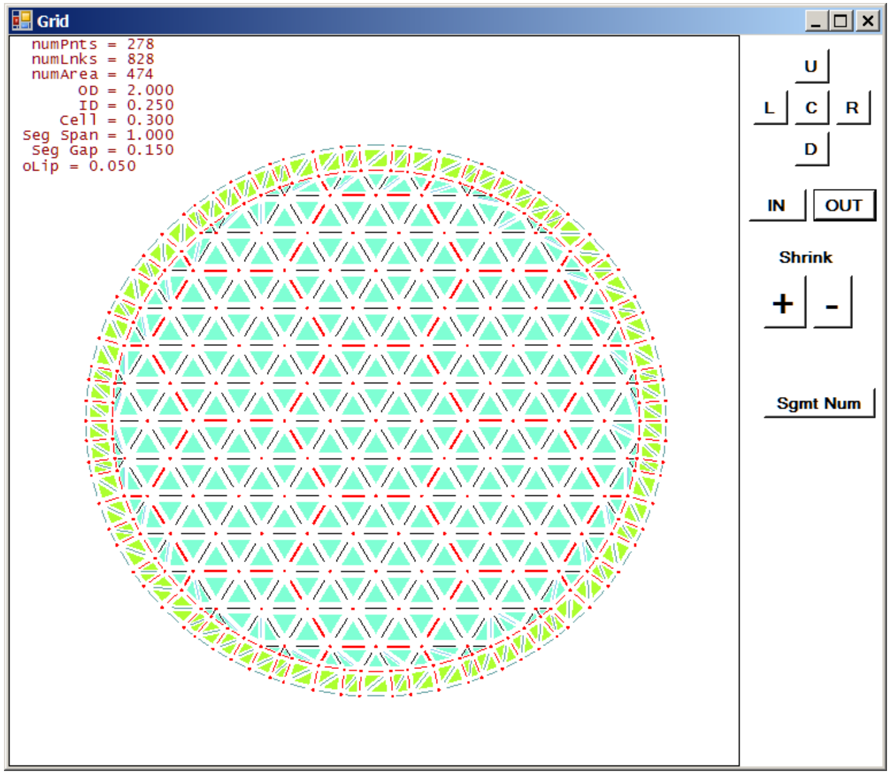
☐ Outer Sgmt Lip
☐ Outer Mirror Lip
☐ Inner Mirror Lip
☐ Circular Segment
☐ Circular Mirror
☑ Seal Ring Outer
☑ Seal Ring Inner
☑ Seal Ring Mirror
☐ Segment Lip Ribs

☐ Isogrid Front
☐ Isogrid Back
☐ Backface Holes
☐ Core Projection
☐ Include Fillets
☐ Off Center Pattern
☐ No Backsheet
☐ Central Hole

○ Cell Level 0
○ Cell Level 1
● Cell Level 2

Status

Monolithic Mirrors



```
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 numLnks = 828
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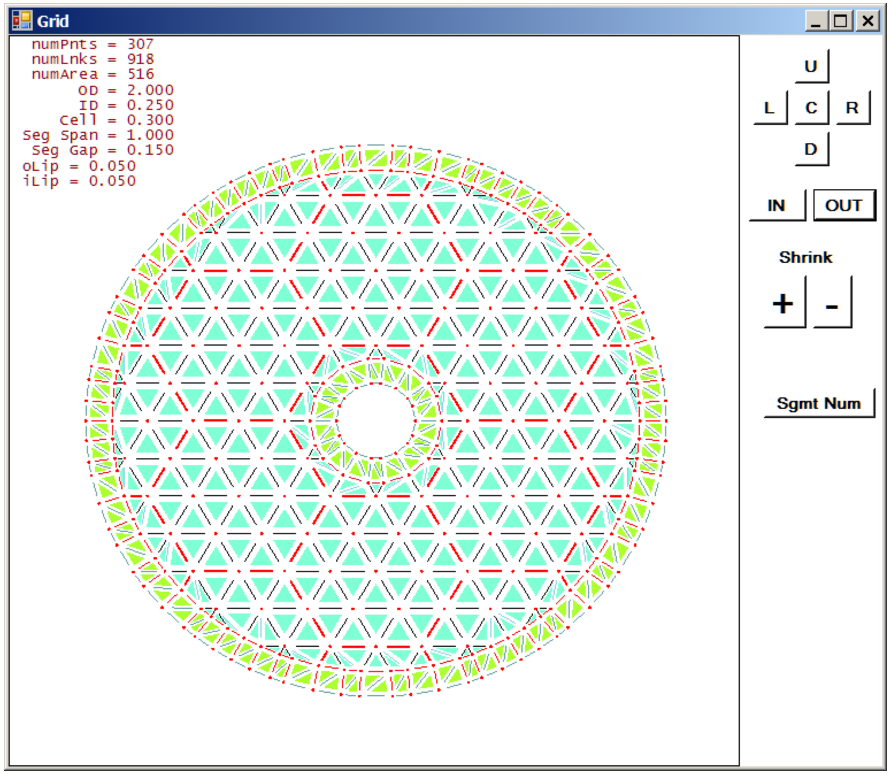
Seg Span = 1.000
 Seg Gap = 0.150
oLip = 0.050
```



```
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 numLnks = 918
 numArea = 516
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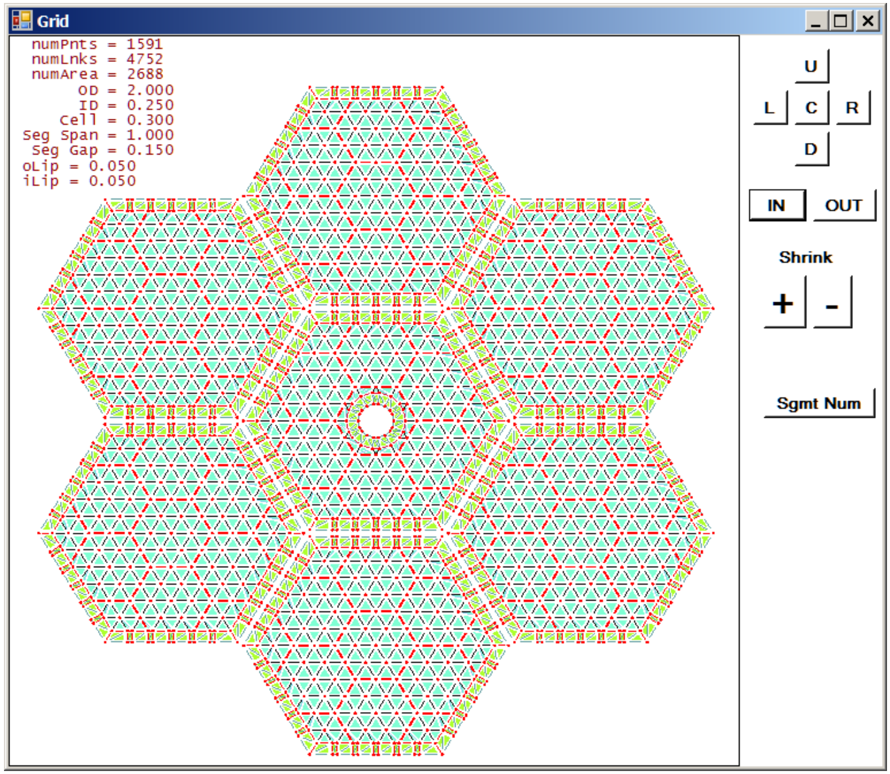
Seg Span = 1.000
 Seg Gap = 0.150
oLip = 0.050
iLip = 0.050
```

Segmented Mirrors



```
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 numLnks = 4752
 numArea = 2688
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      ID = 0.250
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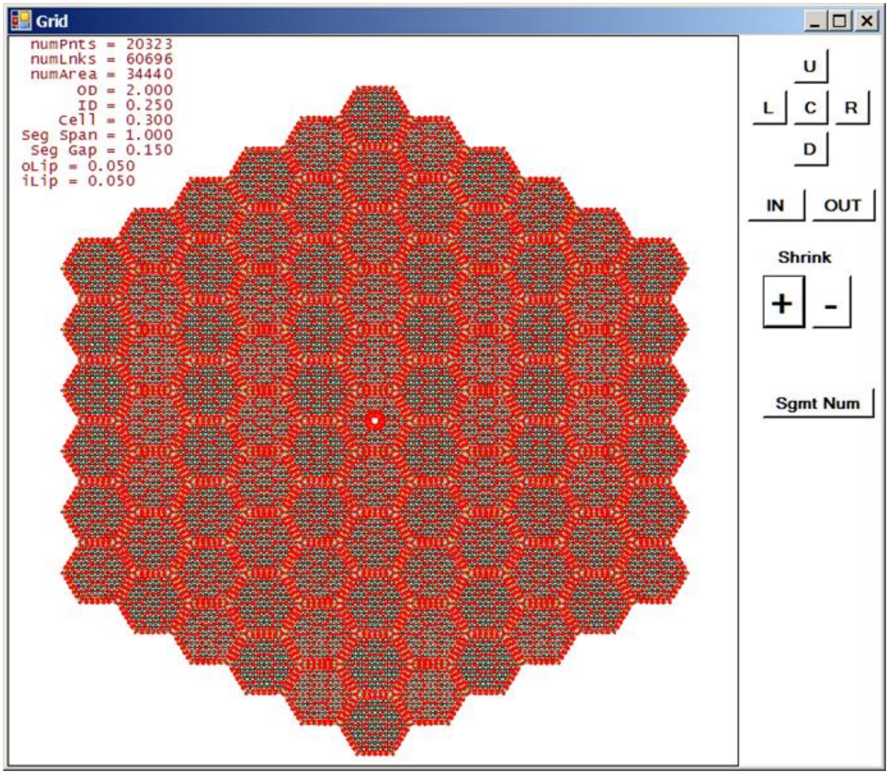
Seg Span = 1.000
 Seg Gap = 0.150
oLip = 0.050
iLip = 0.050
```



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 numLnks = 60696
 numArea = 34440
      OD = 2.000
      ID = 0.250
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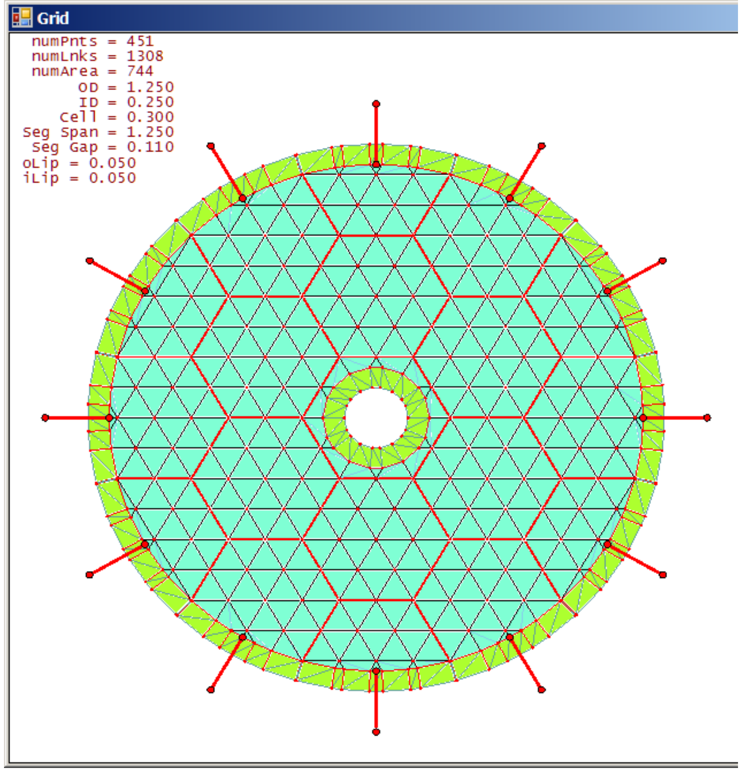
Seg Span = 1.000
 Seg Gap = 0.150
oLip = 0.050
iLip = 0.050
```

Support Systems

Radial



```
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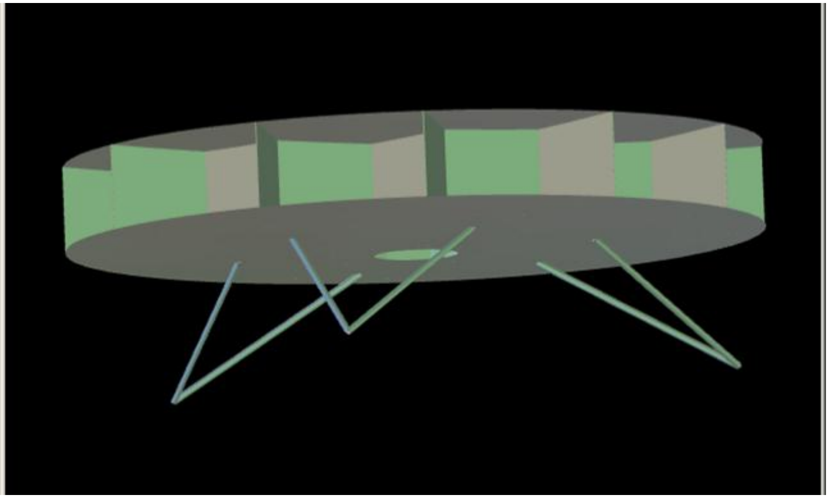
 numLnks = 1308
 numArea = 744
      OD = 1.250
      ID = 0.250
    Cell = 0.300
Seg Span = 1.250
 Seg Gap = 0.110
oLip = 0.050
iLip = 0.050
```

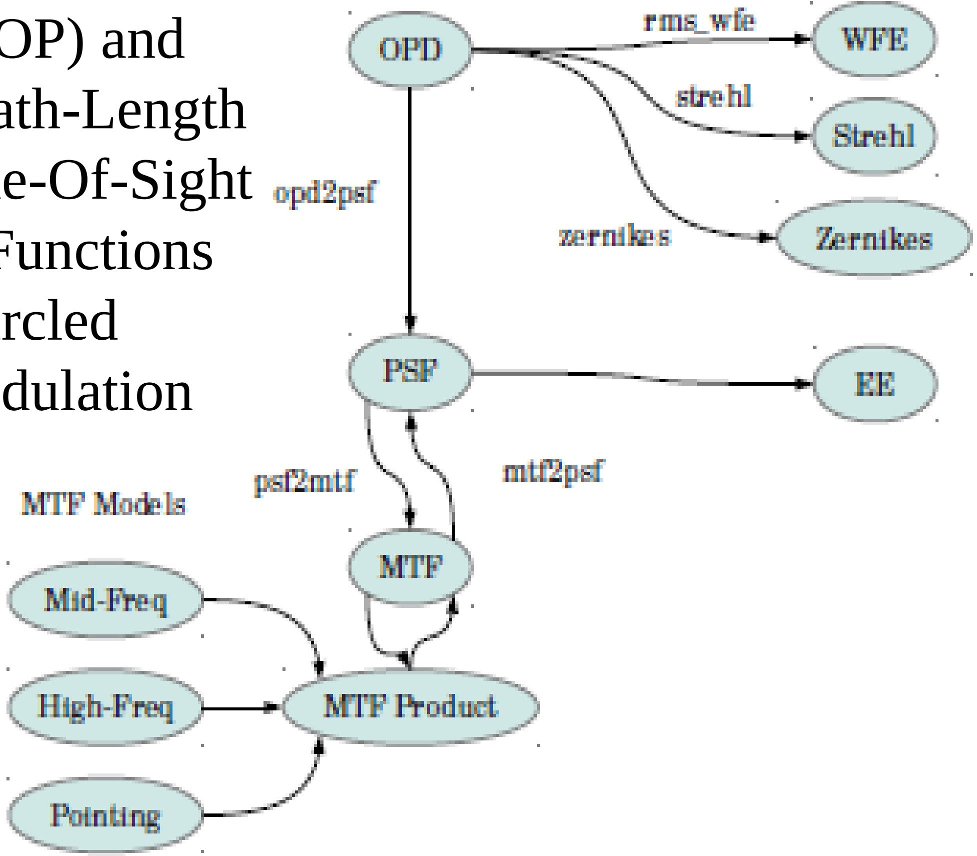
Axial

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)

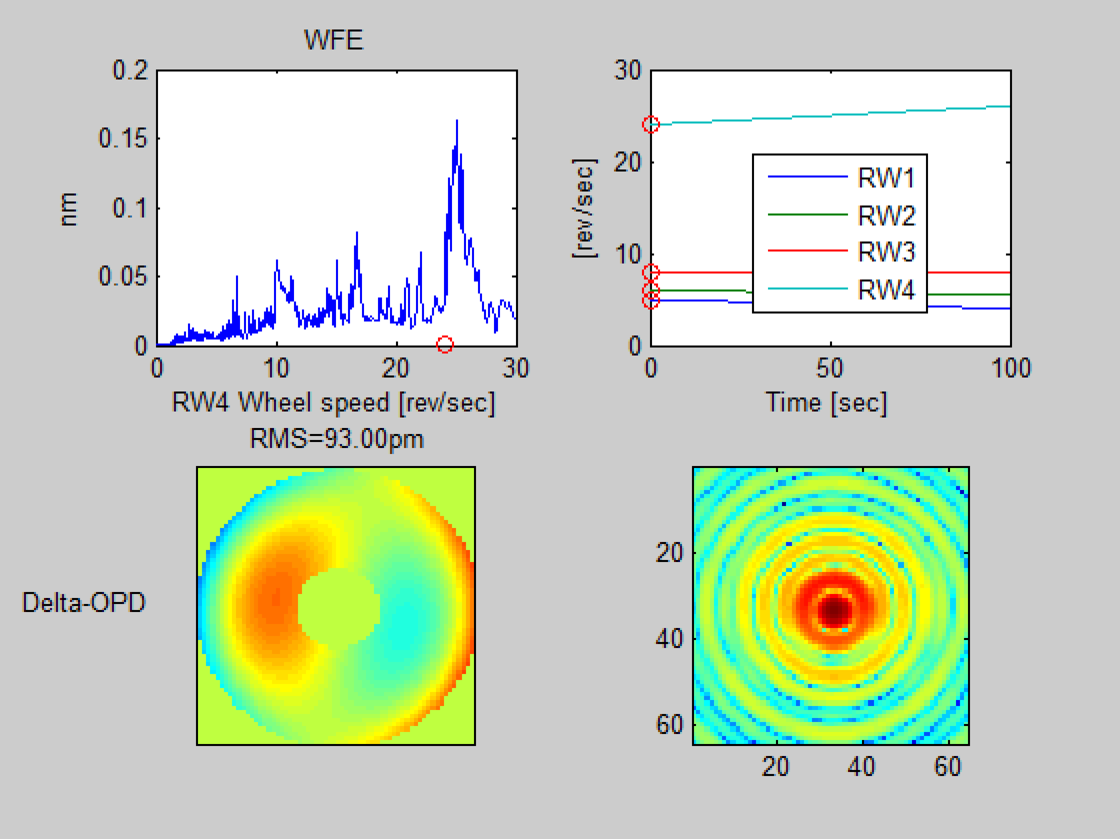
Outputs are OPD maps and LOS versus time

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

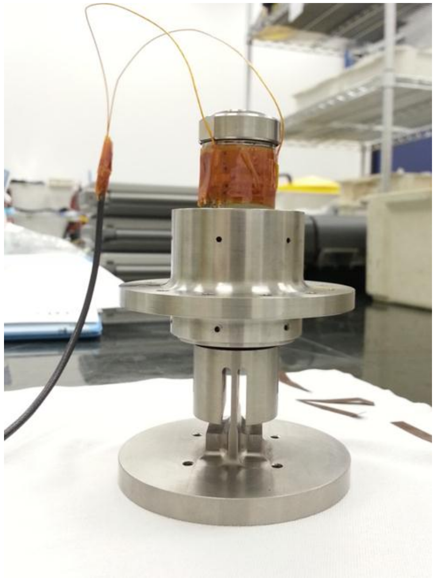
Technical Challenge:

- 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.

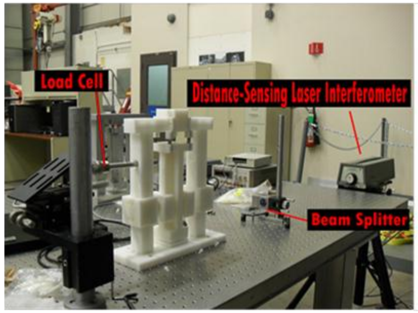


Figure 6: Delron Pendulum Test Setup

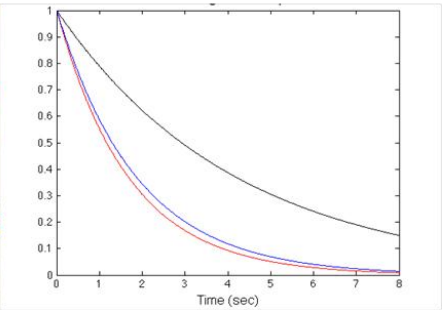


Figure 7: Oscillation Amplitude vs. Time for
Unconstrained (black),
Conventional Magnetic Interface (blue), and
Correlated Magnetic Interface (red)

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

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

11 Publications in Year 2

Mirror Technology Days, Redondo Beach, CA, Oct 1-4, 2013

1) Stahl, "Overview and Recent Accomplishments of Advanced Mirror Technology Development (AMTD) for Very Large Space Telescopes"
2) Stahl, "Engineering Specifications derived from Science Requirements for AMTD"
3) Matthews & Stahl, "Development of stacked core technology for the fabrication and processing of deep lightweight UV quality space mirrors"
4) Eng & Stahl, "Cryogenic optical performance of a lightweighted mirror assembly for future space astronomical telescope: correlating optical test results and thermal optical model"
5) Arnold & Stahl, "Next-generation lightweight mirror modeling software"

American Astronomical Society, Washington, DC, January 5-9, 2014 (poster & presentation)

6) H. Philip Stahl, Advanced Mirror Technology Development (AMTD) for Very Large UVOIR Space Telescopes

SPIE Space Telescopes & Instrumentation Symposia, Montreal, Canada, June 22-27, 2014

7) H. Philip Stahl, Marc Postman, Gary Mosier, W. Scott Smith, Carl Blaurock, Kong Ha and Christopher C. Stark, "AMTD: update of engineering specifications derived from science requirements for future UVOIR space telescopes"
8) Philip Stahl, Marc Postman, Laura Abplanalp, William Arnold, Carl Blaurock, Robert Egerman, Gary Mosier, "Advanced mirror technology development (AMTD) project: 2.5 year status"
9) Gary W. Matthews, Robert Egerman, Steven P. Maffett, H. Philip Stahl, Ron Eng, Michael R. Effinger, "The development of stacked core technology for the fabrication of deep lightweight UV-quality space mirrors"
10) Gary W. Matthews, Charles S. Kirk, Steven P. Maffett and Calvin E. Abplanalp, "Processing of a stacked core mirror for UV applications"

National Space & Missile Materials Symposium, Huntsville, AL, June 23-26, 2014 (presentation only)

11) Michael Effinger, H. Philip Stahl, Scott Smith, Laura Abplanalp, Steven Maffett, Robert Egerman, Ron Eng, Richard Siler, William Arnold, Gary Mosier, and Carl Blaurock, "Advanced Mirror & Modeling Technology Development"