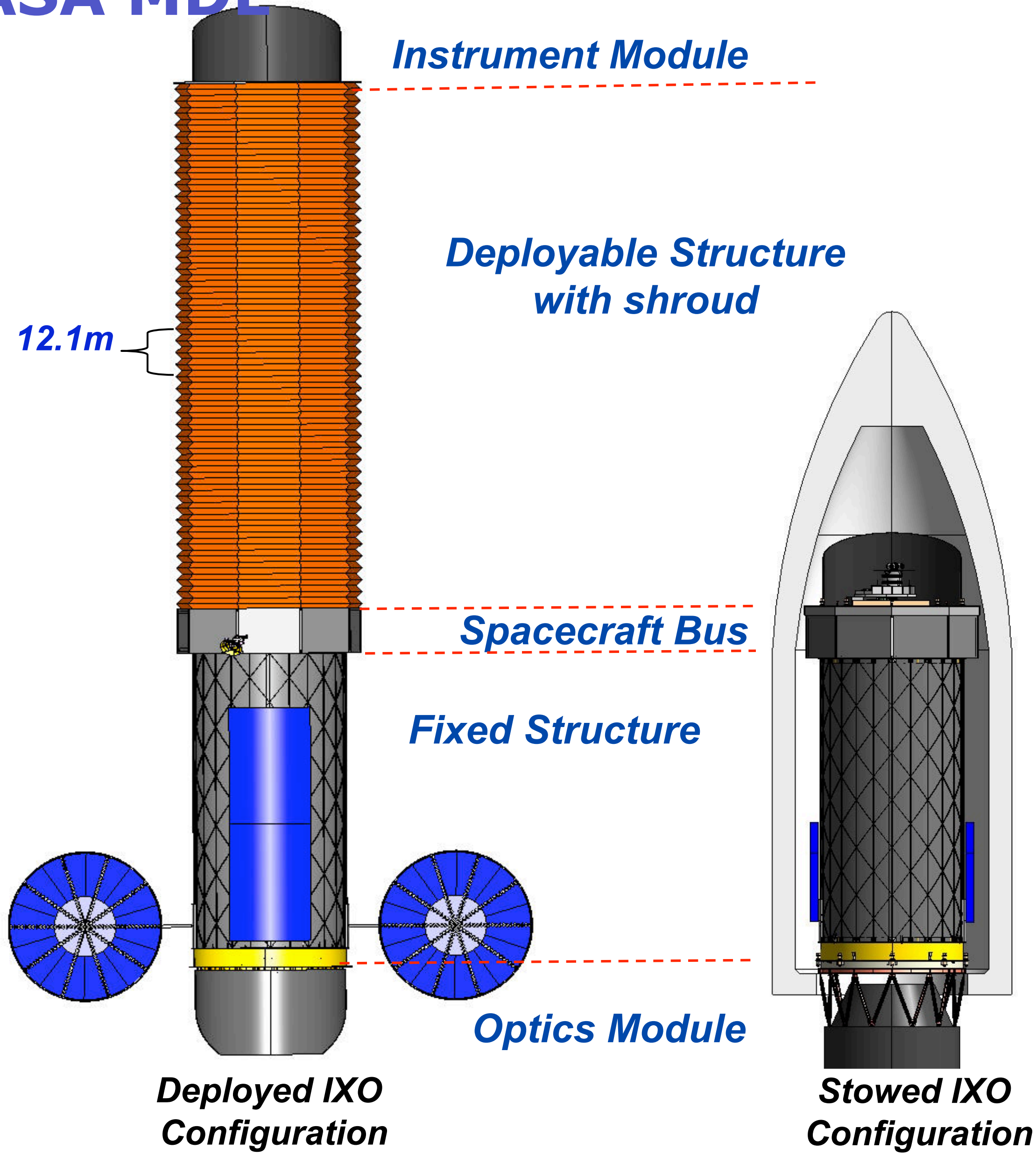
Status of glass mirror technology and design

1/29/2009

Rob Petre

IXO Spacecraft - NASA MDL

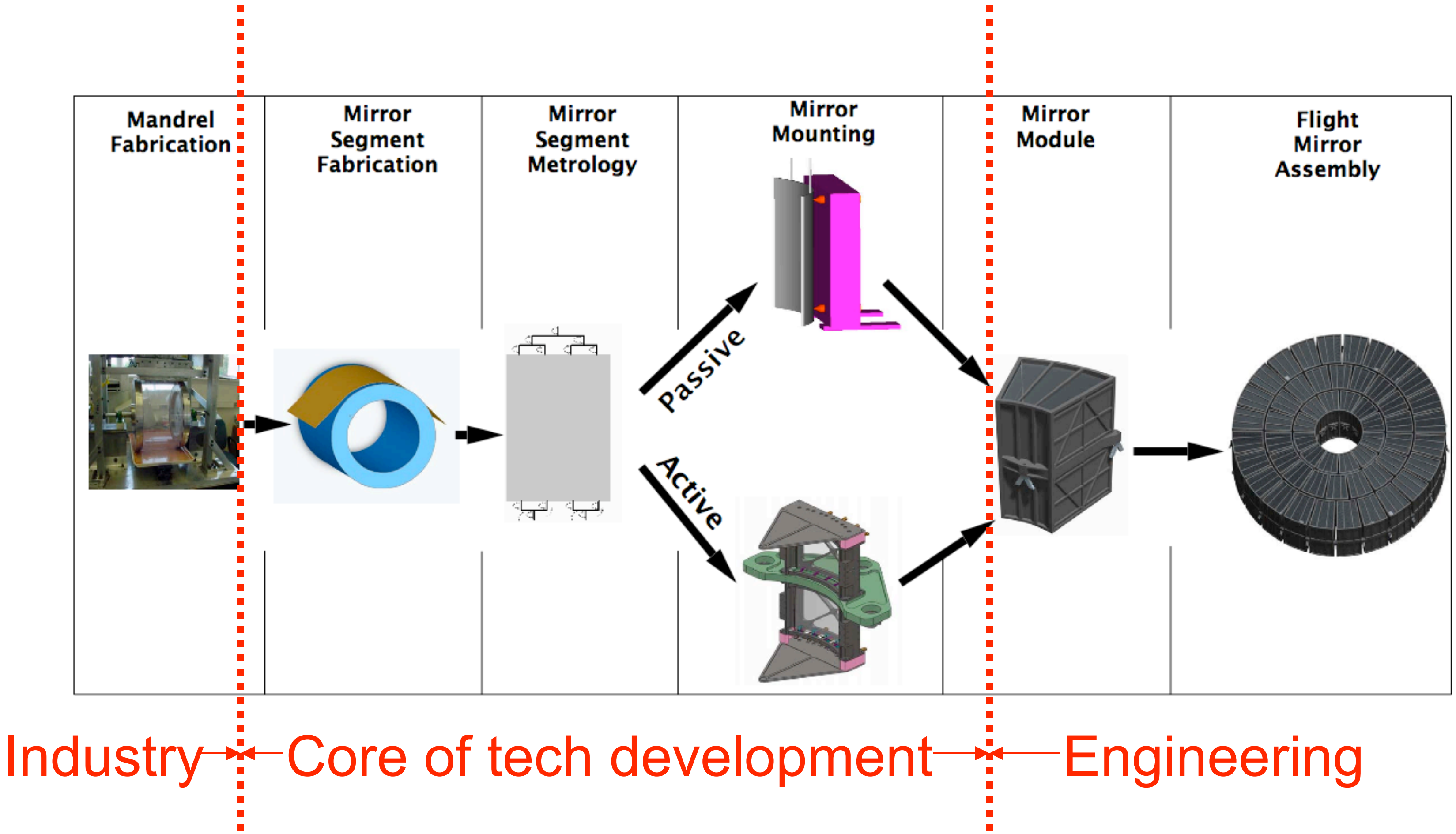
- Observatory Mass ~6300 kg (including 30% contingency)
- Launch on an Atlas V 551 or Ariane V
- Direct launch into an 800,000 km semi-major axis L2 orbit
- The observatory is deployed to achieve 20 m focal length
- 5 year required lifetime, with expendables for 10 year goal



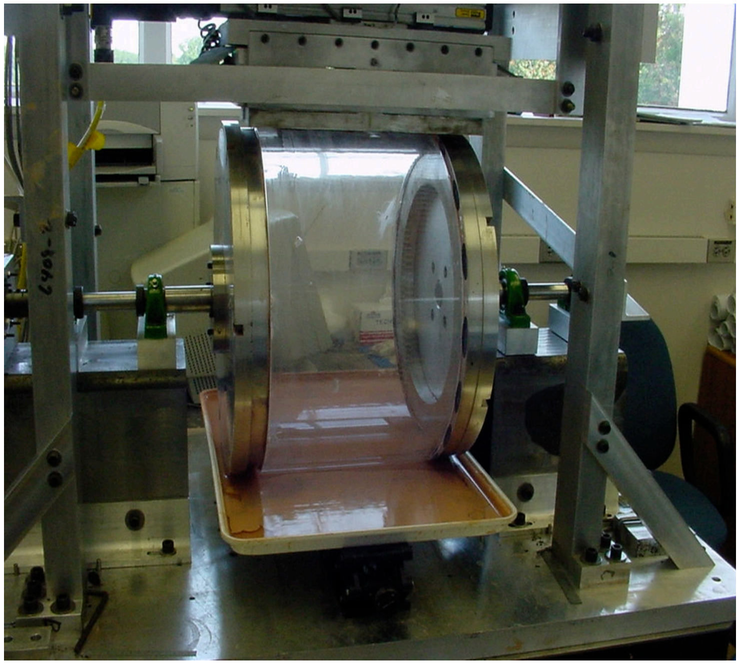
5 arcsec error system budget for glass mirror

	Single mirror + calorimeter Angular Resolution Error Budget - 5"										
	ITEM (HPD - arcsec)	RQMT	Margin		Allocation						RATIONALE
1	Calorimeter Imaging Resolution	5.00	0.62								1 SXT
2	On-Orbit Single Telescope			4.96							RSS
3	Calorimeter pixelization error				0.96						3 arc-second pixels, with sub-pixel resolution
1a	Telescope Resolution (independent of detector type)			4.87							RSS
4	Telescope level effects				1.51						RSS
5	Image Reconstruction errors (over obs)					1.41					RSS
6	Attitude knowledge drift						1.00				Chandra experience
7	FMA/detector relative drift (thermal)						1.00				Chandra experience - includes FID light system
8	FMA/detector vibration effects					0.20					Chandra experience (jitter)
9	FMA/detector misalignment (off-axis error)					0.05					Calc: field dependent aberration due to +/- 30 arc-sec alignment
10	FMA/detector Focus Error					0.50					Allocation - includes focal plane focus adjustment
11	FMA On-orbit performance				4.63						RSS
12	SXT Mirror launch shifts					0.50					Eng est based on Chandra
13	On-orbit Thermally Driven Errors					1.41					RSS
14	Bulk temperature effects						1.00				Engineering judgement for +/- 1 C
15	Gradient effects						1.00				Engineering judgement for 1C gradient
16	Material Stability					1.00					Est based on Chandra work
17	FMA/Telescope mounting strain					1.00					Eng estimate based on Chandra experience
18	FMA, As built					4.14					RSS
19	Gravity Release						1.00				FEA Analysis using vertical assy
20	Bonding Strain						1.00				Allocation
21	Module to Module alignment						1.00				Allocation
22	Module						3.76				RSS
23	Distort. & misalign due to module packing							0.71			Allocation
24	Mirror Pair Co-alignment							0.71			Allocation
25	Mirror Pair							3.63			RSS
26	P-S alignment in module								1.12		RSS
27	Alignment Metrology Dynamic Accuracy									0.50	Allocation - Based upon Chandra CDA alignment metrology
28	Alignment Metrology Static Accuracy									0.50	Allocation - Based upon Chandra CDA alignment metrology
29	Thermal Drift									0.50	Allocation - Based upon Chandra experience
30	Focus and Coma Alignment									0.71	Allocation
31	Segment Installation in module								1.00		Allocation
32	Segment Pair (P-S)								3.30		Est based on tech dev program to date
	Color Code	Rqmt		Margin		RSS Predict			Allocation		

Flight Mirror Assembly Buildup Process



Mandrel Fabrication: Figuring



- **6 mandrel blanks (3 P-S pairs) available**
- First one has been figured to meet IXO 1.5” figure requirement
- **5 additional ones expected to be finished by September 30, 2009**

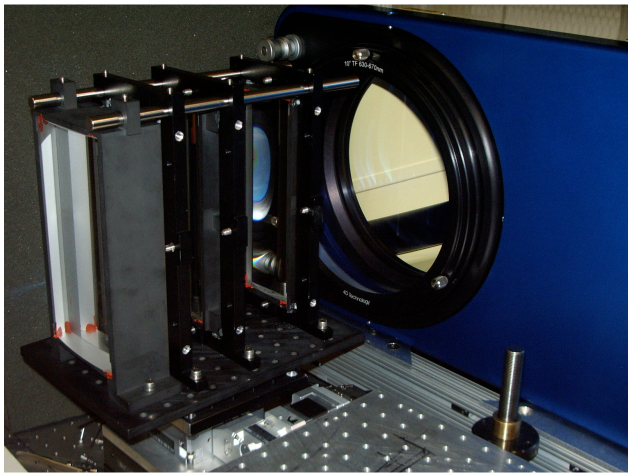
Three Things that We Must Perfect

(Each of these will be repeated ~20,000 times to build IXO mirror assembly)

- **Make mirror segments**
  - Slumping
  - Cutting
  - Coating
- **Measure mirror segments**
  - Mirror support
  - Metrology equipment
- **Align and bond mirror segments into a housing**
  - Temporarily hold/fixture mirror segments
  - Align and transfer to housing

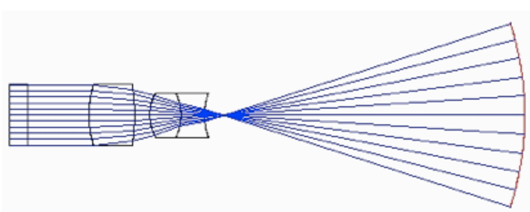
Mirror Segment Metrology: Equipment

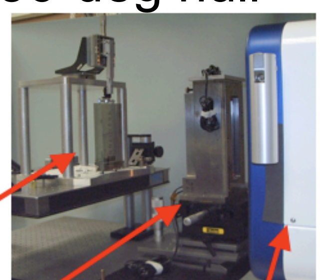
60-deg cylindrical null lens



- Use null lens and interferometer to measure every parameter except Average Cone Angle
- Use Hartmann test to measure Average Cone Angle

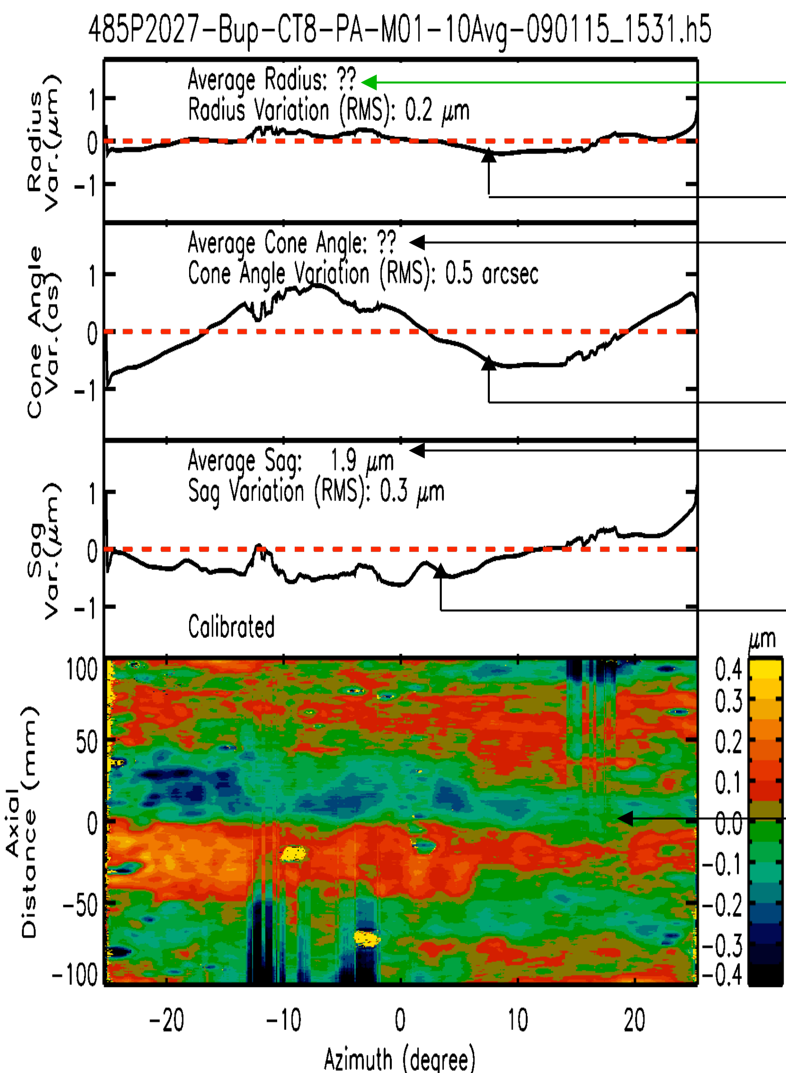
36-deg null





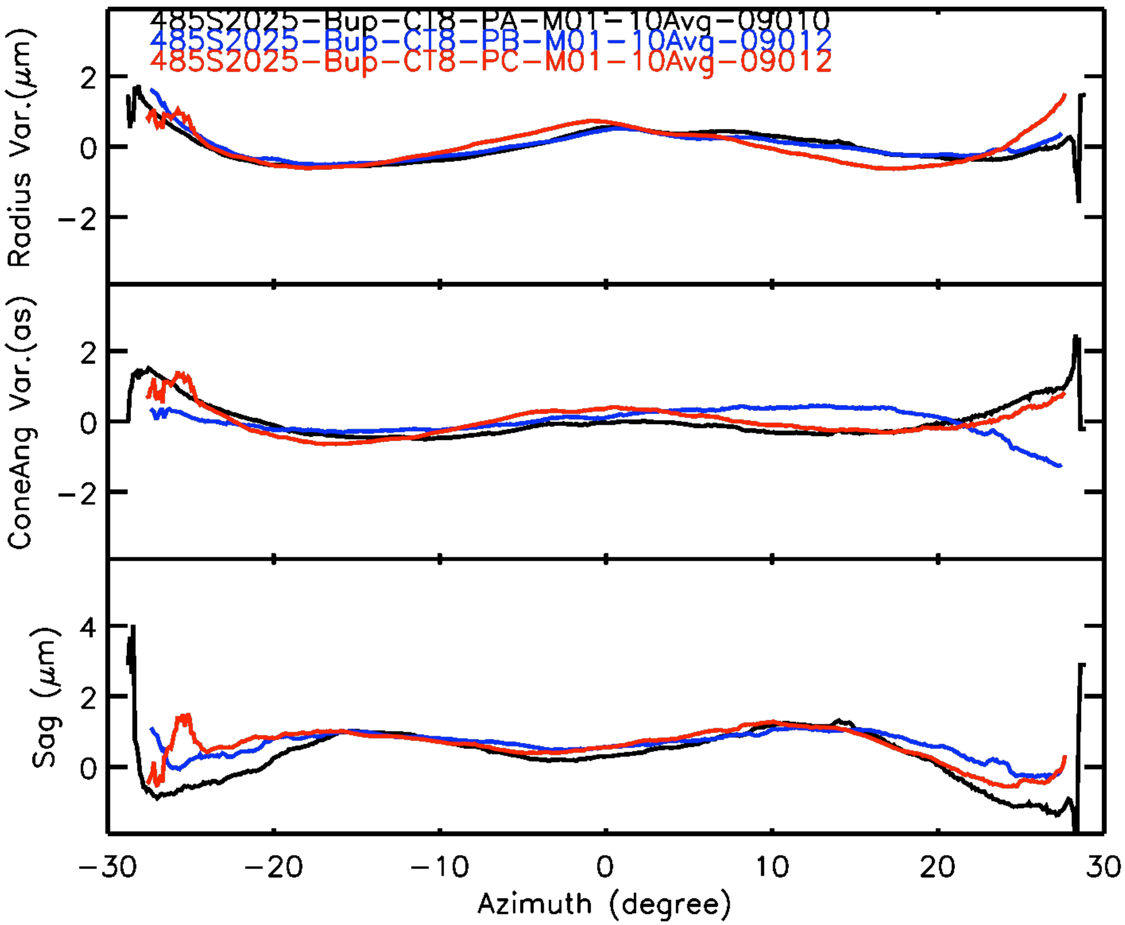
Metrology system: Mirror mount, Null lens, and Fizeau interferometer

Mirror Segment Metrology



$$\rho_0 + \Delta\rho(\phi) + \tan[\theta_0 + \Delta\theta(\phi)]\bullet z + \left(S_0 + \Delta S(\phi)\right)\bullet\left(\frac{2z}{L}\right)^2 + R(z,\phi)$$

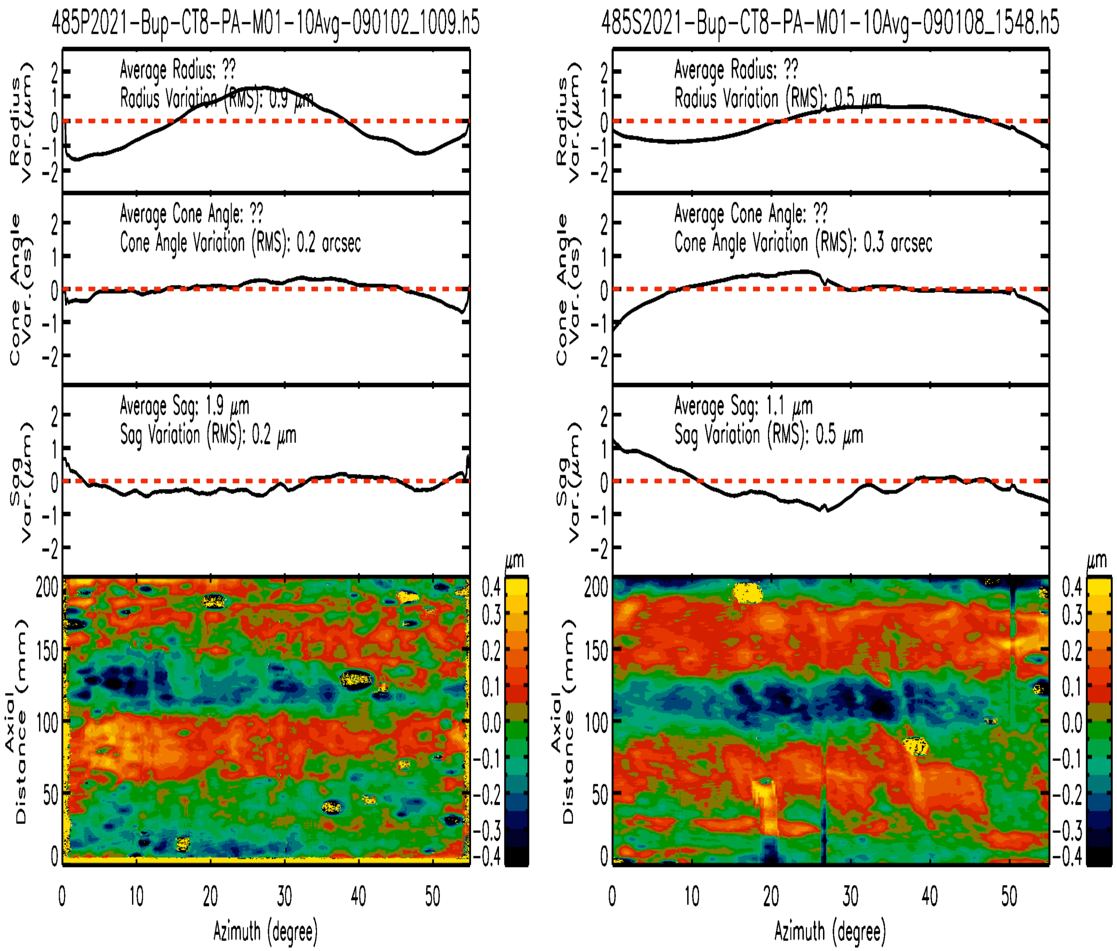
Mirror Segment Metrology: Requirements
(1)Repeatability, (2) Accuracy, and (3) Speed



Mirror Segment Fabrication: Slumping

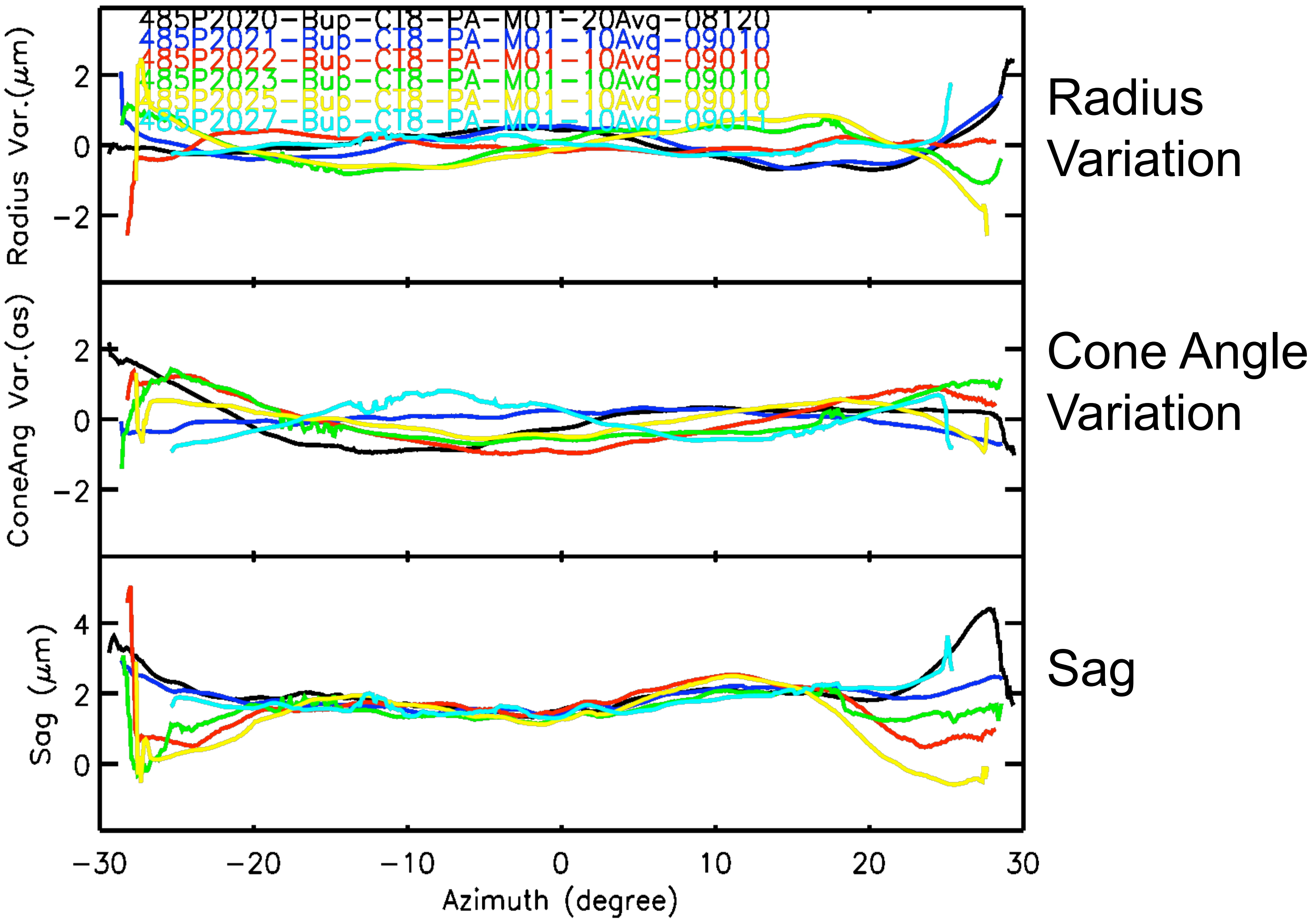
- Three important ingredients
  - Mandrel
  - Release layer application
  - Temperature cycle

A Recent Pair of Mirrors



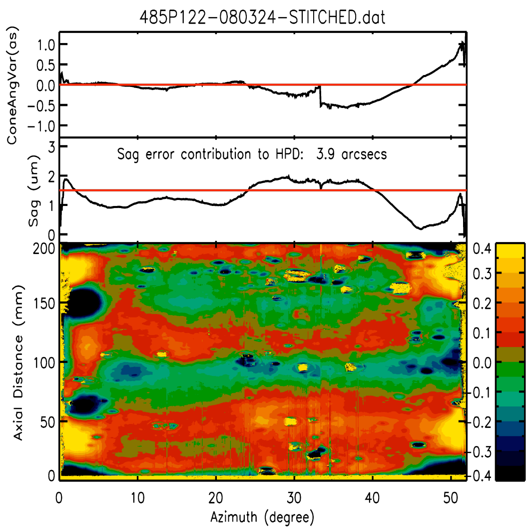
- Very good circularity
- Excellent cone angle variation
- Excellent sag variation
- Strong evidence that slumped glass mirror can meet IXO requirements

Repeatability of Mirror Fabrication

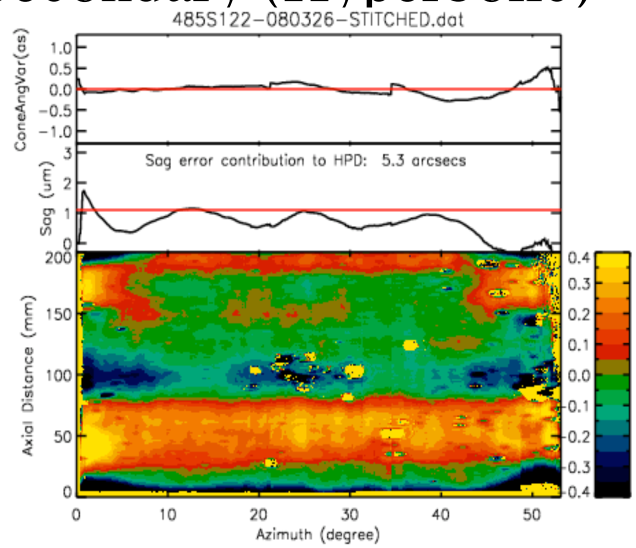


X-ray Performance Prediction
(one of the best pairs)

Primary (Parabolic)



Secondary (Hyperbolic)

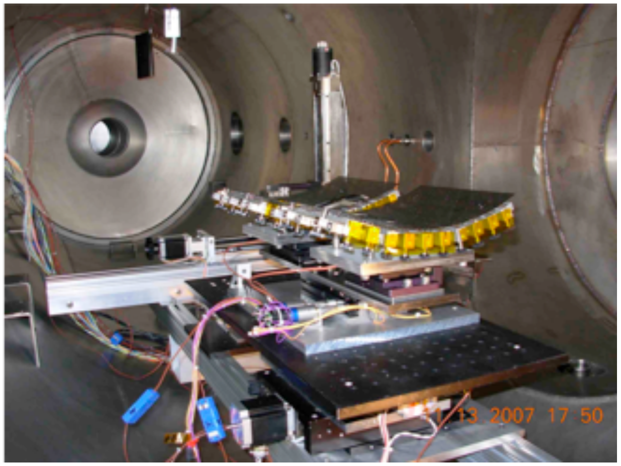


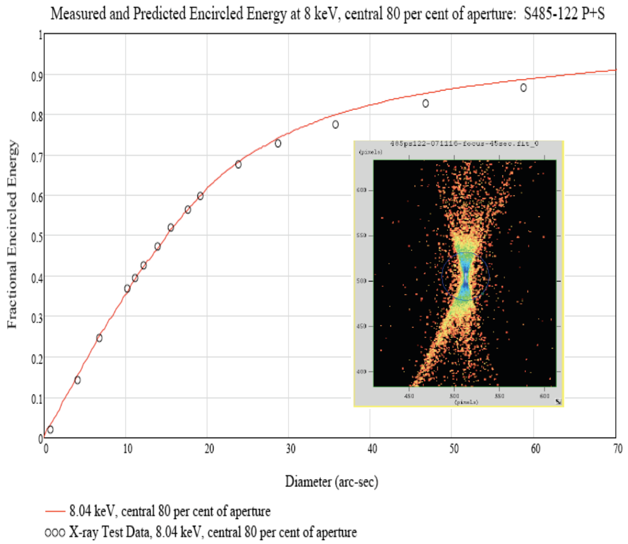
Combined HPD <u>(50% EE Diameter):</u> 10 arcsec (7 due to mandrel)

<u>80% EE Diameter:</u> 22 arcsec

<u>90% EE Diameter:</u> 38 arcsec

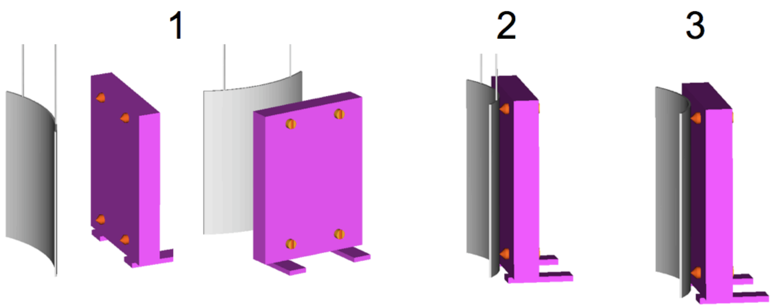
X-ray Test with Cradle and Mattress





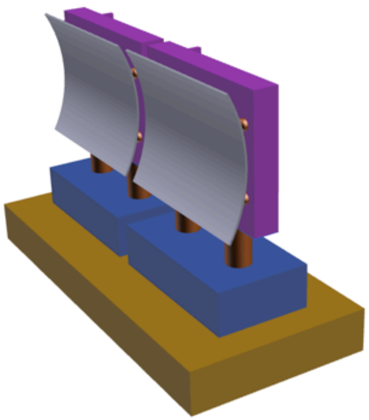
- Achieved 14.7” HPD at 8 keV, full illumination
- Measurement consistent with 3 independent performance predictions
- Demonstrated the validity of optical metrology
- Figure distortion dominated X-ray image quality

Mirror Mounting: Passive



- Repeatability
- Number of bonding points: 4 to 6 to 8
- Speed

CAD Drawing



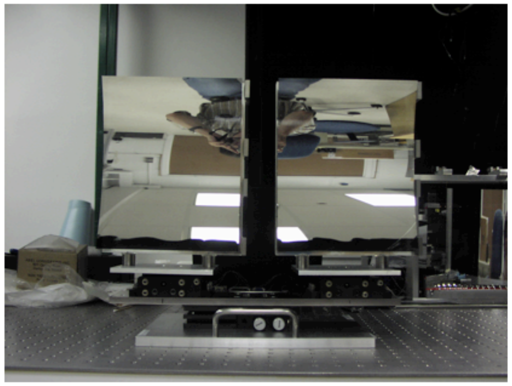
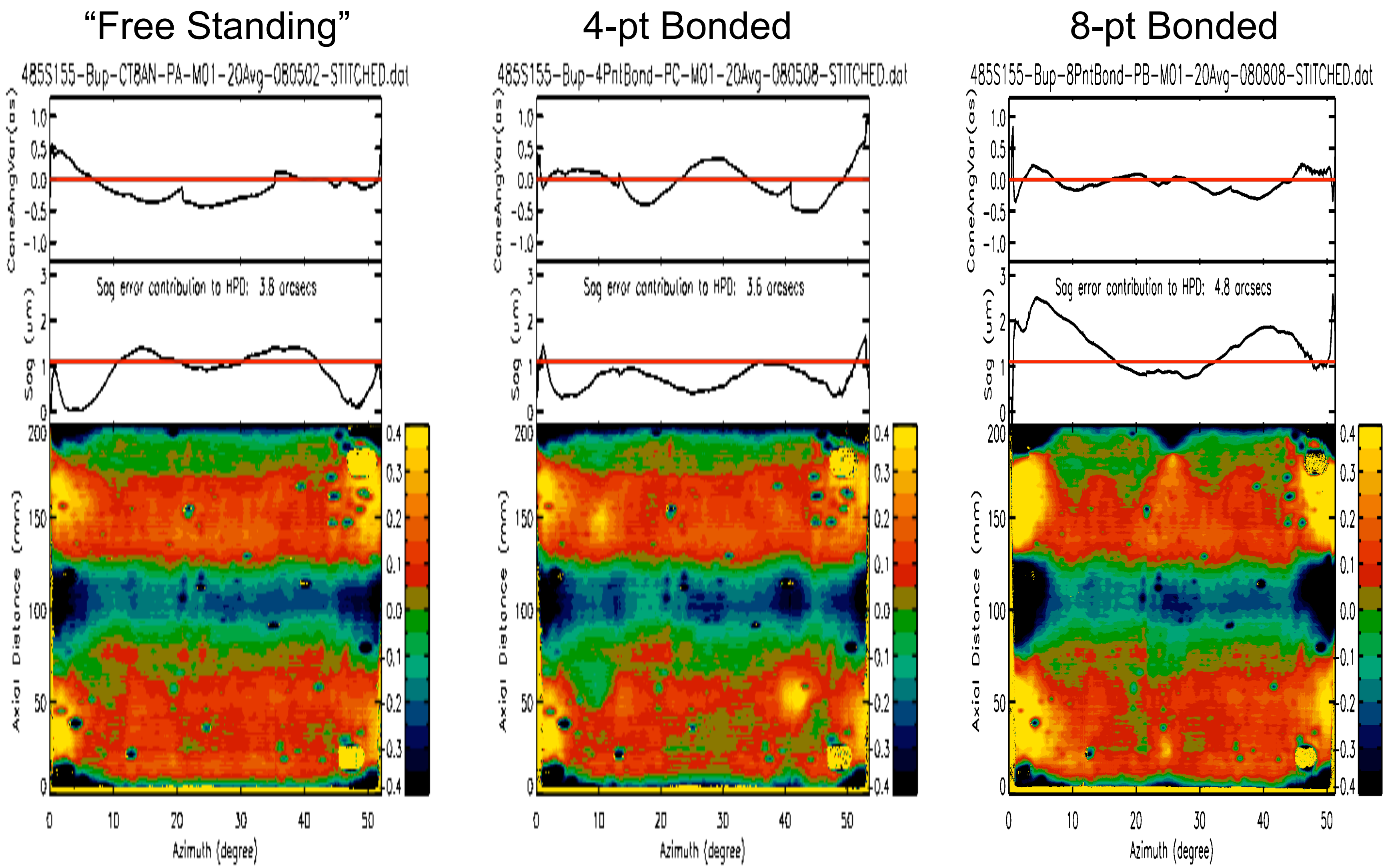


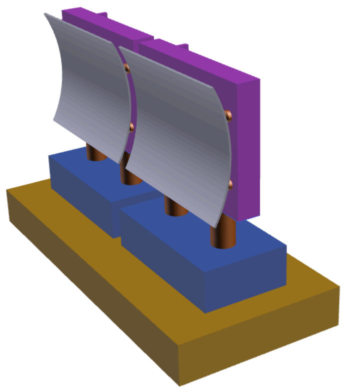
Photo of real setup

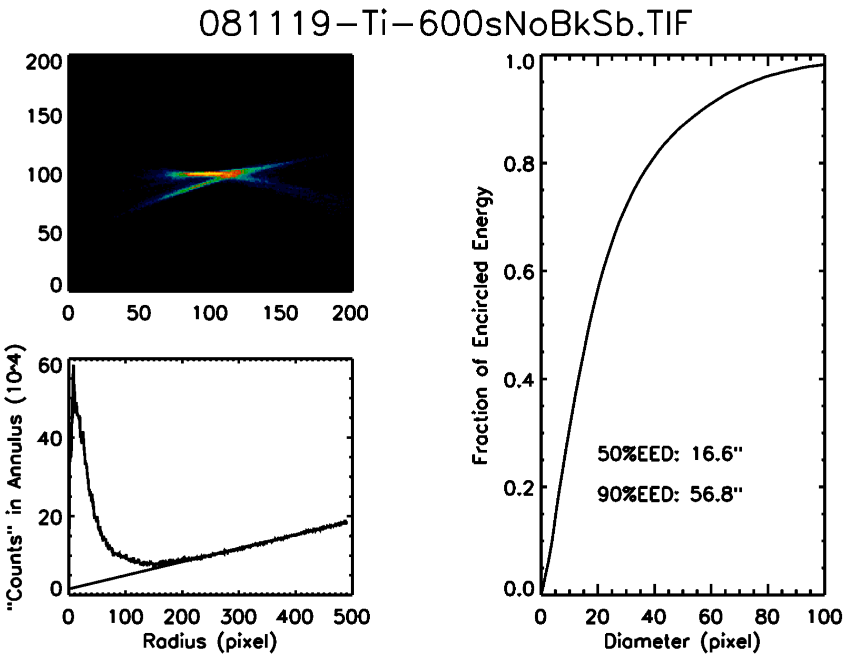
X-ray Test Configuration

Suspension Mount is Accurate



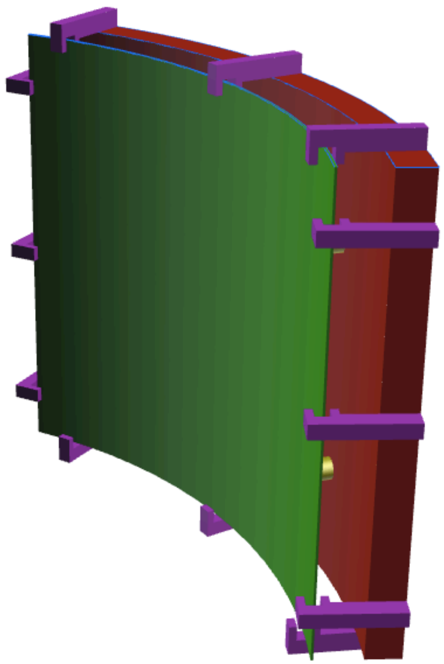
X-ray Test with Suspension Mount





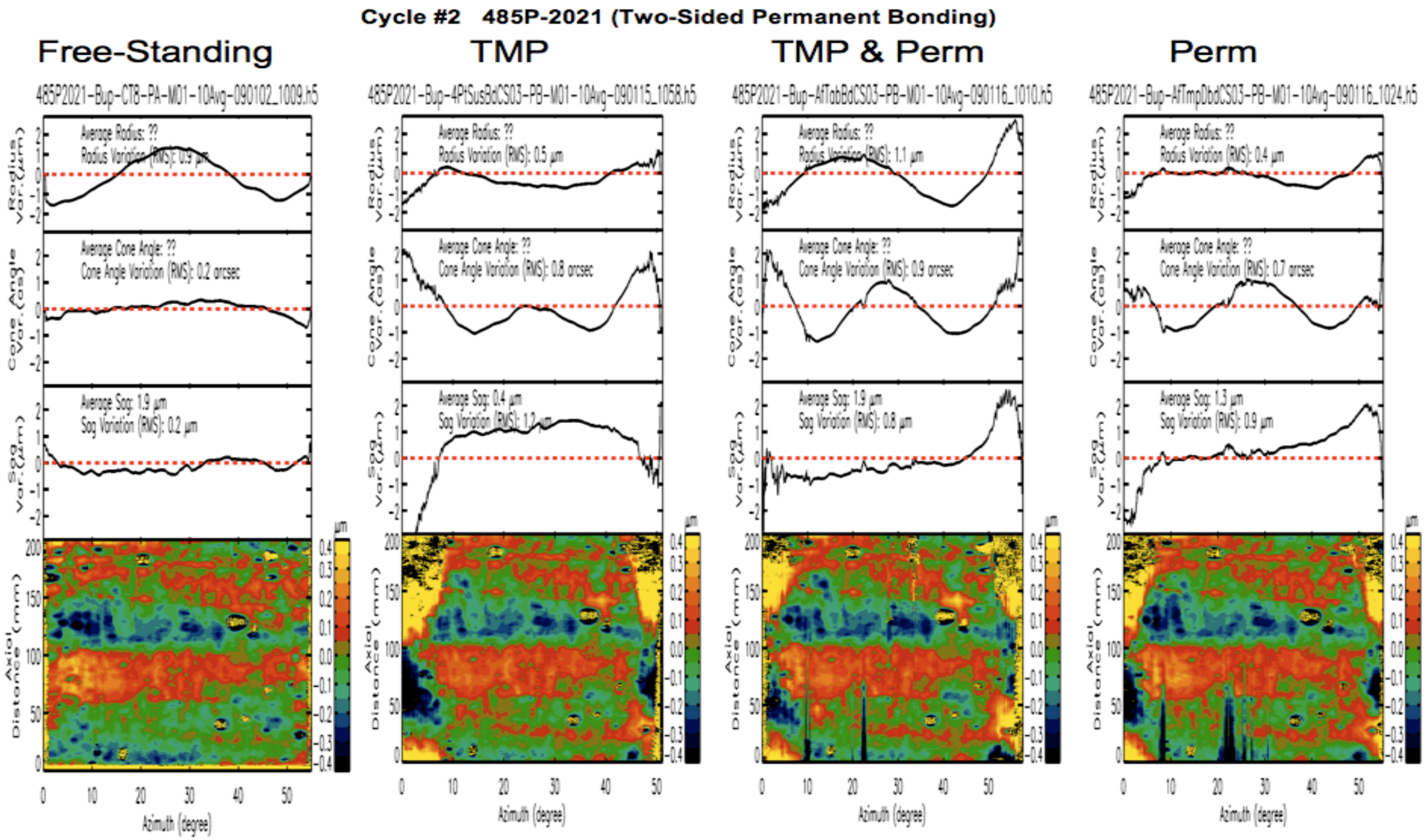
- **Full illumination image HPD: 16.6 arc-sec**
- **Image quality dominated by the quality of mirror segments, mainly mid-frequency errors**

Perfecting the Process of Bonding a Mirror Segment
(Chan et al.)



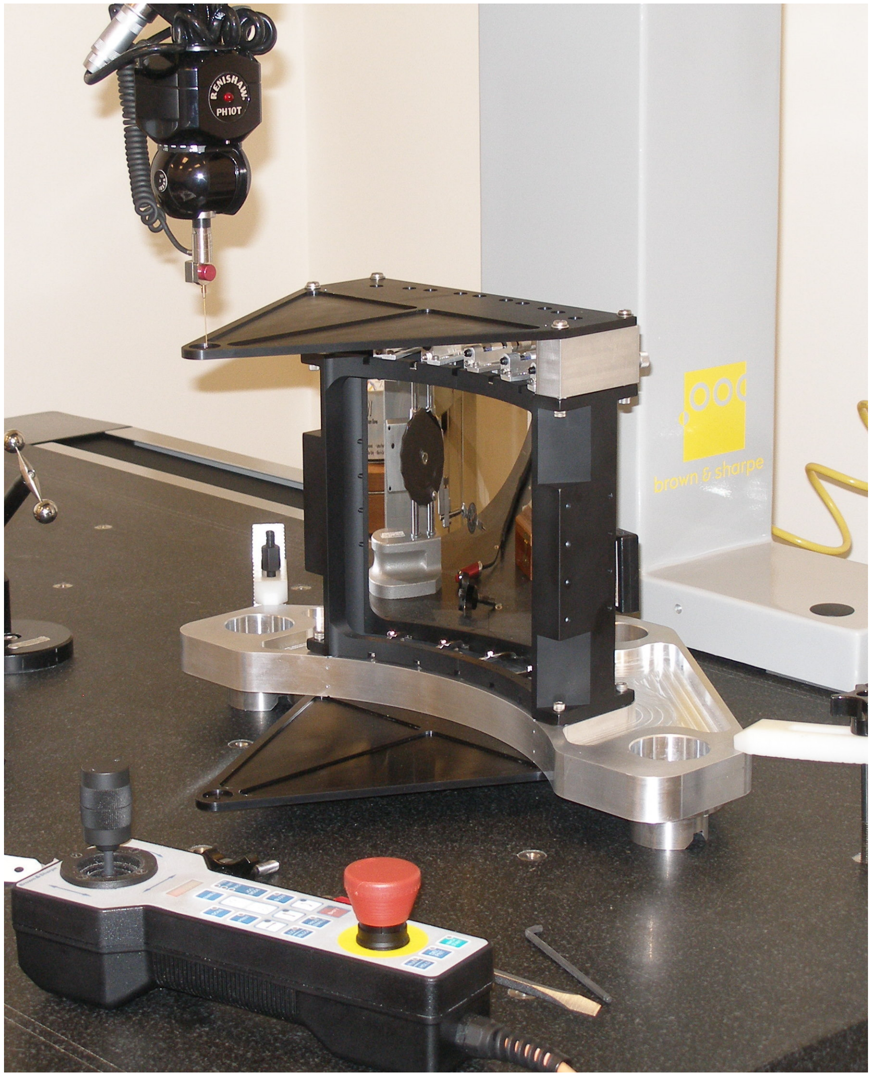
- **Repeatability**
- **Preservation of figure**
- **Preservation of alignment**
- **Bonded at as many points as possible to ensure survivability**
- **Speed**

Permanent Bonding

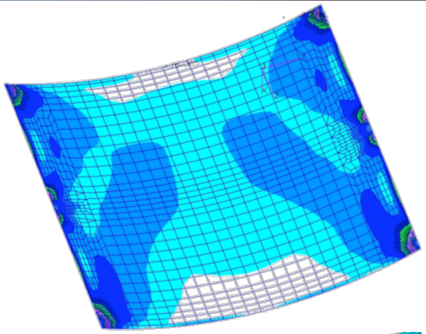


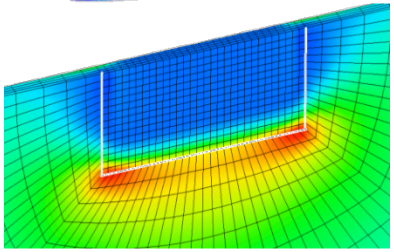
Active Alignment: Optical Assembly Pathfinder (OAP)

- The OAP is an adjustable installation and alignment technique in which the optic is held at 5 points along both the fore and aft end of each optical element, with adjusters at each point to align and bend the optical element prior to bonding.
- The system allows small corrections in average radius, cone angle, and tilt of the optical element to produce correct focus and alignment without comatic aberrations
- In the current approach, OAP3, adjustments are made using a coordinate measuring machine (CMM) for initial installation and alignment, followed by using a double-pass Hartmann test - the Centroid Detector Assembly (CDA), for final alignment (the same test was used for Chandra).

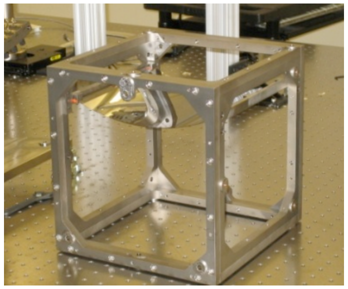


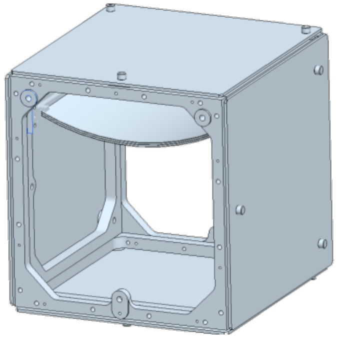
Mirror Segment Survivability





- Materials testing, FEM analysis, and mounted mirror segment environmental testing indicate glass can survive launch.
- Glass strength is sufficient for survivability
  - Design allowable based on recent materials testing and 1/100,000 probability of failure (Weibull distribution) is 16.5MPa (2.4ksi)
  - FEM results for segment held at three points along azimulthal edges show a maximum stress of 14.5MPa (2.1ksi) near the bond area
  - Adding additional bond points can further reduce stress
  - Optimization of size and number of bond points in work
- Structural testing of single mirror segment bonded in permanent housing completed
  - Tested in Titanium ‘Cube’ structure
  - Successfully completed random vibration test up design strength
  - Successfully completed acoustic test up to design strength
  - Mirror optical figure did not change during testing
  - Good correlation between test results and analysis
- Next step is three mirror acoustic test
  - Determine effect of closed out structure which is expected to reduce stress in segment
  - Determine effect of multiple closely spaced mirror segments



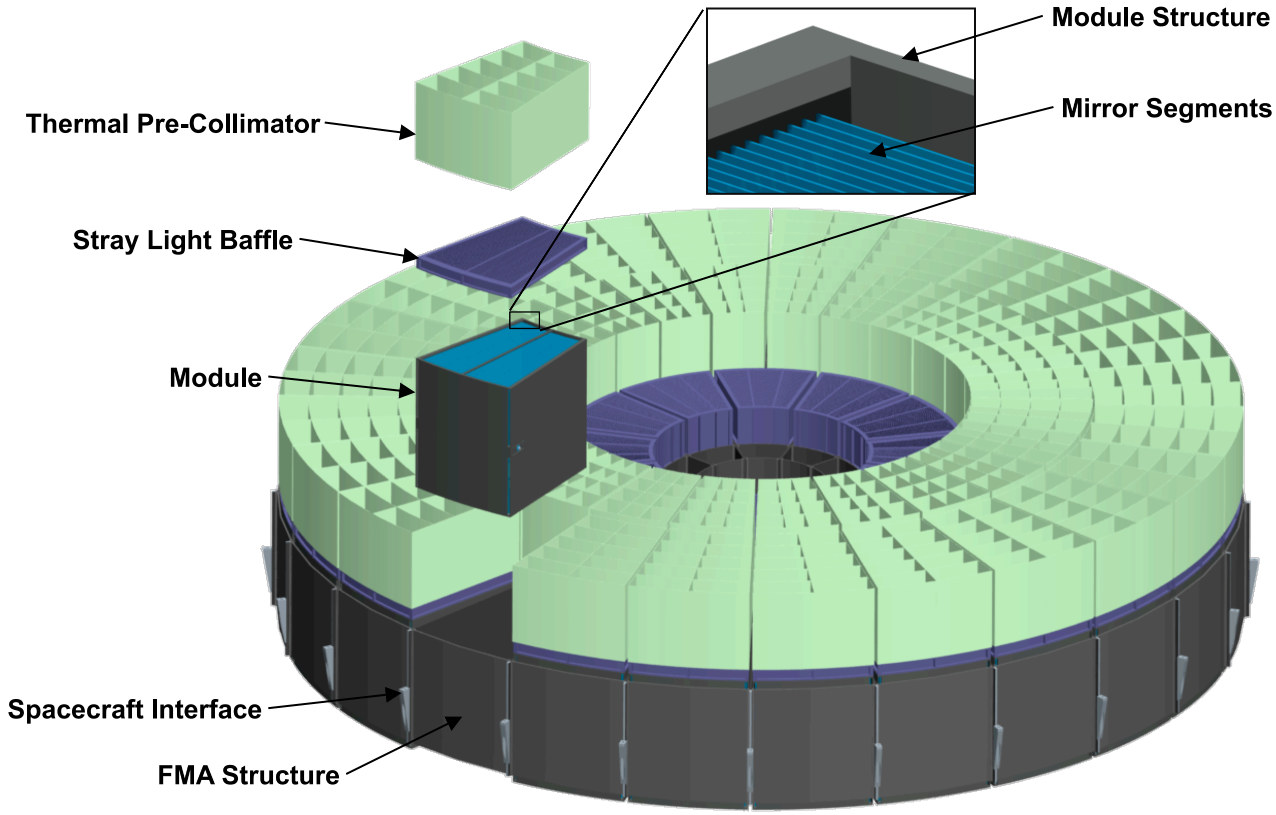


NuSTAR - A Mirror production demonstration

- GSFC is supplying 3000+ slumped glass substrates for NuSTAR by December 2009
- Production commenced in December 2008; producing 270 segments/week
- Facility provides a demonstration of mass production of IXO mirrors
- TWG members were given tour on Jan 27

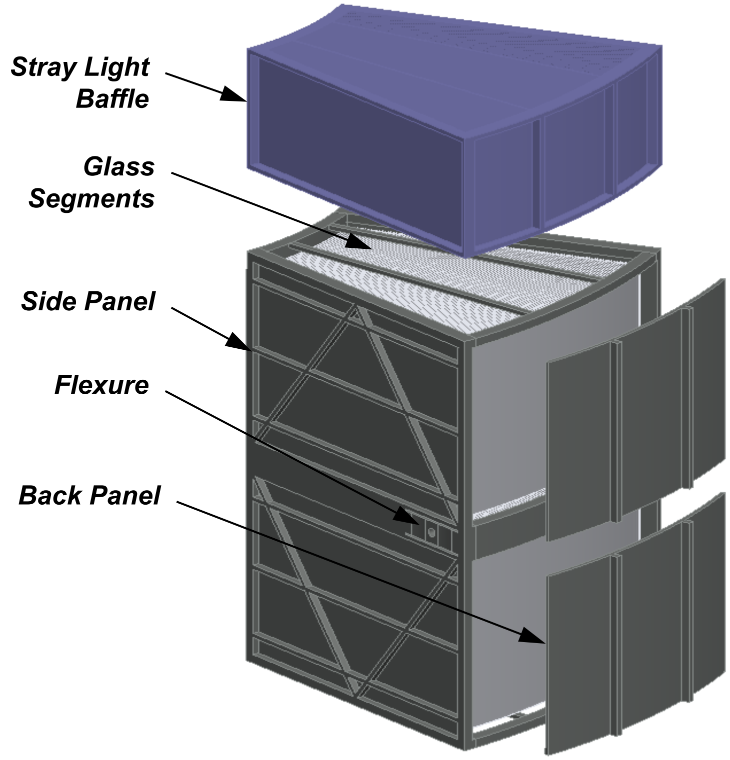
FMA Overview

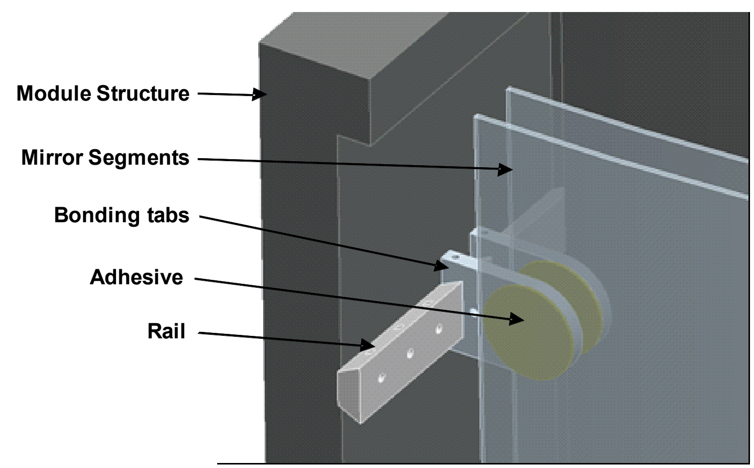
- Carrier structure supporting 60 modules containing 200-300 bonded-in mirror segments (SXT)
  - Overall dimensions: 3.3m OD x 0.8m axial depth
- Hard X-ray Telescope (HXT) located at center of structure (not shown)
  - Built using existing technology
- No new technology required beyond that currently in development
  - Technology development is focused on fabricating segments and assembling them into a module



Module Design

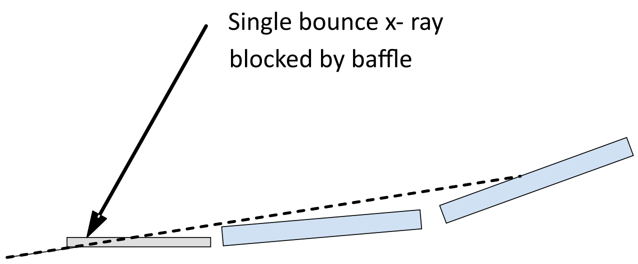
- **Module structure consists of front, back, and side structural panels**
  - Panels provide lightweight structural stiffness needed to keep the segments aligned during integration, testing, and launch
  - Panels protect the mirror surfaces from direct impingement of acoustic energy during launch, reducing launch stresses
  - Panels are as thin as possible to maximize effective area
  - Panels protect the mirror segments from Foreign Object Damage (FOD)
  - Panels can be thermally controlled to reduce thermal distortion of the segments
  - Bonding rails are fastened to inside of panels
- **Modules kinematically mount to FMA structure via three integral blade flexures**

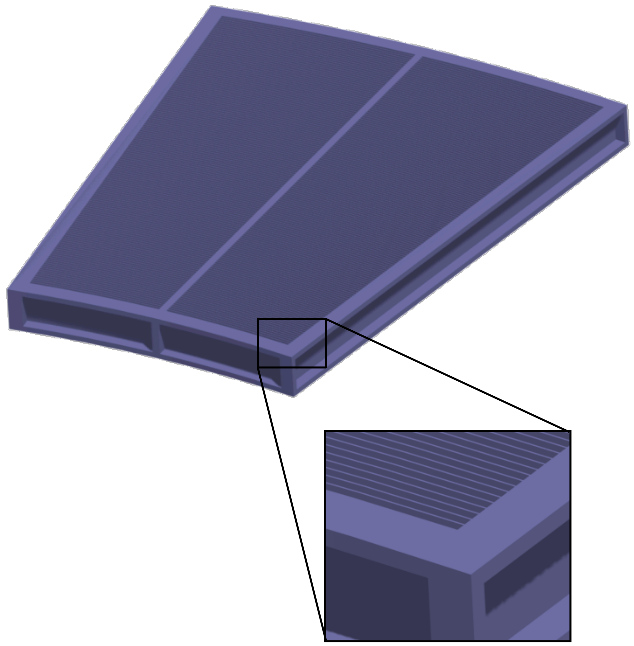




Stray Light Baffles (SLBs)

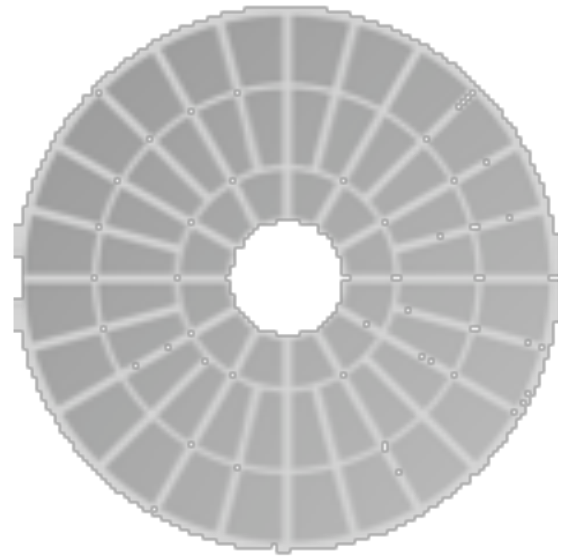
- **Prevent single bounce x-rays from falling on focal plane**
  - **Height of baffle varies with grazing angle of segment**
  - **Only 0.03mm thick aluminum foil needed to block x-rays**
  - **Aligned to mirror segments such that effective area is not reduced**
- **IXO SLB concept based on Suzaku design**
  - **0.12mm thick curved aluminum foils mounted in comb structure**
- **Highly conductive aluminum SLBs is heated to help replace heat lost by mirror segments to space**
- **SLBs are kinematically mounted to models**

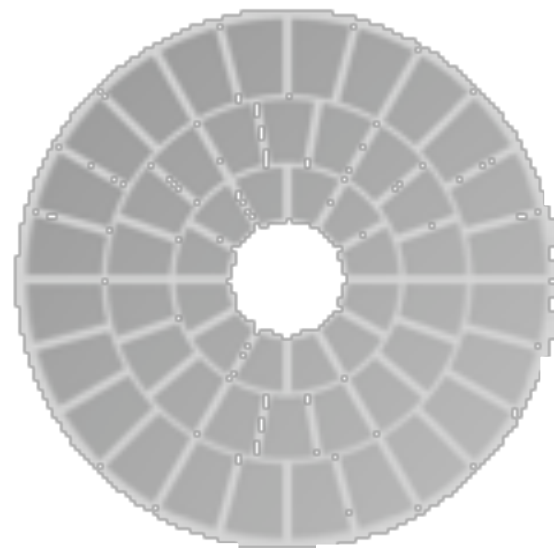




Module Layout

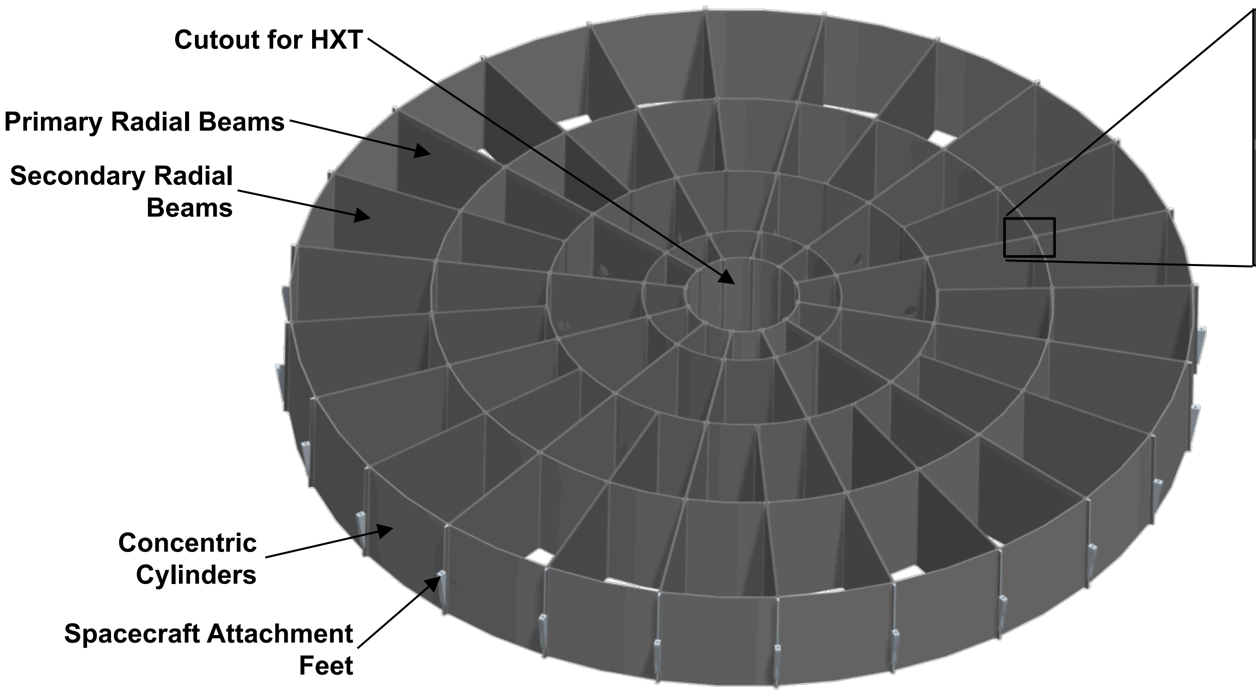
- **Layout consists of three rings of modules, 12 inner, 24 middle, and 24 outer = 60 total**
  - Based on trade studies
- **Modules are a 'handle-able' size**
  - Less than 30kg
  - Enveloping dimensions of all modules 650mm x 500mm x 450mm
- **Radial spaces between modules avoid peak 6 keV energy efficiency**
- **Limits largest segment needed to < 400mm, a limitation of the 0.4mm glass sheets available**
- **Provides a good load path from modules to spacecraft due to 12-fold symmetry**
  - 12/18/24 layout was also considered, but discarded due to poor load path.
  - FEA shows that the 12/24/24 layout yields a 25% lighter structure due to superior load path

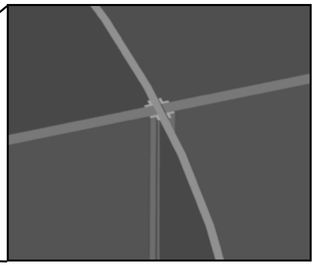


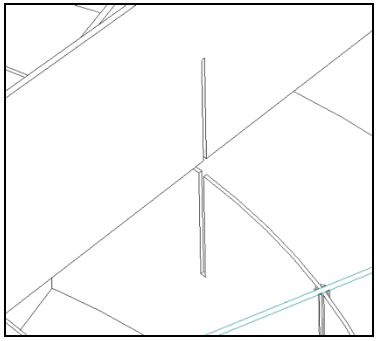


FMA Primary Structure

- Carrier structure supporting 60 kinematically mounted modules totaling ~1300kg
- Constructed using standard aerospace materials and design practices
- All structural members made from M55J/954-3 Carbon Fiber Reinforced Plastic (CFRP) for high stiffness, low weight, and near-zero CTE.
- Primary and secondary radial beams of rectangular cross sections
  - Minimizes beam thickness and maximizes effective area
- Radial beams connected by concentric cylinders
- Bonded 'wine-box' construction with doublers in corners

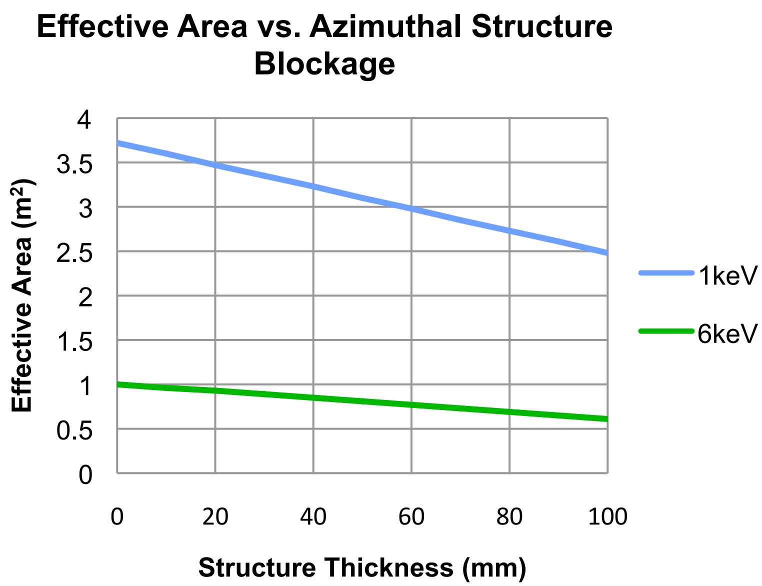


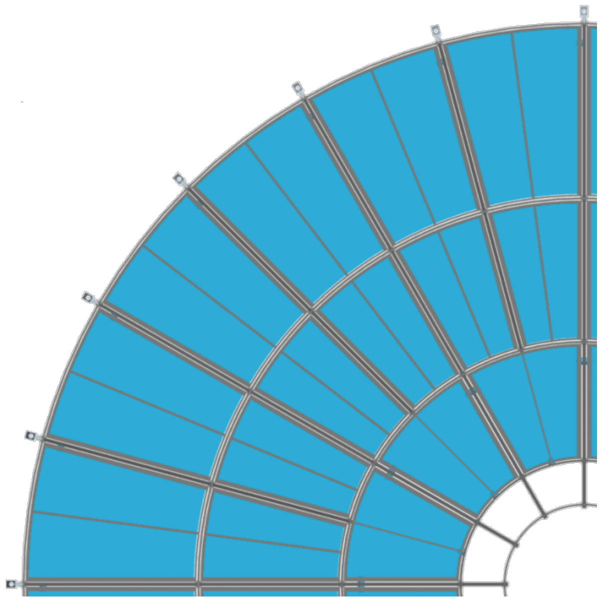




Effective Area Performance

- FMA design optimized to maximize effective area
- $3.2m^2$ at 1.25keV
  - 15% loss due to structure
- $0.8m^2$ at 6.0keV
  - 18% loss due to structure
- 46mm of azimuthal structural per module
- 46mm radial gap between module rings
  - Determines which shells are included

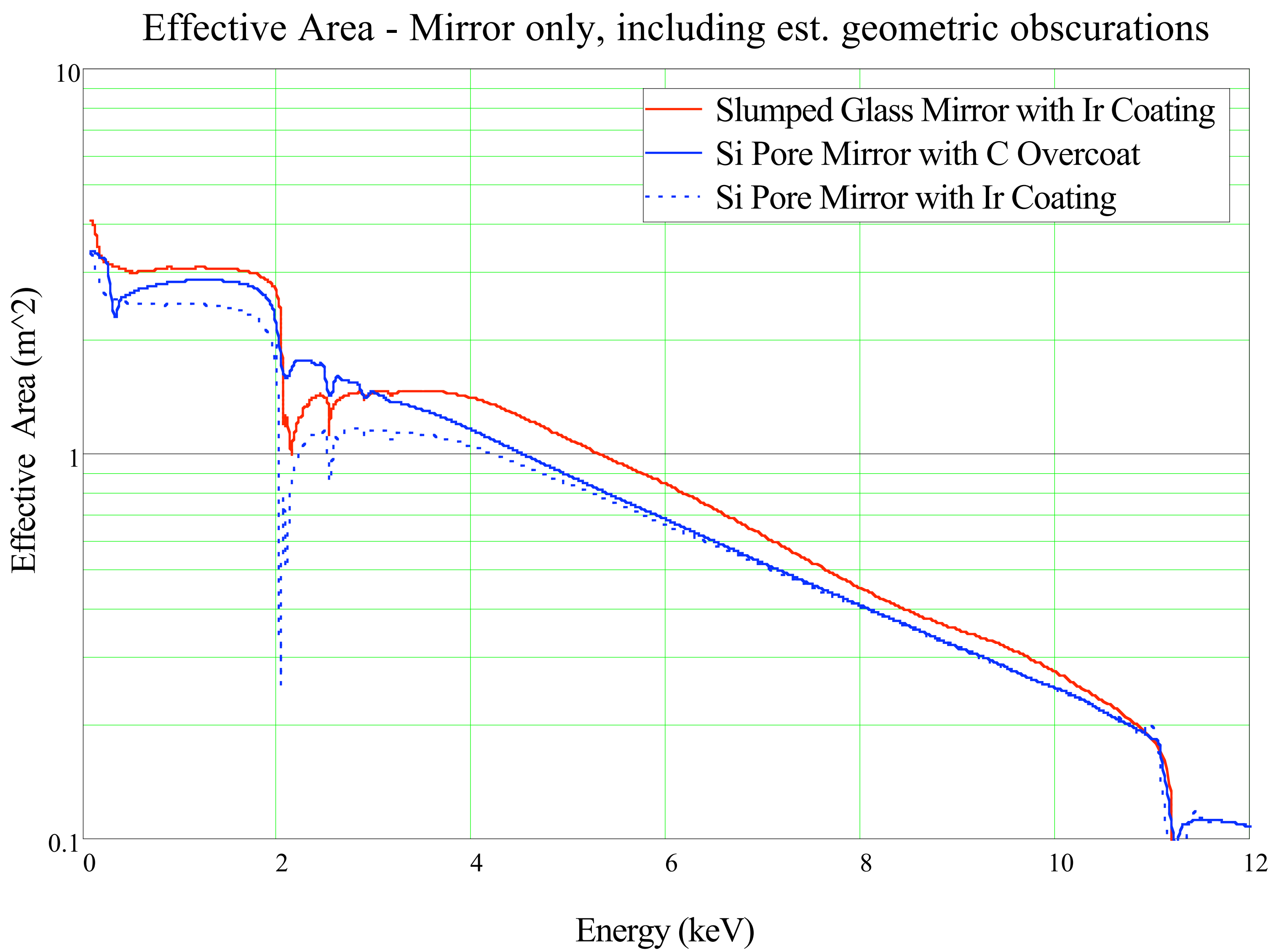




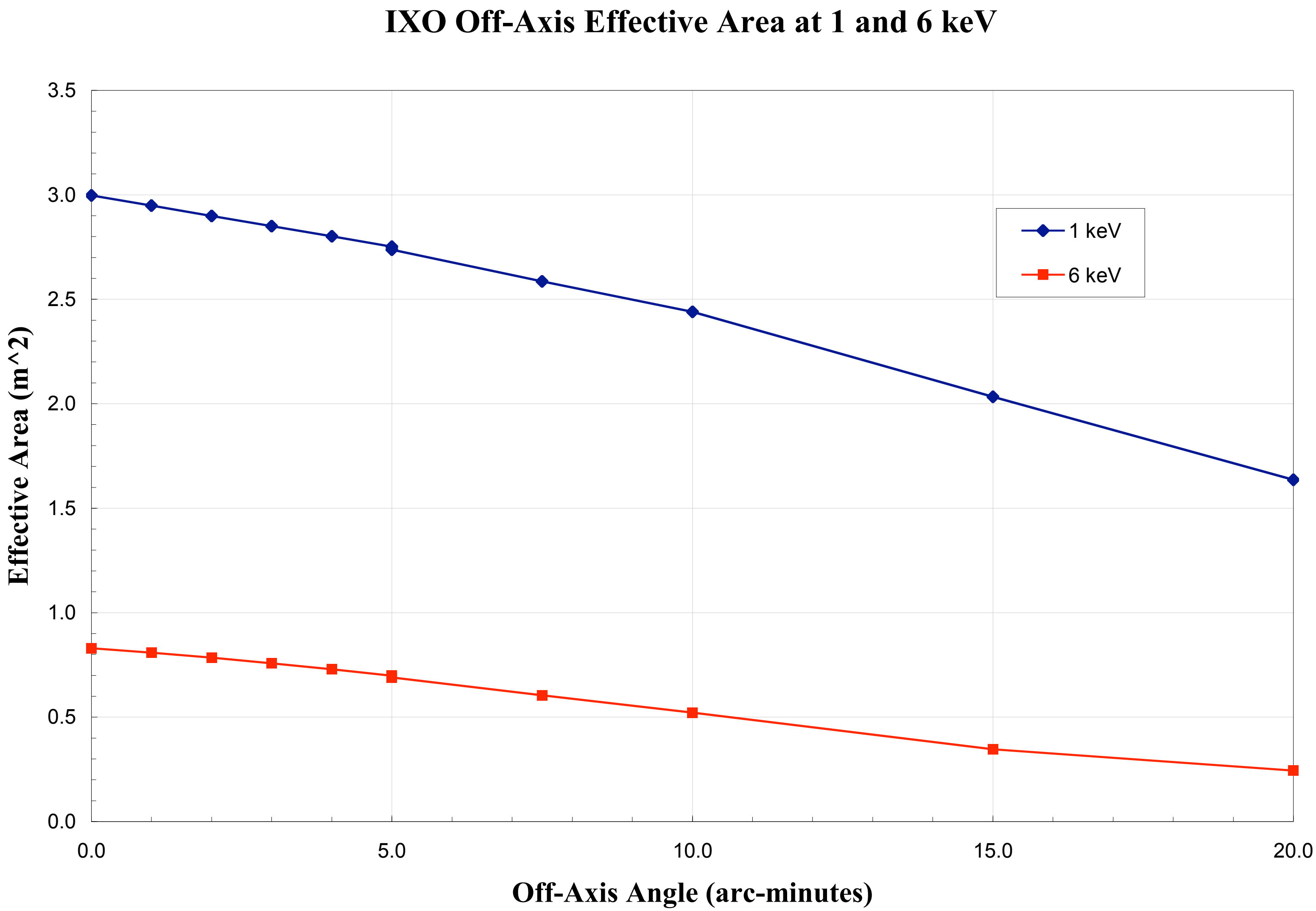
Azimuthal Structure

Source	Amount (mm)
Primary structure	10
Module structure	5 x 2 = 10
Gap between primary structure and module structure	2 x 2 = 4
Gap between module structure and mirror edge	2 x 2 = 4
Bonding points	3 x 6 = 18
Total	**46**

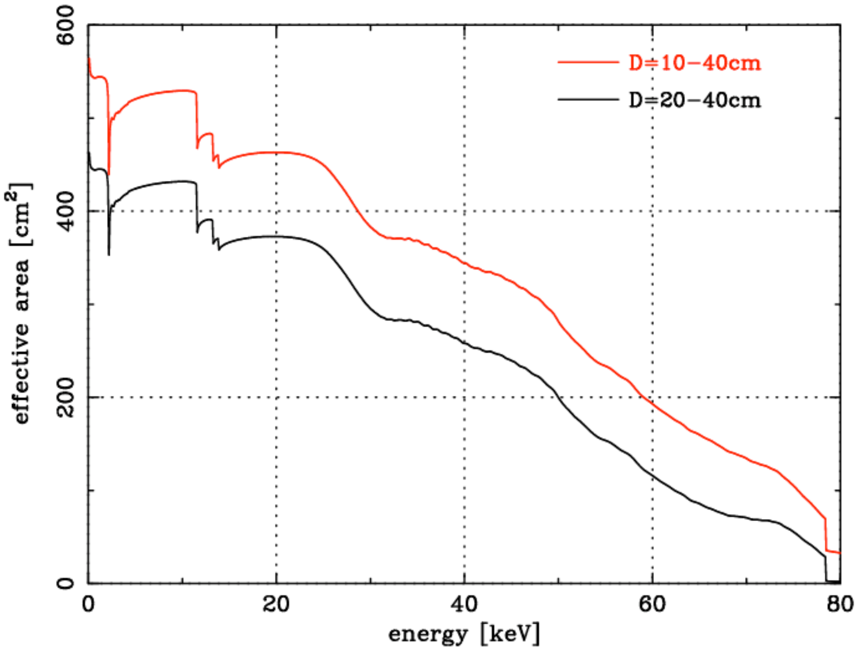
Effective area prediction

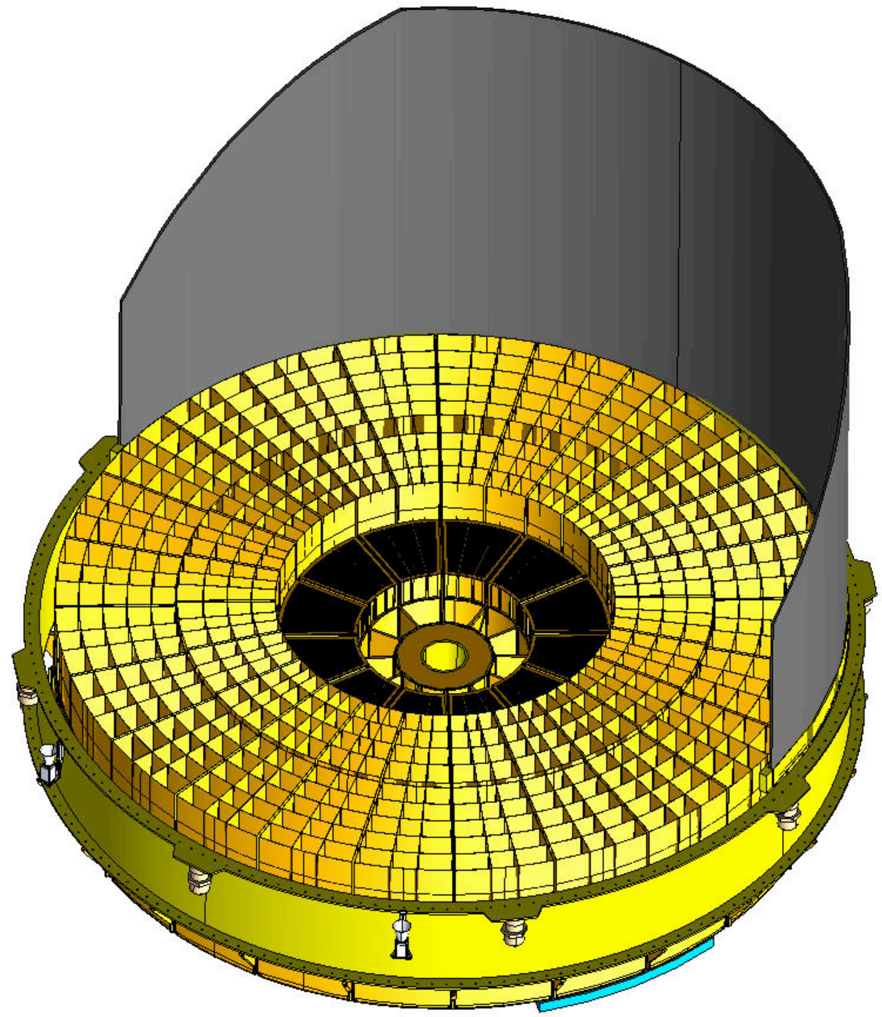


Off axis effective area at 1 and 6 keV – includes loss allocations



Glass mirror HXD



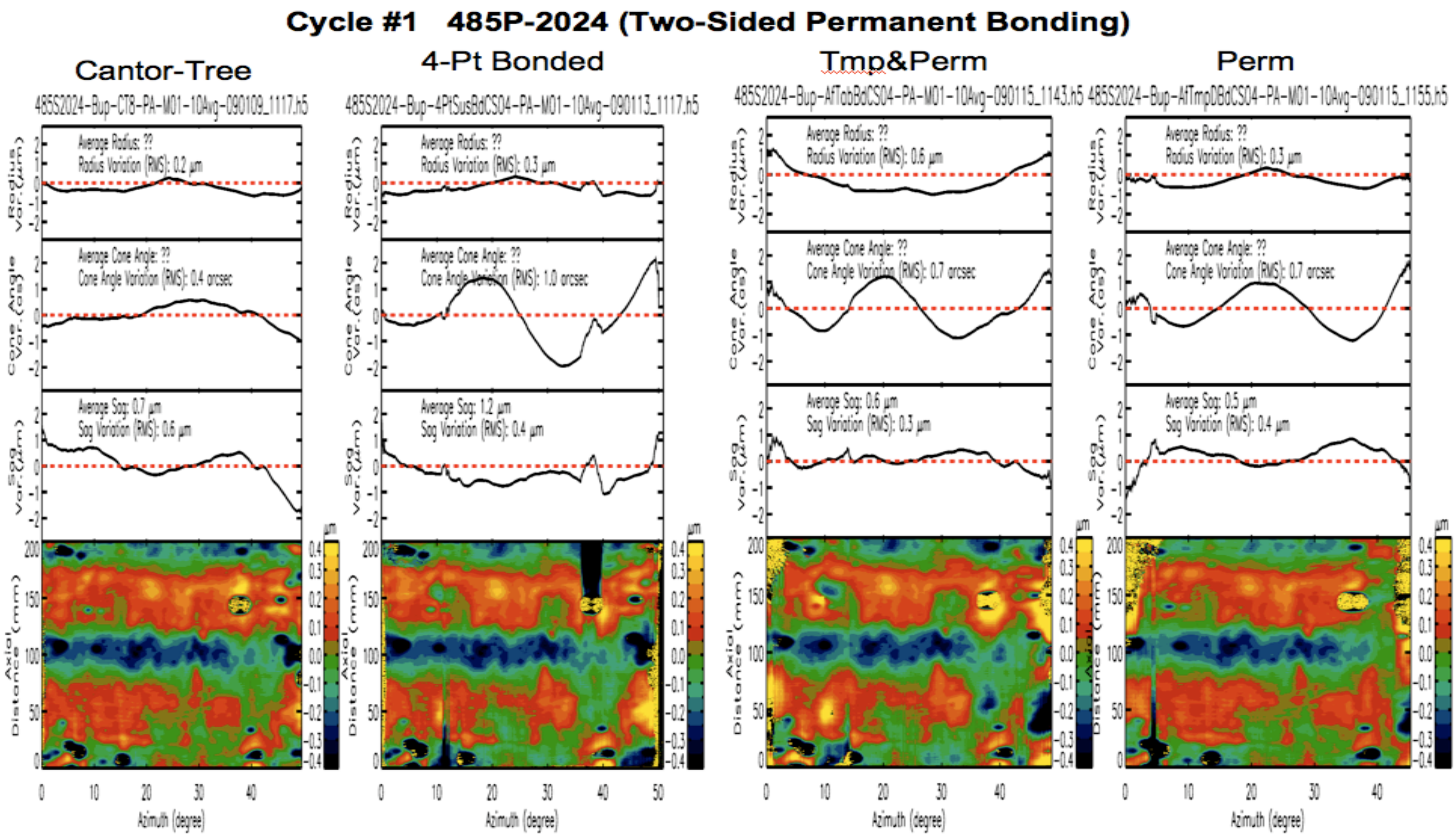


- 40 cm diameter mirror confocal with FMA
- Total mass 50 kg (for 20 cm ID)
- ~300 cm^2 at 30 keV
- 20 cm central clearance required for fiducial system
- Mirror can be supplied as competed instrument

Near term goals

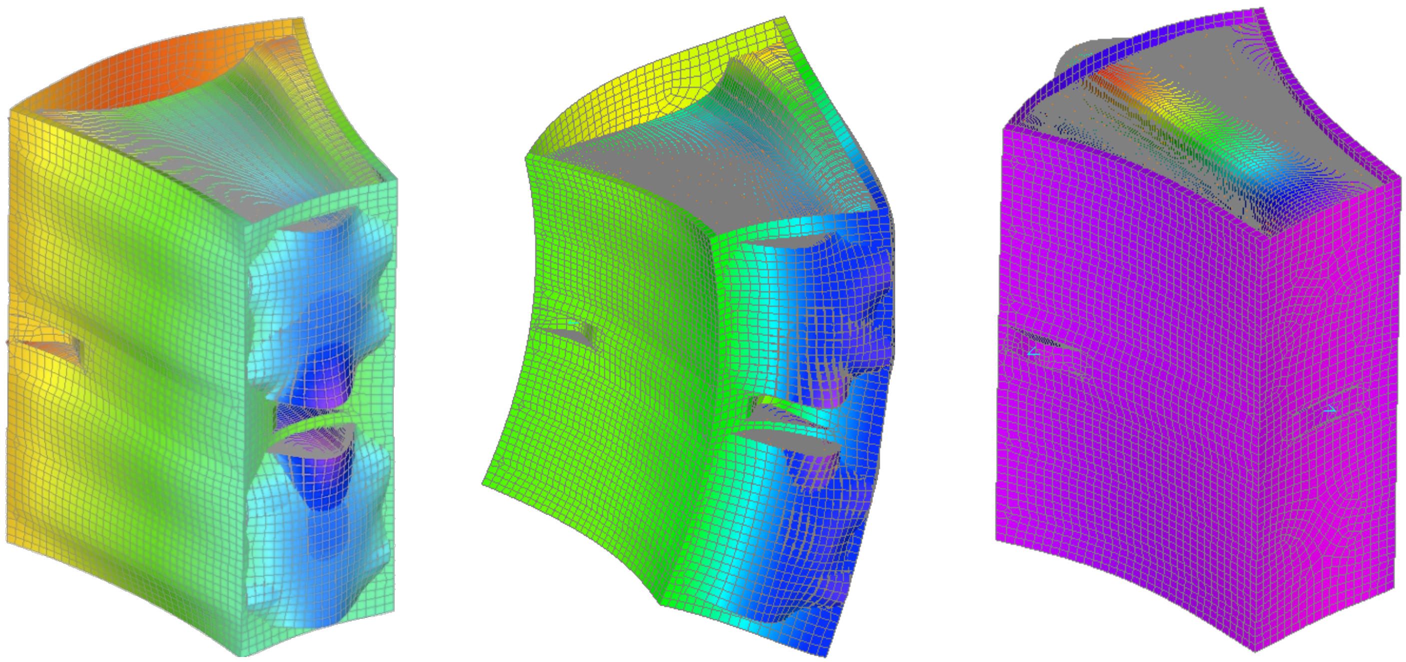
- **Segments**
  - Incorporate higher accuracy mandrels into forming process
  - Continue studies to reduce mid-frequency contribution of release layer
  - Optimize bonding to transfer structure
  - Demonstrate permanent bonding with acceptable level of distortion
  - Demonstrate alignment to requirements using OAP
  - Align and permanently mount multiple mirror pairs in housing
  - Additional X-ray tests of both alignment approaches
  - Perform additional environmental testing including three mirror acoustic test
- **Structure**
  - Continue to optimize FMA structure
  - Optimize number, location, and size of bond points
  - Mature thermal design
  - Complete optomechanical analysis of thermal and gravity distortions

Permanent Bonding



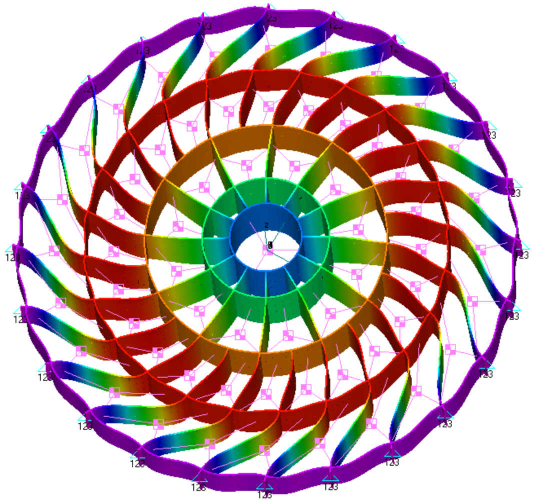
Module Design (cont.)

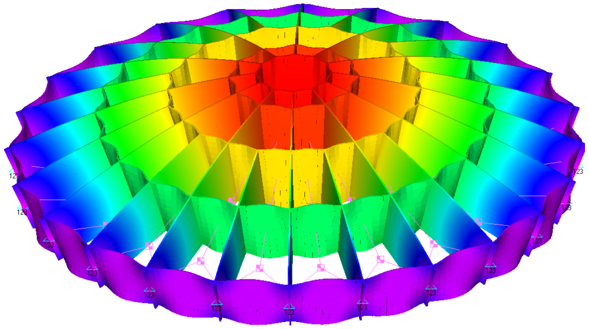
- **Module structure made from Titanium/Molybdenum alloy with CTE matching D263 mirror segments (CTE 6.2ppm/C)**
- **Optomechanical analysis of module with segments in work**
  - **FEMs of all 200-300 segments in module generated from optical prescription using custom software**
  - **Thermal and gravity distortion cases run using NASTRAN**
  - **Performance prediction generated based on deformed model is using custom ray tracing software**

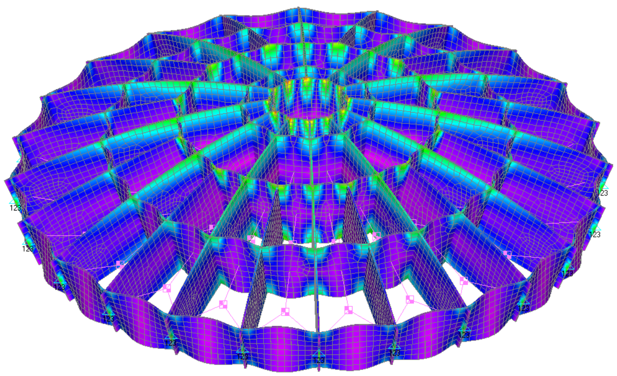


FMA Primary Structure (cont)

- FEM description
  - Members modeled with plate elements assuming isotropic CFRP layup
  - Modules modeled as lump masses with kinematic mounts
    - Assumes modules do not add stiffness to structure (conservative)
  - 3 DOF constraints at bolted interface to spacecraft
  - Member thicknesses optimized using NASTRAN SOL200
- Design performance
  - Structural mass 28% of payload (module) mass
  - 16Hz first torsional mode
  - 60Hz first axial mode
  - 1G axial load maximum displacement 0.1mm
  - 10G axial load maximum stress 30Mpa (4.4ksi)
  - 10G lateral load maximum stress 47Mpa (6.8ksi)
  - Maximum interface force 15,700N (3500lb) due to 10G lateral load
  - 1°C bulk temperature change distortion .002mm
- Significant room for optimization remains!







Thermal Control

- Thermal control system designed to control gradients and bulk temperature changes across modules and segments
  - Room temperature on-orbit
  - Current target 1°C maximum gradient or bulk temperature change
  - Maximum gradient and bulk temperature change will be determined by optomechanical analysis (currently in work)
- Thermal control system needs to replace heat lost from view of segments to space
  - Heaters on stray light baffles
  - Heaters on module structural panels
  - Thermal shields on inner modules where higher energy x-rays can penetrate based on Suzaku design
  - Thermal pre- collimators and/or post collimators for middle and outer ring modules based on Chandra design
  - Thermal shroud may be needed around FMA to distribute heat from sun side of spacecraft to space-facing side
- Thermal design and analysis currently in work