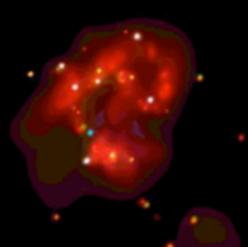
Constellation X

The Constellation X-ray Mission

The Constellation-X Spectroscopy X-ray Telescope: Recent Technology Development

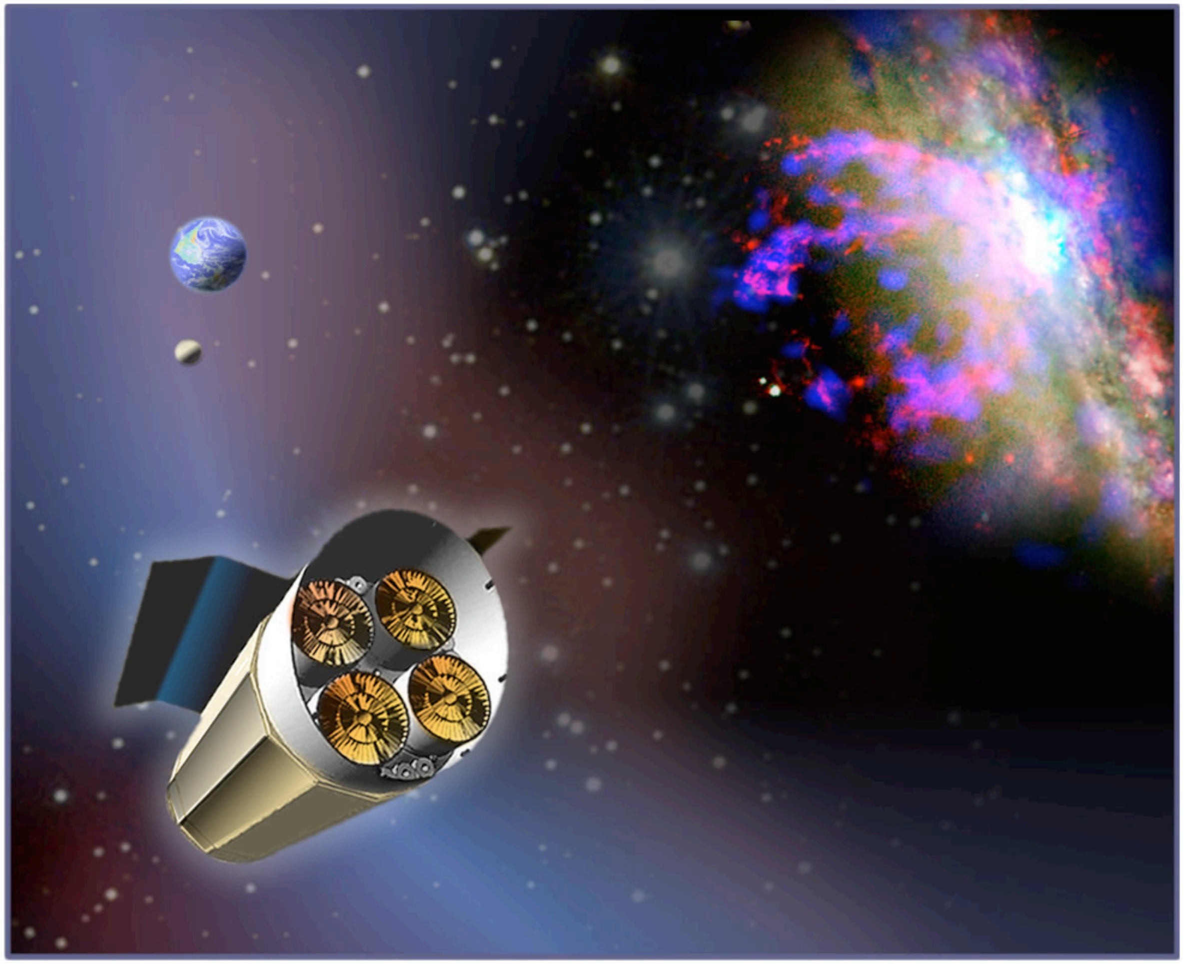


R. Petre, W. Zhang, T. Saha, D. Content, S. Owens, J. Stewart, J. Lehan /GSFC

S.O'Dell, W. Jones / MSFC
P. Reid / SAO

Outline

- SXT requirements and conceptual design
- Recent progress
  - Mirror segment characterization
  - Separating intrinsic segment properties from mounting and metrology
  - Mirror pair alignment
- Near term plans and challenges



The "new" Constellation-X

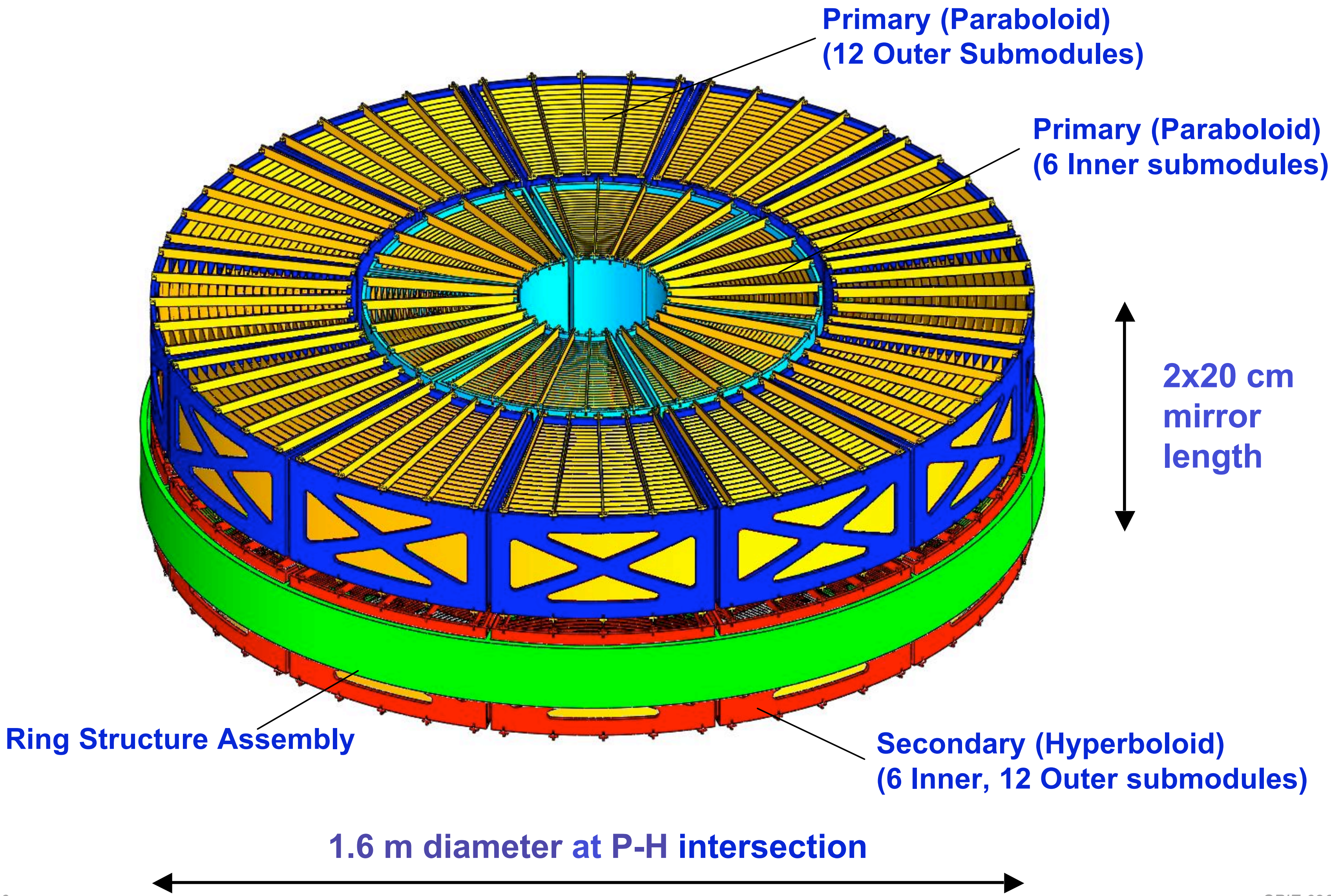
SXT Flight Mirror Assembly Requirements (per mirror)

SXT Performance Requirements		Trace to Top-Level Mission Requirements
Bandpass	0.25 to 10 keV	Allocation of mission bandpass to SXT.
Effective area allocation @0.25 keV @1.25 keV @6 keV	 7,025 cm^2 6,797 cm^2 1,830 cm^2	Includes reasonable-to-conservative allowances for structural blockage and optical losses. Assumes off-plane gratings. Includes margin on effective area of the telescope system.
Angular resolution	12.5 arcsec HPD	Error budget allocation to mirror that allows telescope system to achieve requirement of 15 arcsec with 4 arcsec margin combined by RSS.
Field of view	2.5 arcmin	Defined by detector field of view (FOV)
Derived Requirements: SXT Mirror		**Derivation**
Diameter	1.6 m	To meet mission area requirements with 4 mirrors.
Focal length	10 m	Consistent with grazing angle requirements for 1.6 m diameter mirror.
Axial length	<70 cm	To fit within envelope and meet fabrication considerations
Operating temperature	20±1° C nominal	Range is per allocation from SXT angular resolution error budget; minimizes angular distortions imposed by temperature change to components. Operating temperature is determined by optics assembly temperature.
Mass	642 kg	Allocation (includes thermal collimators)

- The fundamental SXT performance requirements have not changed over the past several years
- Emphasis on performance margin (extra effective area) and need to approach angular resolution goal has increased

SXT Mirror Reference Design Concept

SXT Incorporates Modular Construction and Segmented Wolter I Mirrors



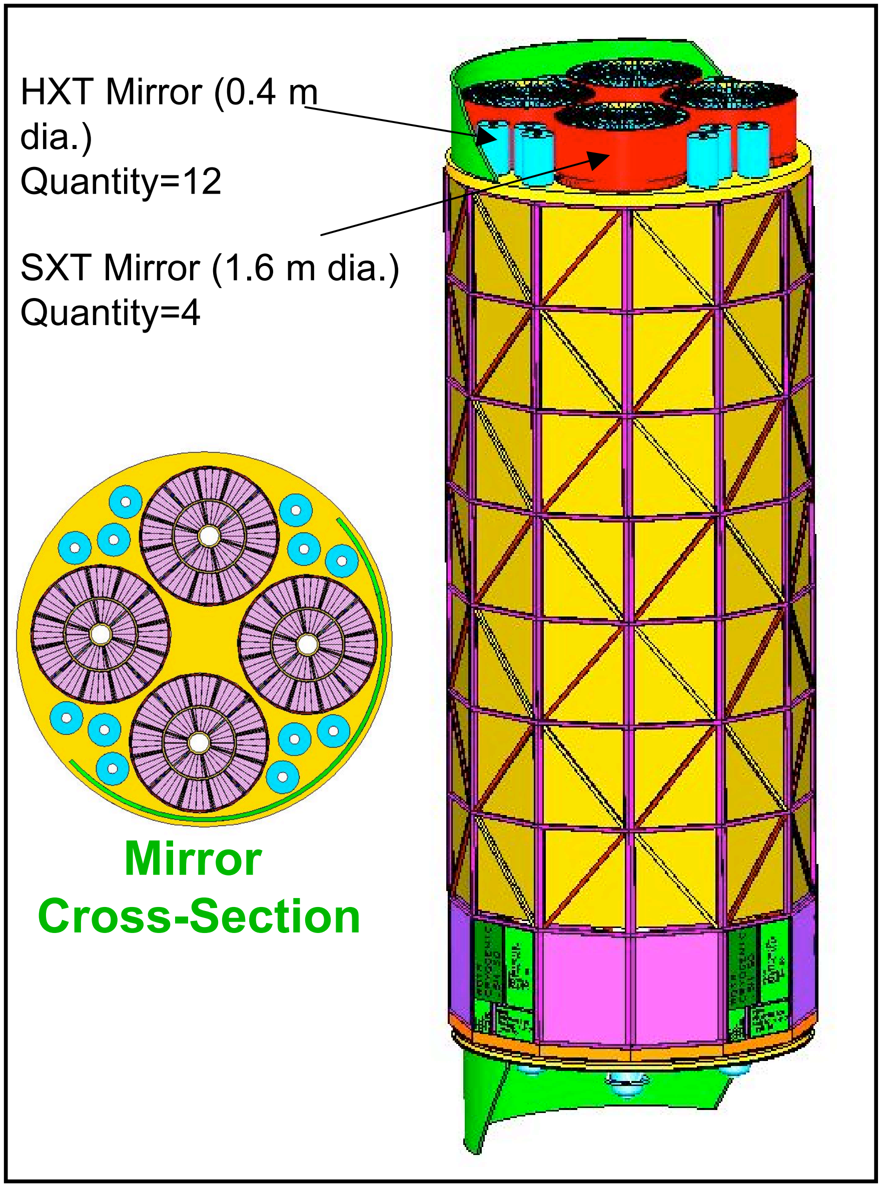
SXT Mirror Reference Design Parameters

Parameter	Description
Design	Segmented Wolter I
Segment substrate material	Thermally formed glass
X-ray reflecting surface	Gold
Number of nested shells	127 (inner); 89 (outer)
Total number of segments	3660
Mirror segment length	20 cm
Number of modules	6 (inner); 12 (outer)
Module housing composition	Titanium alloy, CTE-matched to substrate
Module support structure	Composite
Largest segment surface area	0.08 m^2
Substrate density	2.5 g/cm^3
Mirror segment thickness	0.44 ± 0.02 mm
Mirror segment microroughness	6 Angstrom RMS
FMA mechanical envelope	1.68 m dia x 1.98 m

- Unchanged from four spacecraft configuration

New Constellation-X Configuration

- Single spacecraft consistent with Delta-IV (heavy) mass and size envelope, with no extendable optical bench
- Numerous optical configurations studied
  - Number of mirrors
  - Outer diameter
  - Focal length
- Current configuration is most consistent with mission science requirements and launch constraints
  - 4 mirrors with 10 m focal length and 1.6 m diameter
- Modular design would allow straightforward adaptation to different mirror parameters
- Current technology development derives from 8.6 m focal length design
- *More substantive change to SXT technology development comes from substantial budget cut (February 2006)*



SXT Reference Concept Angular Resolution Error Budget

ITEM (HPD - arcsec)	RQMT			PRED	Allocation			
FMA On-orbit performance	12.5			12.48				
SXT Mirror launch shifts					2.00			
On-orbit Thermally Driven Errors					2.24			
Bulk temperature effects						1.00		
Gradient effects						2.00		
Material stability effects					1.00			
FMA/Telescope mounting strain					1.00			
FMA, As built					12.03			
Gravity Release						1.50		
Bonding Strain						2.00		
Module to Module alignment (using CDA)						2.00		
P-S alignment in module(using CDA)						3.38		
CDA Dynamic Accuracy							0.76	
CDA Static Static Accuracy							1.68	
Thermal Drift							2.00	
Adjustment Accuracy							2.00	
Reflector Housing Installation/Focus Correction						5.00		←
(correction of radius and cone angle)								
Reflector Pair (P-S)						9.90		←
	Rqmt		Margin	RSS Predict		Allocation		

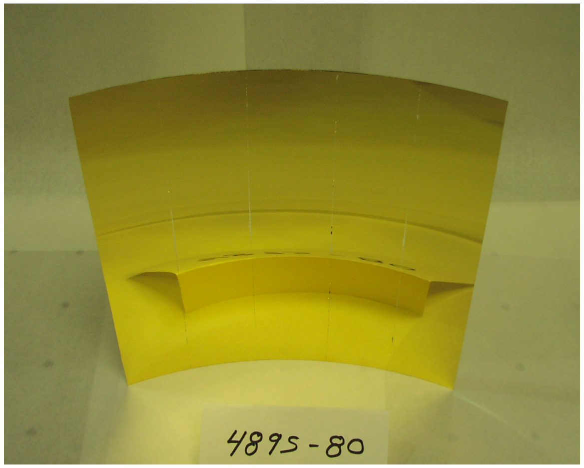
Mirror Segments - Recent Progress

- Demonstrated that formed substrates faithfully and consistently reproduce the forming mandrel surface at low spatial frequencies
- Improved the formed and replicated mirror quality by reduction of size and number of particulates (dust) on surface
  - Invested considerable effort reducing environmental dust in mirror lab
- Demonstrated that replication with ~10 µm epoxy layer can smooth out mid-frequency errors without causing significant distortion to low order figure
- Demonstrated feasibility of producing mirror segments meeting the error budget requirement without replication
  - Low and mid frequency improvement is likely if more precise forming mandrels are used
- Demonstrated that low order figure distortions are very sensitive to segment orientation and how it is held
- Developed a forming mandrel release layer that is very smooth and durable, and reduces mid-frequency roughness introduced by forming
  - Possible to apply using robotic spraying (developed for epoxy)
  - Process improvements still being sought

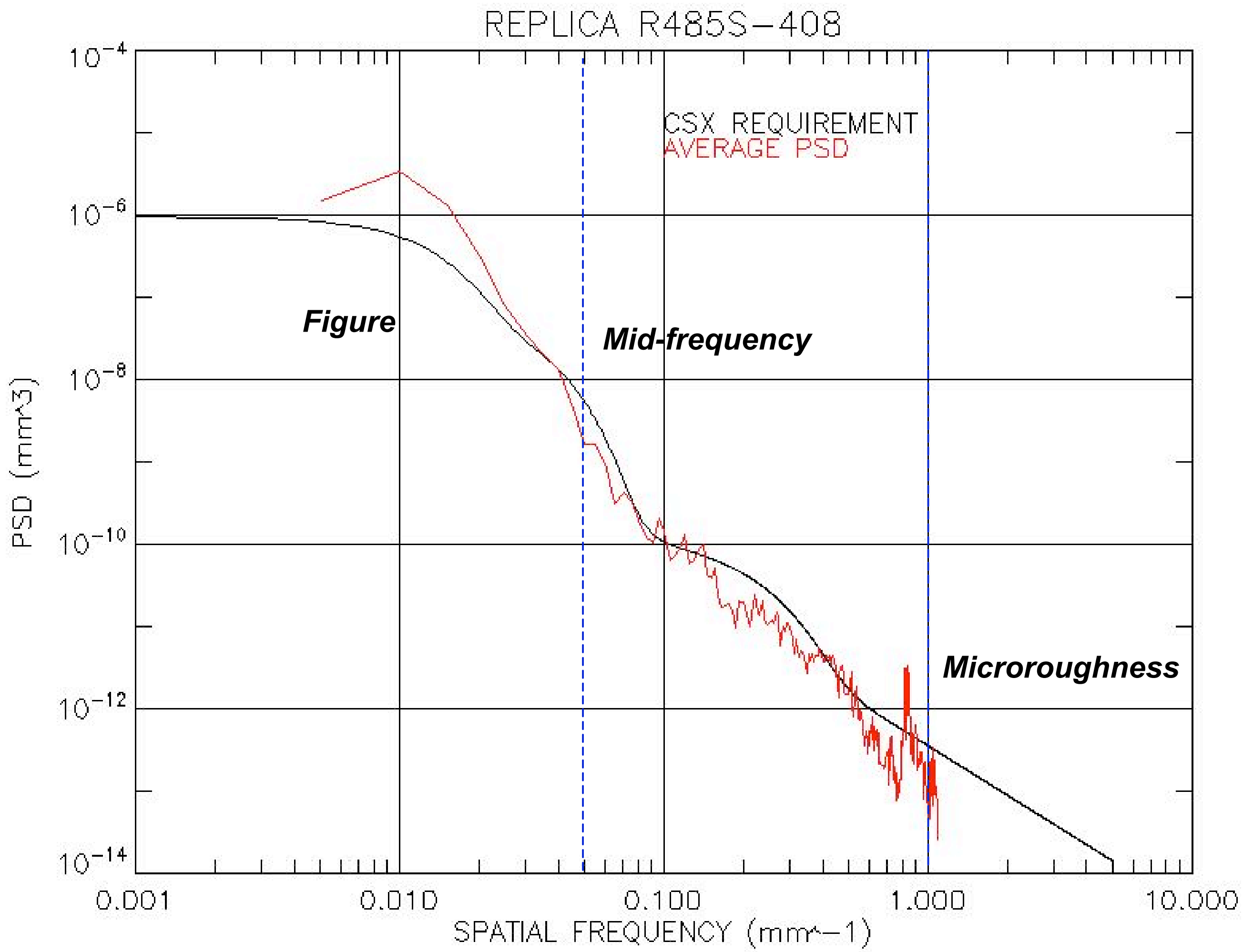
Mirror Segments - Technical challenges

We have a clear understanding of elements of producing mirror segments

- Three largely decoupled spatial frequency domains
  - Low order - 2-20 cm
  - Mid-frequency - 0.1-2 cm
  - High-frequency (microroughness) <0.1 cm
- Low order
  - Determined by forming; not improved by replication
  - Regime where distortions due to gravity, mechanical stresses appear
  - Dictate forming mandrel requirements
- Mid frequency
  - Imparted to substrate during forming
  - Very sensitive dependence on physics of forming process
  - Very sensitive to presence of particulates
  - Corrected by epoxy replication
- Microroughness
  - Substrate material has excellent microroughness; preserved during forming
  - Replication introduces entirely new microsurface - this places requirements on replication mandrel microroughness (superpolishing is necessary)



Spatial Frequency Domains

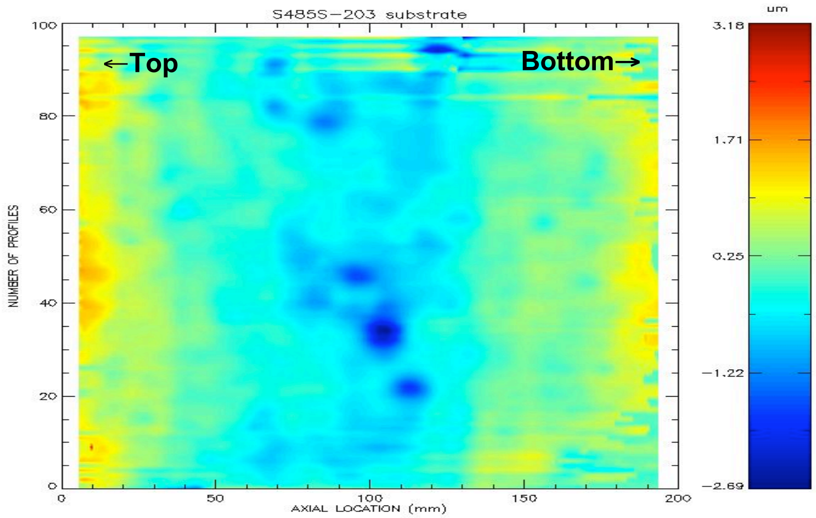


Mirror Segment Metrology Allocation vs. Measurement (ordered by HPD contribution)

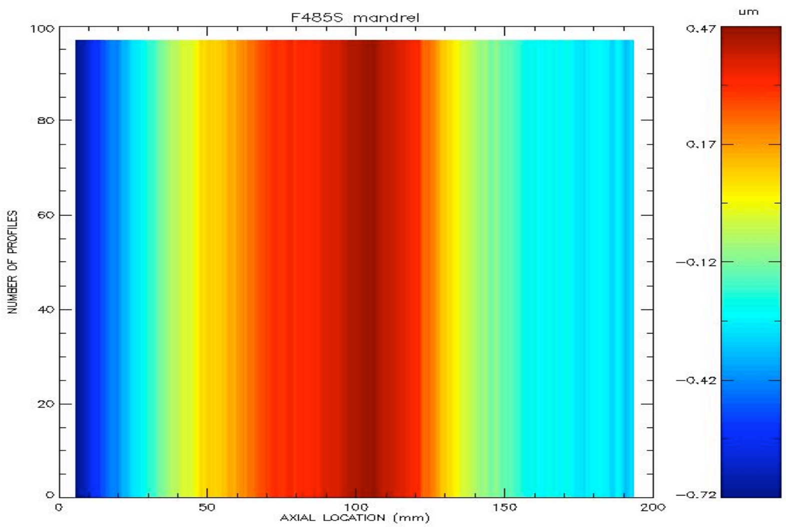
Parameters	Units	Allocation	Status	Instrumentation	Plan/Comments
AXIAL FIGURE					
Slope	arcsec, rms	0.75	0.35	Interferometer	
Mid-frequency	nm, rms	2.53	0.5	Interferometer, Bauer200	
Micro-roughness	nm, rms	0.19	0.1	Microinterferometer	
Sag	µm, pv	0.04	–	Interferometer, MMTC	10-point mount will improve accuracy. Plan for better thermal control. Gravity back out model & verification required.
Delta-delta-radius	arcsec, pv	0.22	–	MMTC, Null lens	MMTC ΔΔR on mirror segment dominated by room thermal changes; Null lens needs permanent mount & calibration.
Roundness	µm, pv	1.58	3.5	MMTC	Dominated by room thermal changes (range during test from 2.7µm to 3.5 µm). Plan for better thermal control.
Cone-angle	arcsec	3.16	–	MMTC	Optipro/MMTC. 10-point mount will improve accuracy. Plan for better thermal control. ±0.65 arcsec measured on solid calibration cylinder.
Average radius	µm	10.4	–	MMTC	Optipro/MMTC. 10-point mount will improve accuracy. Plan for better thermal control. ±1.8 µm measured on solid calibration cylinder.

2D Contour plot of recent substrate

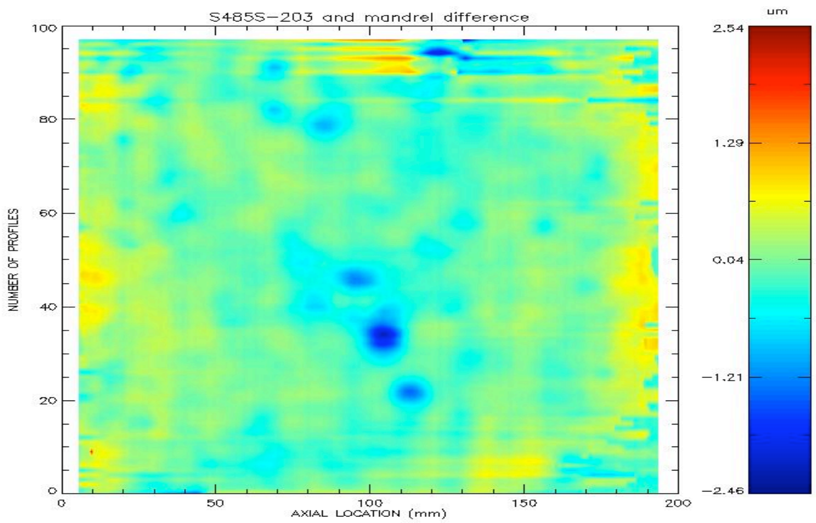
- 98 profiles measured; piston and tilt removed
- Single mandrel profile expanded to 2D
- RMS height error =0.30 µm
- Difference map represents upper limit of actual difference
- Large deviations due to dust particles
- Large deviation at top due to mounting fixture



Measured profile (piston and tilt removed)



1D profile of forming mandrel



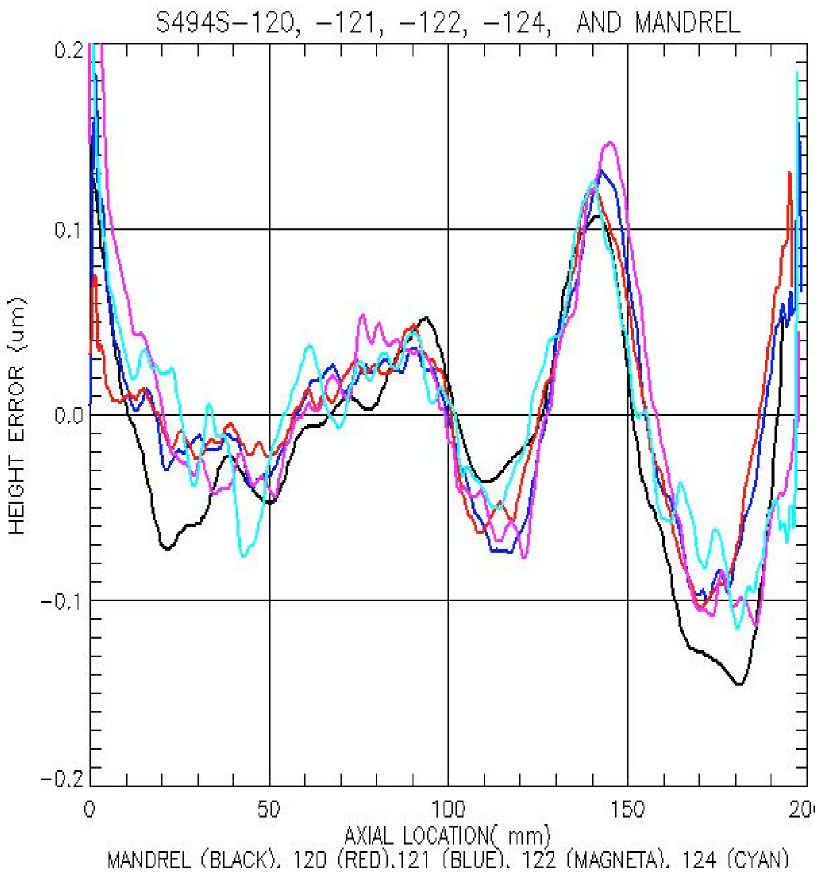
Difference between mandrel and substrate

Comparison of mandrel and four consecutive substrates

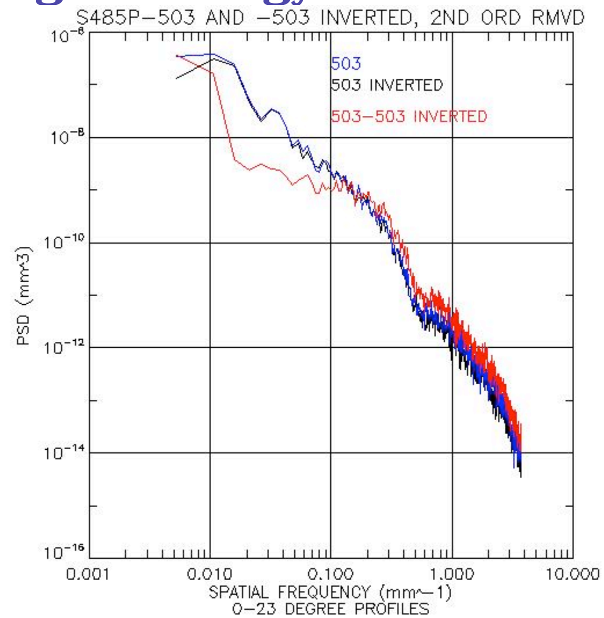
- Compare single substrate (120, 121, 122, and 124) profiles to the mandrel profile
- Low order axial and azimuthal terms removed
- Calculate RMS difference for processed data and scaled data (mandrel axial scale factor 0.97)
- RMS of unscaled data ~50 nm and scaled data ~30 nm
- RMS error is dominated by large differences in the valleys at about 170 mm, 120, and 20 mm axial locations
- Is the mandrel treatment filling the valleys at 20 mm and 170 mm?

Substrates have consistently high quality, and closely match mandrel

	Mandrel-substrate RMS height difference	
	Raw data (nm)	Scaled data (nm)
120	44	30
121	50	32
122	49	28
124	51	32

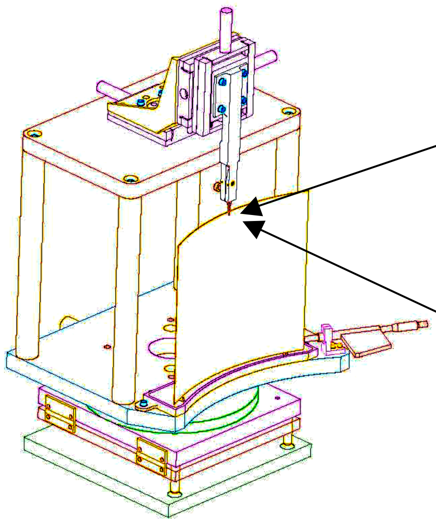


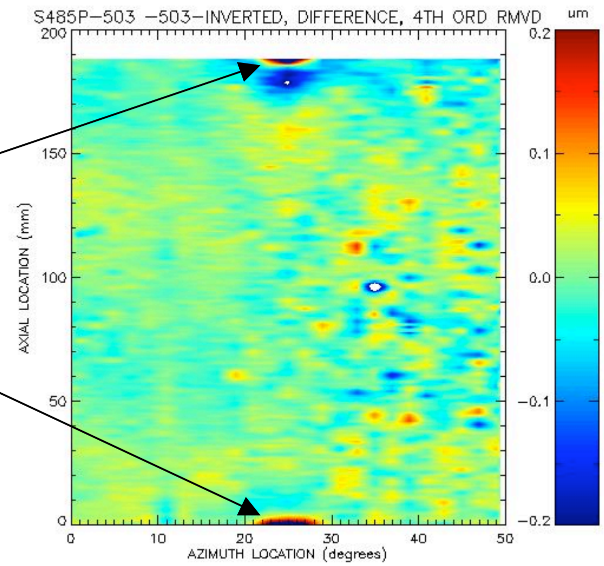
Understanding distortions introduced during metrology



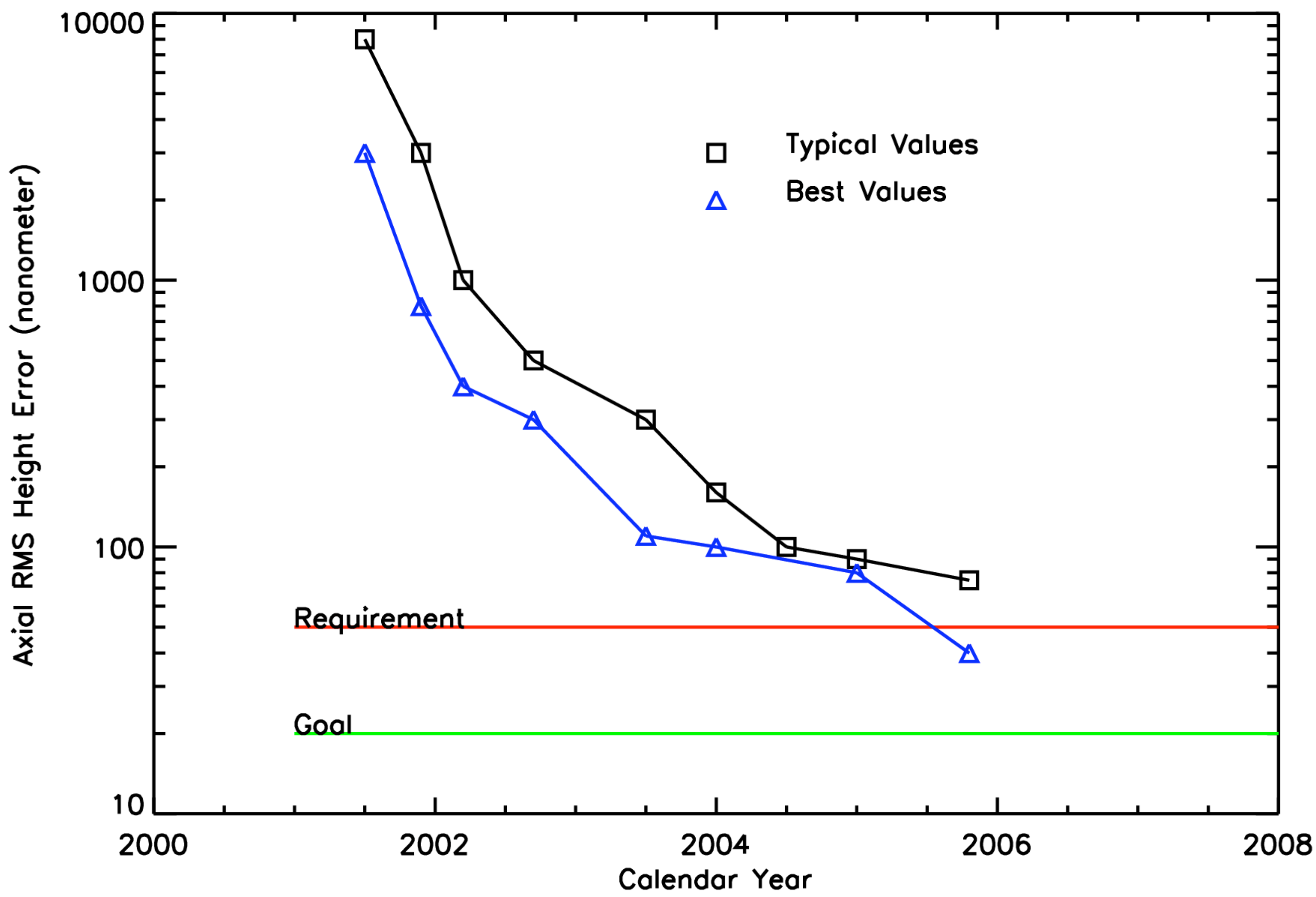
- Measuring axial profiles in the “upright” and “inverted” orientations allow separation of instrinic mirror errors from those induced by mounting
  - 1st through 5th order errors (low frequency) are dominated by mounting stresses, as shown in the PSD plot, top right
  - ~6th order and higher errors are inherent to the part. There errors are only on the order of 10-30 nm
- Scan difference plot reveals distortion due to 3-point mount as well as registration differences due to shift in baseline

Biggest challenge is mounting segments without Imparting stress





Mirror Segment Figure Improvement



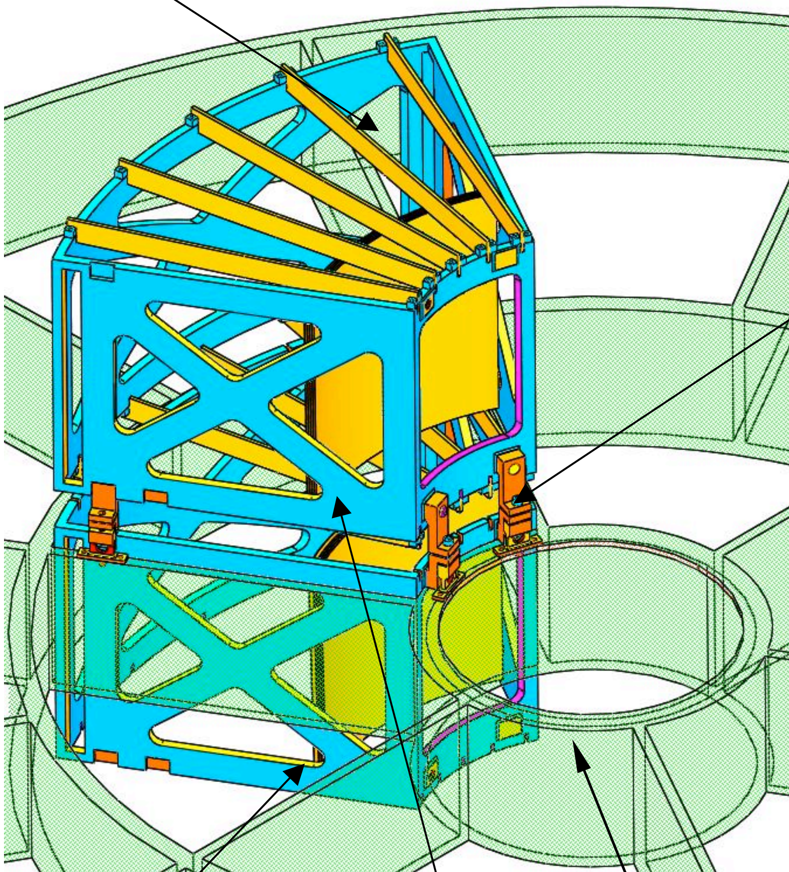
Mirror Segments - Challenges to Consistently Meeting Requirement

- Improvement of glass forming environment, including a clean/vacuum oven
- Better understanding of the surface physics of forming
- Ability to perform mechanical/thermal modeling of forming
- Improvement of the glass sheet cleaning process
- Better control of the epoxy replication environment: a mandrel coating chamber at GSFC
- Improved metrology of segment figure
  - **Virtually impossible to measure free-standing segment, especially 2nd order sag**
  - **Such measurements are largely irrelevant - expect coupling between segment and mount (can't independently determine error budget terms)**
  - **We are building a 10-point mount to emulate conditions in housing, which facilitates 2D surface metrology**

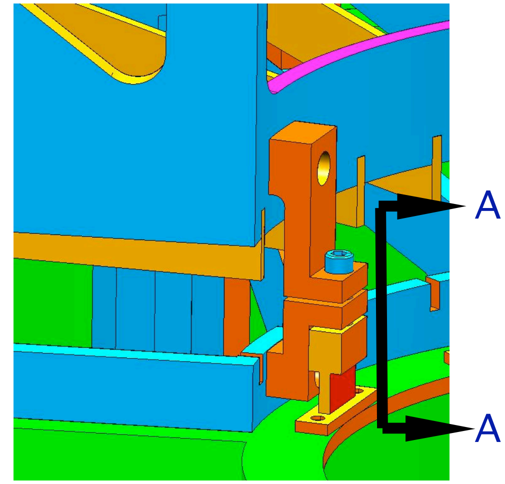
Reference FMA Mounting Concept

- **Typical Primary/Secondary (P/S) Module Stack up:**

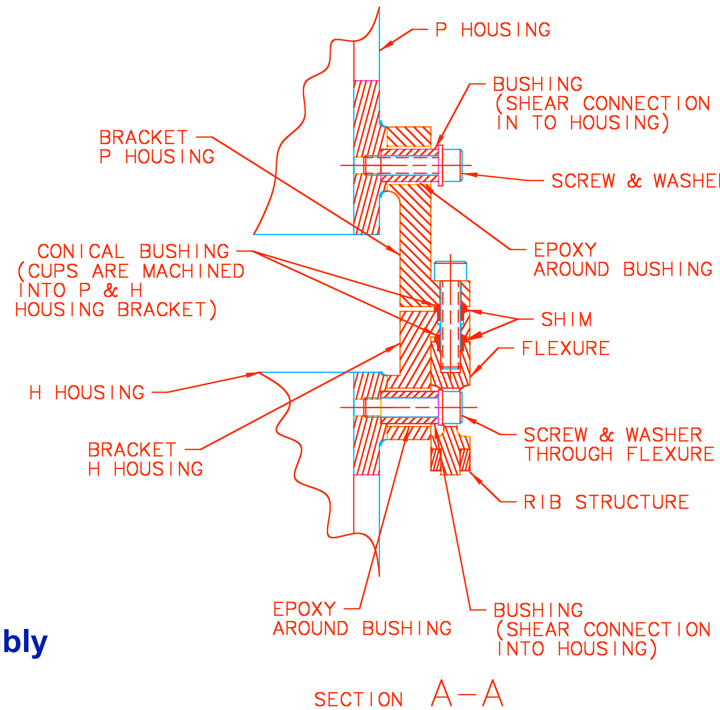
Typical Strut (5 Top, 5 bottom on each Submodule)



This concept uses flexures to attach the P and S sub-modules together, as well as, to the Ring Structure Assembly

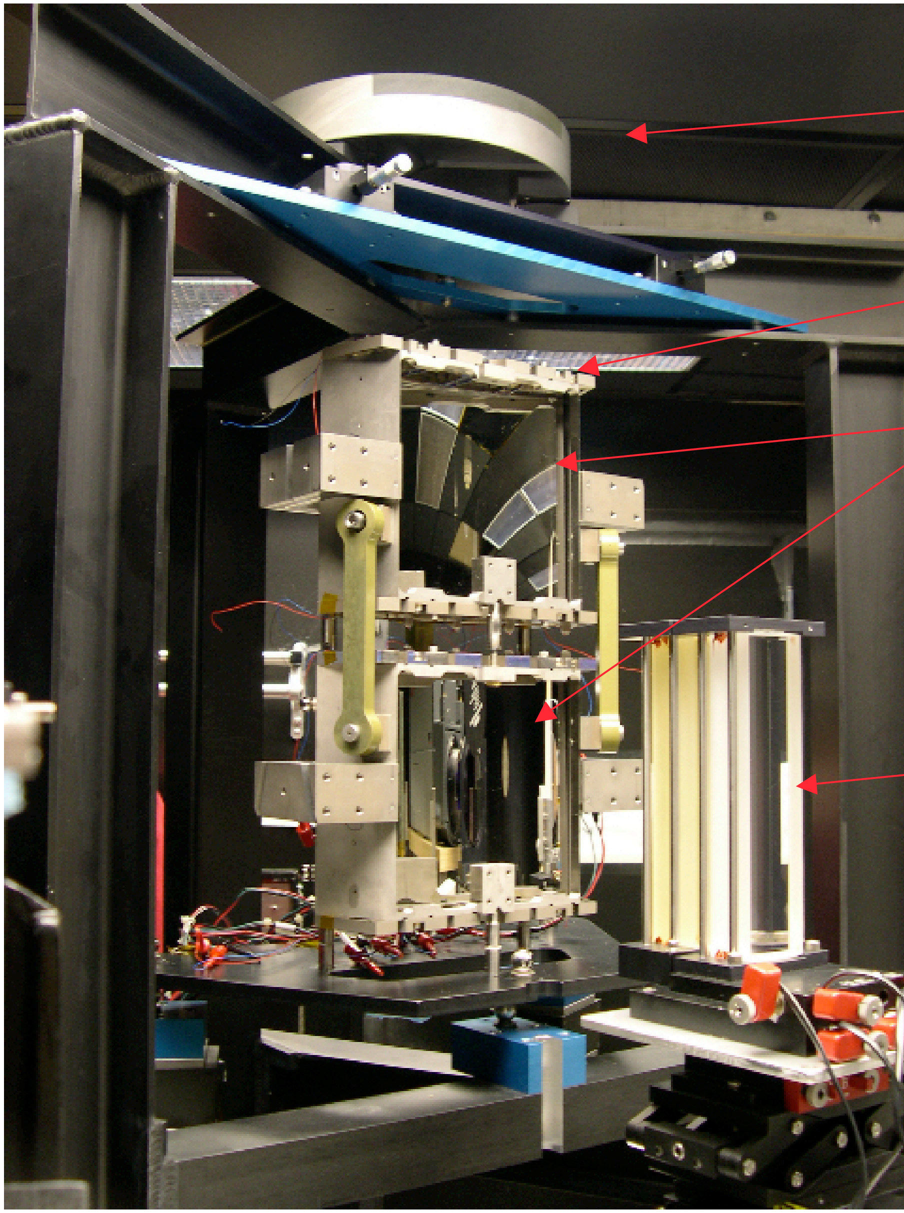


Typical Flexure Assembly 4 Places



S Submodule **P Submodule** **FMA Ring Structure Assembly (“Wagon Wheel”)**

OAP2 unit for mirror pair alignment and mounting demonstration



Retroreflector

Actuator plate
(1 of 4)

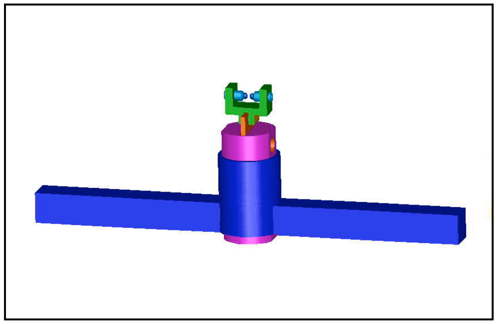
Mirror surfaces

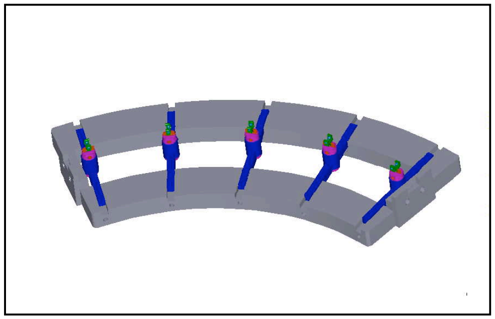
Cylindrical null lens assembly

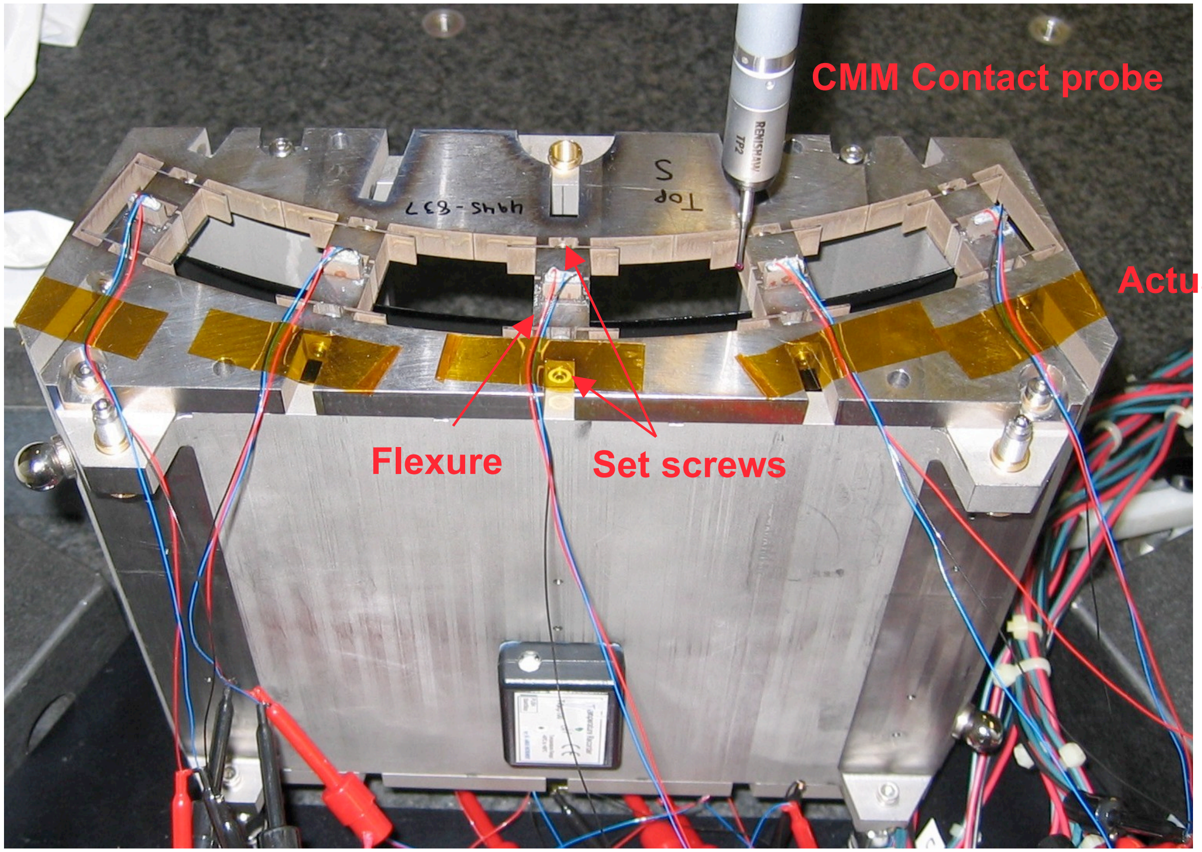
~95 percent of each mirror surface is viewable by instrumentation at normal incidence

Fully assembled OAP2 unit in alignment faclity

Alignments within OAP2 driven by precise piezoelectric actuators

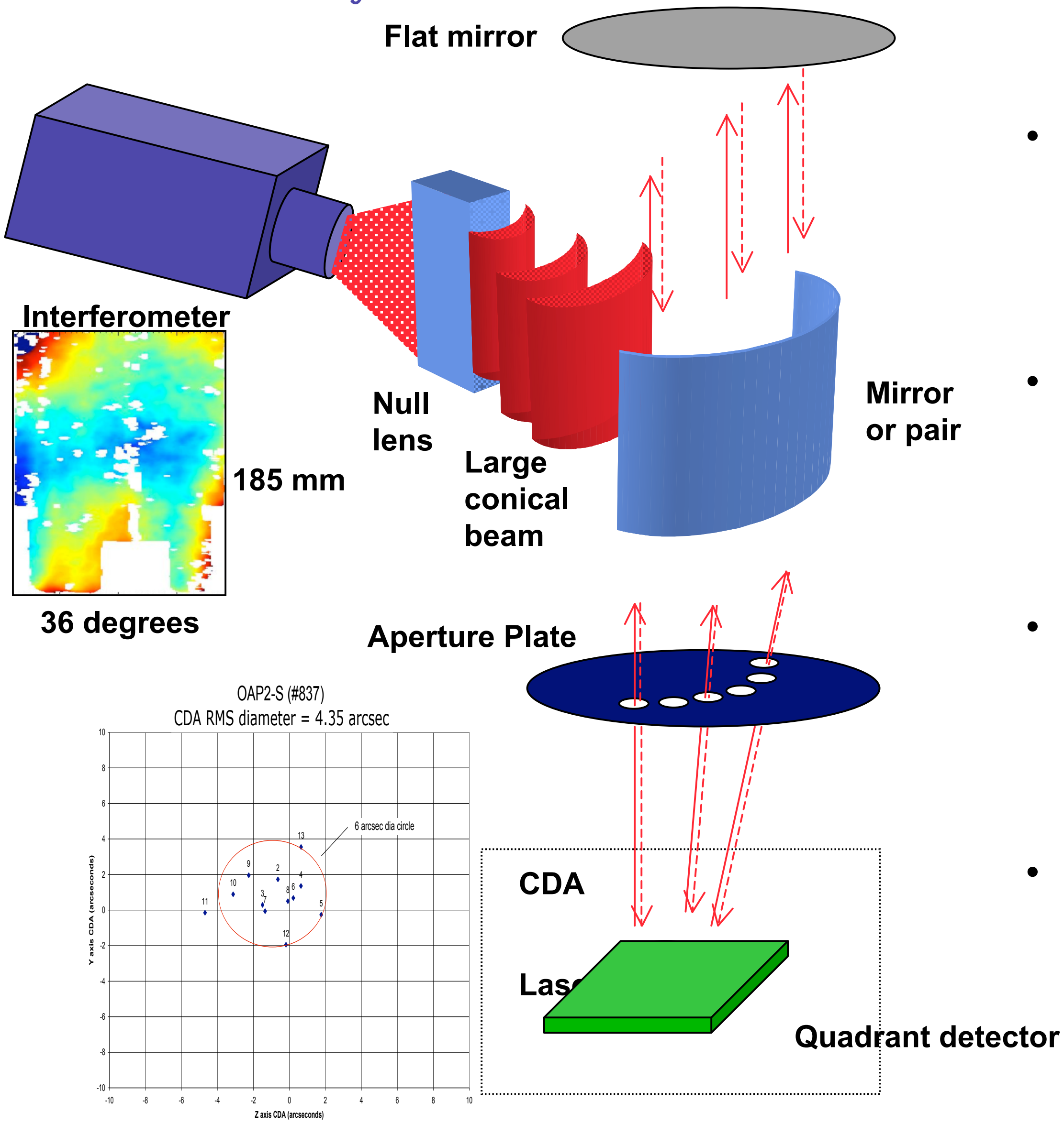






Five bidirectional actuators are located at the entrance and exit aperture of the primary and the secondary mirror. Radial flexures minimize stresses imparted into segments

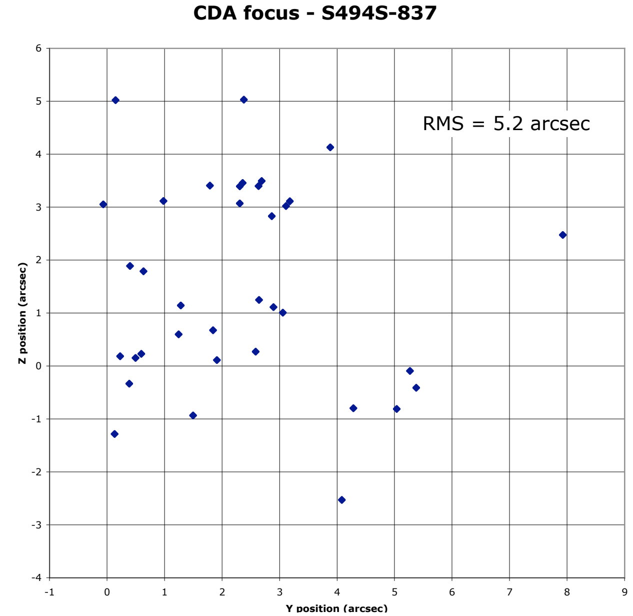
Alignment combines focal plane measurements with surface interferometry

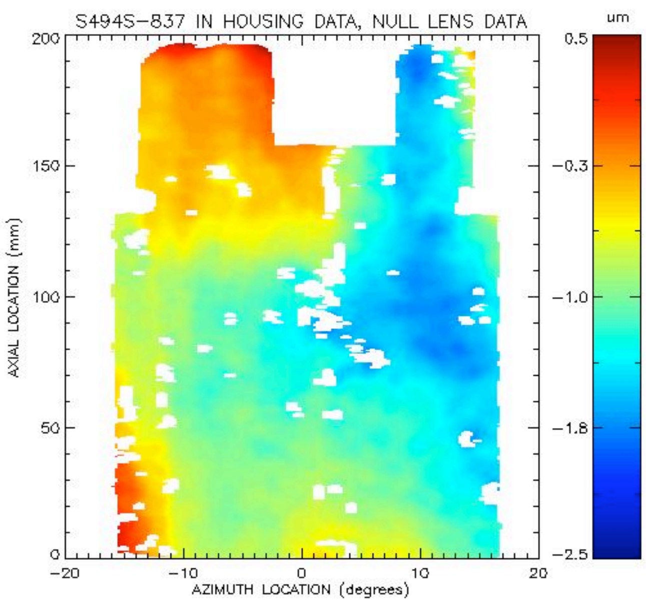


- **Centroid Detector Assembly (CDA) originally developed for aligning AXAF mirrors (<0.1 arc second accuracy)**
- **CDA samples only a portion of surface, defined by aperture stops; only locates centroid of return beam**
- **Observed patterns are ambiguous; prealignment using collimated beam breaks degeneracy**
- **Only way to determine shape of segment is simultaneous figure measurement using interferometer**

OAP2-S alignment status

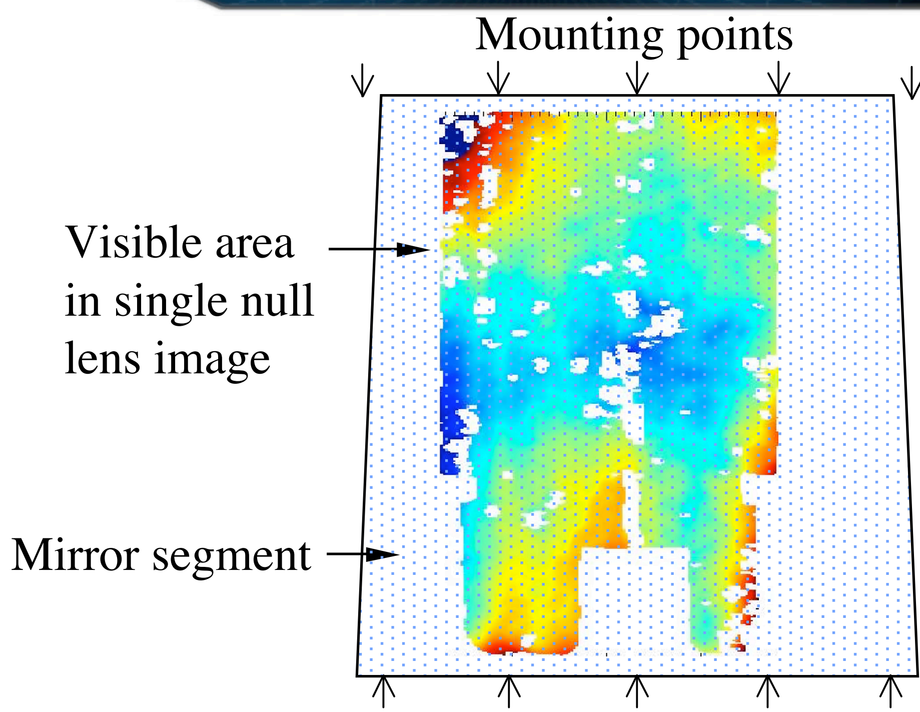
- A secondary mirror segment has been aligned in the CDA facility and simultaneously imaged with an interferometer through the conical null lens.
- The "best" alignment is a compromise between the best mirror segment focusing that can be achieved by monitoring the CDA only, and the best mirror segment figure that can be achieved by monitoring the interferogram only.
- Graphs to the right show the CDA focus and "first light" alignment using the conical null lens.
- Better alignment has since been achieved. It appears that we can routinely achieve alignment quality on the order of 16" HPD (2-reflection equivalent).
- Details in S. Owens talk



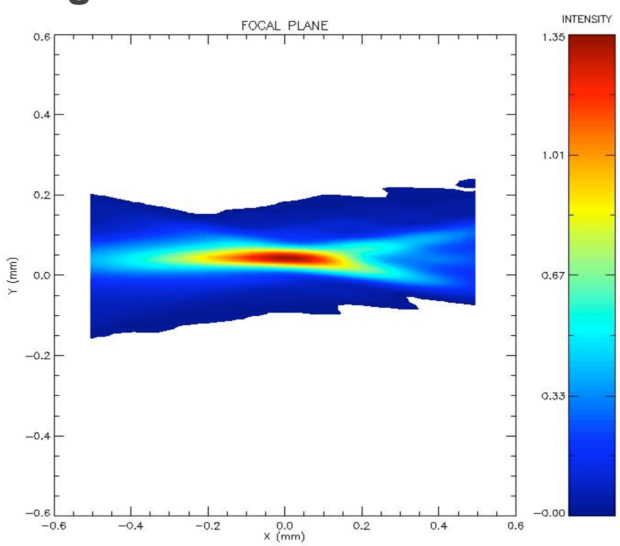


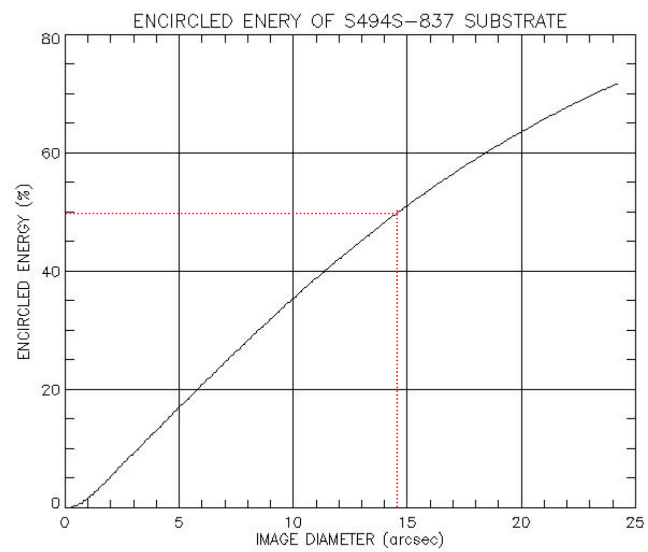
Mirror Pair Performance Prediction

- **Performance prediction based on ray trace using fit data from area of mirror segment visible in null lens (37 deg x 185 mm)**
- **Measured figure error of secondary applied to ideal primary mirror segment to get a 2-reflection model**
- **HPD = 5.1" (no scatter)**
- **HPD = 14.6" (figure error and scatter models on both surfaces)**
- **Major unknowns are primary figure and misalignment**



Ray traced 2-reflection image in focal plane

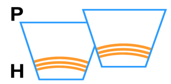
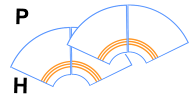




Plans for Coming Year (and Beyond)

- ***Mount and align one or more pairs of mirror segments***
  - *Perform in situ full surface metrology within OAP2 mount*
  - *Demonstrate that aligned segments meet the Constellation-X HPD requirement*
  - *Quantify residual errors to determine most significant contributions*
  - *Compare 3D segment surface measurements and distortions (using special metrology mount) with optical and mechanical models*
- ***Verify performance of aligned mirror pair(s) in X-rays; compare with predictions from metrology***
- ***Continue development of alignment procedures***
  - *Introduce next generation Piezo actuators*
  - *Integrate collimated beam, surface profile interferometry, and CDA*
- ***Refigure forming mandrel pair to allow 3 arc second HPD (Con-X goal)***
- ***Procure and test 50 cm "slab" forming mandrel***
  - *Couple with thermo-mechanical modeling of forming process*
  - *Initiate conversion of forming to "flight-like" mandrels*
- ***Involve industry in studies of Flight Mirror Assembly and mandrel fabrication***
  - *Mandrel fabrication is critical path of the program - need to identify multiple suppliers*
  - *Mounting process could benefit from independent engineering study*
- ***New funding reductions will significantly delay all mirror technology development, and could result in irretrievable loss of knowledge***

Technology Development Roadmap Summary

	Optical Assembly Pathfinder		Mass Alignment Pathfinder	Engineering Unit	Subassembly	
	OAP #1	OAP #2				
Configuration						
Module Type	Inner	Inner	Inner	Two inner modules	NASA Testbed – Outer + Inner	Industry Prototype – Outer + Inner
Housing Material	Aluminum	Titanium	Titanium	Titanium	Titanium	Titanium
Focal Length	8.4 m	8.4 m	8.4 m	10 m or 8.4 m (TBD)	10.0 m	10.0 m
Nominal mirror segment Diameter(s)	50 cm	50 cm	50 cm±	50 cm±	160 cm 120 cm± 100 cm, 50 cm±	160 cm± 120 cm± 100 cm±, 50 cm±
Goals	• Align 1 mirror segment pair (P&H) • Evaluate mirror assembly design, alignment and metrology	• Align 1 mirror segment pair • Evaluate segment performance and stability in mount • Evaluate mirror bonding • X-ray test • Vibration test	• Align up to 3 mirror segment pairs to achieve <12.5 arcsec • Evaluate tooling for mass alignment • Vibration & X-ray tests	• Fabricate segments from slab mandrels • Align module to module. • X-ray and environmental tests • Technology transfer to industry • Evaluate assy gravity sag	• Form largest mirror segments • Demonstrate reference subassembly design • Environmental and X-ray test	• Demonstrate flight prototype • Environmental and X-ray test • Industry build
TRL – Mirror segment	TRL 3	TRL 4/5		TRL 6		
TRL – Assembly	TRL 3	TRL 3/4	TRL 5	TRL 6		
Timeframe	Q2 of FY03	Q2 of FY06	2006 - 2009			
Technology Gate			υ		υ	

Summary

- ***Significant progress made in some areas of SXT mirror development despite substantial funding reduction***
  - *High quality substrates made reliably and faithfully reproduce mandrel surface*
  - *We understand the origin of many of the substrate errors and how to remove them*
  - *Substrate performance is limited by mandrel figure*
  - *Alignment principles have been demonstrated; we are close to having a segment pair aligned*
  - *Substantial evidence exists that mirrors have correct overall shape*
- ***Metrology uncertainties limit our knowledge of the segment quality***
  - *Two new tools (MMTC, high speed interferometer) coming on line to address these uncertainties*
  - *Mounting has been a crucial limitation of metrology*
  - *We have not yet measured the true 3D shape of a segment*
- ***Strong coupling between mounting and alignment is becoming understood***
  - *See talk by Scott Owens*
- ***X-ray test using aligned segment pair should yield performance consistent with Con-X requirement***
  - *Supporting metrology data will ensure an accurate performance prediction*