Optics for AXIS

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Next Generation X-ray Optics Team

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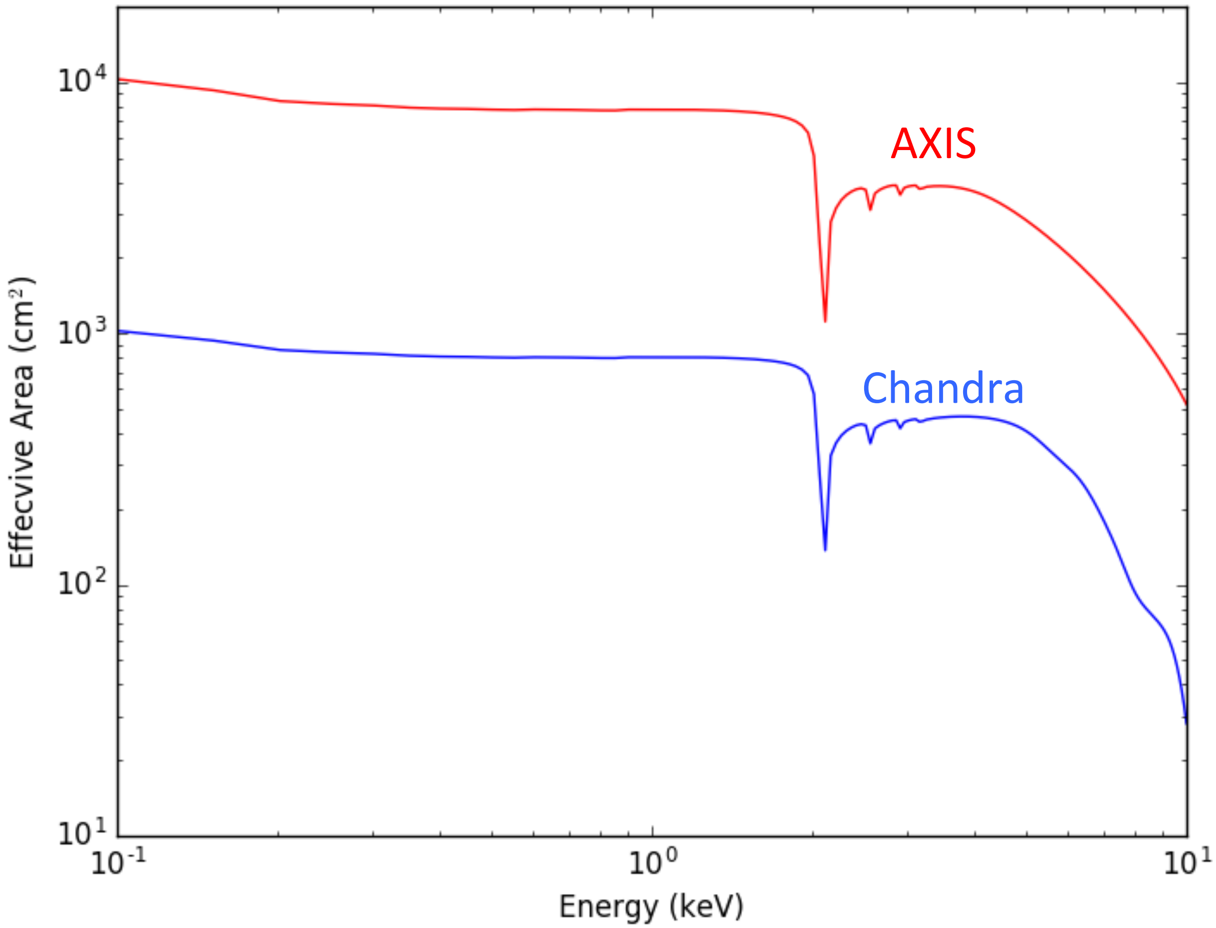
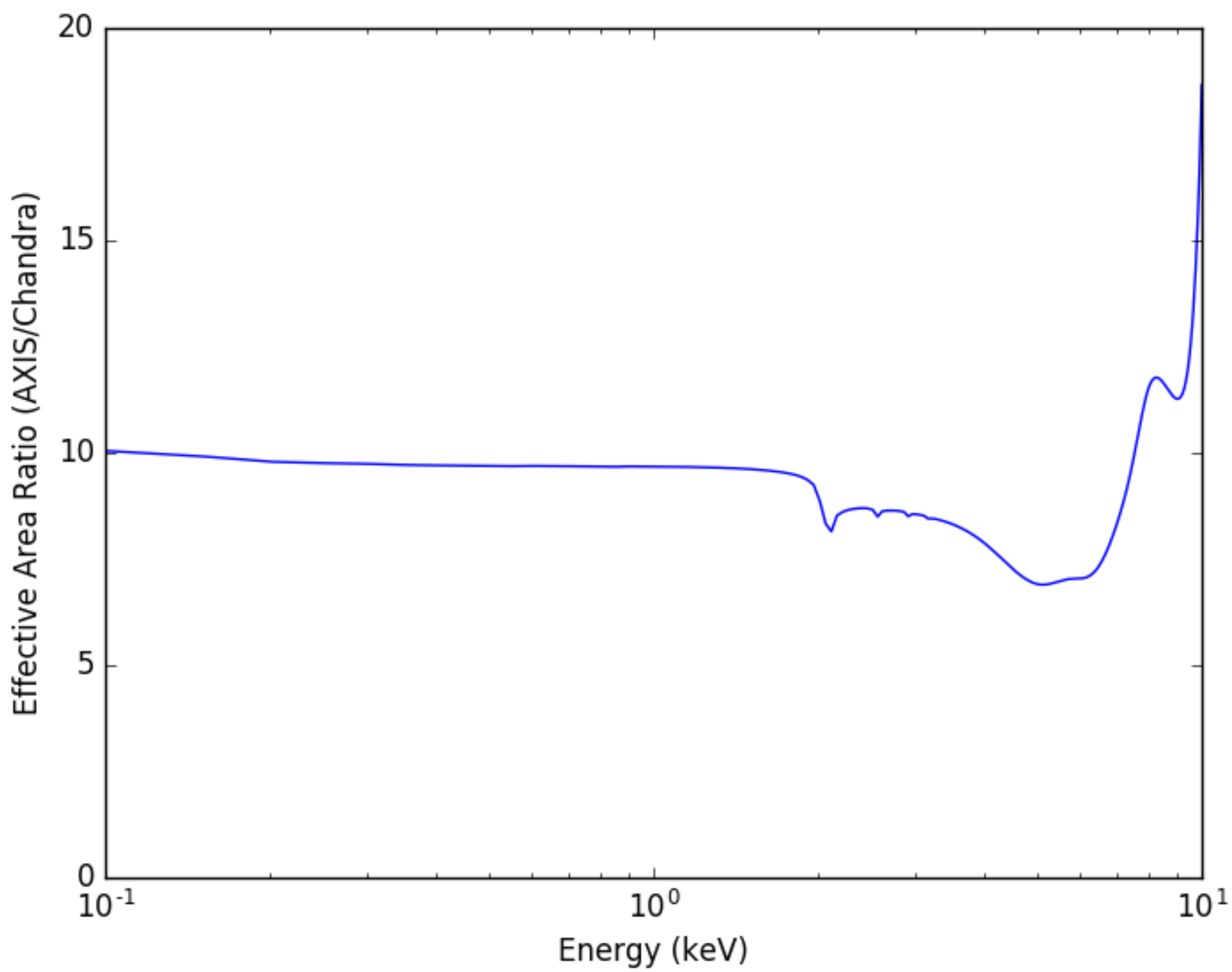
Key Features of AXIS Optics

- **High angular resolution**
  - **0.5"** HPD on axis, similar to Chandra's
  - Can be better, but at expense of FOV
- **Large field of view (FOV)**
  - **15** arc-min diameter with 0.5" PSF
  - Cf. **4** arc-mins of Chandra-ACIS-I
- **Large effective area**
  - **10X** Chandra's at 1 keV
  - **15X** Chandra's at 10 keV

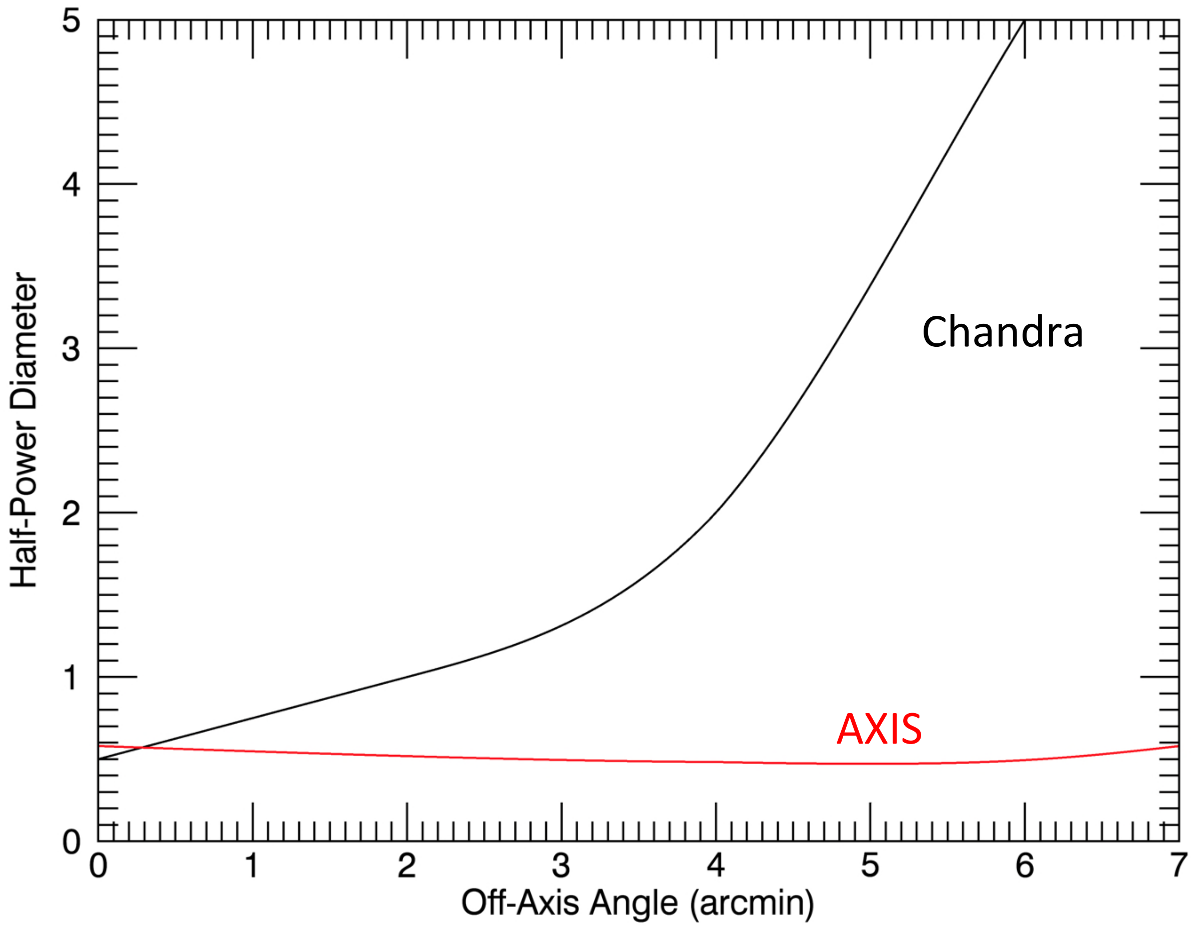
Eff. Area vs. Energy (optics only)



Effective Area Ratio vs. Energy



PSF vs. Off-axis Angle



Optics Top Level Error Budget

Parameter or Process		Contribution to HPD (")	Notes
Mirror Segment	Axial figure (sag)	0.1	Shown as of June 2017
	Axial figure (other than sag)	0.2	Shown as of June 2017
	Focus (roundness, cone angle and its variation)	0.2	Probably can be shown by 2018
	Coating (distortion to axial figure and focus)	0.1	Difficult to assess due to inssufficient data.
Integration of segments to meta-shells	Alignment	0.1	By 2019
	Bonding	0.2	**Difficult to assess. Emphasis of work in coming years. Tallest pole!!!**
Integration of meta-shells to assembly		0.1	Can be done relatively easily.
Launch shift		0.1	Need to be looked at.
Thermal gradients		0.1	Shown by analysis as of June 2017.
Gravity release		0.1	Shown by analysis as of June 2017.
Mirror Assembly Fabrication Total		**0.4**	RSS of all above numbers.
Mirror Assembly Optical Design Total		**0.3**	Timo Saha's design memo.
Mirror Assembly On-Orbit Performance		**0.5**	**RSS of above two numbers.**

Outline of Presentation

- **Optical design**
  - Fundamental geometry and physics
  - AXIS mirror design
- **Technology**
  - Substrate fabrication
  - Coating
  - Alignment and bonding
- **Engineering**
  - Structural, thermal, and optical performance
- **Making the case to the Decadal**
  - Case for technical readiness
  - Case for cost and schedule

Optical Design

Geometry and Physics (1/2)

- **X-rays reflect only at grazing angles**
  - Grazing angles decrease with energy
  - → Field of view decreases with energy
- **An X-ray telescope is really a “light bucket”**
  - Many concentric shells
  - X-rays from different shells add incoherently

Geometry and Physics (2/2)

- **Diffraction limits are a weighted average of many shells**
  - Each shell's diffraction limit is proportional to f / (H*r*E), where f is focal length, H shell length, r shell radius, and E x-ray energy
  - Each shell's effective area is proportional to $H*r*R^2(E,r/f)$, R is reflectivity and depends on E and r/f.
- **Off-axis PSF is weighted mean of many shells**
  - Each shell's being proportional to $theta^2*H/r$, where theta is off-axis angle

Practical Implications

- **On-axis PSF conflicts with FOV**
  - Good on-axis PSF demands long shells
  - Good off-axis PSF demands short shells
- **Dichotomy of Soft and Hard X-rays for a nearly diffraction-limited Telescope**
  - Soft X-rays: poor on-axis PSF because of diffraction, but large FOV because of geometry
  - Hard X-rays: good on-axis PSF because of diffraction, but small FOV because of geometry and basic physics

An Example Design for AXIS

Parameters	Values
Focal length (mm)	9,000
Outer Diameter (mm)	1,500
Inner Diameter (mm)	400
Mirror Segment Axial Length (mm)	200
Mirror Segment Thickness (mm)	0.5 (**1.0**)
Unobstructed FOV (arcmin)	15
Coating	iridium
No. of shells	163
Diffraction limits (arcsec 90%dia.)	0.2 @ 1 keV
Mass of Mirror Assembly (kg)	~500 (**~1,000**)

Takeaway Messages

Under reasonable assumptions:

Focal length: 9 meters

Outer diameter: 1.5 meter

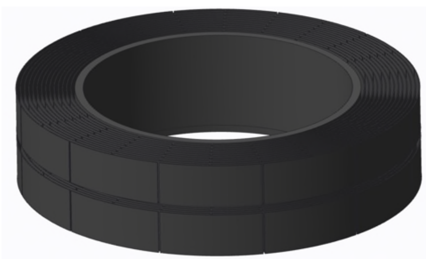
Mirror thickness: 0.5 mm

- **AXIS can have effective areas (optics + detector)**
  - >5,000 cm^2 at 1 keV
  - >1,000 cm^2 at 5 keV
- **AXIS's PSF and FOV**
  - More or less uniform 0.5" HPD in a 15-armin dia. FOV
  - Better PSF on-axis at expense of off-axis PSF.
    For example, 0.1" on-axis, 1.5" at 6-arcmin off-axis

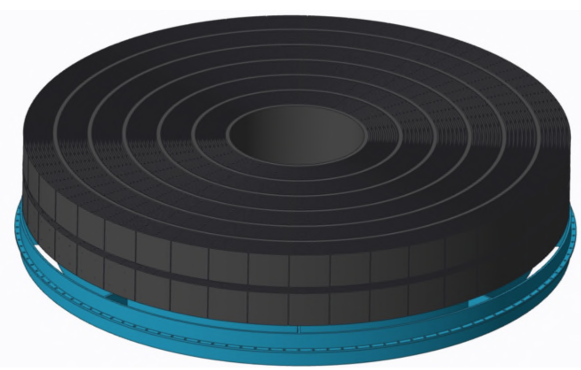
Technology

The Meta-Shell Paradigm

Mirror Segment



Meta-shell



Mirror Assembly

- Each mirror segment is fabricated, qualified, and then aligned by and bonded to four spacers which kinematically constrain it.
- Several hundred mirror segments are aligned and bonded to form a meta-shell.
- A dozen or so meta-shells of different diameters form the final mirror assembly

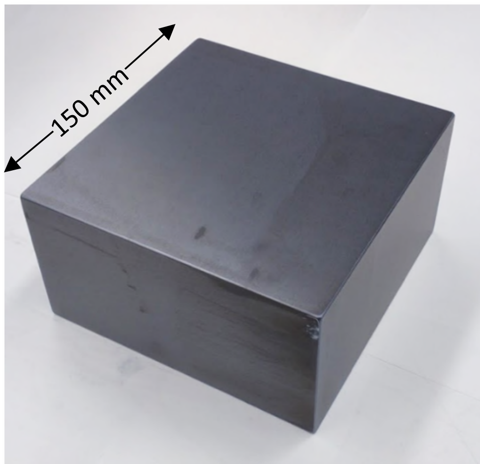
Three Basic Elements

- **Segment or Substrates**
  - Figure quality, including micro-roughness
  - Thickness and mass
- **Coating**
  - High reflectance
  - No figure degradation
- **Alignment and Bonding**
  - Locating and orienting each mirror segment
  - Keeping it there for good
  - Doing so without causing figure distortion

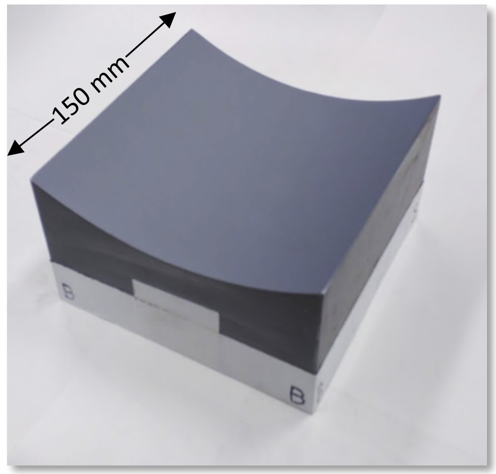
Substrate Fabrication

- **Material: mono-crystalline silicon**
  - Free of stress
  - Low density: 2.35 g/cm^3
  - High thermal conductivity: 150 W m^{-1} K^{-1}
  - High elastic modulus: 130 – 188 Gpa
  - Low thermal expansion: 2.6 ppm/K
  - Commercial availability
  - Best studied and understood material
- **Fabrication process: polishing**
  - Grinding, lapping, slicing, acid etching, full-aperture polishing, & sub-aperture polishing , etc.
  - Best possible figure and finish quality
  - Mass production and robotics to minimize cost

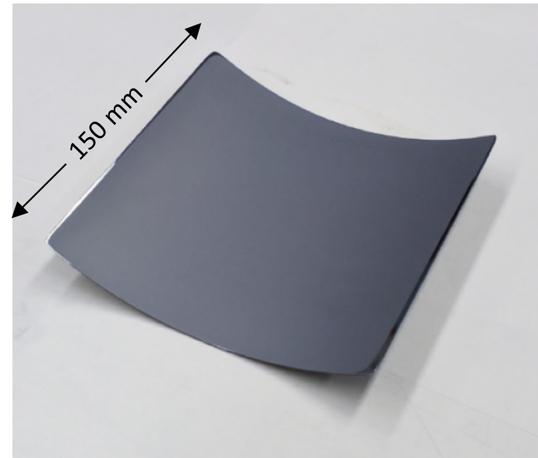
Fabrication Steps



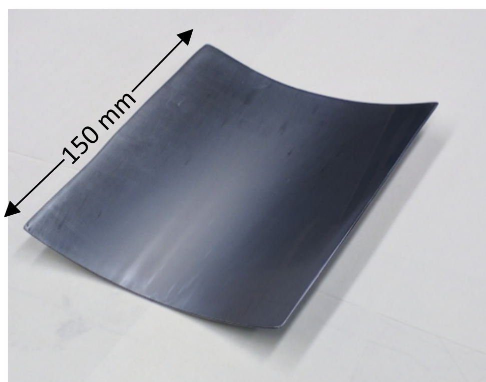
Monocrystalline silicon block



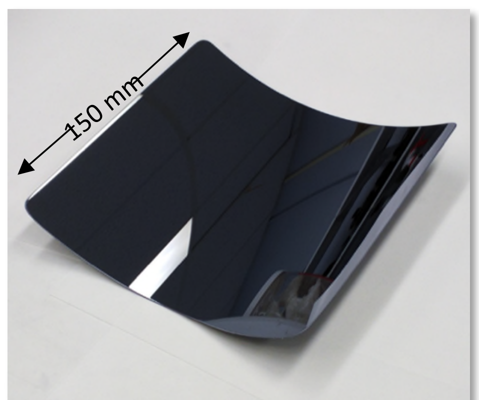
Conical form generated



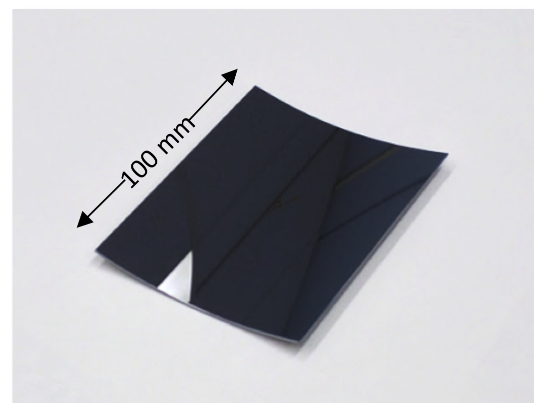
Light-weighted substrate



Etched substrate



Polished mirror substrate



Trimmed mirror substrate

Status of Substrate Fabrication

Slope Power Spectral Density

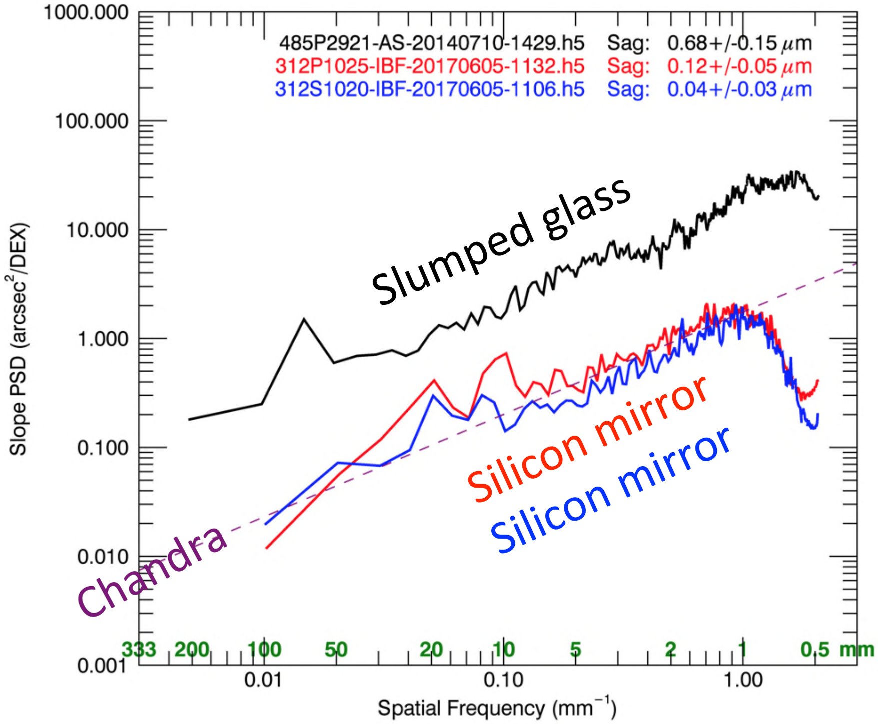
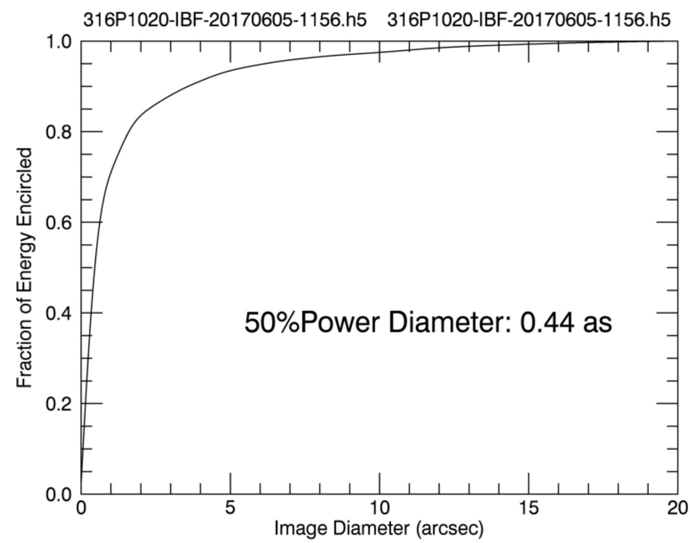


Image Performance Prediction of a Pair Silicon Mirrors: 0.44” HPD



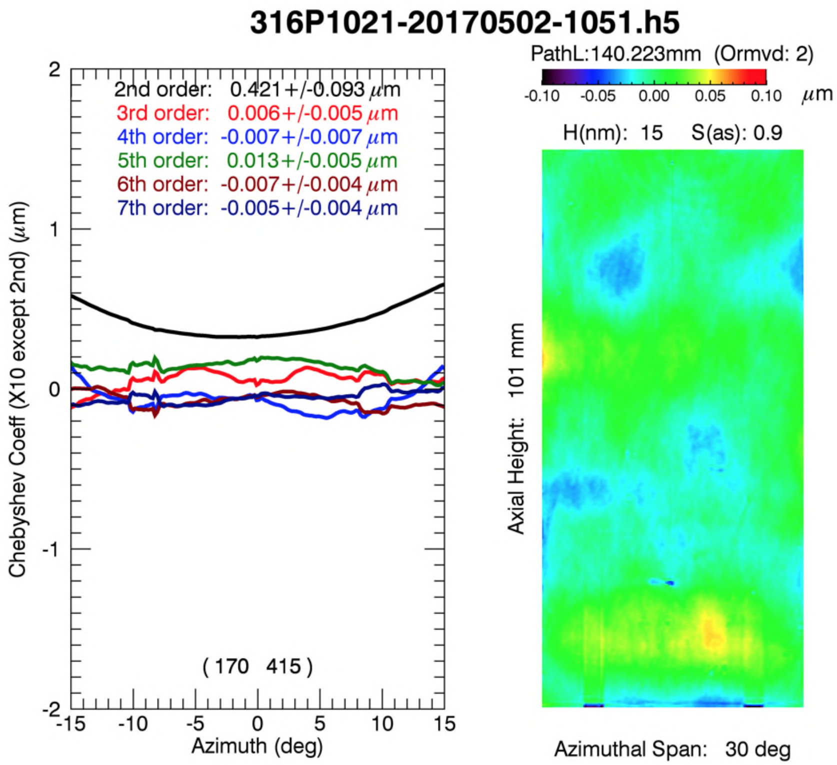
Substrate Fabrication Summary

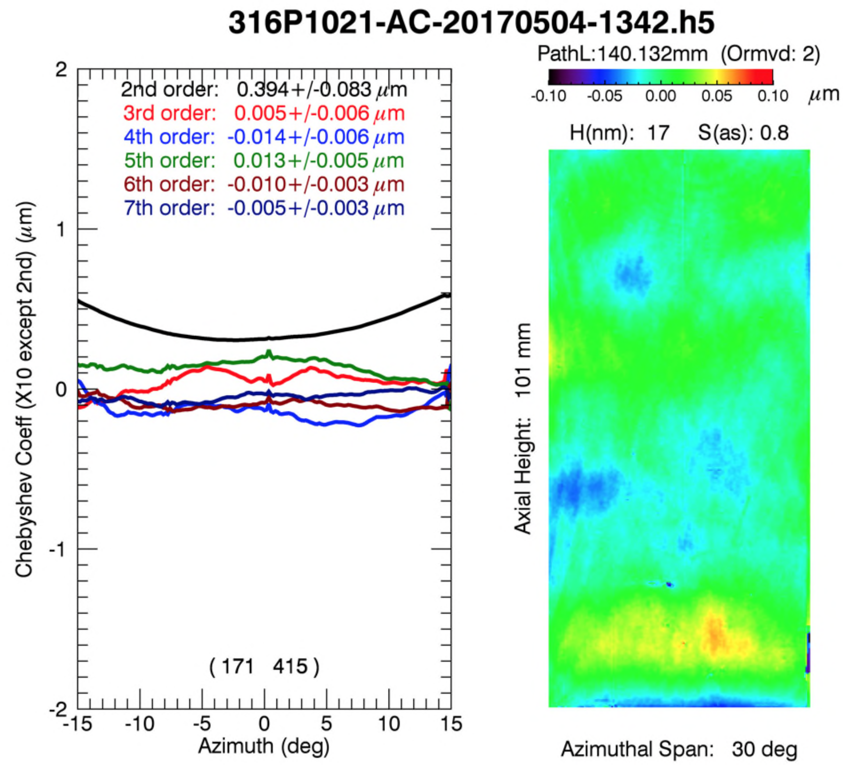
- **Can realize any optical design**
  - Wolter-I
  - Wolter-Schwarzschild
  - Or any other: equal-curvature, polynomial, etc.
- **Can make substrates better than Chandra's**
  - Better micro-roughness → better-behaving PSF
  - Thickness from 0.5 to 1.5mm (cf. Chandra's 10-25mm)
- **Use no special or custom equipment**
  - All equipment are commercial off the shelf.
  - All tooling can be made in ordinary machine shops.
- **High throughput and low cost**
  - Fabrication process is highly amenable to automation & mass production

Coating

- **Coating is an essential part of a strategy to meet effective area requirements**
  - A good coating is a necessity, not an option
- **Noble metal coating**
  - **Au:** Low stress ←→ Low reflectivity
  - **Pt:** Medium stress ← → Medium reflectivity
  - **Ir:** High stress ← → High reflectivity
- **Other possibilities**
  - An iridium layer plus an overcoat of B_4C or Al_2O_3

Effect of 15nm Pt Coating





P-V Sag change 54 nm → 0.32" in HPD change

Solutions being Pursued

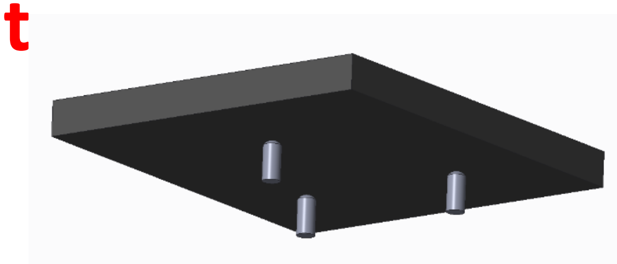
- **Balance front and back**
  - Investigating Pt coating now
  - If successful with Pt, will investigate Ir
- **Balance thin-film stress on the front with SiO_2 stress on the back**
  - Coatings typically have compressive stress
  - SiO_2 also has compressive stress. Its growth can be controlled to an accuracy of 1 nm.
- **Polish a figure error in the substrate that will cancel distortion caused by coating stress, if the effect of coating stress is highly repeatable & stable.**

Approach to Alignment & Bonding

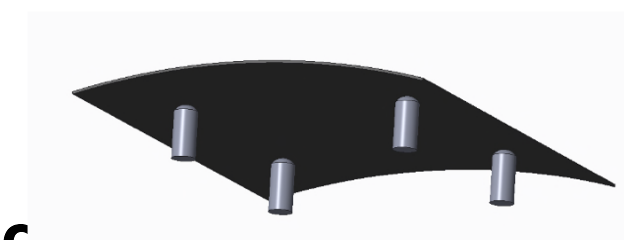
- Use **kinematic mount** to minimize/eliminate distortion to mirror segments
- Use **finite element analysis** to optimize locations of supports
- Use epoxy as **adhesive only**, not as a filler of any space that is not precisely controlled
- Use **gravity**, the most repeatable force, as the nesting force

Minimal Constraints

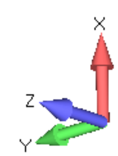
- **Three spacers or posts fully determine the orientation of a flat mirror:**
  - pitch, yaw, & x by gravity
  - roll, y, and z by friction



- **Four spacers or posts fully determine the orientation of an X-ray mirror:**
  - pitch, yaw, x, and y by gravity
  - z and roll by friction



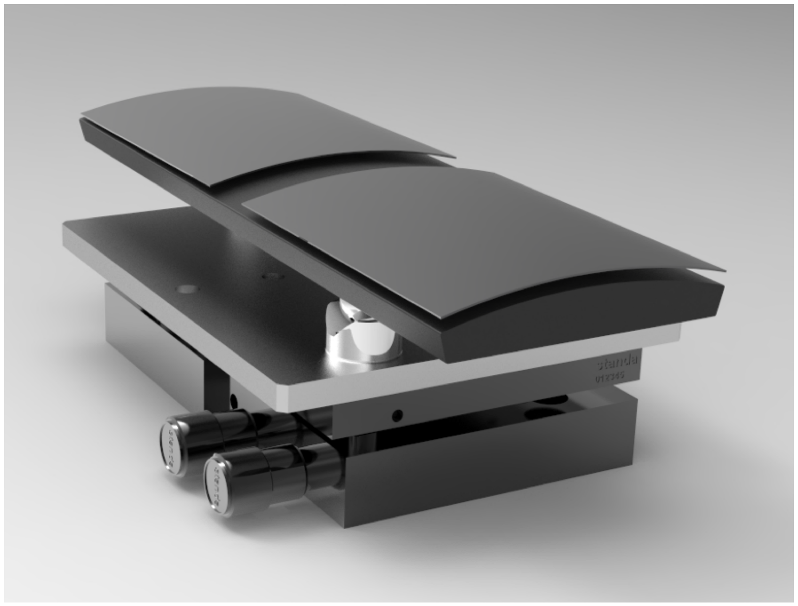
- **Use vibration of optimal frequency and amplitude to overcome friction**



Proof of Concept

- **Placement repeatability**
  – The same mirror from placement to placement
  – From one mirror to another of the same prescription
  – Stability over long periods of time: ~10 hours
- **Precision machining of posts**
  – Current precision at 25 nm, limited by metrology
  – Enables sub-arcsecond mirrror alignment
- **Bonding mirror with epoxy**
  – Preserves alignment: no indication of alignment shift
  – Preserves figure: only localized distortions due to epoxy cure stress

Proof of Concept Module

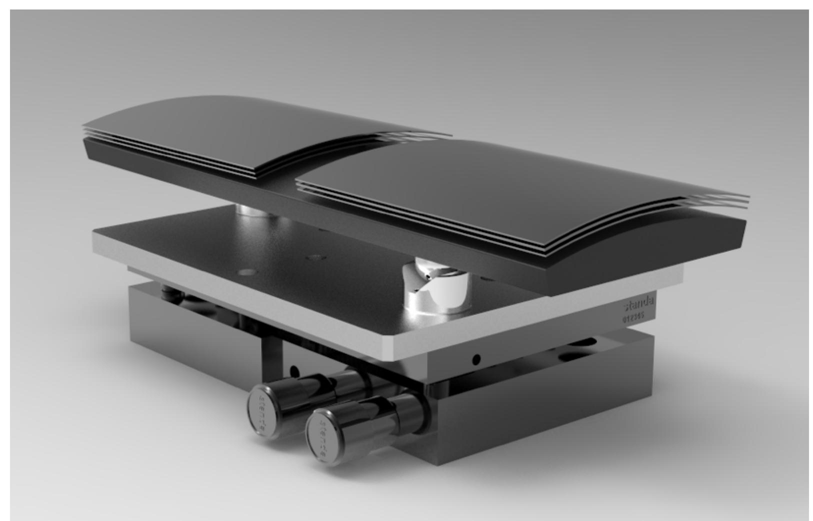


Accomplished as of May 2017

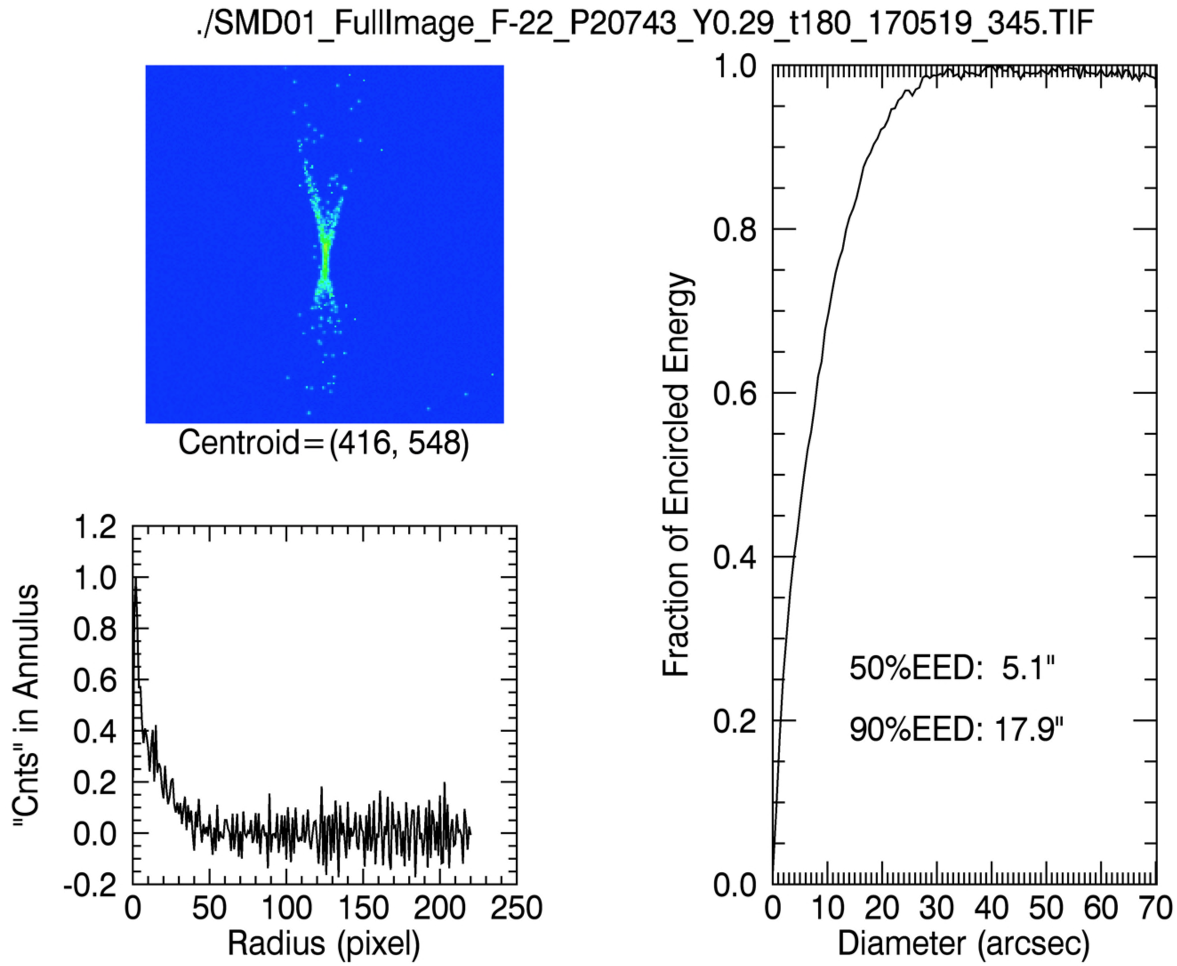
Single pair of mirrors aligned, bonded, and X-ray tested.

Expected to be accomplished by December 2017

Multiple pairs of mirrors aligned, bonded, and X-ray tested.



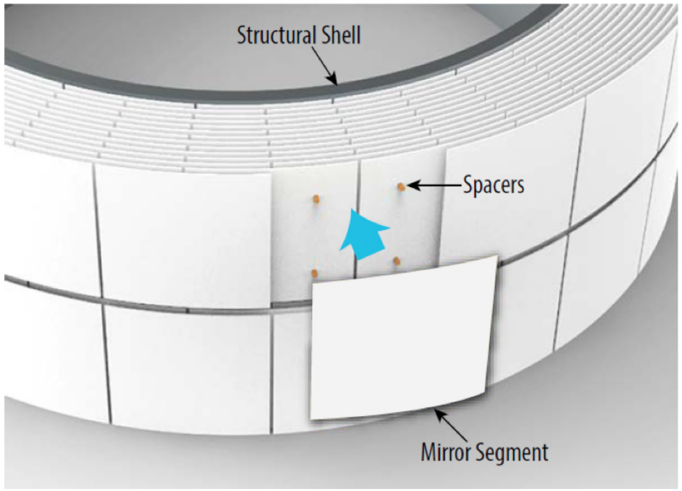
X-ray Test Result

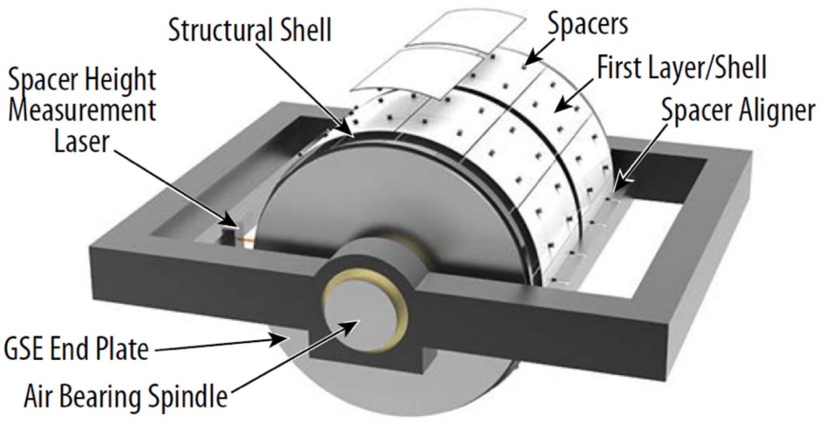


Engineering:
Structural, Thermal, & Systems

Meta-Shell Approach

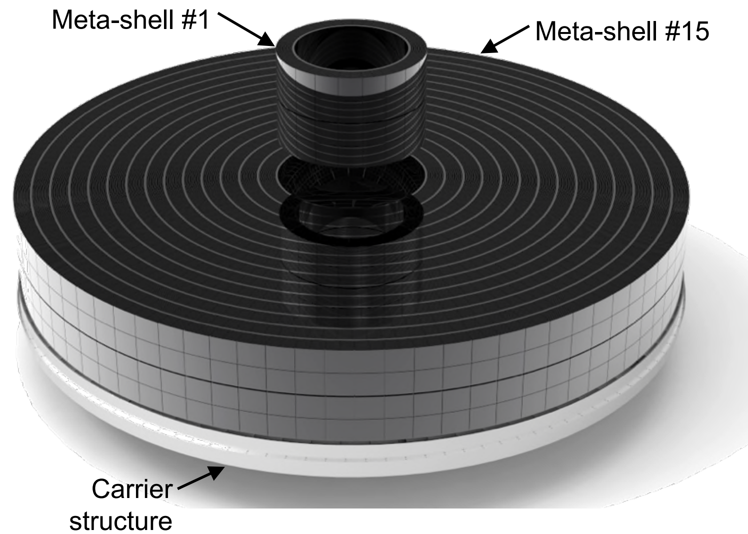
- **Meta-shell integrates many four spacer mounted segments**
  - Interlocking layers of mirror segments bonded onto a central structural shell (silicon)
  - Mirrors are cantilevered off structural shell similar to NuSTAR
  - Brick-like buildup spreads the load
- **Once complete, meta-shell is similar to a full shell with an order of magnitude more collecting area**
  - Structurally stiff (all silicon)
  - Rotationally symmetric
  - Insensitive to tilt
  - Leverage Chandra and XMM-Newton heritage
- **Integrated on a precision air bearing**
  - Creates an optical axis reference
  - Post heights determined by Hartmann test
  - Bonded in distortion 0.05” HPD (gravity release error)

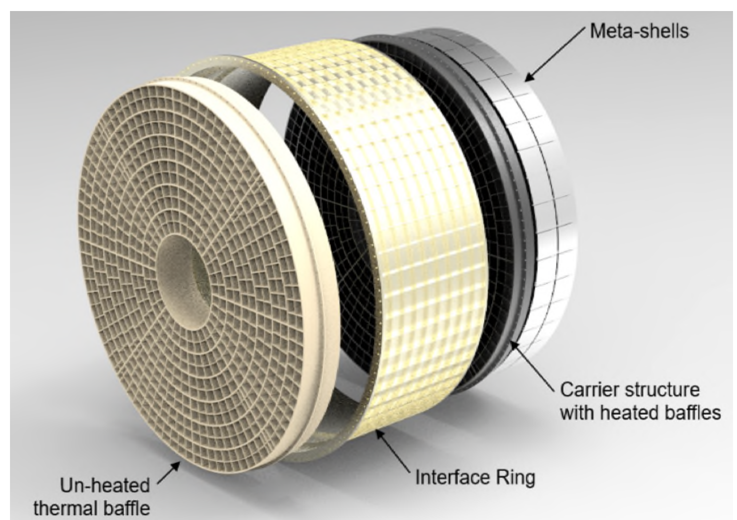




Mirror Assembly

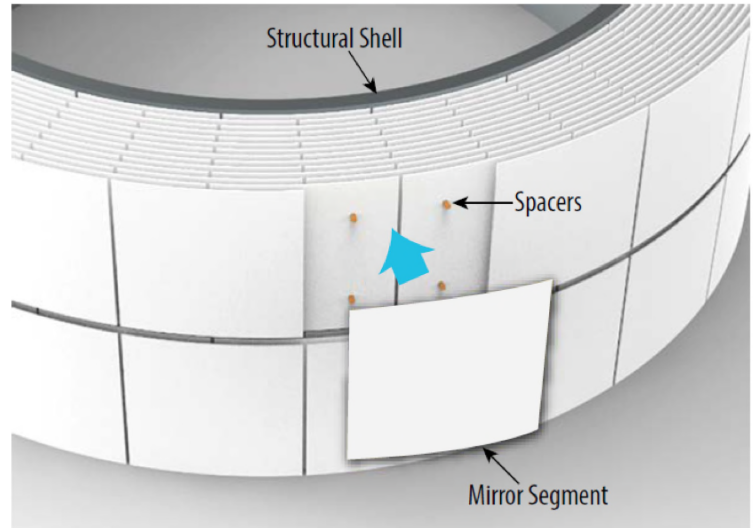
- **Multiple concentric meta-shells co-aligned and mounted into a carrier structure**
  - Similar to Chandra (CAP) and XMM-Newton (Spider)
  - Aluminum structure (or CFRP)
  - Co-align and bond meta-shells using Chandra techniques (CDA with retro-reflecting flat)
  - Chandra-like flexure mount allows for mechanical isolation
- **Heated stray-light / thermal baffles integral to carrier structure (Aluminum)**
- **Mount within Interface Ring that provides interface to telescope/ spacecraft (Aluminum)**
- **Un-heated thermal baffles (G10)**

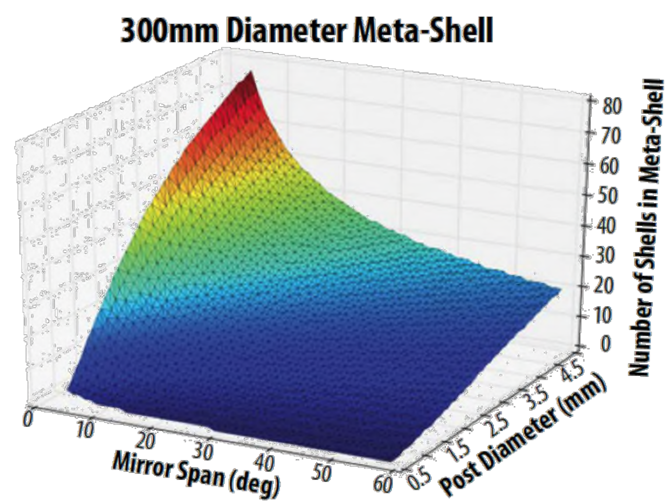




Structural Analysis

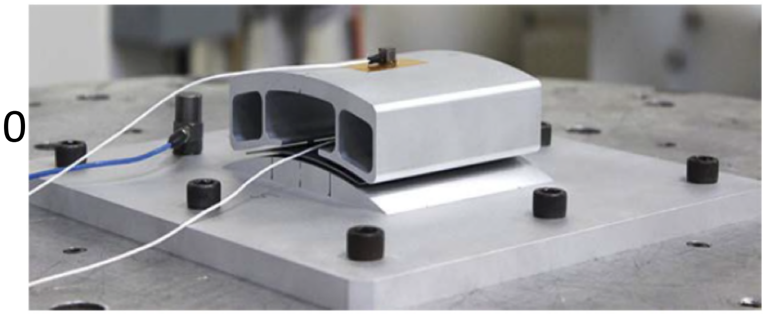
- **Analysis and test show weak point is innermost bond**
- **Bond stress is determined by:**
  - Bond / spacer diameter
  - Number of segments around the circumference, i.e., number of bonds per layer
  - Number of layers
- **Mathematic model of bond stress developed**
  - Determines feasible meta-shell designs
  - Verified by detail FEA and coupon tests
- **Deterministic method to derive all meta-shell design parameters**



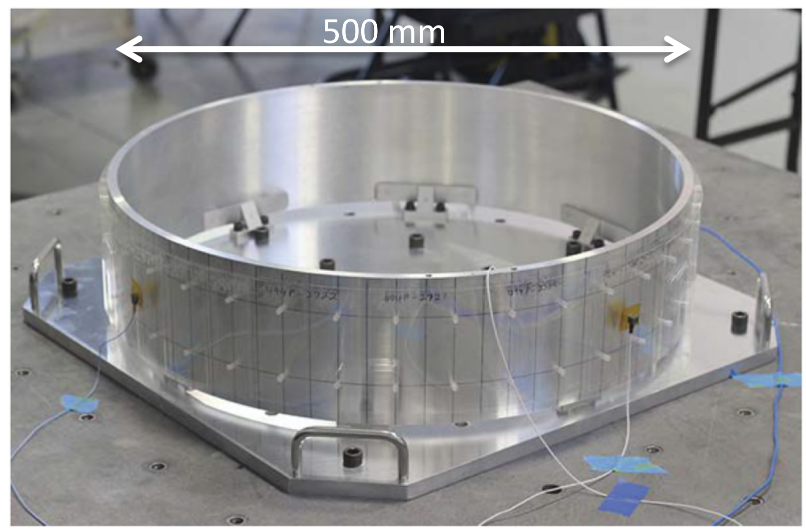


Prototype Environmental Testing

- **Developed conservative preliminary requirements**
  - Quasi-static design loads for IXO CLA with 2.0 MUF
  - Random loads from GEVS
  - Shock loads from Falcon 9

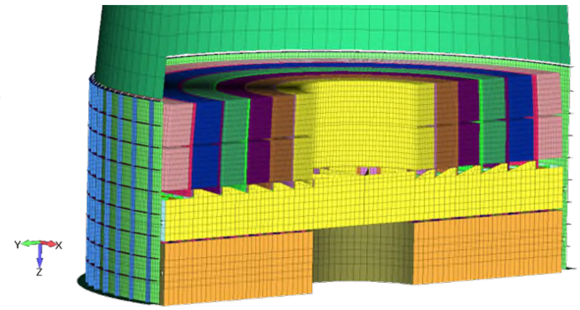


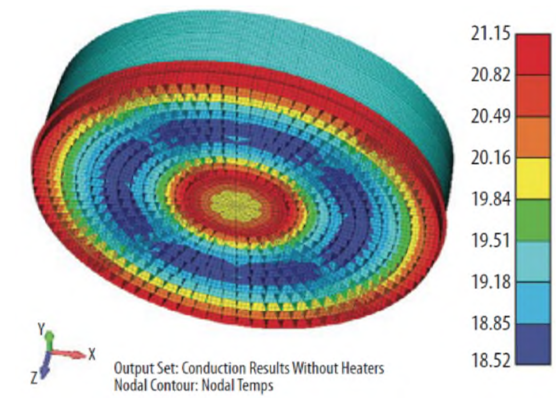
- **Cantilevered mass prototype**
  - Dummy mass simulates layers of mirrors
  - Single silicon segment with four spacer bonds
  - Survived required random vibration
  - Survived required shock (200 g)
  - Silicon is strong (if treated properly), has good damping, and bonds well
- **Meta-shell mechanical mock-up**
  - Aluminum and glass meta-shell
  - Bonded flexures
  - 3 layers (54 mirrors, 432 bonds)
  - Survived required random vibration
  - Survived required quasi-static load (12.3 g)

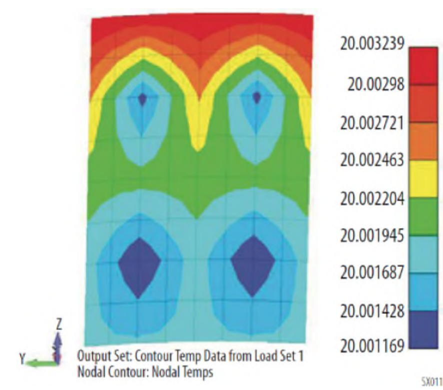


Thermal Control

- **Follow Chandra approach**
  - Optics operate at 20°C (baseline, colder possible)
  - Heat lost to cold space is replaced by heaters surrounding the optical cavity
  - View to cold space is limited by thermal baffle vanes (heated and un-heated)
- **Design verified by preliminary Structural Thermal Optical Performance (STOP) analysis**
  - Thermal model predicts temperatures
  - Temperatures mapped to structural FEM
  - Distortion predictions ray-traced
- **Low CTE and high thermal conductivity of silicon result in low thermal sensitivity**
  - Minimal gradients over a mirror segment
  - Current result 0.16" HPD, room for optimization
  - Best STOP result from IXO 6.6" HPD with glass

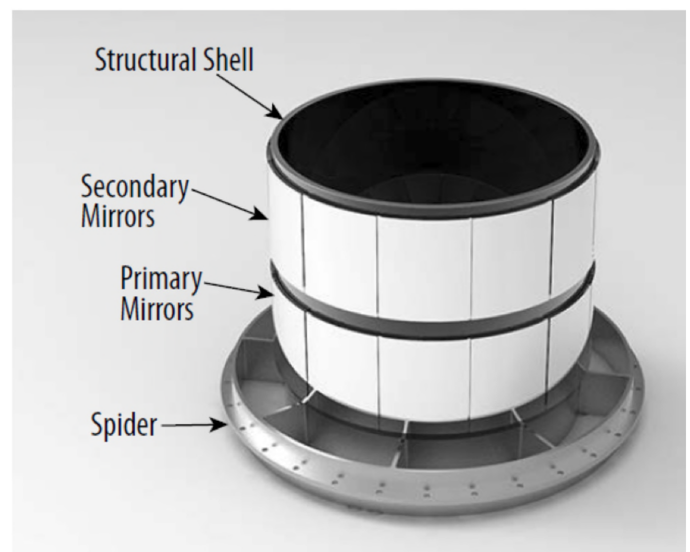






Summary of Engineering

- **Meta-shell approach**
  - Advantages of full shell optics but with an order of magnitude more collecting area
- **Preliminary structural, thermal, and optical analysis completed to mature the system design**
  - Shows 0.5” mission is feasible
- **Prototype load testing demonstrates the meta-shells are robust**
- **Development continues: design, analysis, testing**



Making the Case to the Decadal

Need to convince the Decadal!

- **Performance**
  - Effective area
  - Angular resolution
- **Mass**
  - Mass is money!
  - AXIS mirror assembly ~ 500 kg
- **Cost/Schedule**
  - Should be less than \$160M + 30%=\$200M in RY\$. (Cf. Chandra's FY99\$600M for 1,500kg → \$0.4M/kg). AXIS's mirror is also \$0.4M/kg, but with RY\$.
  - Must be done in less than 5 years, preferably in 4 years.

Between Now and Decadal

- **Empirically demonstrate that mirror segments meeting (or close to meeting) requirements can be made**
  - Repeatedly (high yield),
  - Quickly (production rate), and
  - Cost effectively
- **Build and test small mirror modules**
  - Basic alignment & bonding procedure is sound & efficient
  - They meet performance and environmental requirements
- **Build and test reasonably-defined meta-shells**
  - Meet (or close to meet) both performance and environmental tests
  - Reach **TRL-5** by 2020
  - Show a clear path to **TRL-6** once the observatory is defined with sufficient fidelity

Mirror Assembly Production (1/2)

~**15,000** mirror segments

→ ~**6** meta-shells

→ **1** mirror assembly

~**2-3** mirror fabricators

→ ~**1-2** meta-shell makers

→ **1** integrator/tester

Distributed production → Competition → Cost/Schedule risk reduction

Mirror Assembly Production (2/2)

- **One prime contractor with TBD sub-contractors**
  - Two to four parallel lines of production of mirror substrates
  - Two parallel lines of meta-shell construction
  - One mirror assembly integrator and tester (I&T)
- **Detailed production facility and schedule**
  - All needed information in hand for making step-by-step or blow-by-blow schedule
- **Detailed grass-roots cost estimate**
  - Production and engineering costs understood
  - Management cost to be estimated based on past experience

Acknowledgements

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