Next Generation X-ray Optics (NGXO): High Resolution, Light Weight, and Low Cost

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NGXO Team

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Guiding Principles

- Use segmented (not full shell) design
  - Achieve scalability and mass production advantage
  - Enable missions of all sizes: small, medium, and large
- Maximize use of commercial materials and processes
  - Utilize industrial and commercial technology and manufacture infrastructure
  - Adapt and optimize existing technologies to the making of x-ray optics
- Keep it simple, minimize complexity
  - "Build it and forget it." - Mel Ulmer
  - Define, isolate, develop, qualify, and perfect each step of telescope construction process

Three Metrics

- Angular resolution
  - Started with Suzaku's ~100" in 2002
  - Implemented NuSTAR's 58" in 2011
  - Realized XMM-Newton's 15" in 2012
  - Expect to meet AXSIO's 10" requirement in 2014 (TRL-5)
  - Work toward realizing Chandra's 0.5" in 2018
  - Eventually achieve the diffraction limit at 1 keV in the 2020's
- Effective area (per unit mass)
  - Preserve Suzaku's lightweight advantage
  - 10 times better than XMM-Newton's
  - 40 times better than Chandra's
- Production cost (per unit effective area)
  - Simplify and perfect process to minimize cost and schedule

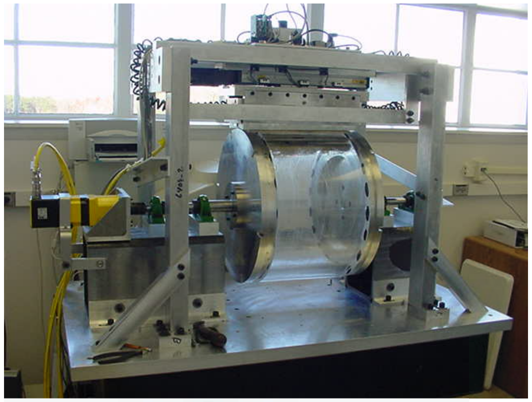
Three Key Technical Steps

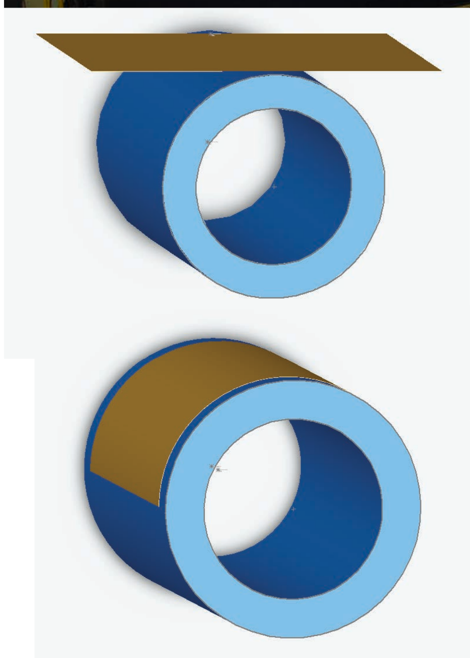
- Mirror substrate fabrication
  - Present: slumped glass that has achieved 6" to enable missions in this decade
  - Near Term: polished and light-weighted silicon to achieve 1" or 0.5" to enable missions in the 2020's
  - Far Term: polished and light-weighted silicon to achieve diffraction limit at 1 keV
- Coating (20nm of iridium)
  - Sputter or atomic layer deposition
  - Will consider other supplementary coatings, such as boron carbide, to maximize effective area
- Assembly: alignment and bonding
  - Near term: develop and perfect edge-bonding
  - Long term: probably develop a method based on precision spacers

Development History & Future

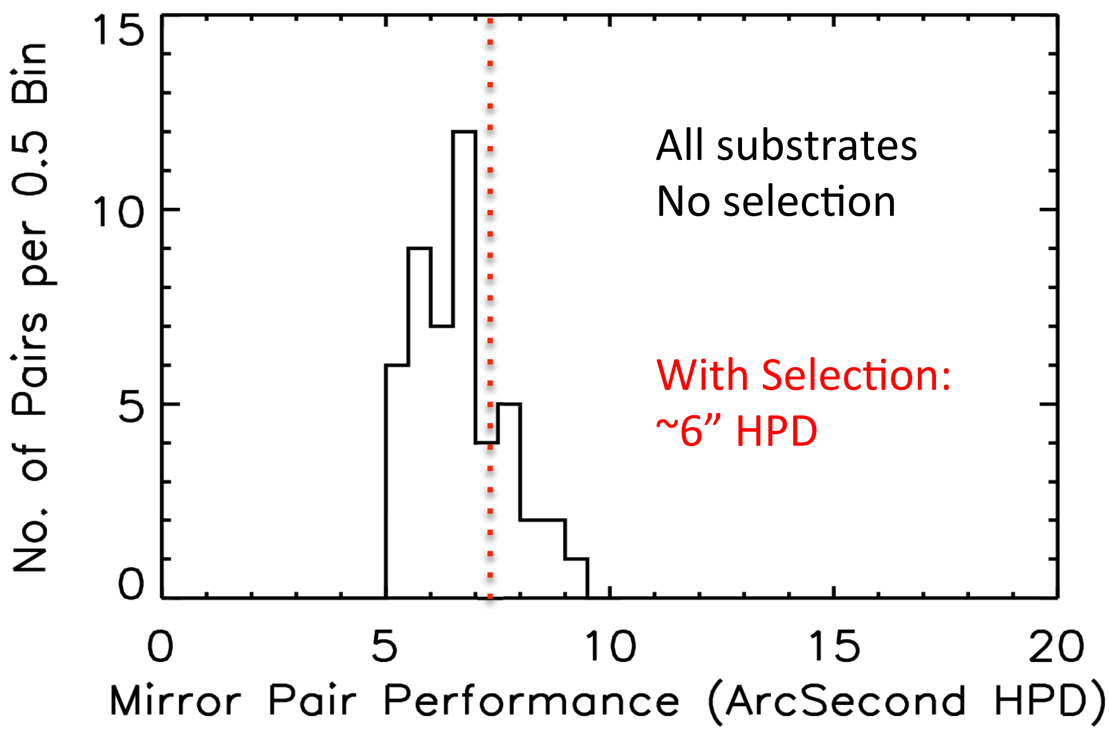
Year	Mirror Segment		Coating		Alignment & Bonding		
	Technique	Contribution to HPD (")	Technique	Contribution to HPD (")	Technique	Contribution to Single Pair HPD (")	Contribution to Multiple Pair HPD (")
2002	Slumped glass with epoxy replication	60	Sputtered gold	~0	Optical Alignment Pathfinder	?	?
2007	Slumped glass	10	Sputtered iridium	~15	Mattress	12	?
2010		8			Smart Bonding	10	?
2012		6			Edge Bonding	8	12
2013	Single Crystal Silicon (Machine & Polish)	~1	ALD or sputtered iridium; and annealed	1		6	11
2014		~0.1		?	?	?	?
2018		~0.1		?	?	?	?

State of the Art of Glass Slumping





- Simple, inexpensive, reliable, mature
- Producing good and consistent results
- Need to reduce mandrel cost & schedule



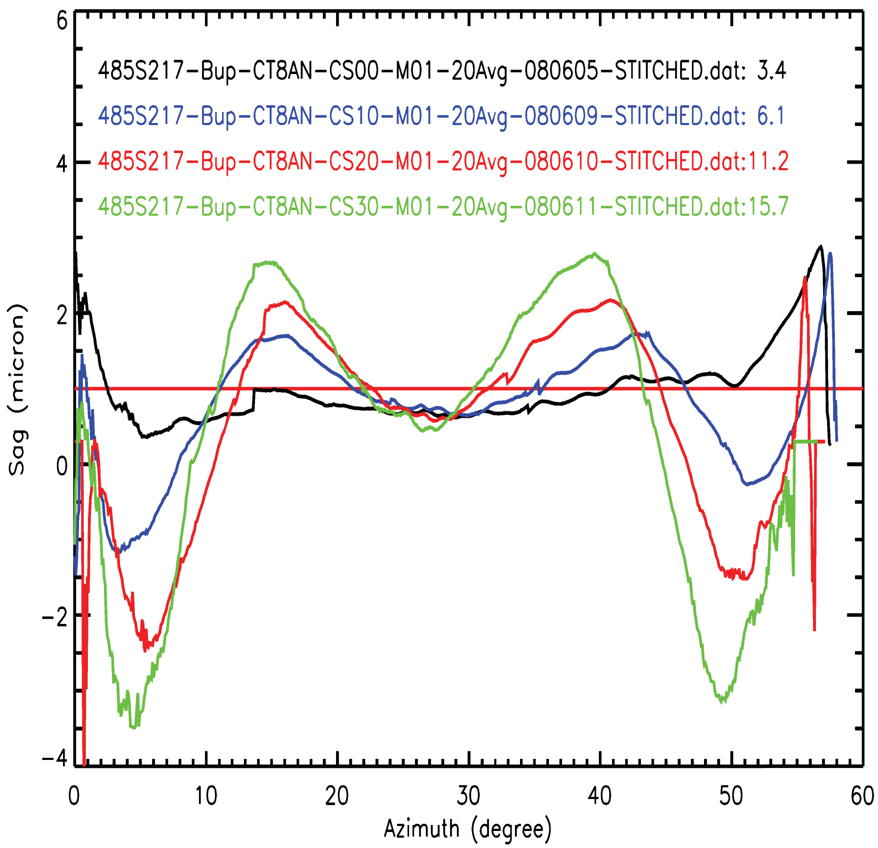
Glass Slumping Technology Status

- Past: Successfully made substrates for NuSTAR
  - Achieved 58” HPD system level, dominated by distortions caused by multi-layer coating and assembly process
  - Accomplished on time, 10% under budget
- Present: Fallback option for making substrates for 5” to 10” telescopes
  - Advantage: mature and inexpensive; the most accurate mirror replication tech.
  - Disadvantage: requiring mandrels
- Future 1: improve the slumping process
  - Further improvement of boron nitride release layer (Zhang et al., GSFC)
  - “Mandrel-less” slumping (Schattenburg et al., MIT)
  - “Indirect” slumping (Friedrich et al., MPE)
  - “Vacuum-Forced” slumping (Ghigo et al., Brera)
  - “Double-mold” slumping (Hudec et al., Czech Republic)
- Future 2: improve slumped glass substrates
  - Improve figure using piezo actuators (Feldman et al., Leicester; Reid et al., SAO)
  - Improve figure by addition of material using coating (Ramsey et al., MSFC; Windt, RXO)
  - Improve figure using magneto-strictive actuators (Ulmer et al., Northwestern)

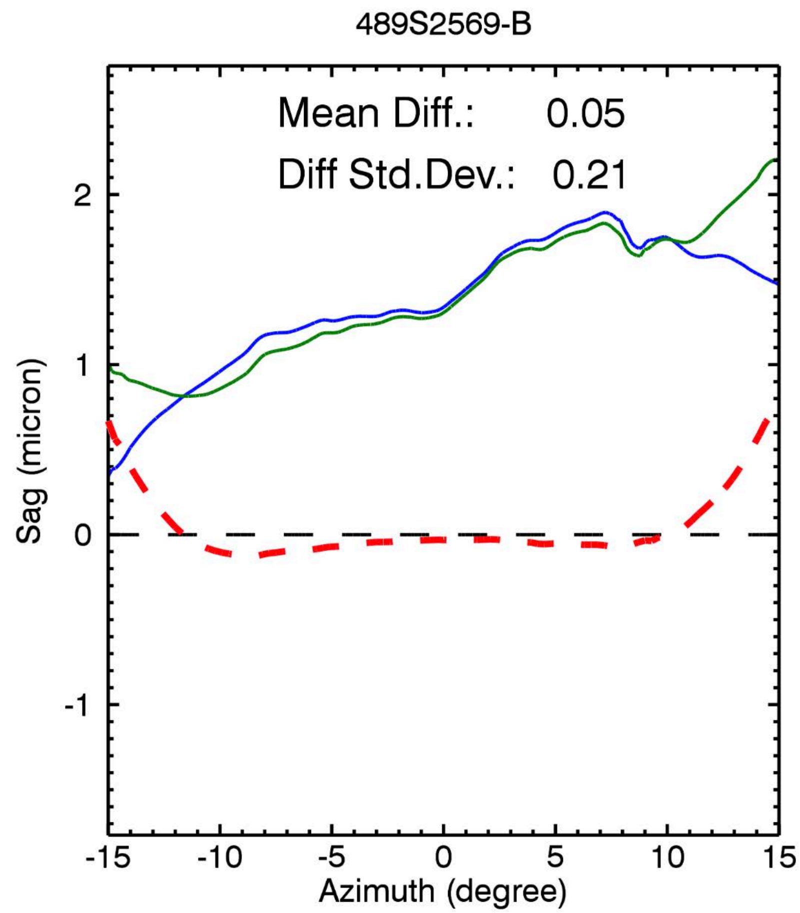
Coating

- 20nm of iridium is required to maximize x-ray reflectivity in 0.1 to 10 keV band
- Both magnetron sputter and atomic layer deposition can meet micro-roughness and density requirements
- Both sputter and ALD produce film with *very high stress*, totally ruining mirror figure
- A post-coating annealing process can significantly reduce or even totally eliminate coating stress, while preserving micro-roughness and density

Efficacy of Annealing



2012: Iridium coating causes severe distortion

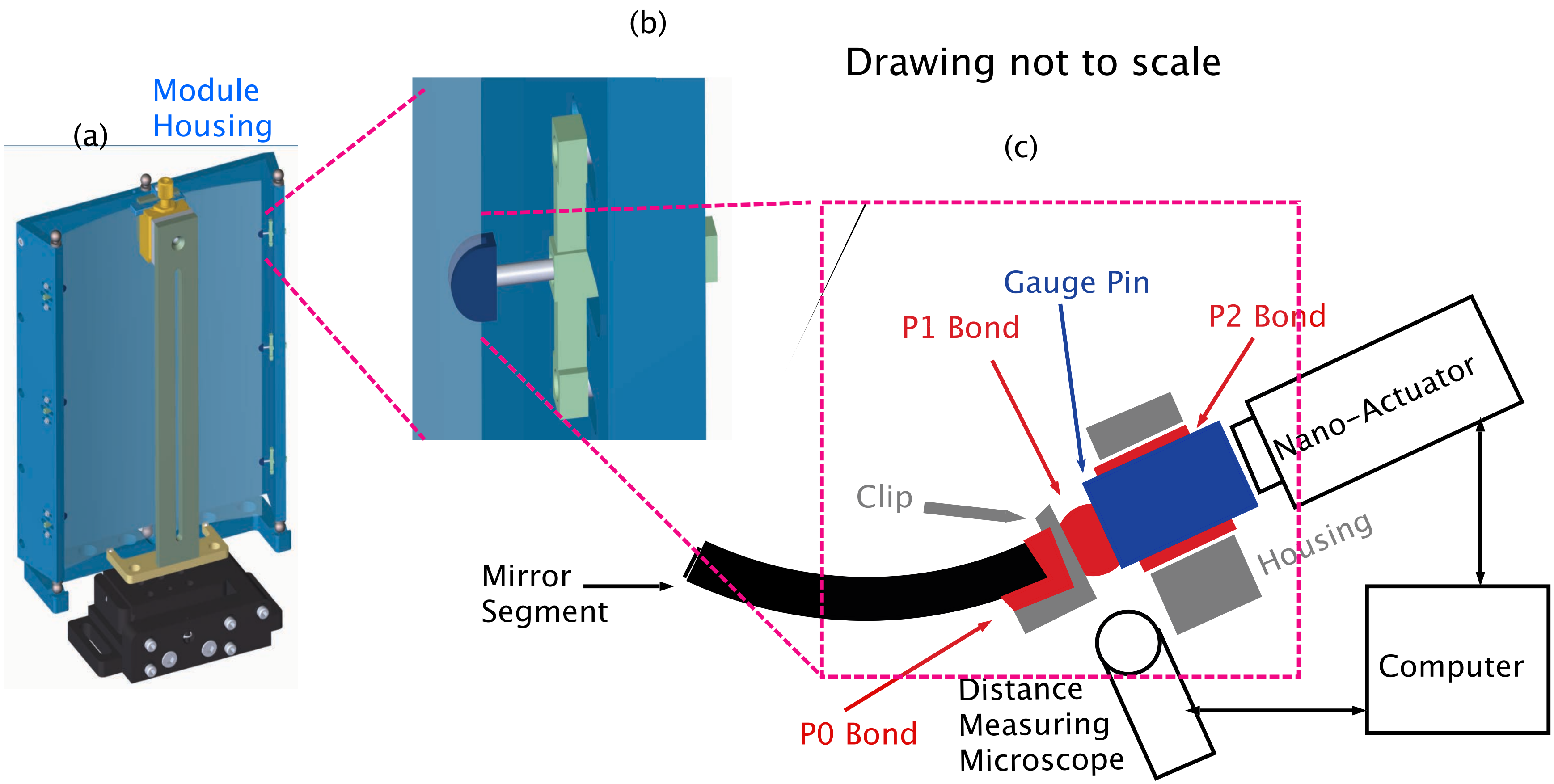


2013: Before (blue) and after (green) coating and annealing

Future Work on Coating

- Use ALD to coat both sides to minimize distortion and to minimize thermal emissivity
- Optimize annealing process to eliminate coating stress
  - Maximum temperature
  - Dwell time
  - Ramp-down time

Edge-Bonding Technique



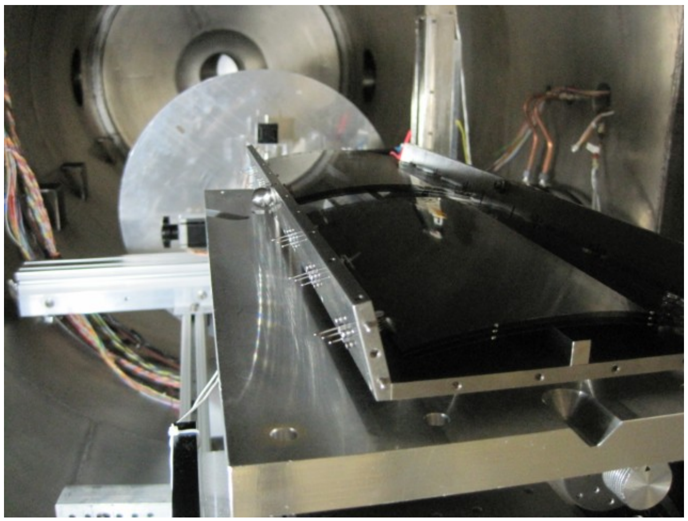
Status of Bonding

- Consistent bonding of single mirrors with negligible distortion (<< 6”)
- Consistent bonding of co-aligned mirrors and mirror pairs, achieving full-illumination x-ray images ~11” HPD (at 7.9 keV)
- Technology development modules have passed all environment tests: vibration, acoustic, and thermal vacuum

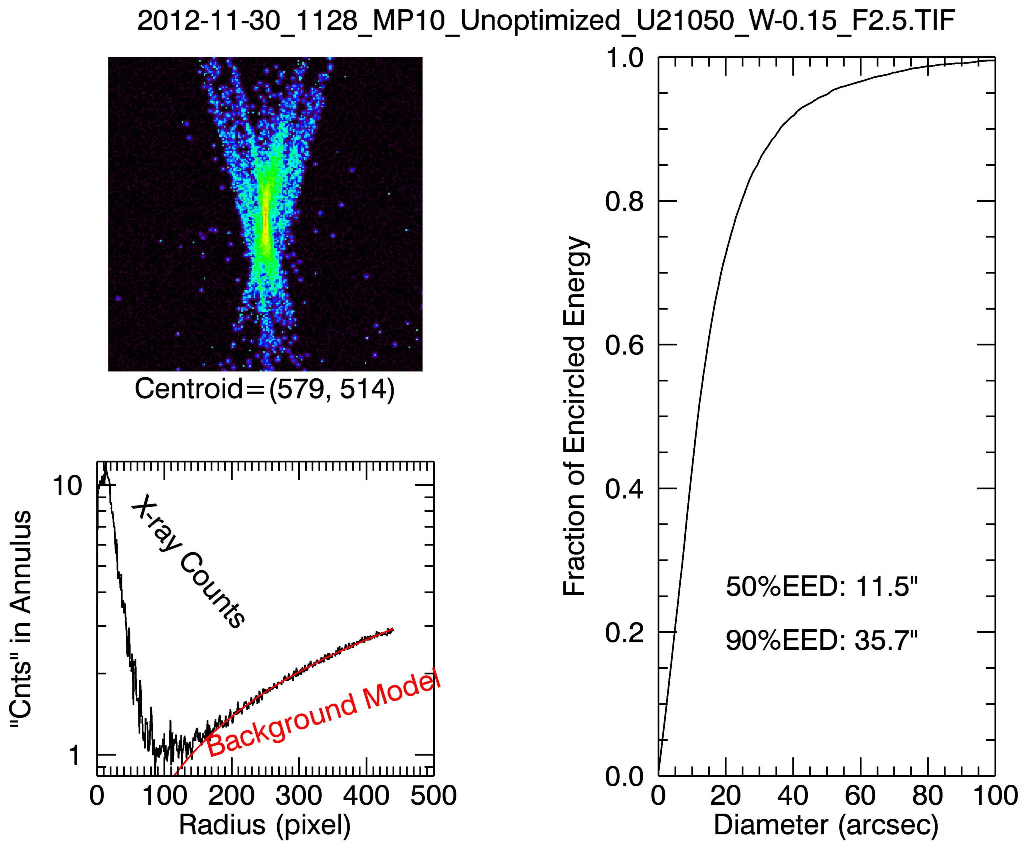
Technology Demonstration Modules (TDM)

- Three modules made consecutively, demonstrating consistency and robustness of alignment and bonding process
- Each module contains three pairs of P-H mirror pairs
- Each tested in an x-ray beam, producing ~11” HPD images
- One environmentally tested: vibration, acoustic, thermal vacuum, demonstrating the module construction process ready for making spaceflight modules

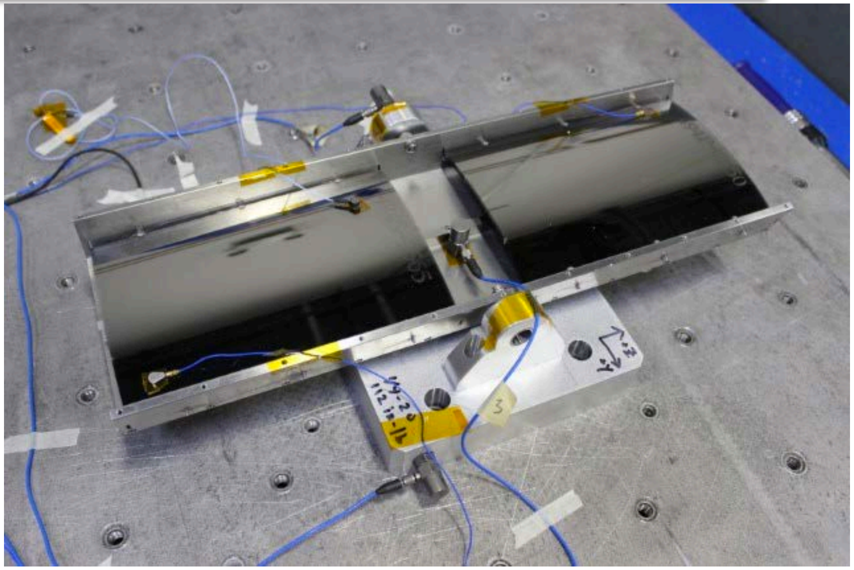
TDM Performance Tests: X-rays



TDM in vacuum chamber for X-ray test

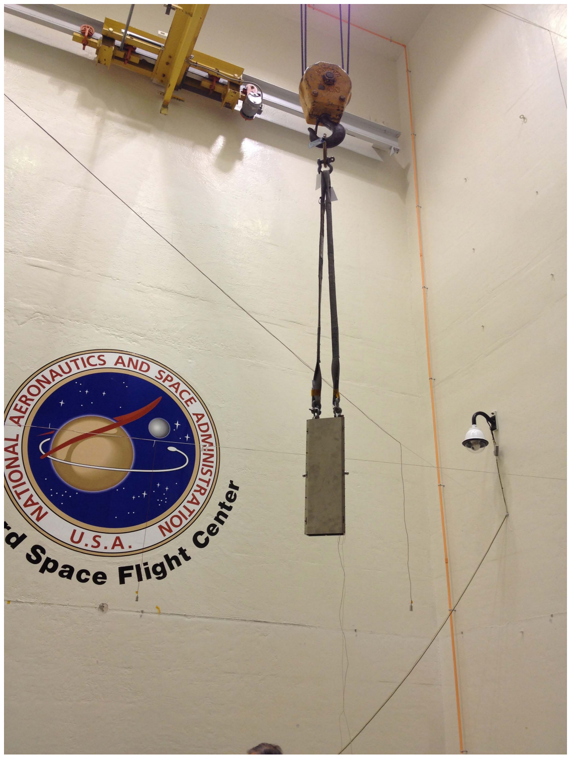


TDM Environmental Test: Vibrations



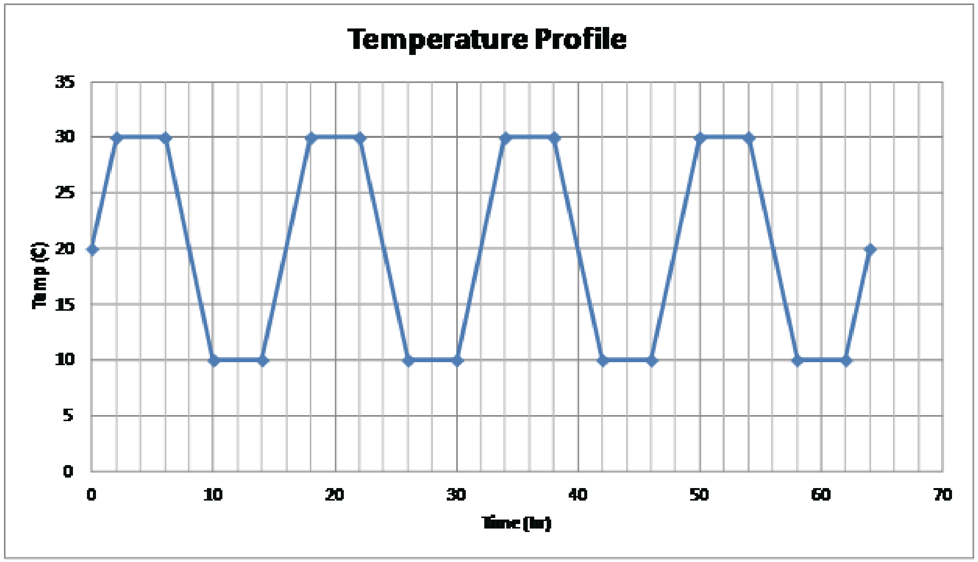
- Multiple tests conducted at Washington Laboratories LLC in Frederick, MD
- TDM mirrors and bonds survived tests
- Mirror alignment and x-ray performance remained the same after tests

TDM Environmental Test: Acoustics



- Test conducted in Bldg 7 of GSFC
- TDM mirrors and bonds survived tests
- Mirror alignment and x-ray performance remained the same after tests

TDM Environmental Test: Thermal Vacuum



- Test conducted in Bldg 30 of GSFC
- TDM cycled between 10 and 30C
- TDM cycled again between 0 and 40 C
- Mirror alignment and x-ray performance remained the same after test

Technology for Making 10” Telescopes

- Substrate fabrication process fully demonstrated
- Coating process fully demonstrated
- Alignment and bonding process close to meeting requirements
  - Achieved required bonding accuracy and speed
  - Modules passed all environment tests
  - X-ray images worse than expected from optical metrology, potential causes include
    - Thermal environment
    - Gravity distortion
- Address those potential causes and achieve x-ray images better than 10” HPD
- Request PCOS Technology Management Board to conduct TRL-5 certification by December 2013

Work to Achieve Higher Angular Resolution Using Single Crystal Silicon

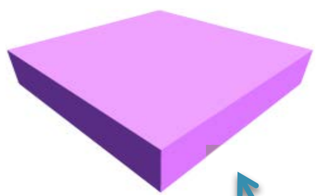
Strategic Considerations

- Use existing and the most reliable way of making high resolution optics: *polishing*
- Use a material that can be light-weighted without loss of figure quality: *single crystal silicon*

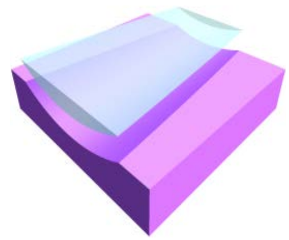
Three Developments Since Chandra

- **Fast and accurate measurement of thick and heavy segmented mirrors (developed and built at GSFC)**
  - Fizeau interferometers
  - Easily designed and built cylindrical null lens
- **Commercially available deterministic polishing machines**
  - QED: Magneto-Rheological Finishing (MRF)
  - ZEEKO: Intelligent Robotic Polishing (IRP)
  - Others….
- **Abundantly and cheaply available large blocks of mono-crystalline silicon**
  - “Perfect” single crystals: “Free” of internal stress
  - High thermal conductivity and relatively low CTE
  - Can be machined using precision wire-EDM

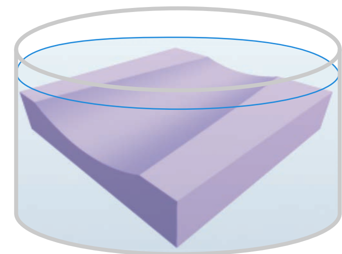
Process of Making a Lightweight Single Crystal Silicon Mirror Substrate



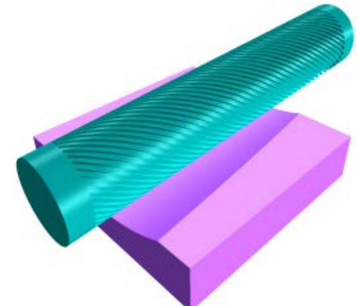
✔ 1. Procure doped single crystal silicon



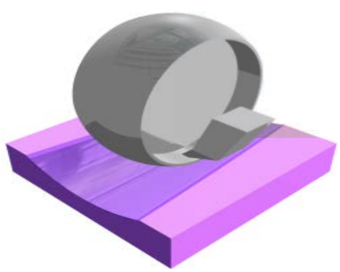
✔ 2. Generate conical contour using WEDM



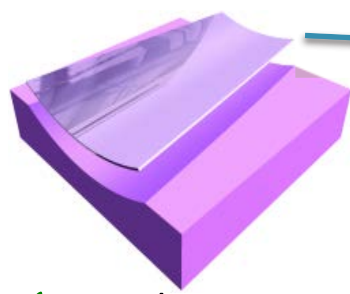
✔ 3. Acid-Etch to remove sub-surface damage



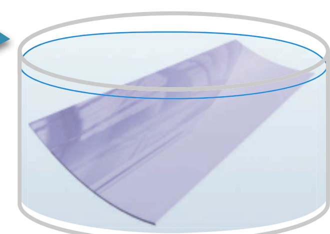
4. Polish to a high quality conical surface: focus of technology development



✔ 5. MRF finish to Wolter-I figure and µRoughness

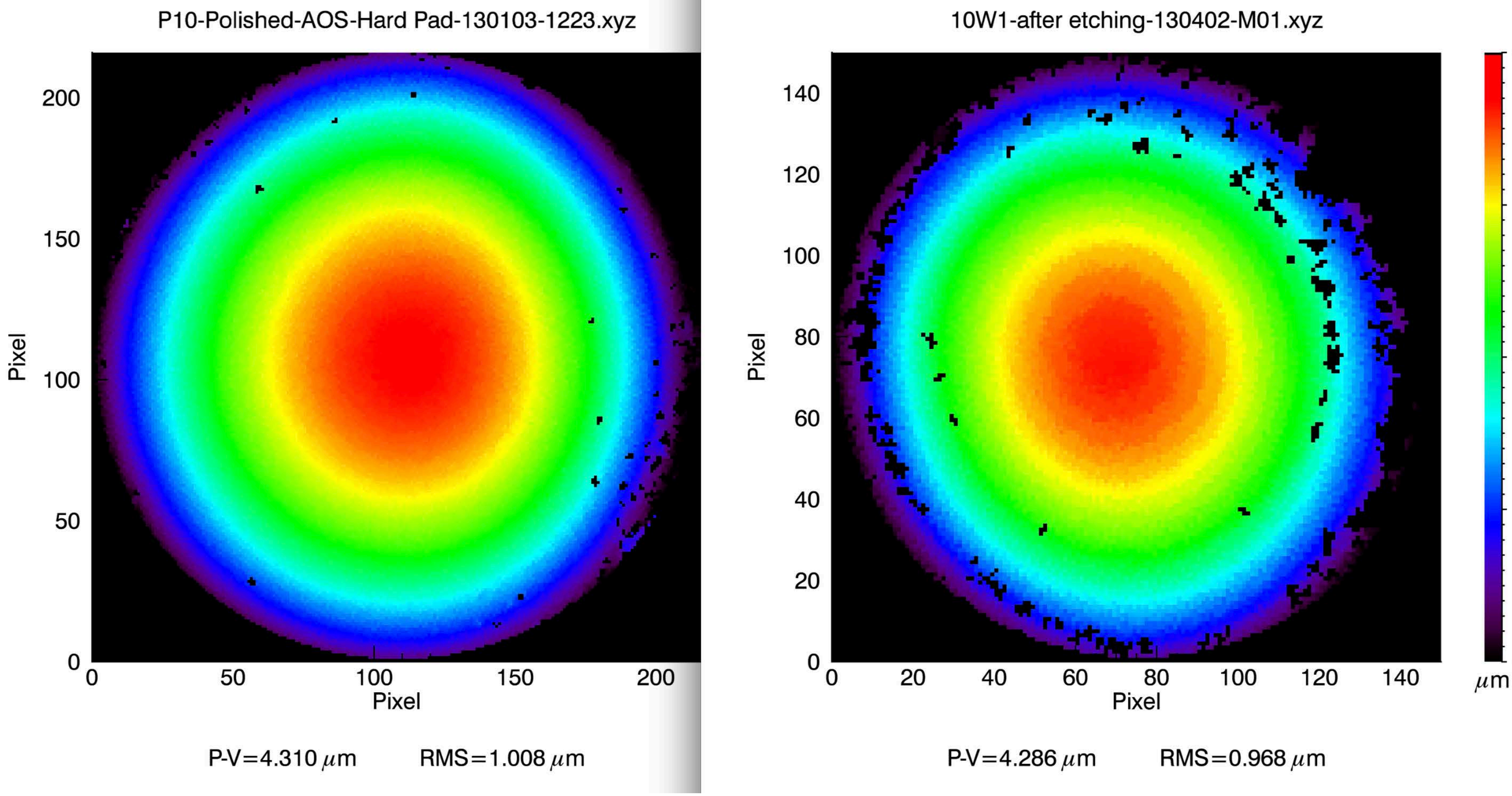


✔ 6. Light-weight using WEDM



✔ 7. Acid-Etch to remove sub-surface damage

Comparison of mirror figures before and after light-weighting



Thickness before light-weighting: 25 mm

Thickness after light-weighting: 0.42 mm

Status and Prospect Silicon Optics

- The entire process has been demonstrated to be valid with flat mirrors: no measureable (<< 1”) distortion caused by the light-weighting process
- Work in progress to make Wolter-I mirrors. First set of mirrors expected for late 2013 or early 2014
- Once coated and qualified, they will be aligned, bonded, and x-ray tested. Expect to achieve ~1” x-ray images by late 2014 or early 2015.

Summary

- Near term objective: making 10” telescopes
  - Slumped glass mirrors consistently made that meet AXSIO requirements
  - Modules containing 3 co-aligned pairs consistently constructed and x-ray tested, producing images ~11” HPD
  - Modules passed all environment tests
  - Need to understand why the x-ray images are not better than 10” which is expected from optical measurements, potential culprits including *thermal and gravity* distortion
- Long term objective: making ~ 1” or < 1” telescopes
  - Process of making lightweight single crystal silicon mirror demonstrated with flat mirrors
  - Effort underway to make Wolter-I mirrors
  - ~1” X-ray images expected for late 2014 or early 2015

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