



X-ray Optics at NASA

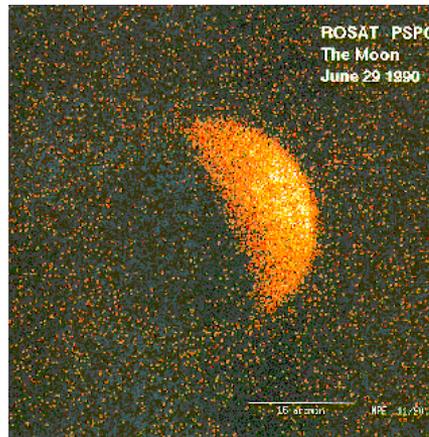
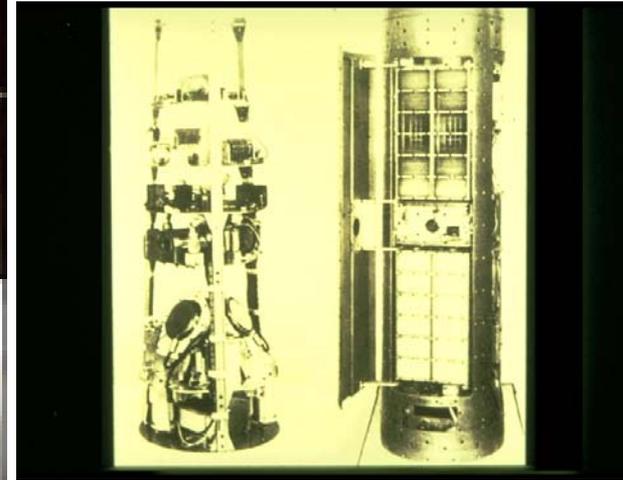
Brian Ramsey
Astrophysics Office
NASA / Marshall Space Flight Center

X-Ray Astronomy



Birth of X-Ray Astronomy

- In 1962, Riccardo Giacconi and colleagues at AS&E flew sounding rocket to look at x-ray fluorescence from the moon
- Lunar signal was overshadowed by very strong emission from the Scorpius region
- Discovered the first extra-solar x-ray source, Sco X-1, and pervasive x-ray background
- This was the effective birth of x-ray astronomy



X-Ray Astronomy

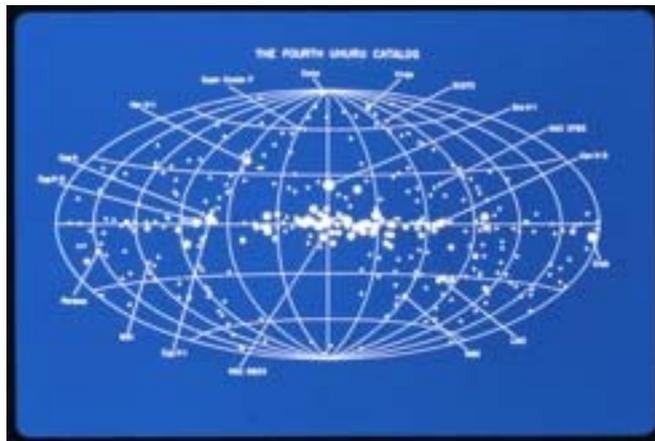


First X-Ray Satellite

The UHURU spacecraft was launched in 1970

It weighed just 140 pounds, not much more than the rocket experiment

It operated for 3 years and discovered 339 sources in the whole sky



Today .. The Chandra Observatory



- *School-bus-size x-ray observatory*
- *100,000 times more powerful than UHURU*
- *Uses special mirrors to form highly detailed images*
- *In deep fields, more than 1000 new sources per square degree*





X-Ray Optics

Why focus x rays ?

1) Imaging - obvious

2) Background reduction

- Signal from cosmic sources very faint, observed against a large background
- Background depends on size of detector and amount of sky viewed
 - Concentrate flux from small area of sky on to small detector
 - ⇒ *enormous increase in sensitivity*

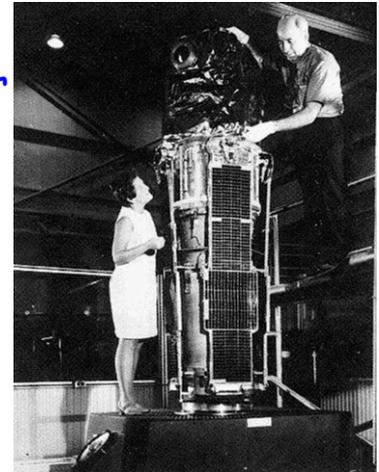
First dedicated x-ray astronomy satellite - UHURU →

mapped 340 sources with large area detector (no optics)

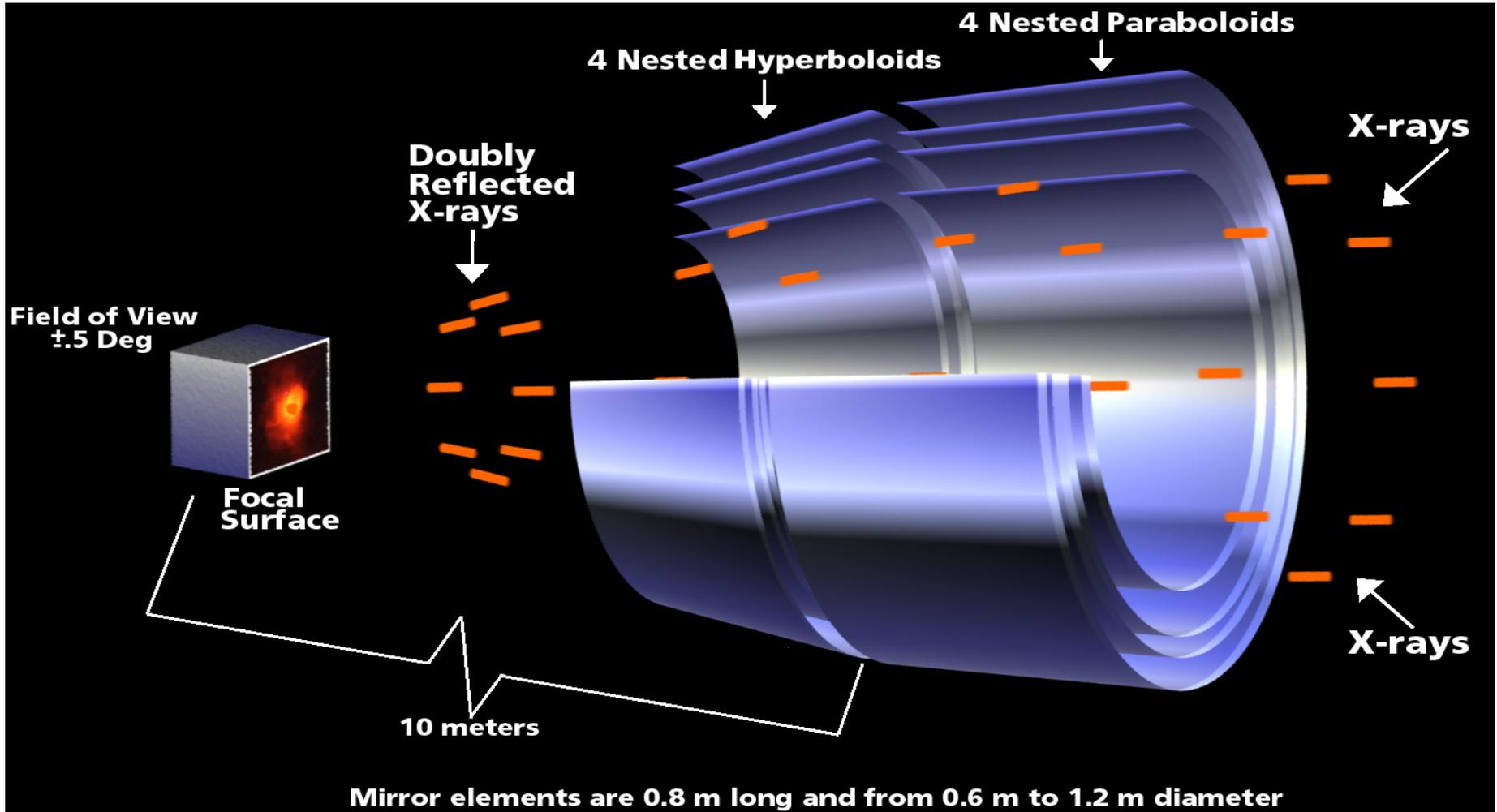
Chandra observatory - ~ same collecting area as UHURU

- *5 orders of mag more sensitivity --- 1,000 sources / sq degree in deep fields*
- *1 background count / keV year !*

X-Ray Optics has revolutionized x-ray astronomy



Chandra X-ray Optics



Approaches: Chandra



- Fabricated using thick ceramic, which is meticulously polished and figured, one shell at a time.
- Obtain superb angular resolution ----- 0.5 arcsecond HPD
- But very costly to fabricate and very heavy (1000 kg)

- *BUT How do we follow on from Chandra ... need 10-100 x area and similar or better resolution ?*
- *Need thinner (to nest), much lighter (to launch) optics, while preserving or improving resolutionand all somehow affordable !*

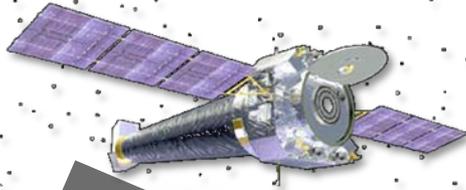
Mission Requirements / Future Challenges



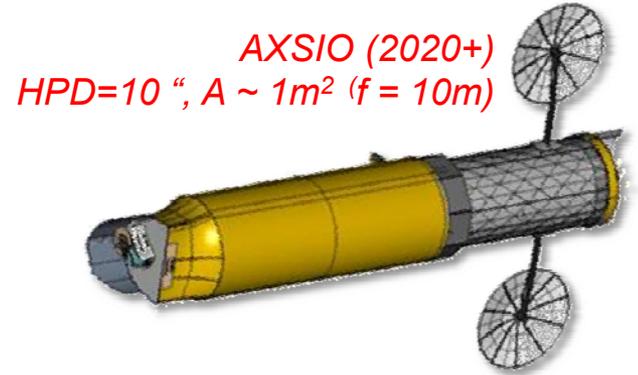
Einstein Observatory (1978-1981)
HPD = 10", $A = 0.04 \text{ m}^2$ ($f = 3.3 \text{ m}$)



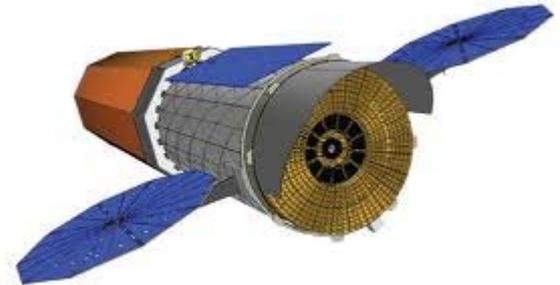
ROSAT (1990-1999)
HPD = 5", $A = 0.10 \text{ m}^2$ ($f = 2.4 \text{ m}$)



Chandra X-ray Observatory (1999-?)
HPD = 0.6", $A = 0.11 \text{ m}^2$ ($f = 10 \text{ m}$)



AXSIO (2020+)
HPD = 10", $A \sim 1 \text{ m}^2$ ($f = 10 \text{ m}$)



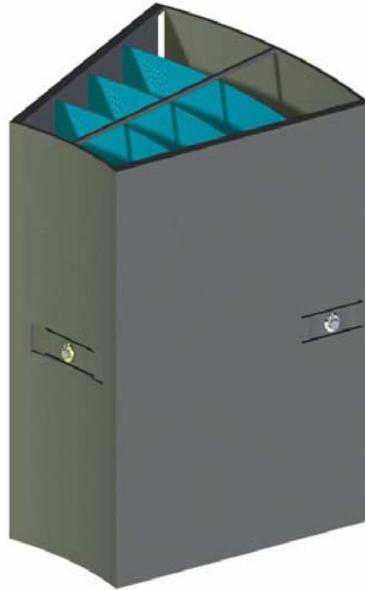
SMART-X (2030)
HPD = 0.5", $A \sim 2.3 \text{ m}^2$ ($f = 10 \text{ m}$)

XMM-Newton (1999-?)
HPD = 14", $A = 0.43 \text{ m}^2$ ($f = 7.5 \text{ m}$)

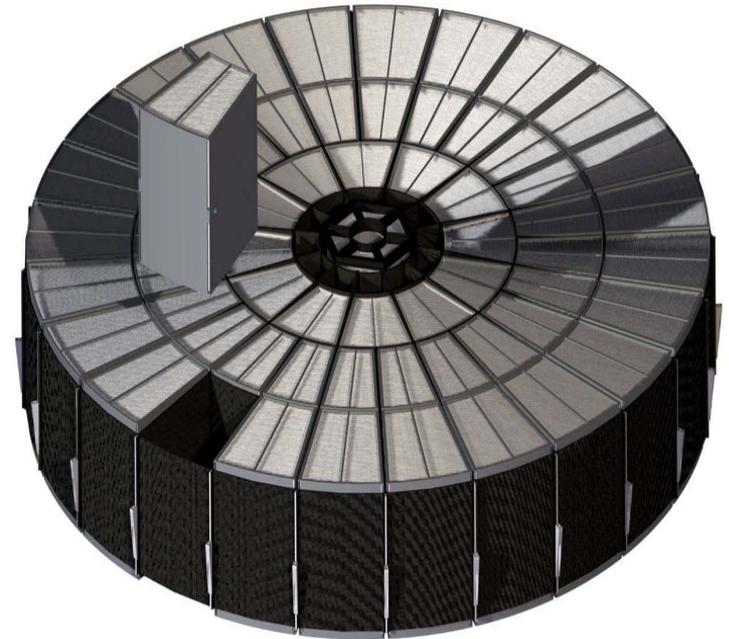
Process of Building a Telescope



*$\sim 10^4$ Mirror
Segments*



*$\sim 10^2$ Modules
Each containing
 $\sim 10^2$ mirror segments*



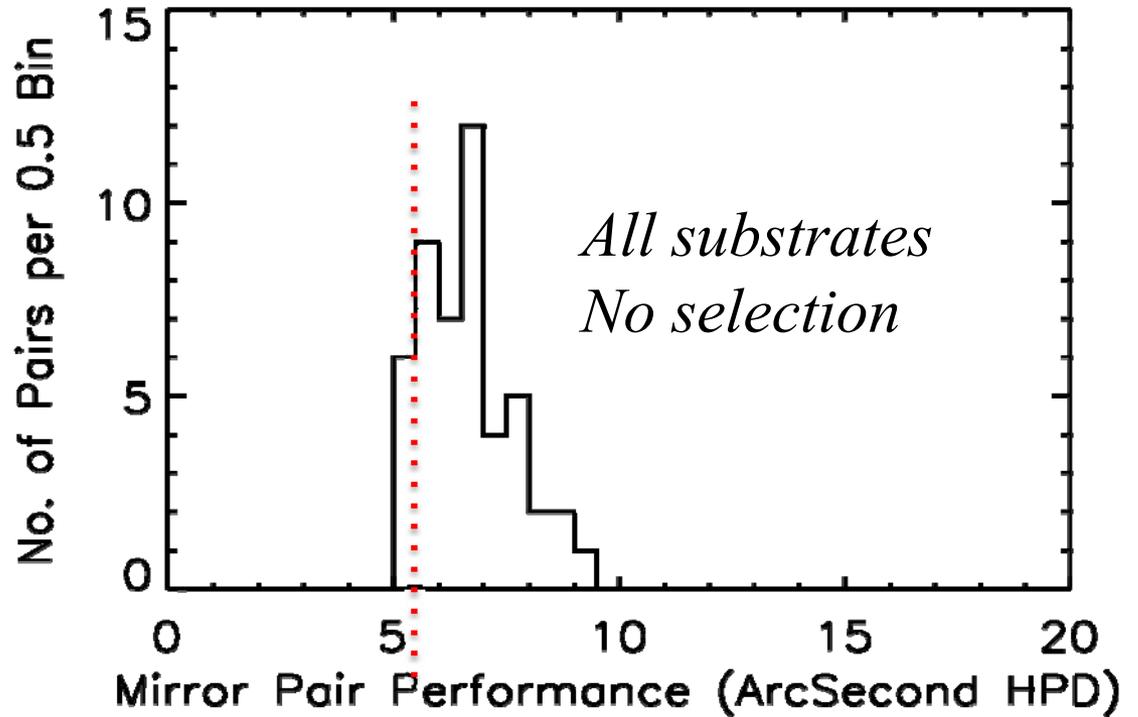
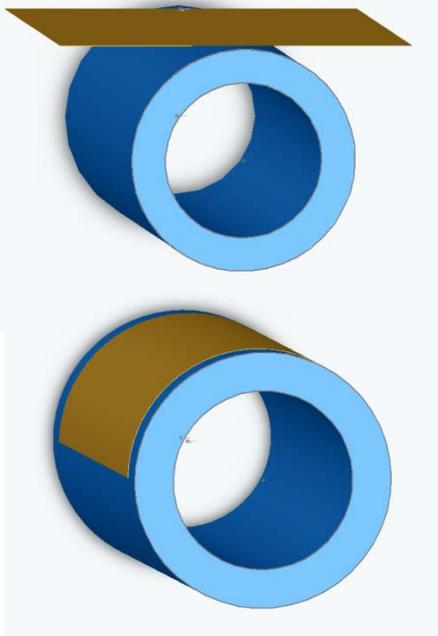
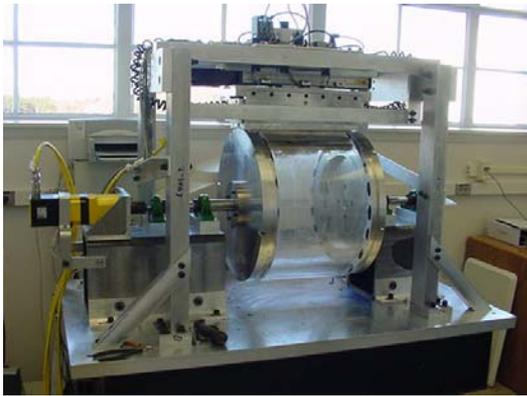
*One or several
mirror assemblies*

Will Zhang / GSFC

Glass Slumping



- Simple, Reliable, Mature
- Producing good and consistent results
- Need to reduce mandrel cost & schedule



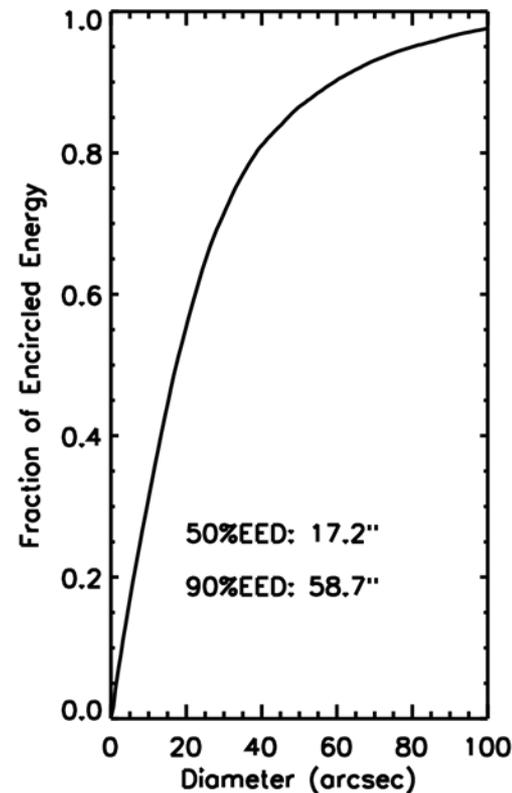
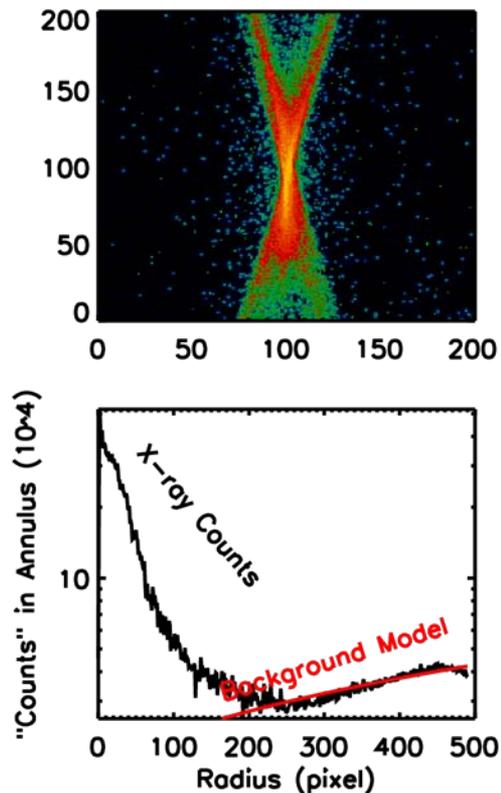
Will Zhang / GSFC

Technology Development Module (X-ray Performance Test)



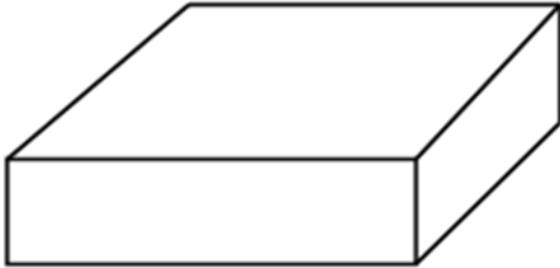
*3 Pairs
Co-aligned
Bonded*

MP05_334_120606_1144_3Pair_100sec_Full.TIF

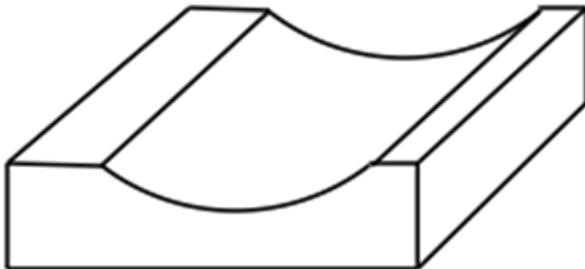




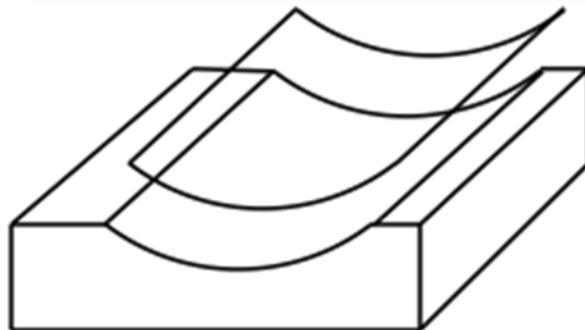
New Method for Fabricating Mirror Segment



1. Procure mono-crystalline silicon: **easy and cheaply** available.
2. Apply heat and chemical treatments to remove all surface/subsurface damage (**fast & cheap**)



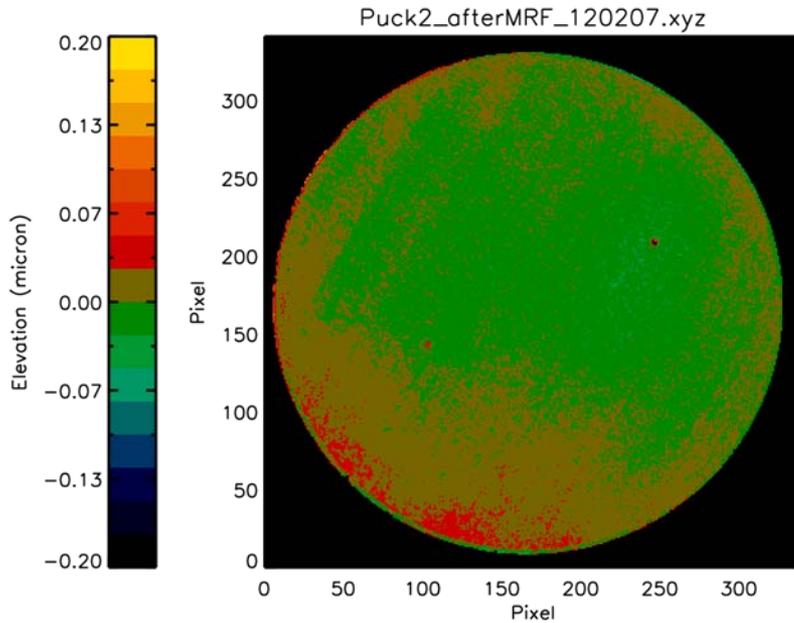
1. W-EDM machine conical shape (**fast & cheap**)
2. Apply heat and chemical treatments to remove damage (**fast & cheap**).
3. Polish using modern deterministic technique to achieve excellent figure and micro-roughness (**fast & cheap? Need demonstration**)



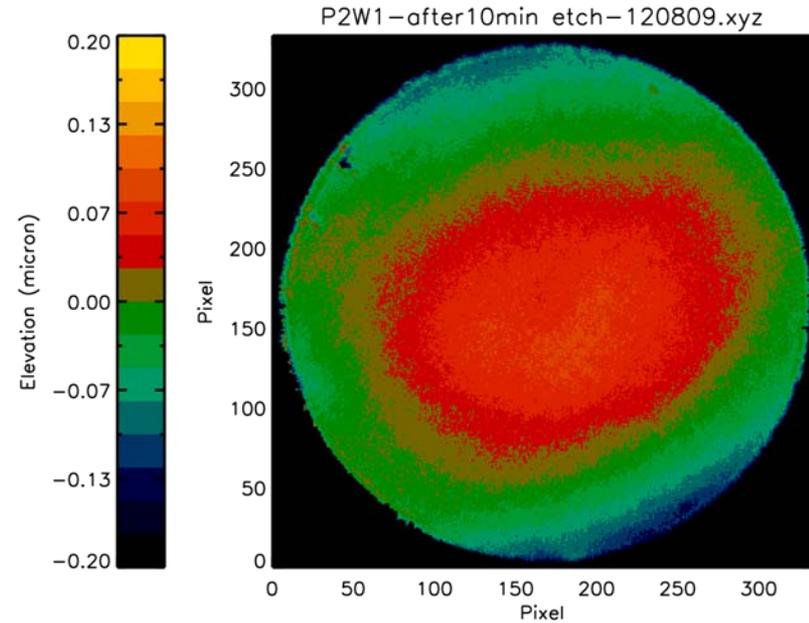
1. Slice off (using W-EDM) the thin mirror segment (**fast & cheap**)
2. Apply heat and chemical treatment to remove all damage from back and edges (**fast & cheap**)

Will Zhang / GSFC

Proof of Principle:



*Before Light-weighting
55 mm thick (~0.1")*



*After Light-weighting:
~2 mm thick (~0.5")*

1. *What's causing the degradation from ~0.1 to ~0.5"?*
2. *Would light-weighting to 0.5mm work as well?*

Will Zhang / GSFC

Progression of Work



- FY2102: Demonstrate principle using flat mirrors - 2012 (**almost done**)
 - Polish a thick 55mm flat mirror
 - Slice off a wafer ~1mm thick
- FY2013: Make separate parabolic/hyperbolic segments or combined P-H segment (**lining up companies**)
- FY2014: Minimize cost maximize production efficiency

W. Zhang / GSFC

Active Figure Control



- Large normal-incidence telescopes (ground-based & JWST) use active optics, BUT required mirror surface area is a couple of orders of magnitude larger than the aperture area.
 - At grazing angle α , mirror surface area $A_{\text{surf}} \approx (2/\alpha)A_{\text{ap}}$.
 - E.g., for SMART-X $A_{\text{ap}} \approx 2.4 \text{ m}^2 \Rightarrow A_{\text{surf}} \approx 500 \text{ m}^2$.
- Launch considerations limit mass and volume.
 - Mass constraints \Rightarrow very lightweight mirrors.
 - Volume constraints \Rightarrow many hundreds of highly nested (few mm), thin mirrors (0.4 mm).
- Other considerations
 - Very large number of actuators to fit in and control (10^6)
 - > Correction strategy to converge
 - Thermal effects
 - Voltage stability
 - Radiation damage sensitivity

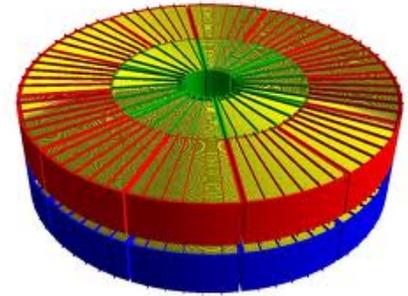


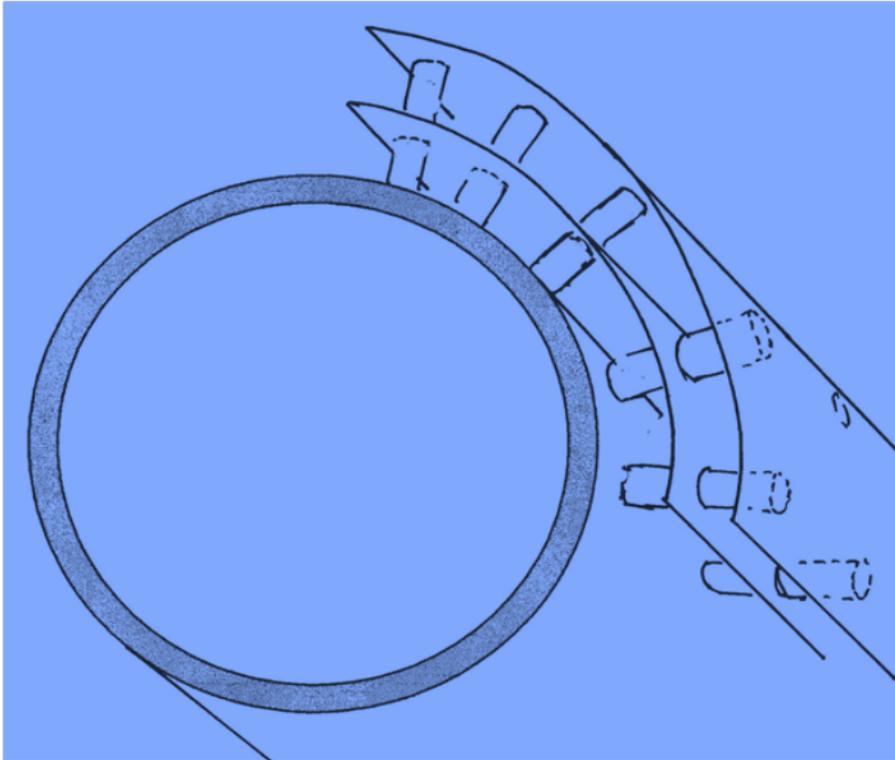
Figure Control Technologies



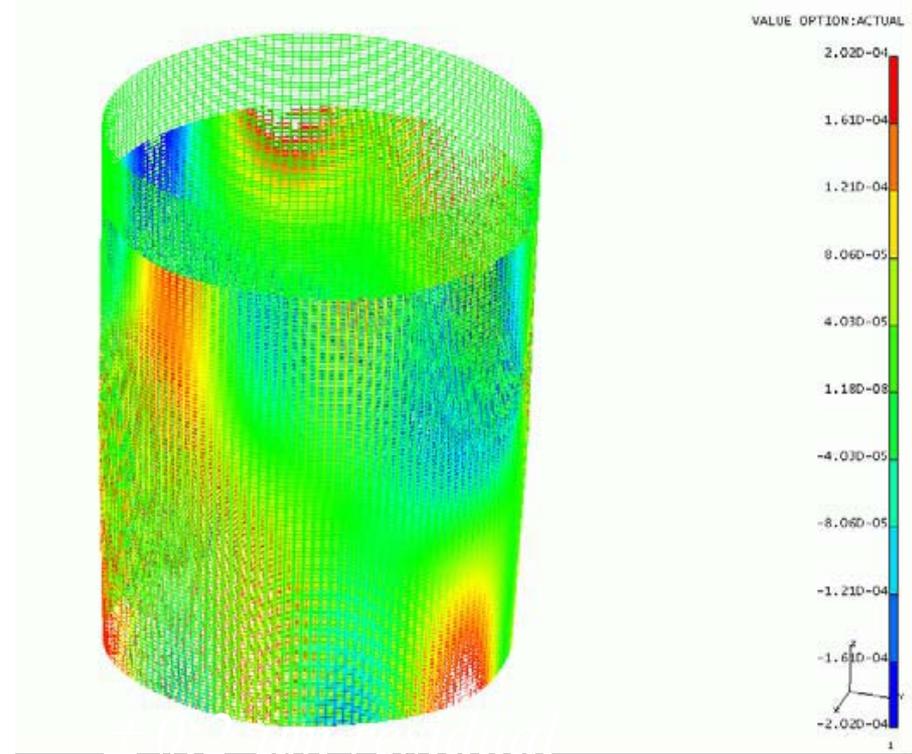
Actuator technologies under development

- *Surface-normal actuators (SNA)*
- *Surface-tangential actuators (STA)*
 - *Patterned-electrode thin-film piezoelectric array*
 - *Magnetically writable magnetostrictive film*

Discrete electroactive pistons provide surface-normal actuation (SNA).



Surface normal actuation requires reaction structure.
Nested geometry limits SNA uses.
Position and steer mirror segment.



Correct large-scale distortions of full-shell mirrors.
➤ FEA uses 8×10 radial adjusters.

Paul Reid /SAO

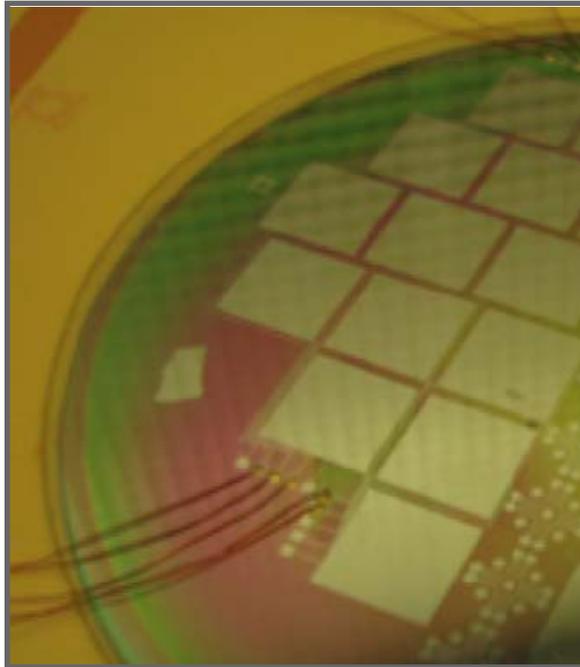
Adjustable Bimorph Mirror: a path to large area, high-resolution X-ray telescopes



- *Thin ($\sim 1.5 \mu\text{m}$) piezoelectric film deposited on mirror back surface.*
- *Electrode pattern deposited on top of piezo layer.*
- *Energizing piezo cell with a voltage across the thickness produces a strain in piezo parallel to the mirror surface (in two orthogonal directions)*
- *Strain produces bending in mirror — **No reaction structure needed***
- *Optimize the voltages for each piezo cell to minimize the figure error in the mirror.*

Major accomplishment:

- *Deposition of piezos on glass (Penn State Materials Lab).*
- *First time PZT deposited on glass for such large areas.*

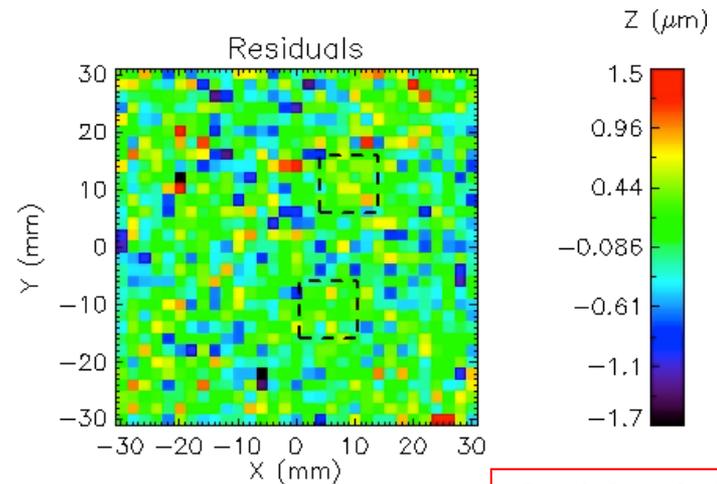
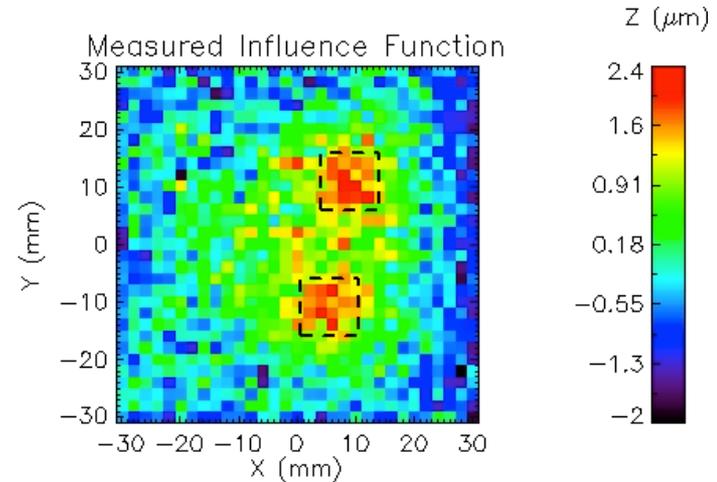
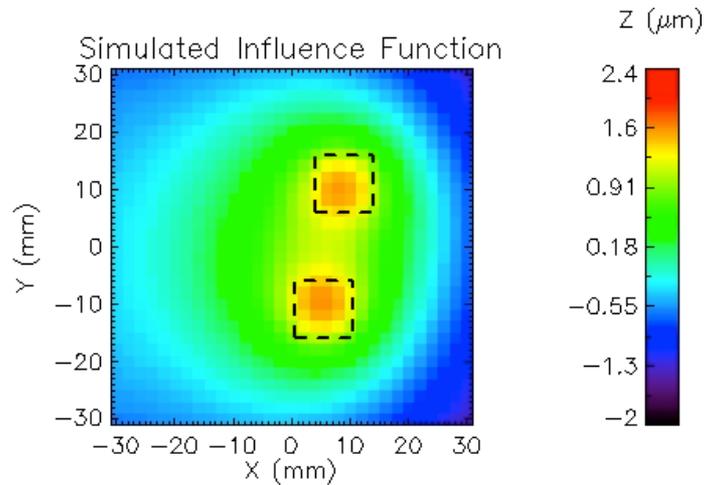


*Flat test mirror – 100 mm diameter
0.4 mm Corning Eagle glass with
 $1.6 \mu\text{m}$ PZT and 1 cm^2 electrodes
Also shows pattern of strain gauges
(lower right) deposited on PZT.*

Paul Reid / SAO



Proof of Concept



*Test using Corning Eagle™ flat glass, 0.4 mm thick, 100 mm diam., 1 cm² piezo cells
Deflection at 10V is equivalent to 700 ppm strain — meets SMART-X 500 ppm requirement.*

Residual (measured minus modeled) is the same amplitude as metrology noise.

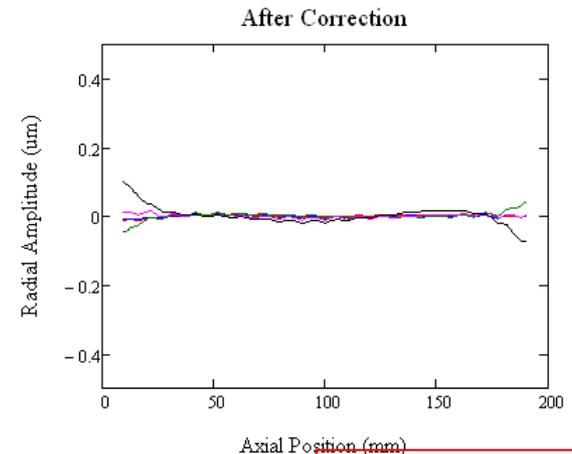
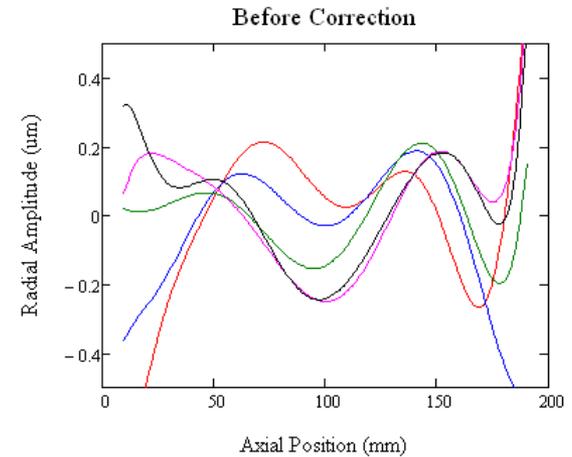
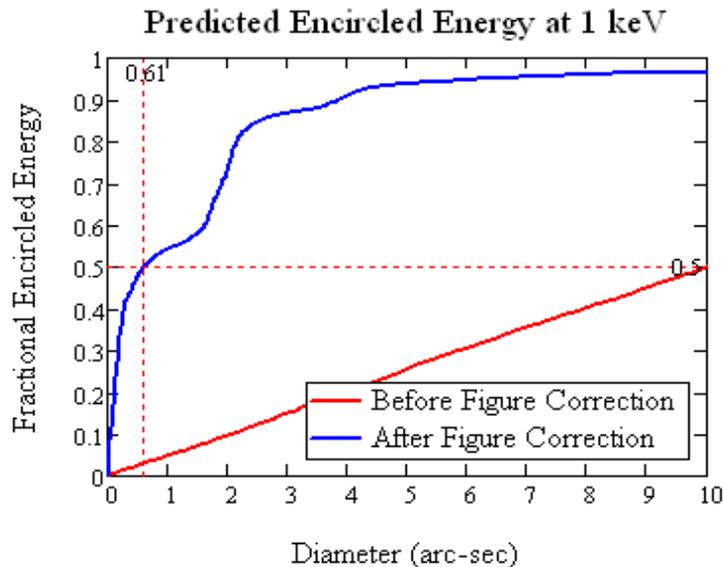
Paul Reid / SAO

Simulated correction of measured data yields 0.6 arc sec HPD for initial 10 arc sec mirror pair



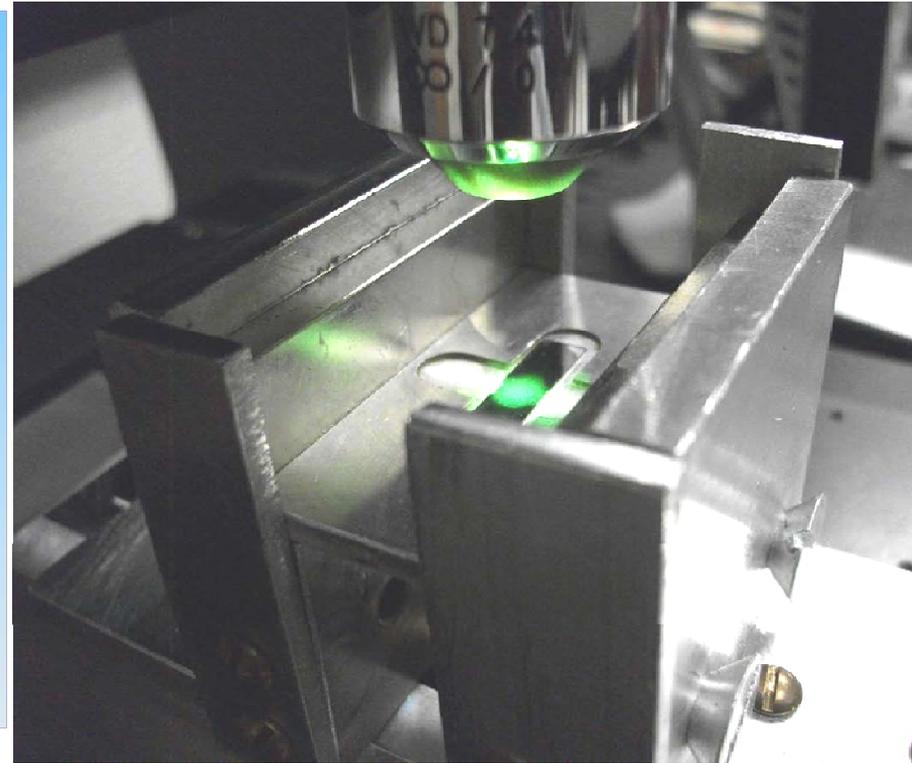
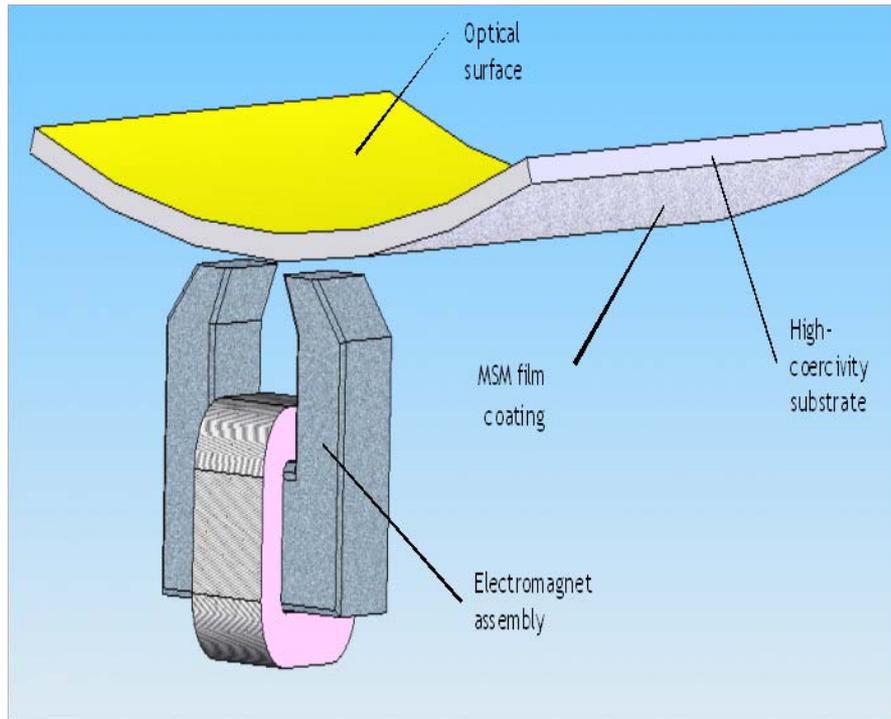
Use modeled influence functions to correct representative data:

- 'Before Correction' = interferometer measurement of mounted IXO mirror (ca. 2008).
- 'After Correction' = residual after least squares fit of ~ 400 influence functions.
- Compute PSF using full diffraction calculation:



Paul Reid / SAO

A magnetic smart material MSM provides magnetically writable (bimorph) STA.



- Form substrate with 10" resolution.
- Use a magnetically hard substrate or coated layer on substrate.
- Deposit MSM thin film on back.

Measure magnetically written deformation with interferometer.

Mei Ulmer / NWU

Active Control - Summary



1. **Extremely challenging requirements for future x-ray astronomy missions**
 1. Requirement for large area implies highly nested very thin mirror shells
 2. Requirement for sub-arcsecond resolution necessitates very stiff structures or active control
2. **Active control in its infancy for x-ray astronomy. Many issues to work out**
 1. Large net area to effective area means extremely large number of actuators (10^6 - 10^7) to control precisely
 1. Convergence ? Stability in hostile environment, etc
 2. Estimate of cost ~ \$100M
3. **Other ideas for sub-arcsecond optics ?**

MSFC Developments : Electroformed Nickel Replication

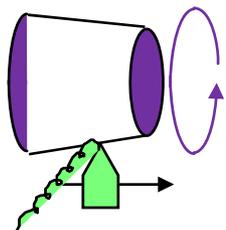


Mandrel - machining Al bar, electroless Nickel coating, diamond turning and polishing

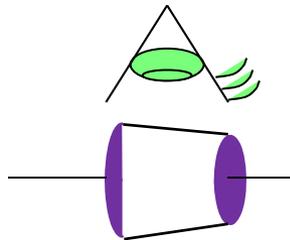


X-ray mandrel

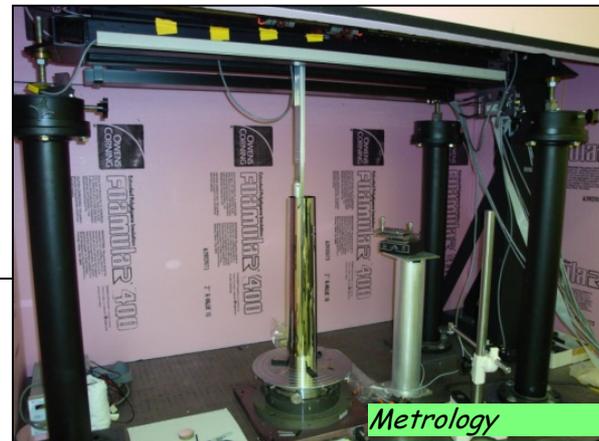
Metrology on mandrel



Mandrel polishing

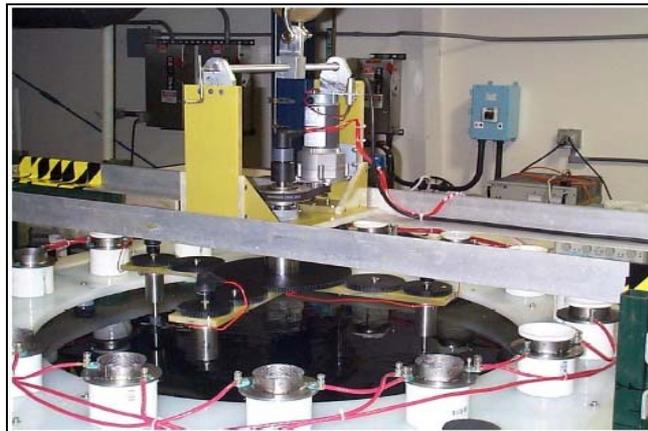
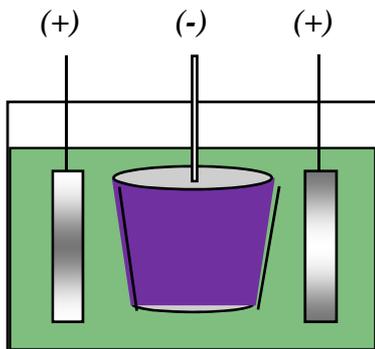


X-ray shell Replication

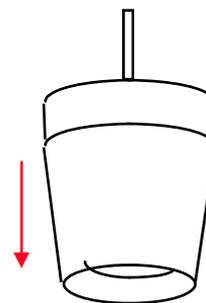


Metrology

Electroform Ni/Co shell onto mandrel



Separate optic from mandrel in cold water bath



Replicated X-ray shells

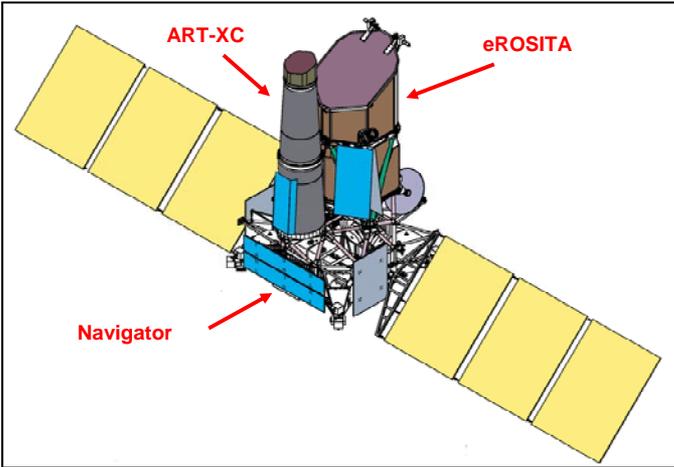


Replicated X-ray optic projects at MSFC



Astronomical applications

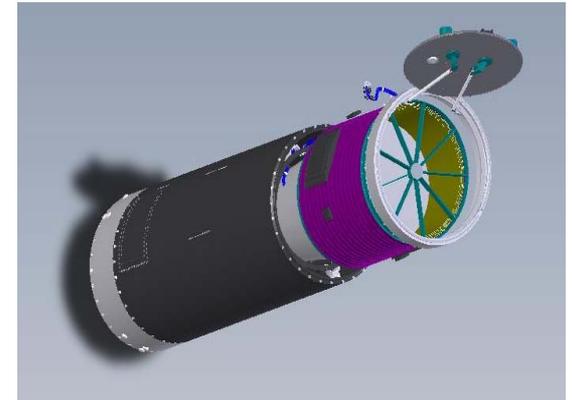
ART



FOXSI



MicroX



HEROES

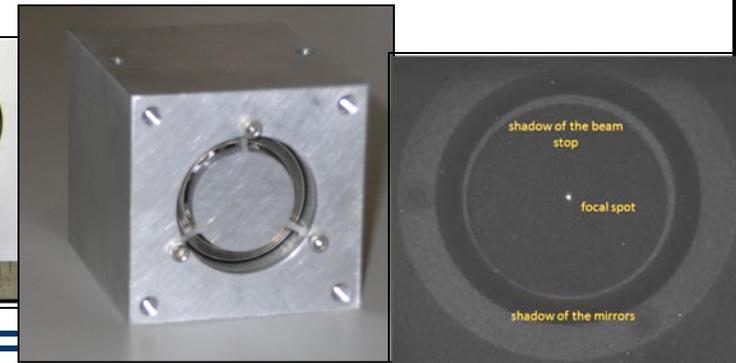


Non-astronomical applications

Medical imaging



Neutron imaging

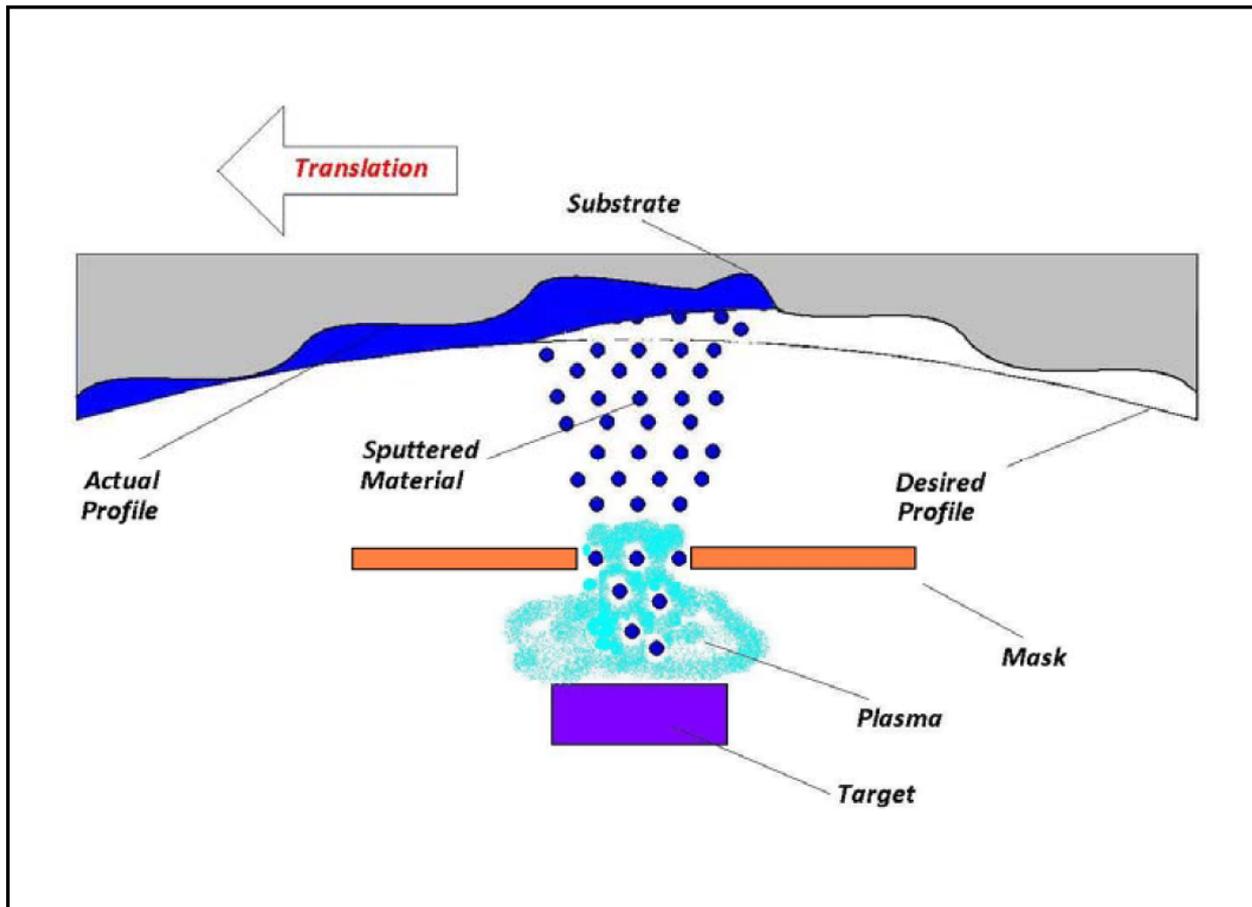


Mirrors for Future Missions – Differential Deposition



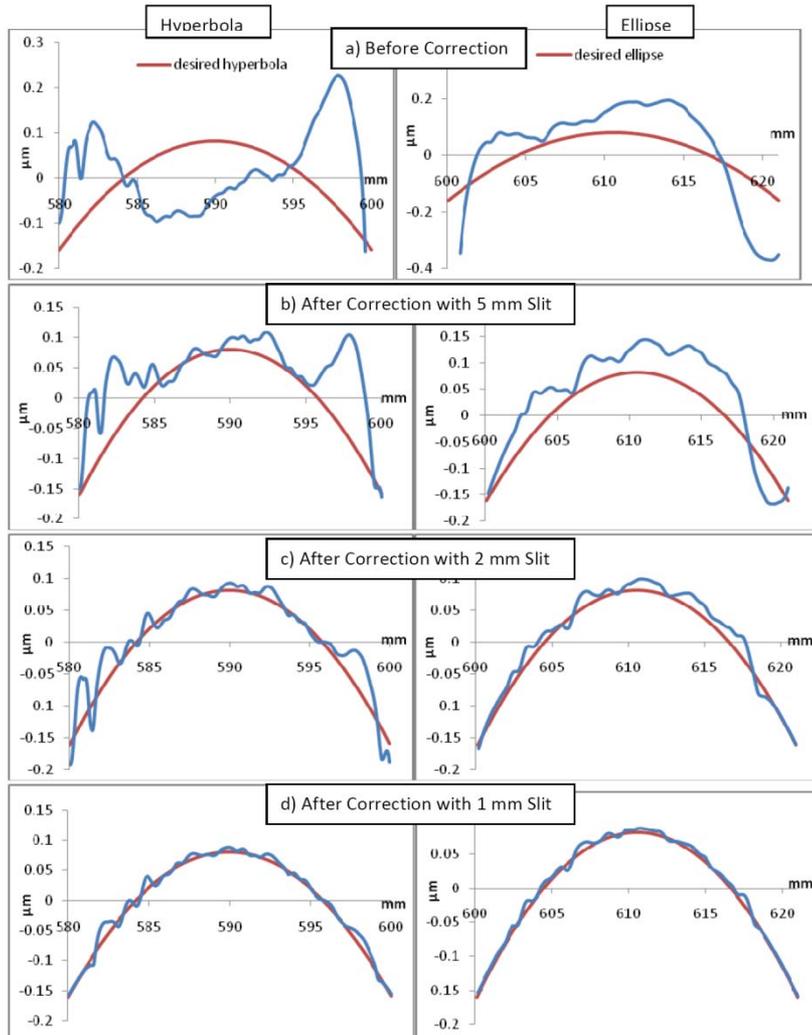
Vacuum deposit a filler material to compensate for figure imperfections

Proof of concept work underway at MSFC

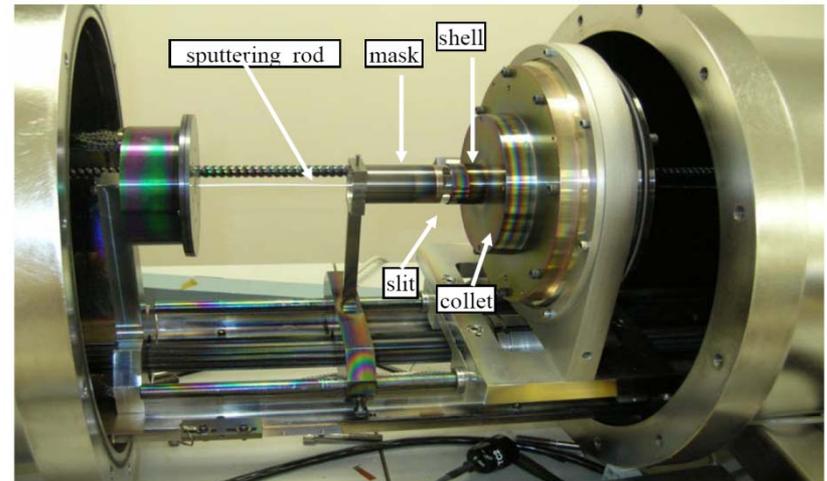




Mirrors for Future Missions – Differential Deposition



Correction stage	Average deposition amplitude (nm)	Slit-size (mm)	Amplitude uncertainty (nm)	Angular resolution (arcsec)
1	300	5	± 0	3.6
			± 10	3.6
			± 50	7.3
2	40	2	± 0	0.6
			± 1	1.0
			± 5	2.0
			± 10	3.5
3	4	1	± 0	0.2
			± 0.5	0.2
			± 1	0.5
			± 2	0.8





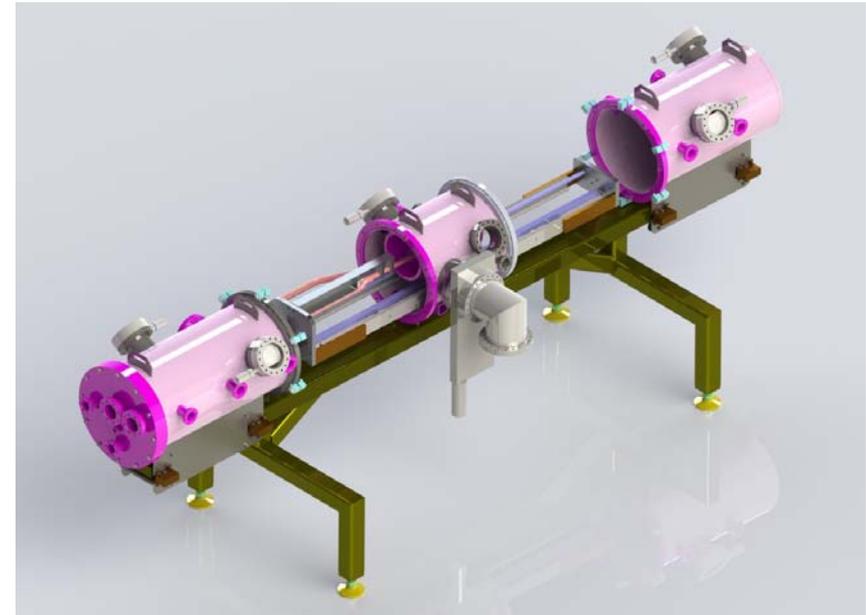
Current Status

- MSFC has received funding for larger coating chambers for astronomical-size full shell and segmented optics
- Work has started on chamber fabrication
- 3-year program

New coating systems

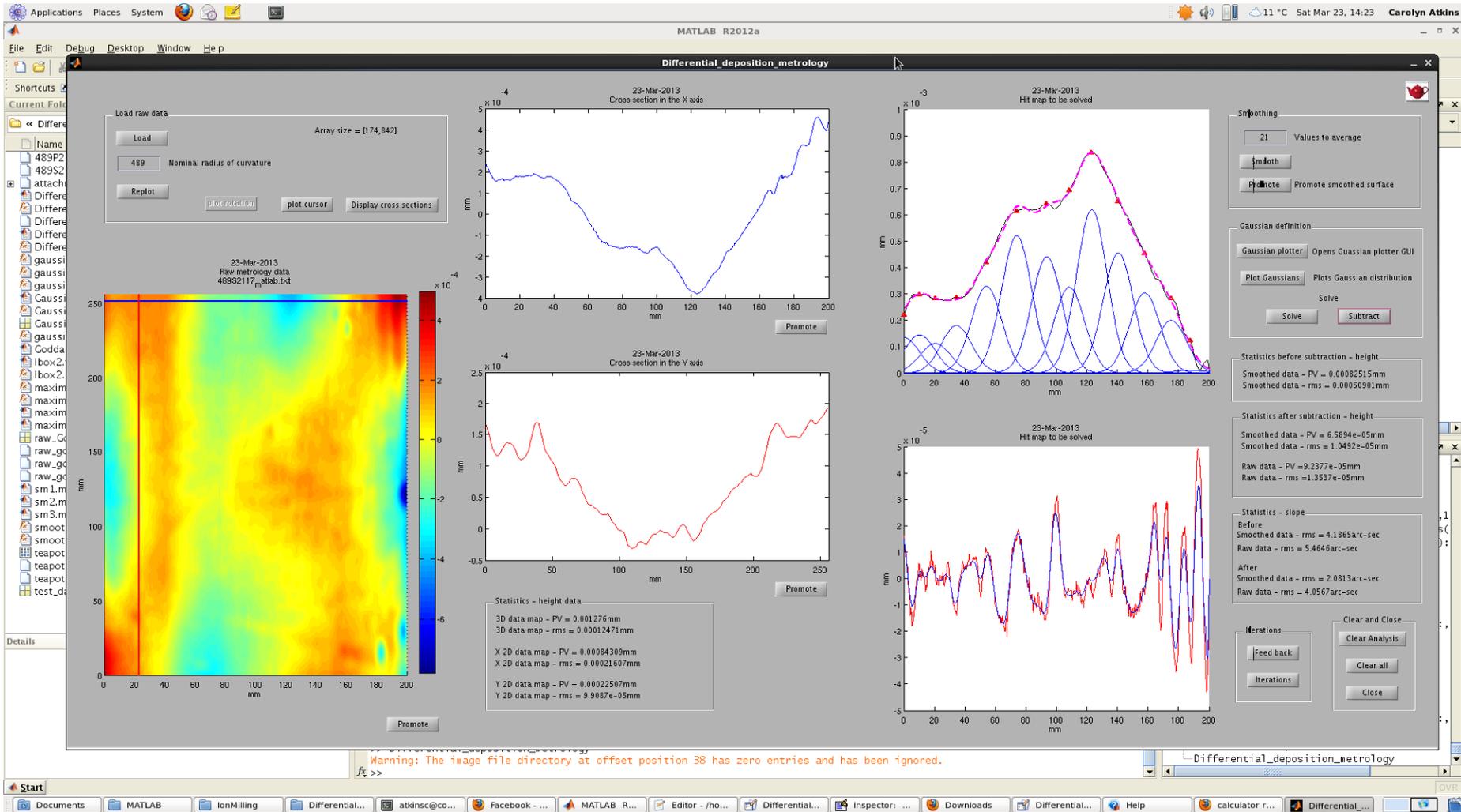


Vertical chamber for segmented optics

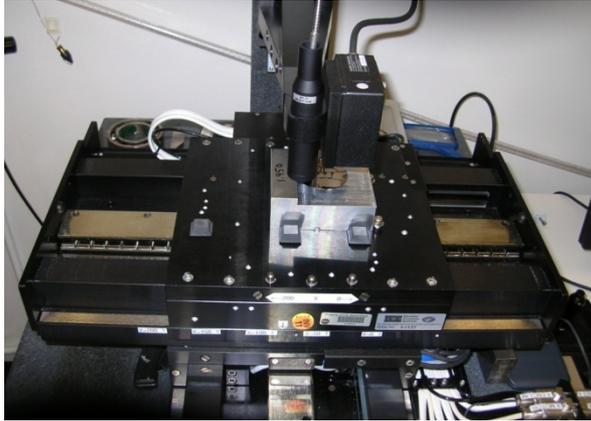


Horizontal chamber for 0.25-m-scale full shell optics

Differential Deposition - Software Interface

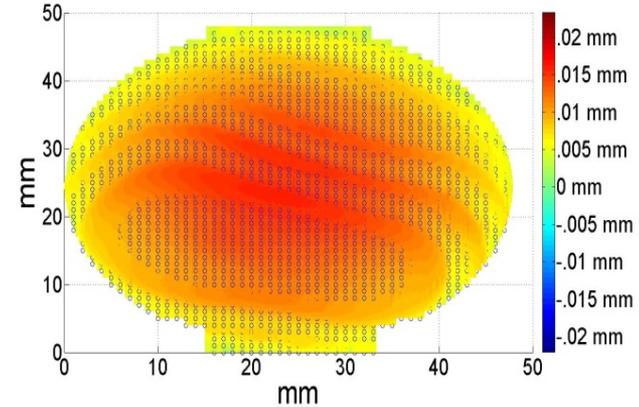


Stress measurements on silicon wafers



Solarius laserscan profilometer

Difference: Si Wafer 2 After - Si Wafer 2 Before



Deformed wafer

Experimental Stress Measurements of Nickel Thin Films and Associated X-ray Optic Applications

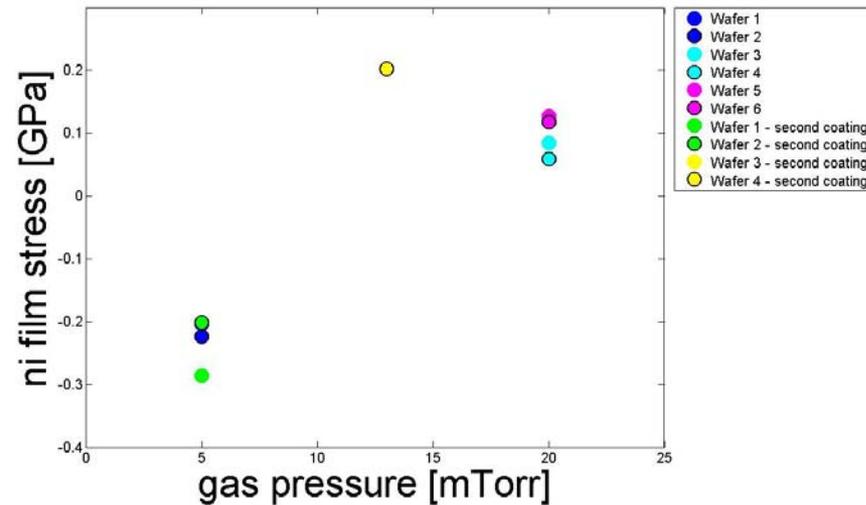
Danielle N. Gurgew

Emory University, Atlanta, GA, 30322

Intern, High Energy Astrophysics,

Marshall Space Flight Center, Emory

University.



Measured Stress

Other developments: Full-Shell Direct Fabrication

