Optics Development for X-ray Astronomy

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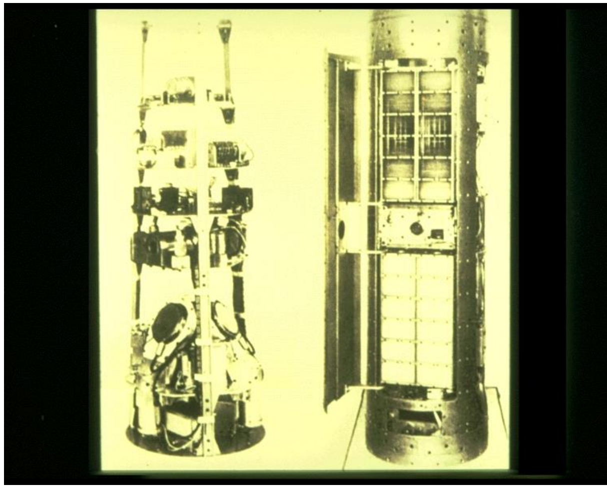
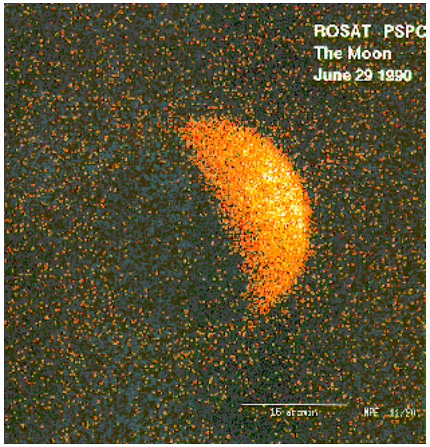
X-Ray Astronomy

<u>Birth of X-Ray Astronomy</u>

- 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 Scorpious 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





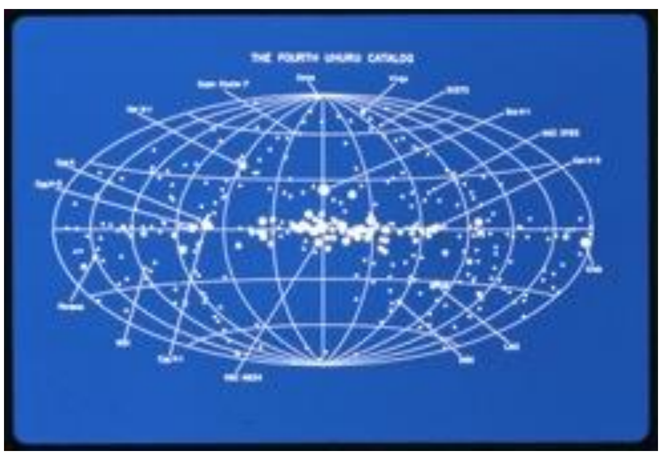
X-Ray Astronomy

<u>First X-Ray Satellite</u>

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

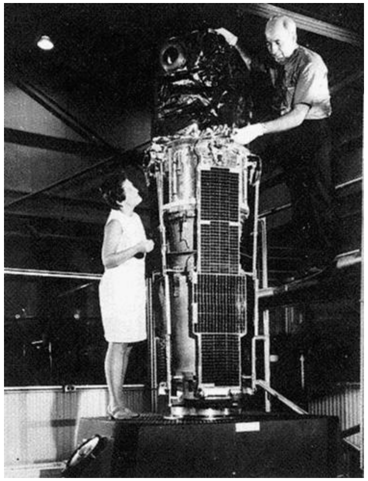
Why focus x rays ?

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

$\Rightarrow$ *enormous increase in sensitivity*



First dedicated x-ray astronomy satellite – UHURU →

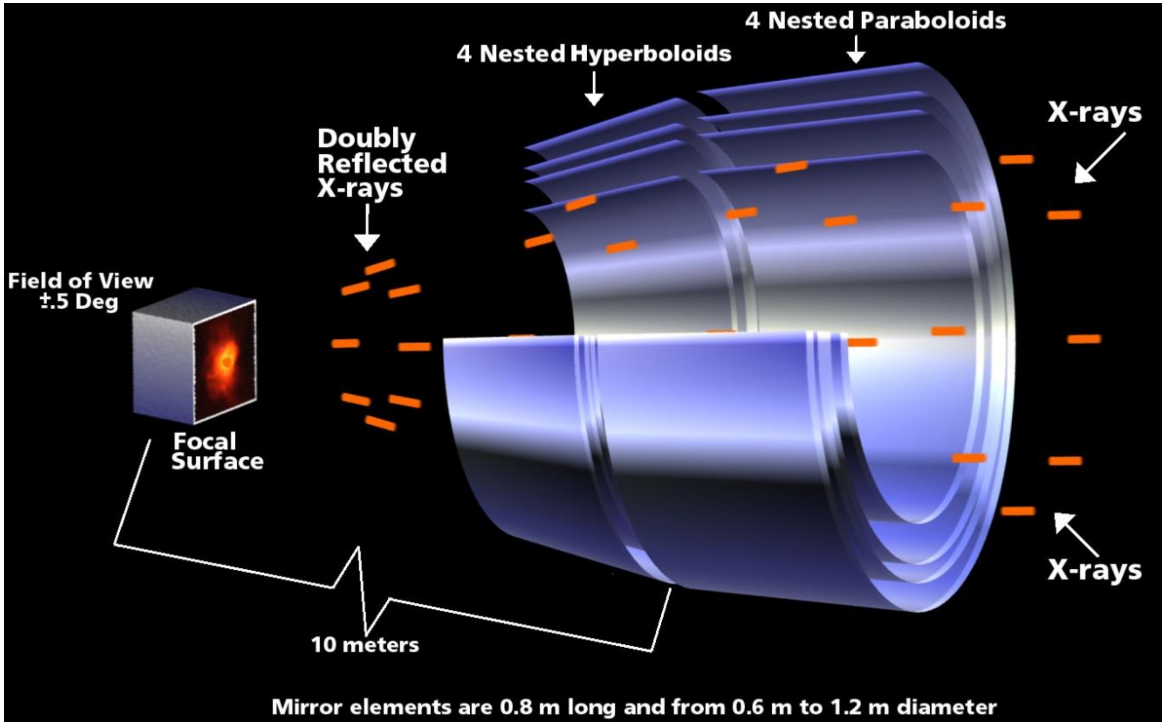
mapped 340 sources with large area detector (no optics)

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

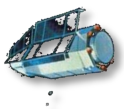


Approaches: Chandra

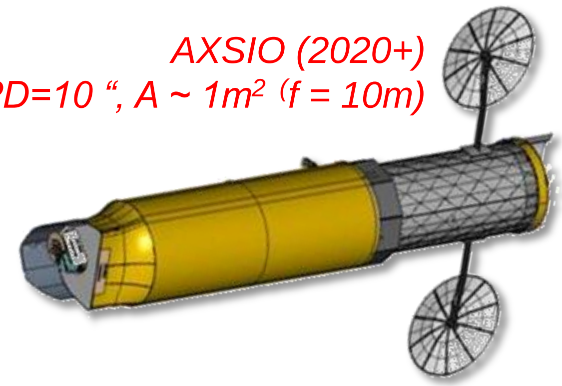
- Fabricated using thick ceramic, which is meticulously polished and figured, one shell at a time.
- Obtain superb angular resolution ------ 0.5 arcsecond HPD
- But very costly to fabricate and very heavy (1000 kg)

- *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 resolution ….and all somehow affordable !*

Mission Requirements / Future Challenges

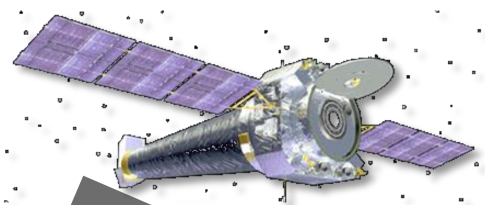


Einstein Observatory (1978-1981)
HPD =10″, A = 0.04 m^2 (f = 3.3 m)

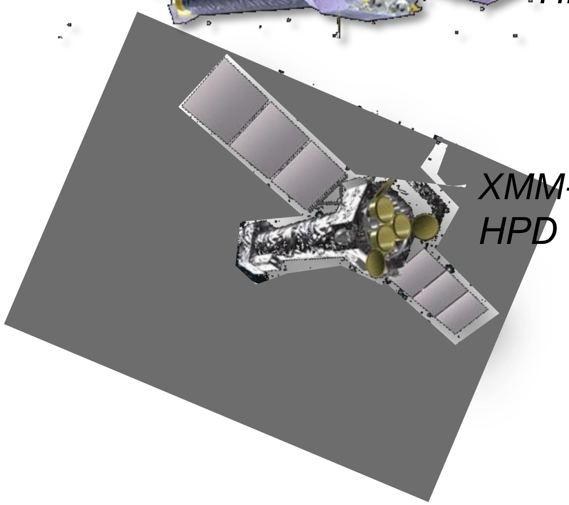


AXSIO (2020+)
HPD=10 “, A ~ 1m^2 (f = 10m)

ROSAT (1990-1999)
HPD = 5″, A = 0.10 m^2 (f = 2.4 m)



Chandra X-ray Observatory (1999-?)
HPD = 0.6″, A = 0.11 m^2 (f = 10 m)



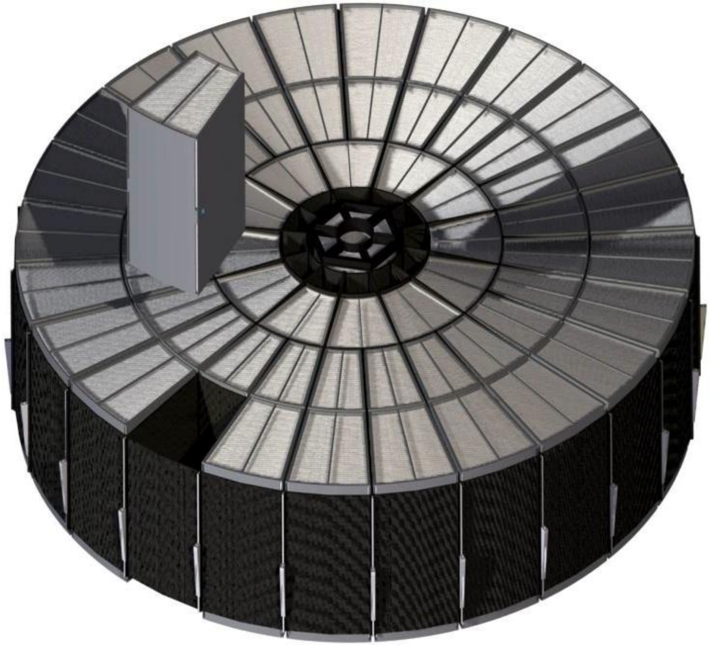
XMM-Newton (1999-?)
HPD = 14", A = 0.43 m^2 (f = 7.5 m)

SMART-X (2030)
HPD = 0.5", A ~ 2.3 m^2 (f = 10 m)

Process of Building a Telescope

~10^4 Mirror Segments

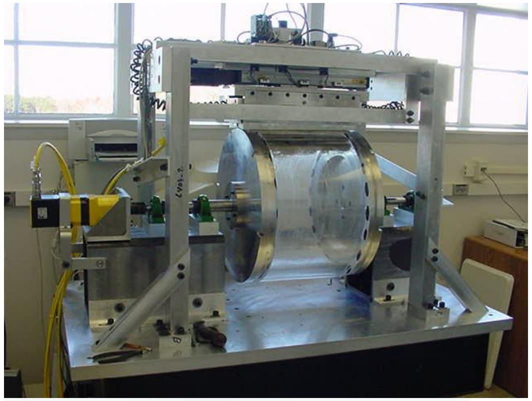
~10^2 Modules
Each containing
~10^2 mirror segments

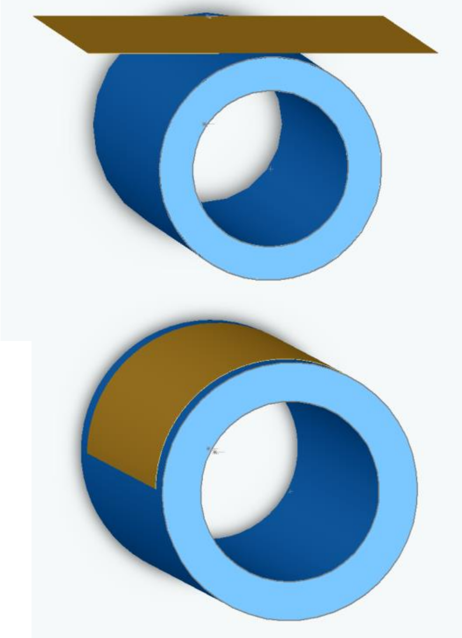


One or several mirror assemblies

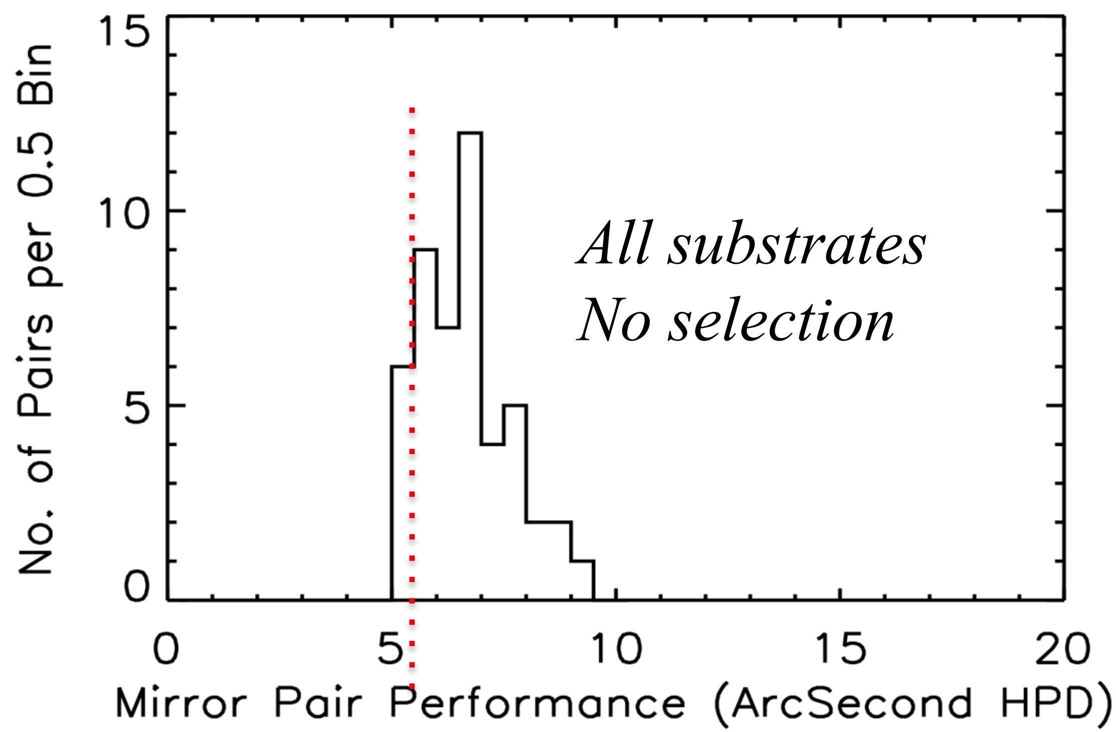
Will Zhang / GSFC

Glass Slumping



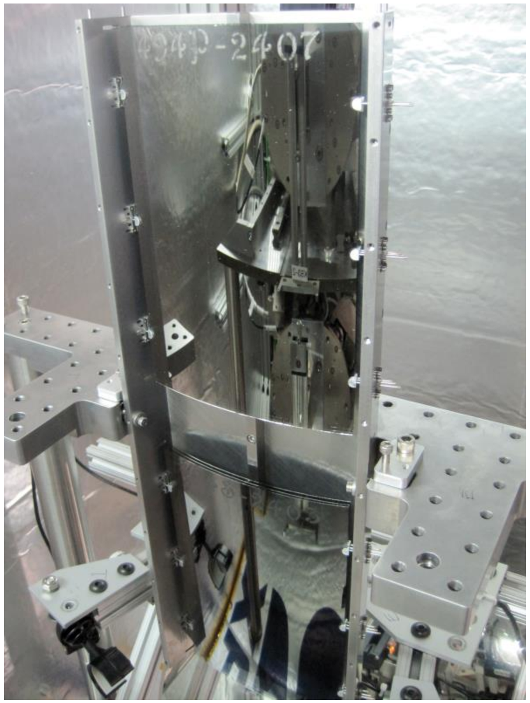


- Simple, Reliable, Mature
- Producing good and consistent results
- 400 Micron-thick glass

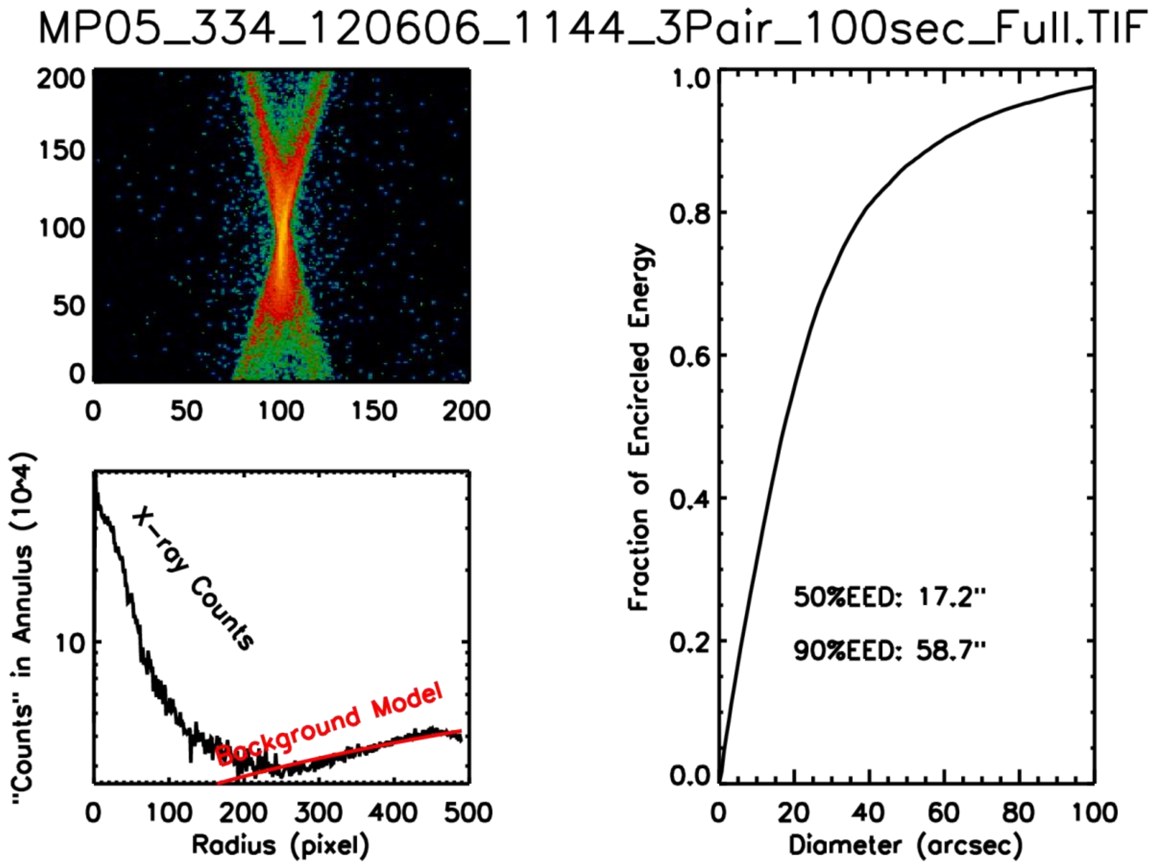


Will Zhang / GSFC

Technology Development Module
(X-ray Performance Test)

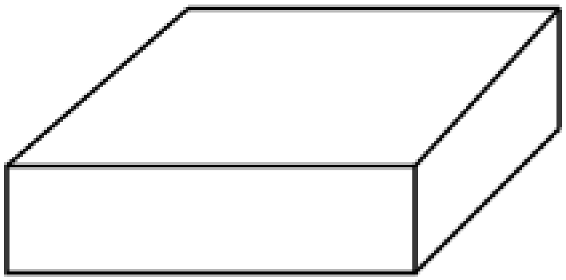


3 Pairs
Co-aligned
Bonded

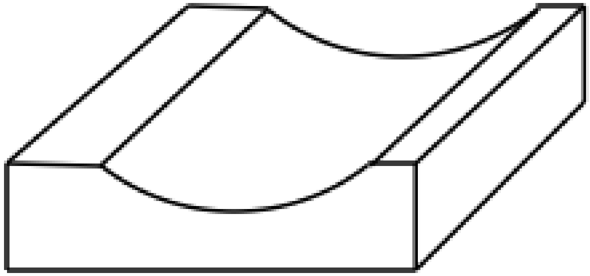


Will Zhang / GSFC

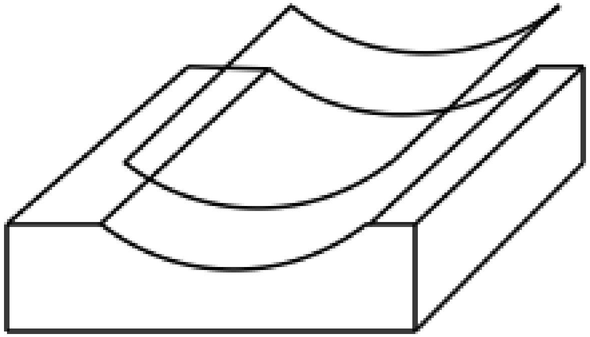
New Method for Fabricating Mirror Segment



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



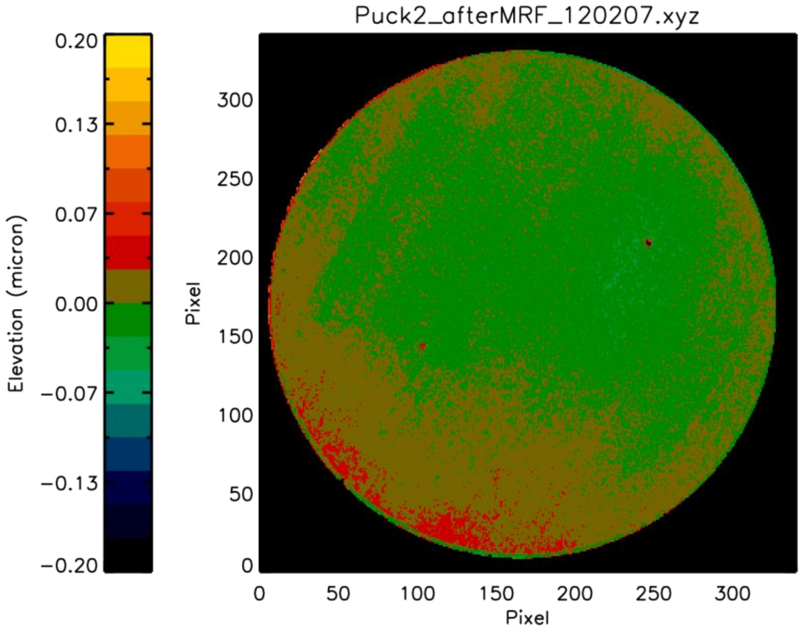
1. *W-EDM machine conical shape (**fast & cheap**)*
2. *Apply heat and chemical treatments to remove damage (**fast & cheap**).*
3. *Polish using modern deterministic technique to achieve excellent figure and micro-roughness (**fast & cheap? Need demonstration**)*



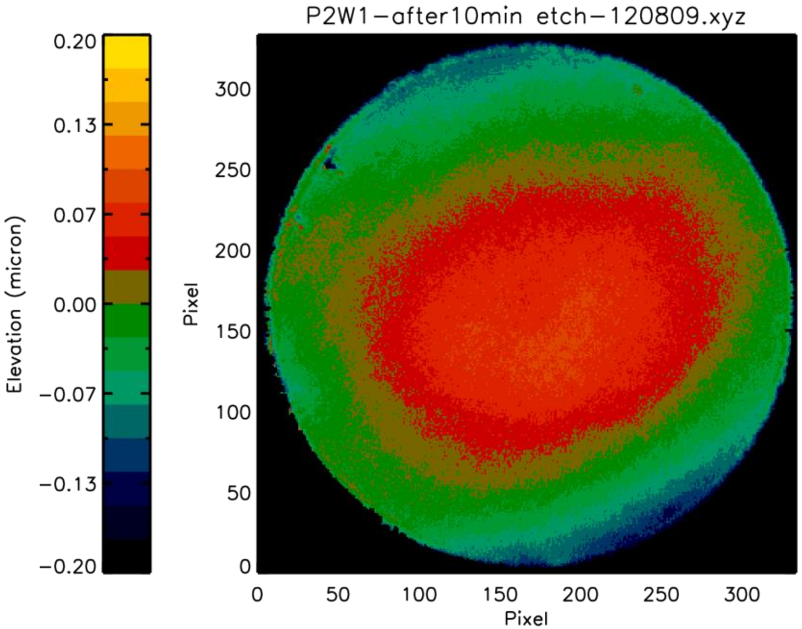
1. *Slice off (using W-EDM) the thin mirror segment (**fast & cheap**)*
2. *Apply heat and chemical treatment to remove all damage from back and edges (**fast & cheap**)*

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

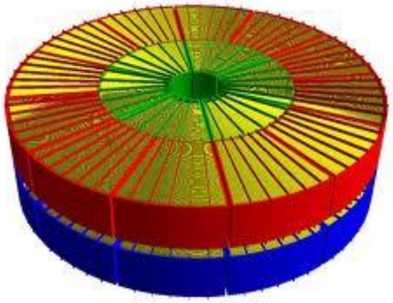
Progression of Work

- 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 $A_{surf} \approx (2/\alpha)A_{ap}$.
  - E.g., for SMART-X $A_{ap} \approx 2.4\ \mathrm{m}^2 \Rightarrow A_{surf} \approx 500\ \mathrm{m}^2$.



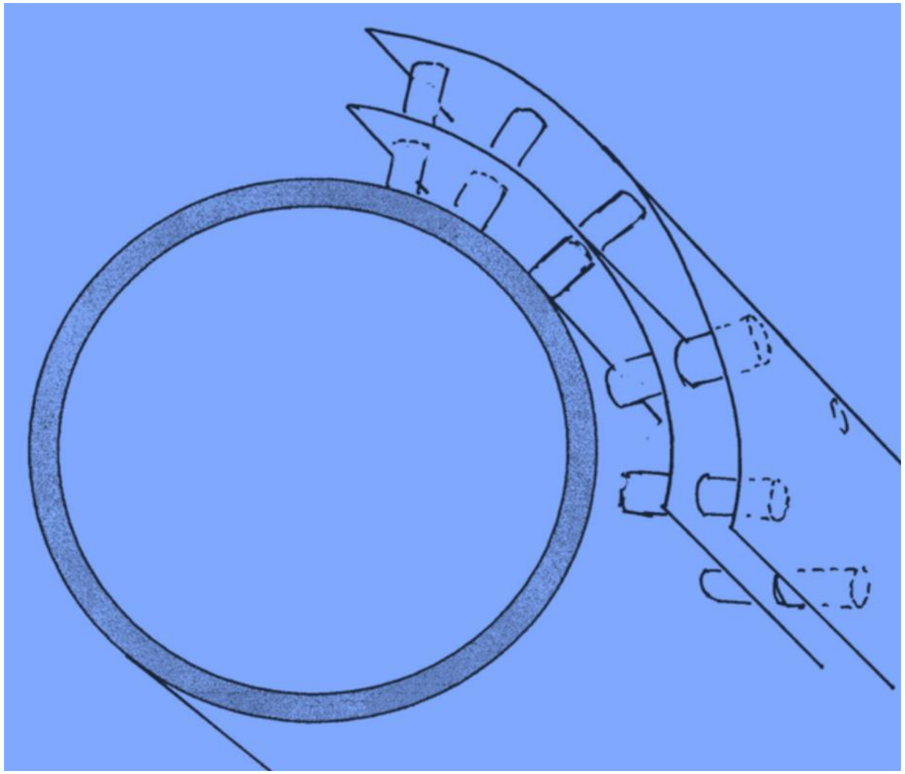
- **Launch considerations limit mass and volume.**
  - Mass constraints $\Rightarrow$ very lightweight mirrors.
  - Volume constraints $\Rightarrow$ many hundreds of highly nested (few mm), thin mirrors (0.4 mm).
- **Other considerations**
  - Very large number of actuators to fit in and control (10^6)
    - Correction strategy to converge
  - Thermal effects
  - Voltage stability
  - Radiation damage sensitivity

Figure Control Technologies

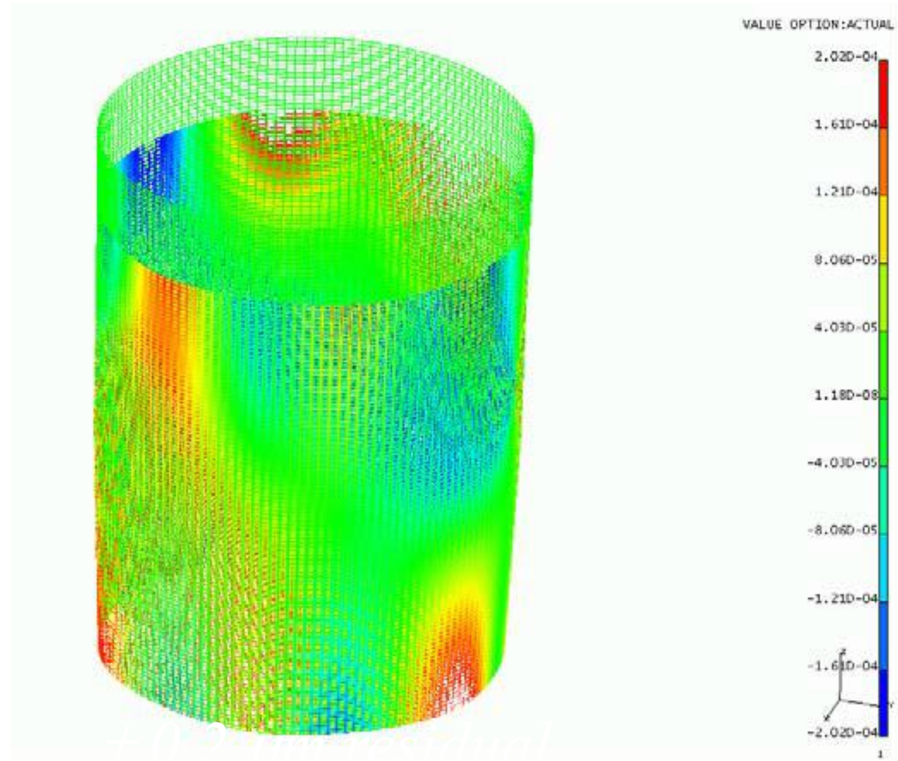
Actuator technologies under development

- ***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.

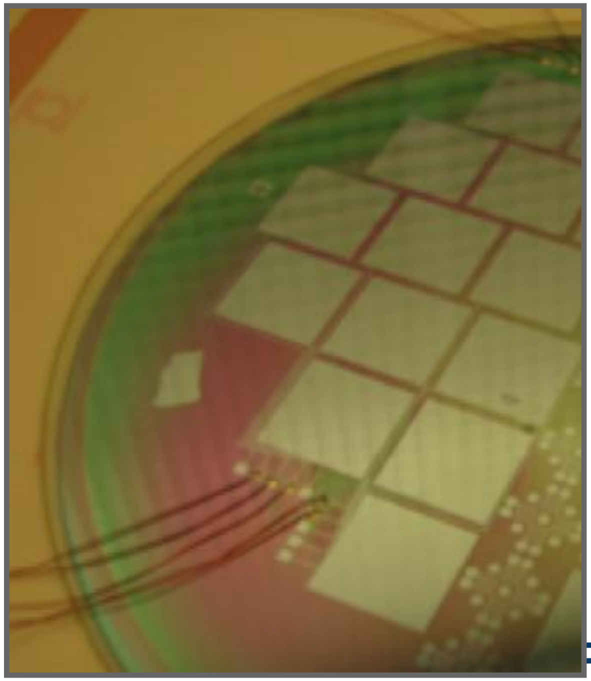
Paul Reid /SAO

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

- *Thin (~ 1.5 μm) 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.

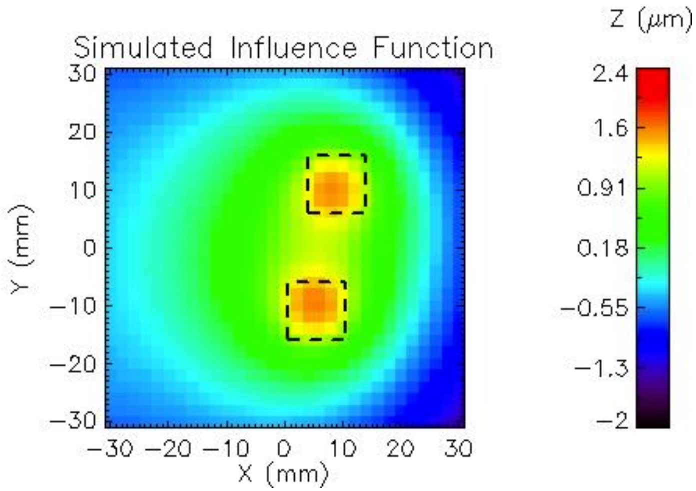
Raegan Johnson-Wilke / PSU

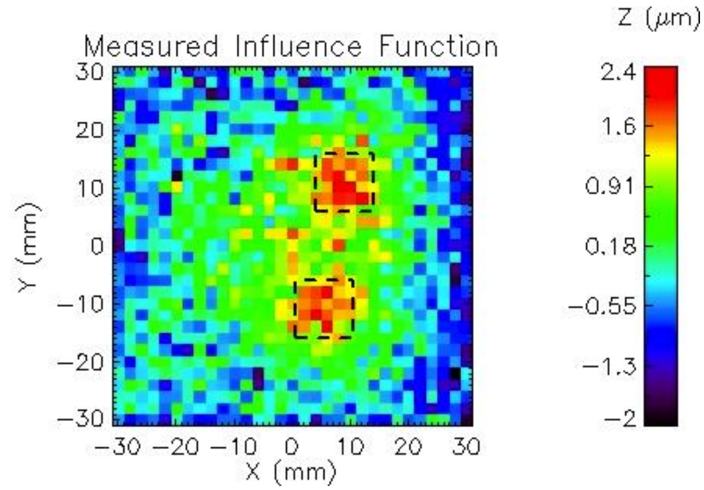


Flat test mirror – 100 mm diameter 0.4 mm Corning Eagle glass with 1.6 μm PZT and 1 cm^2 electrodes Also shows pattern of strain gauges (lower right) deposited on PZT.

Paul Reid / SAO

Proof of Concept

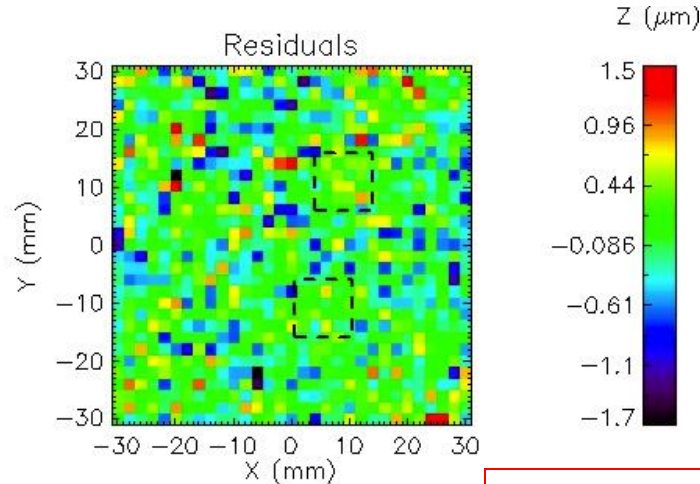




Test using Corning Eagle™ flat glass, 0.4 mm thick, 100 mm diam., 1 cm² piezo cells

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.

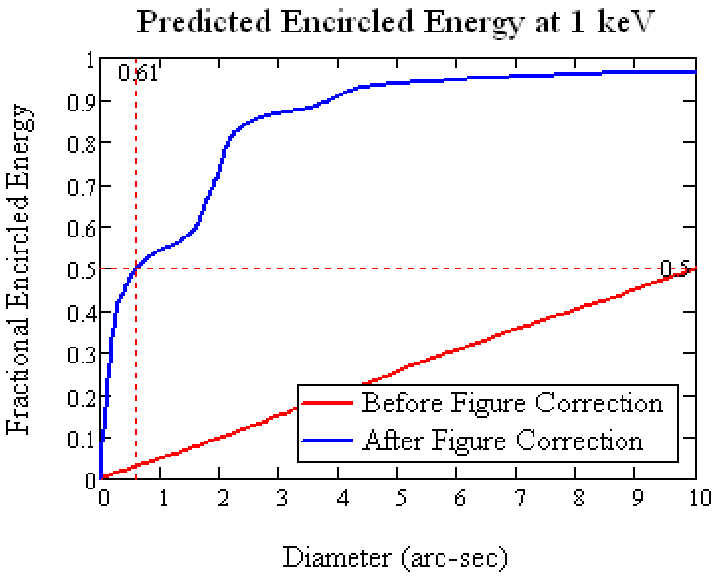


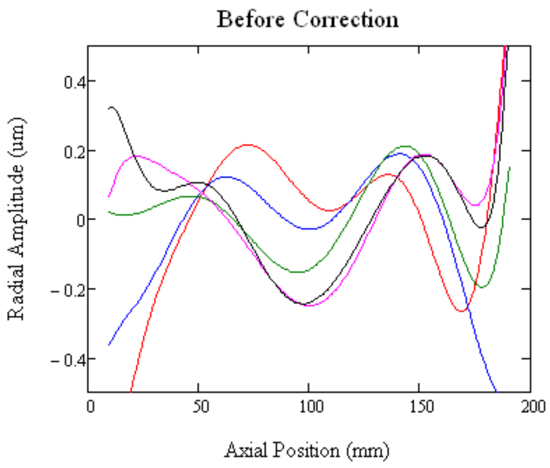
Paul Reid / SAO

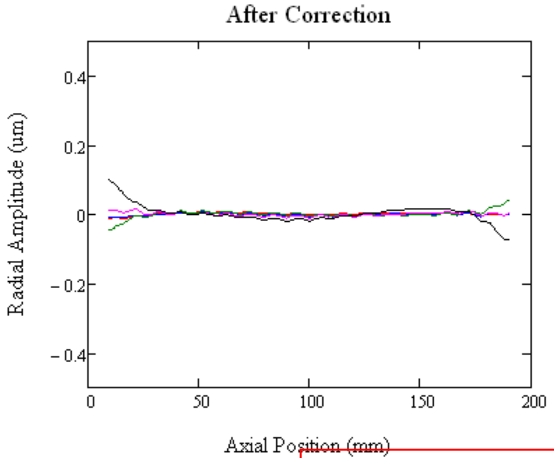
Simulated correction of measured data yields 0.6 arc sec HPD for initial 10 arc sec mirror pair

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:

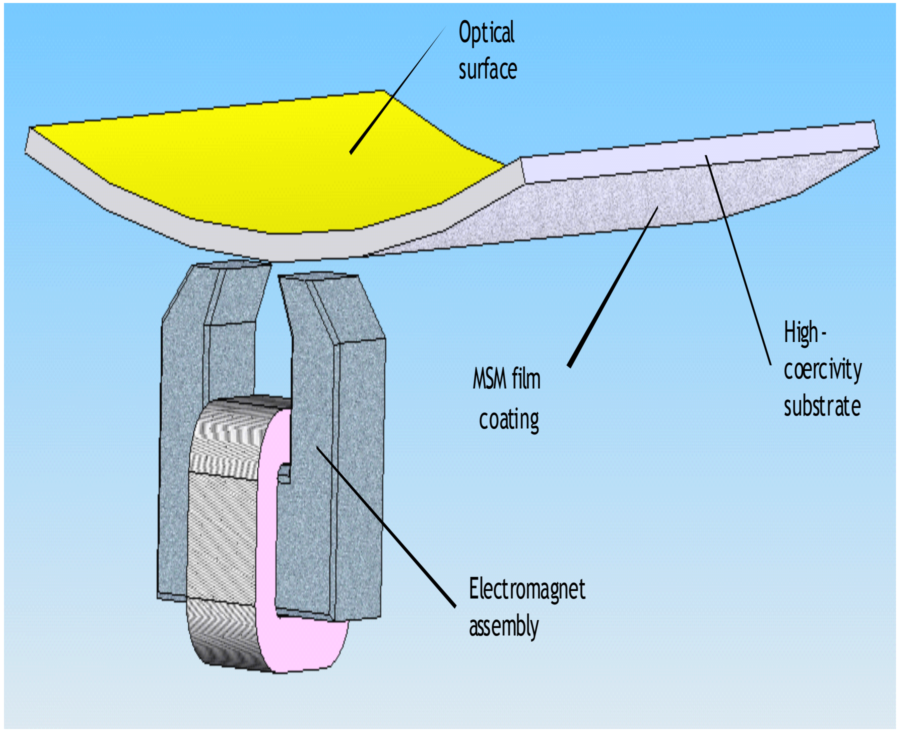


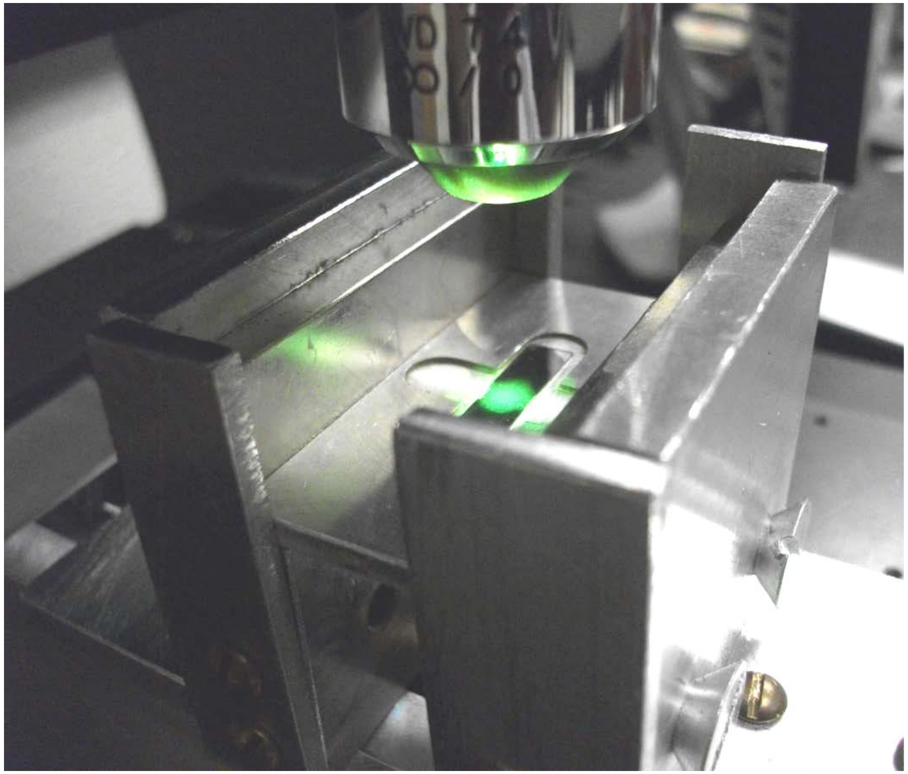




Paul Reid / SAO

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.

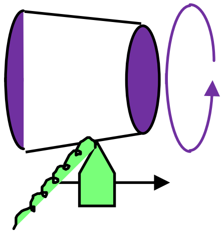
Mel Ulmer / NWU

Active Control - Summary

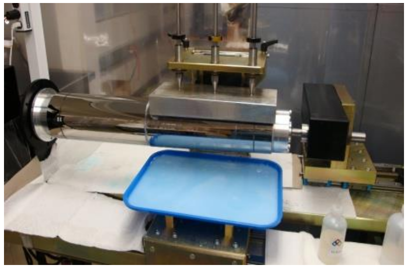
1. **Extremely challenging requirements for future x-ray astronomy missions**
    1. Requirement for large area implies highly nested very thin mirror shells
    2. Requirement for sub-arcsecond resolution necessitates very stiff structures or active control
2. **Active control in its infancy for x-ray astronomy. Many issues to work out**
    1. Large net area to effecticve 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

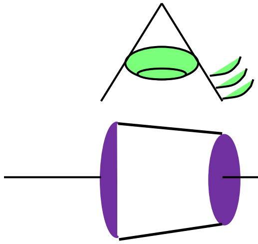


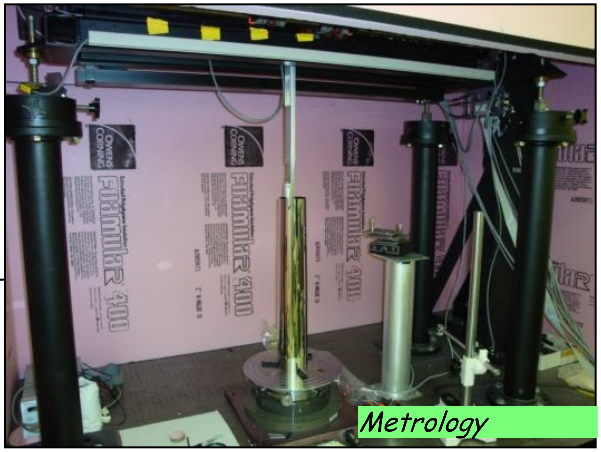
X-ray mandrel



Mandrel polishing

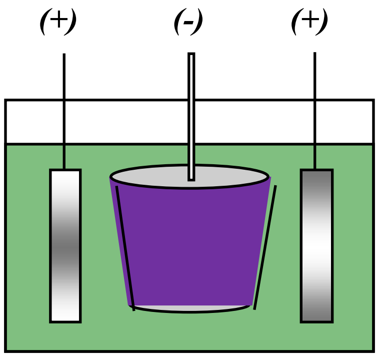
Metrology on mandrel



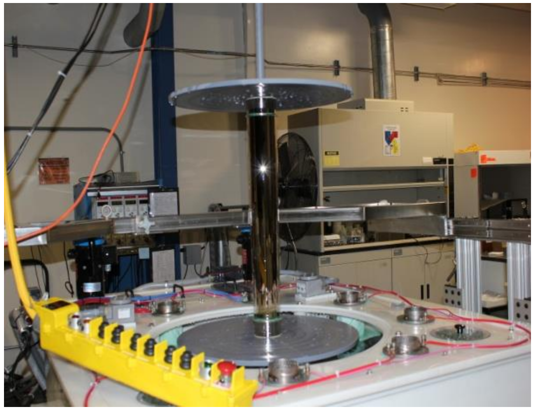


Metrology

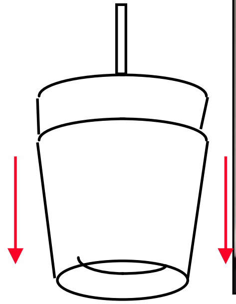
Electroform Ni/Co shell onto mandrel



X-ray shell electroforming



Separate optic from mandrel in cold water bath

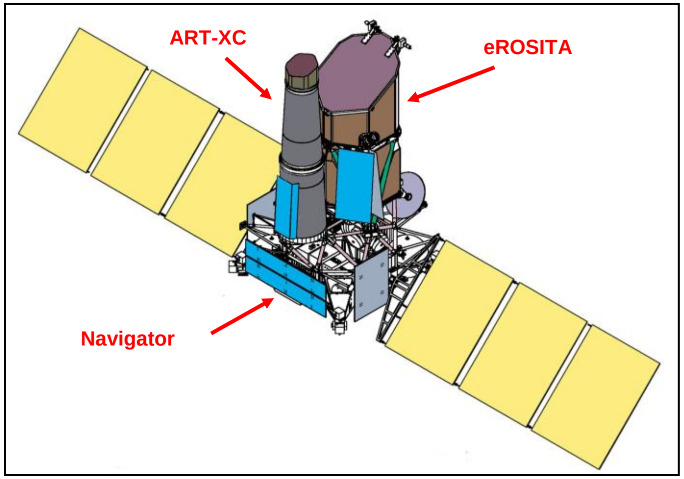


Replicated X-ray shells

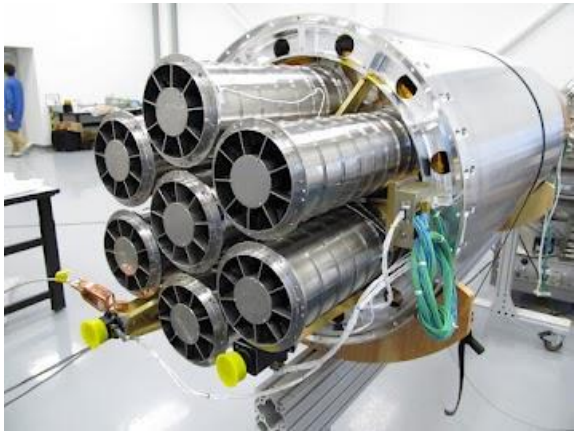
Replicated X-ray optic projects at MSFC

Astronomical applications

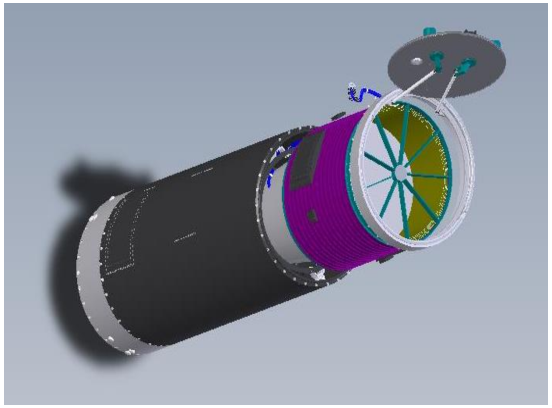
ART



FOXSI



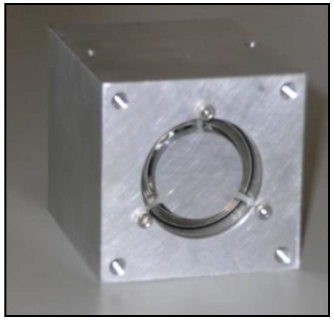
MicroX



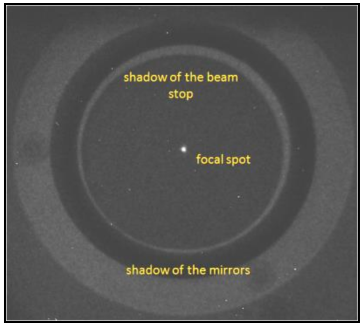
HEROES

Non-astronomical applications

Medical imaging



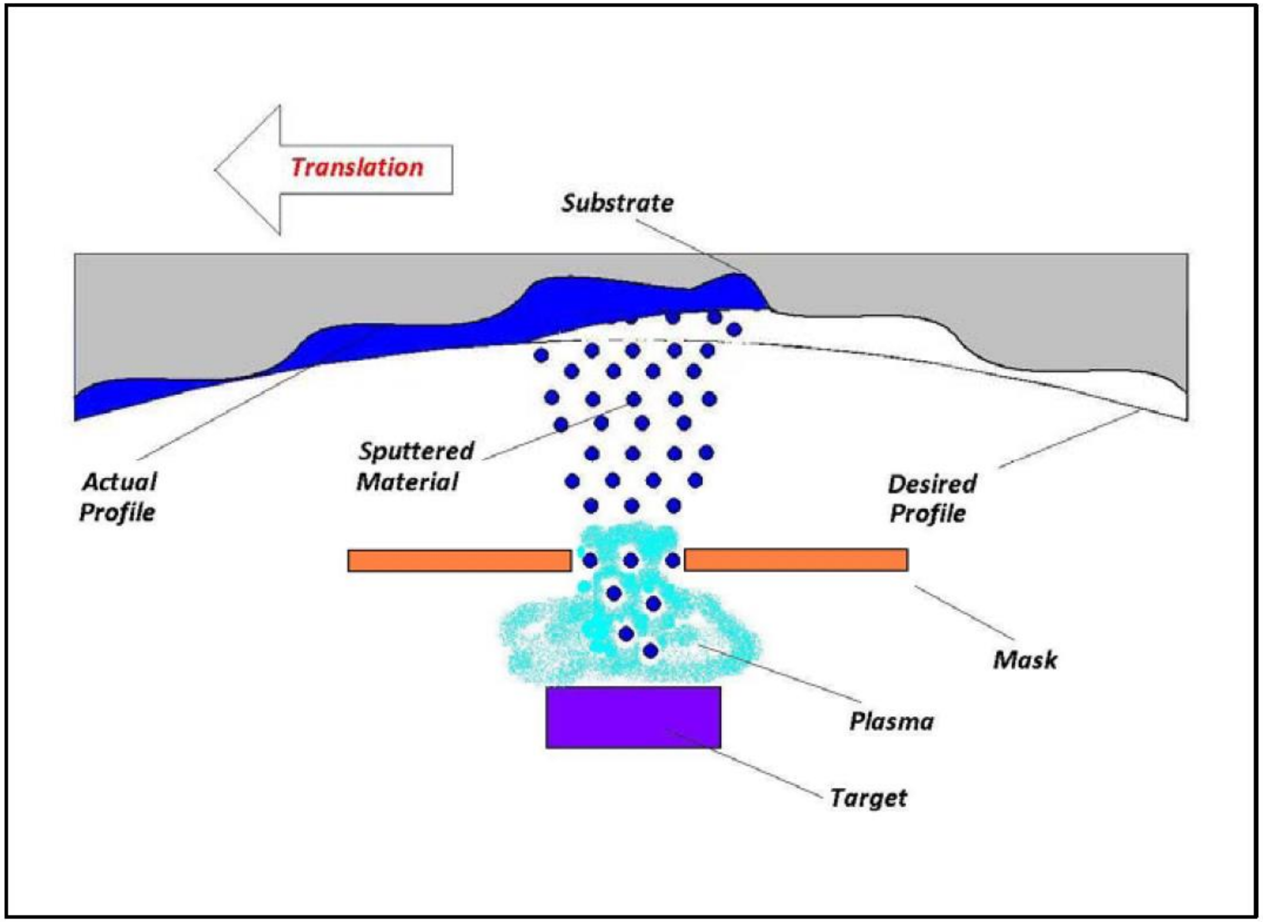
Neutron imaging



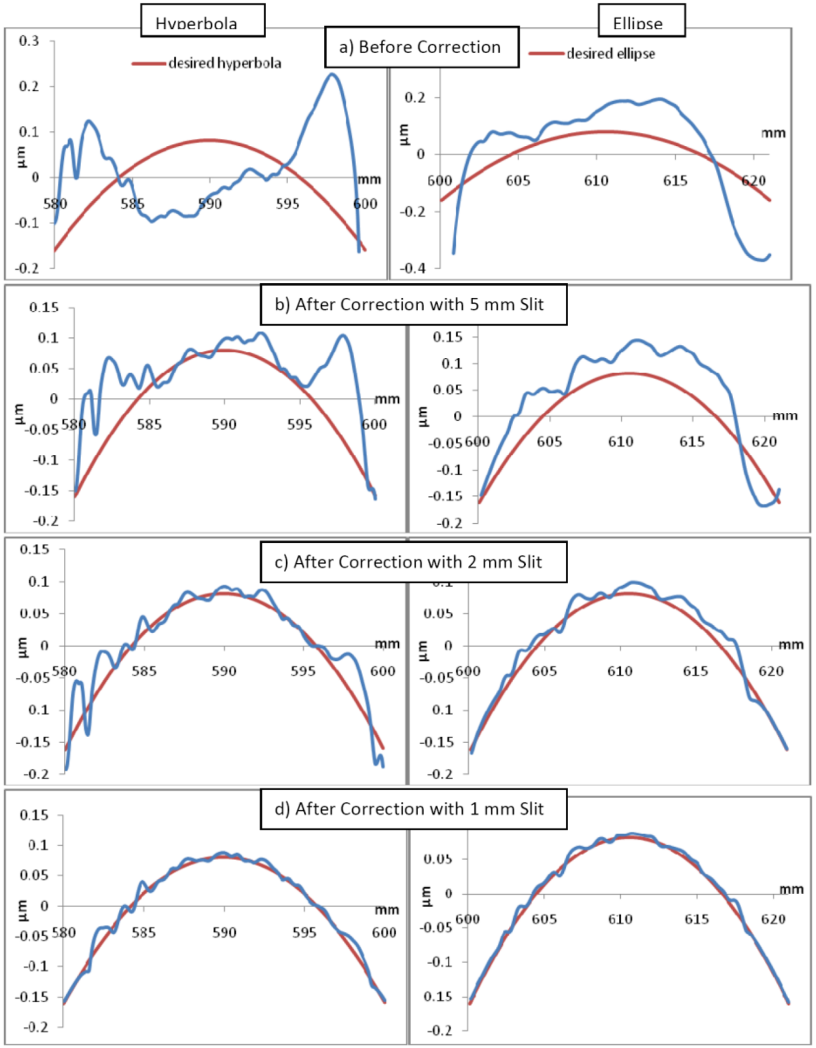
Mirrors for Future Missions – Differential Deposition

Vacuum deposit a filler material to compensate for figure imperfections

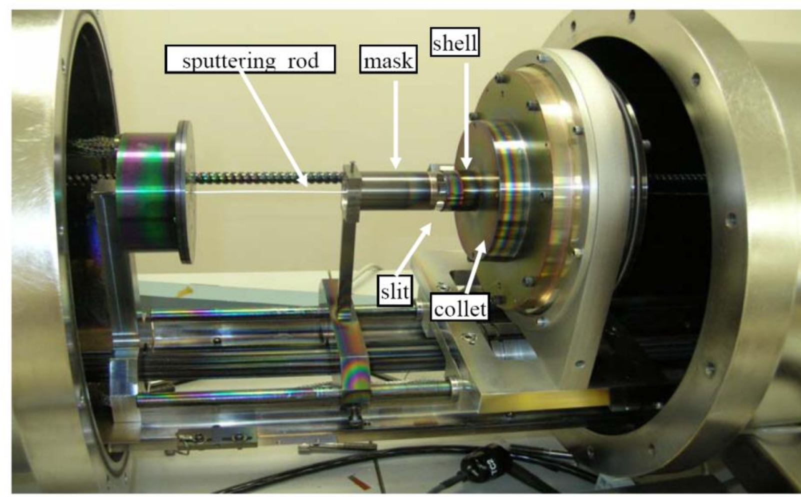
Proof of concept work underway at MSFC



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



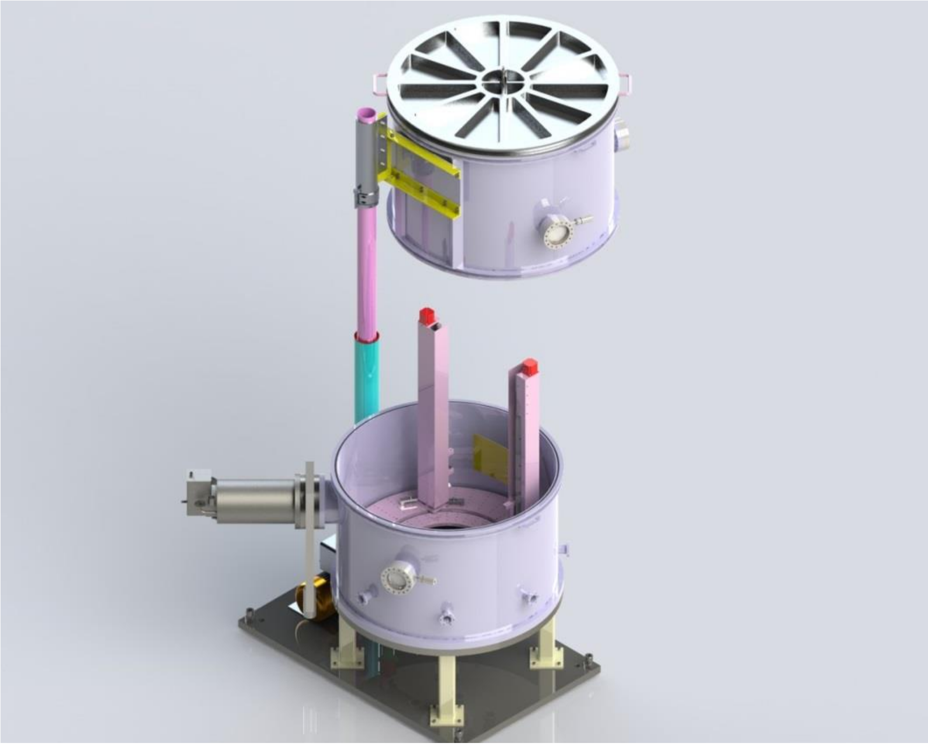
Current Status

- MSFC has received funding for larger coating chambers for astronomical-size full shell and segmented optics

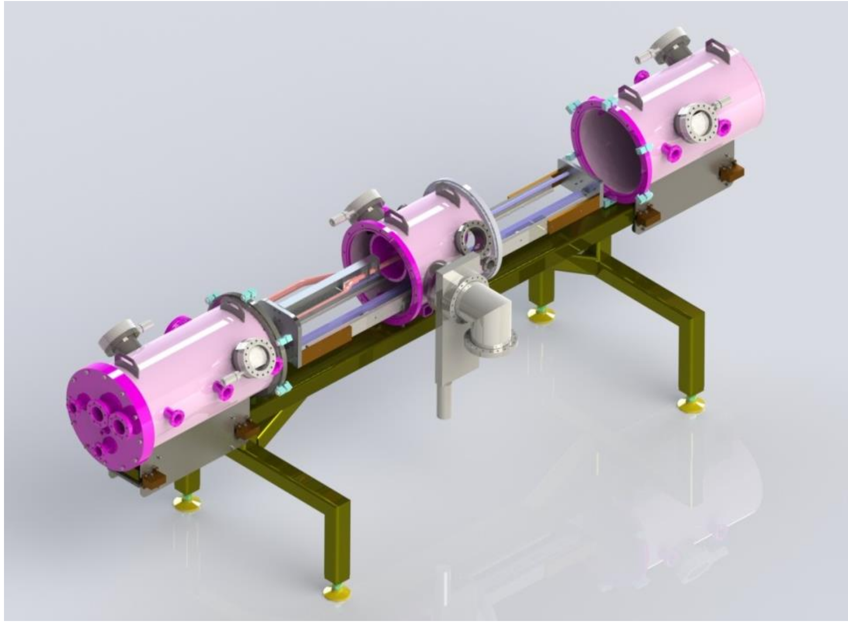
- Work has started on chamber fabrication

- 3-year program

New coating systems

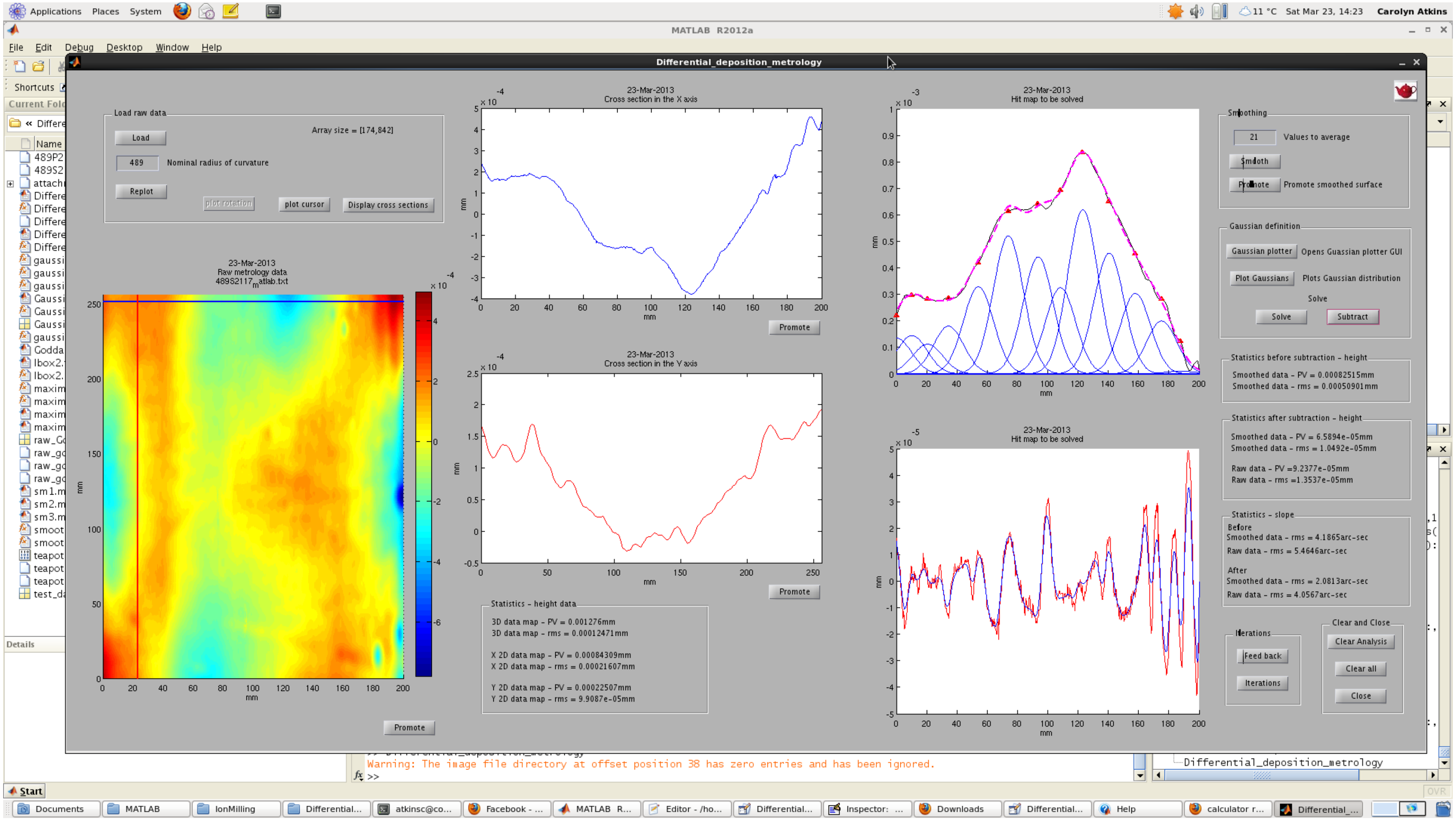


Vertical chamber for segmented optics



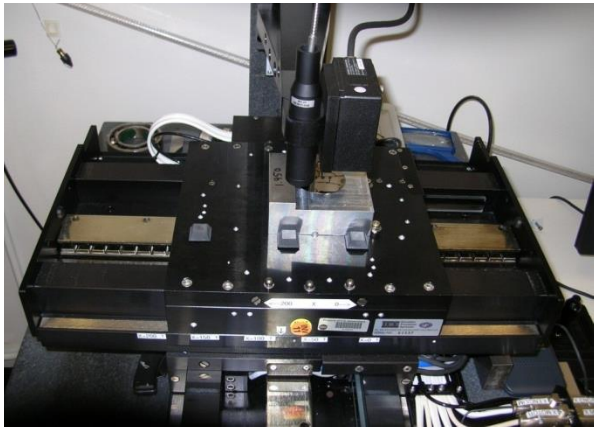
Horizontal chamber for 0.25-m-scale full shell optics

Differential Deposition - Software Interface

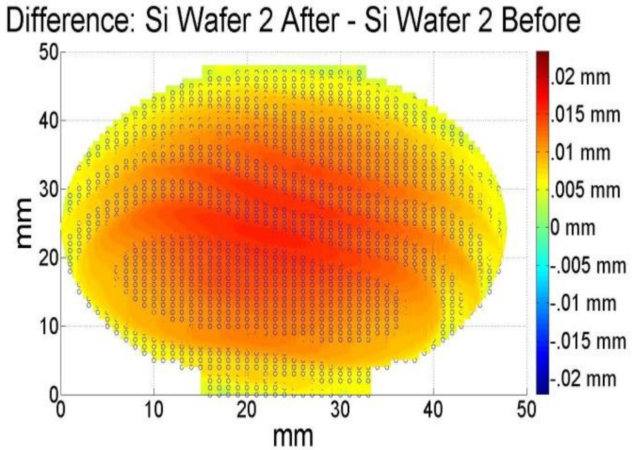


DoE Workshop in X-Ray Optics

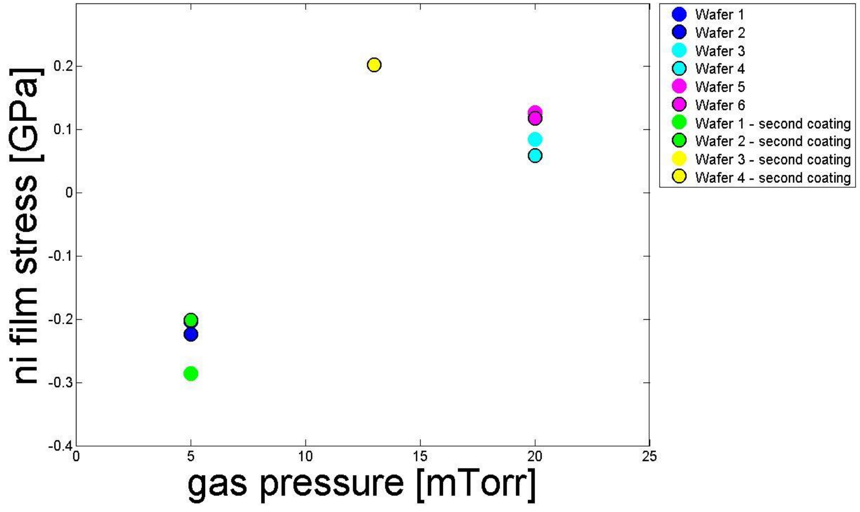
Stress measurements on silicon wafers



Solarius laserscan profilometer



Deformed wafer



Measured Stress

Experimental Stress Measurements of Nickel Thin Films and Associated X-ray Optic Applications
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Other developments: Full-Shell Direct Fabrication