Developments in X-Ray Optics

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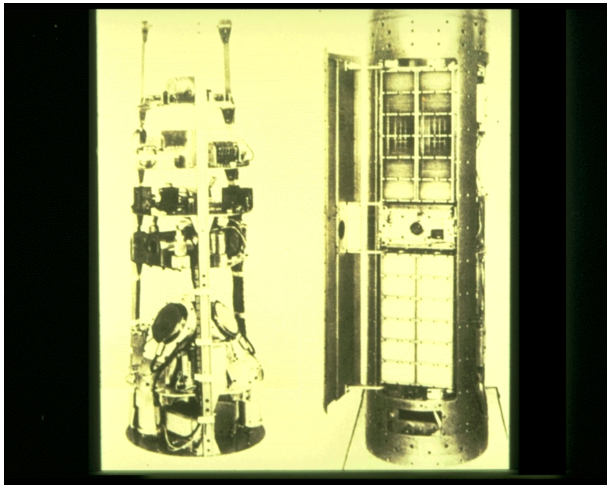
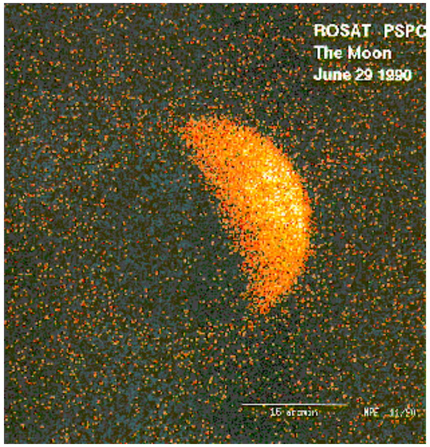
X-Ray Astronomy

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 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

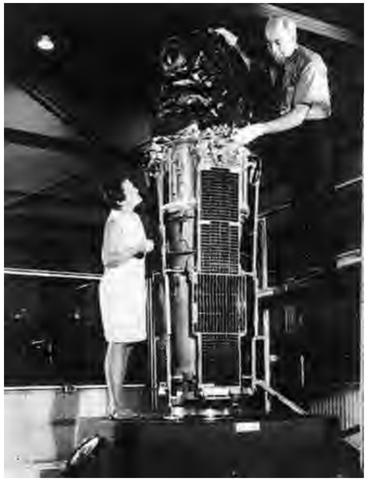
Why focus x rays ?

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

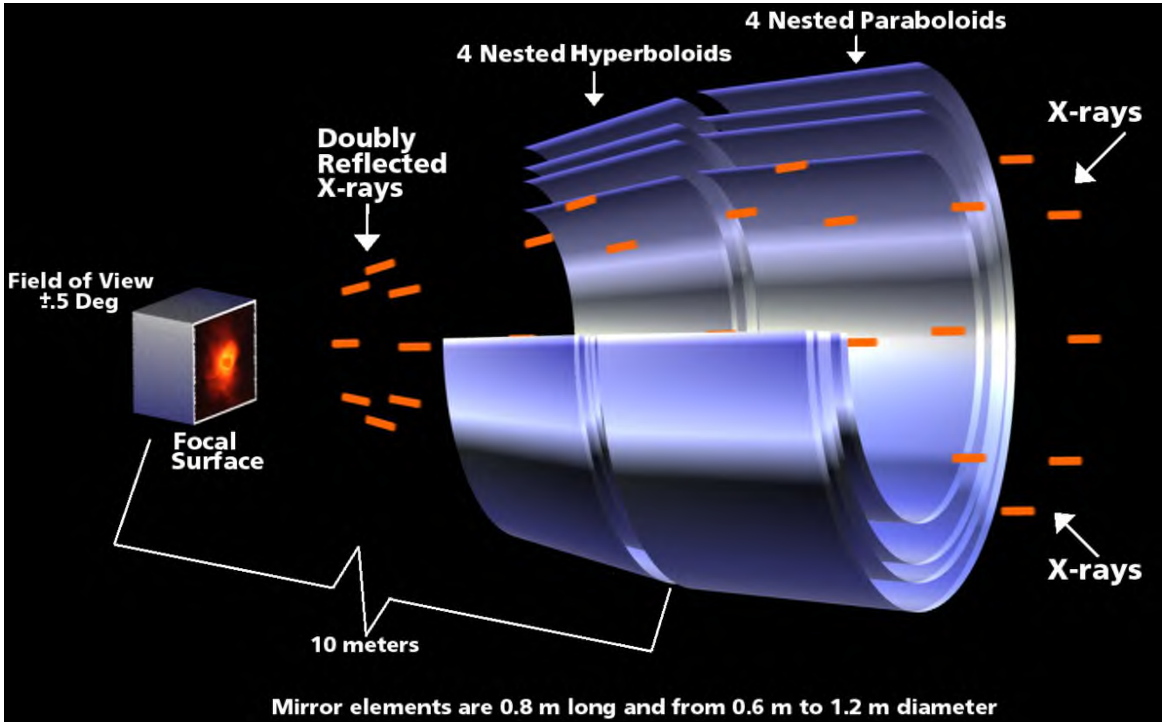
mapped 340 sources with large area detector (no optics)

Chandra observatory - ~ same collecting area as UHURU

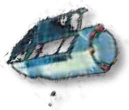
- ***5 orders of mag more sensitivity --- 1,000 sources / sq degree in deep fields***
- ***1 background count / keV year !***

X-Ray Optics has revolutionized x-ray astronomy!

Chandra X-ray Optics

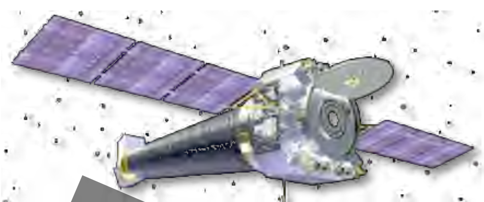


Mission Requirements / Future Challenges

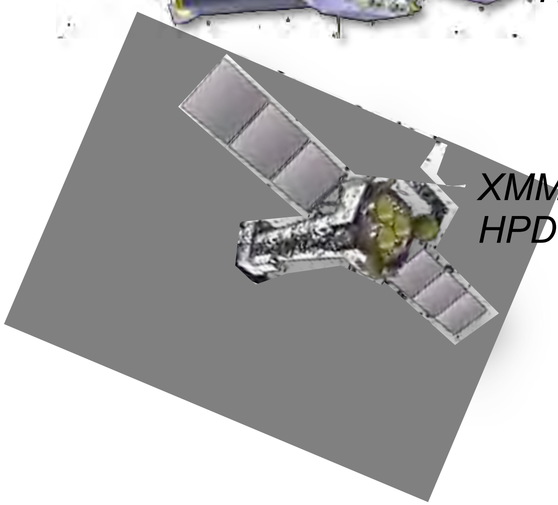


Einstein Observatory (1978-1981)
HPD =10″, A = 0.04 m^2 (f = 3.3 m)

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)

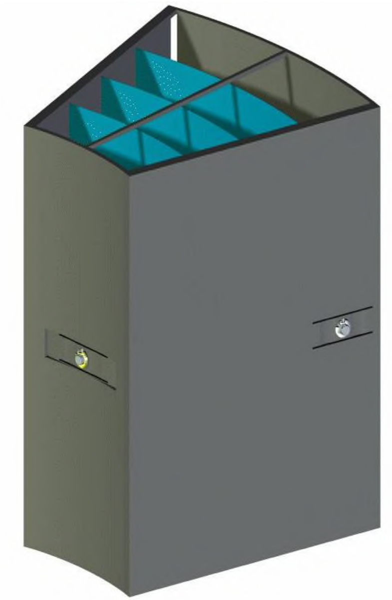


XMM-Newton (1999-?)
HPD = 14", A = 0.43 m^2 (f = 7.5 m)

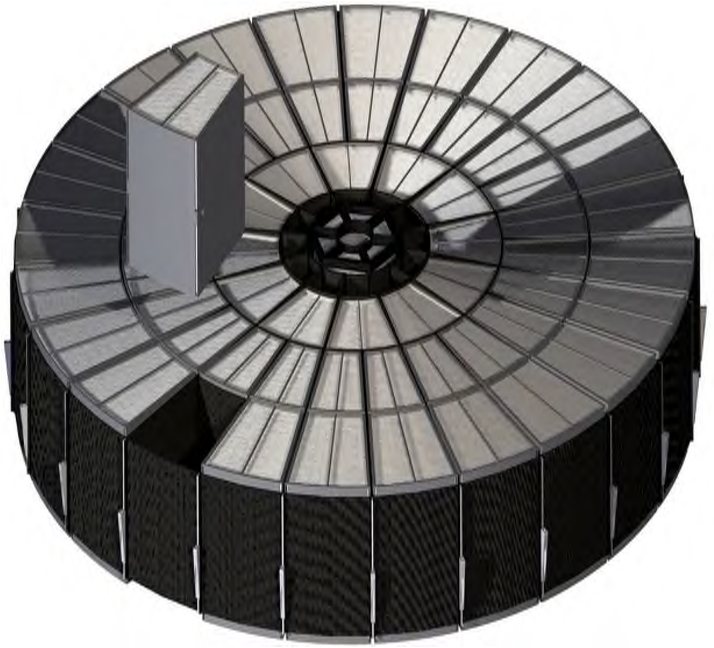
X-Ray Surveyor (2030 ?)
HPD = < 0.5", A ~ 2.3 m^2 (f = 10 m)

Process of Building a Telescope

~10^4 Mirror Segments!



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

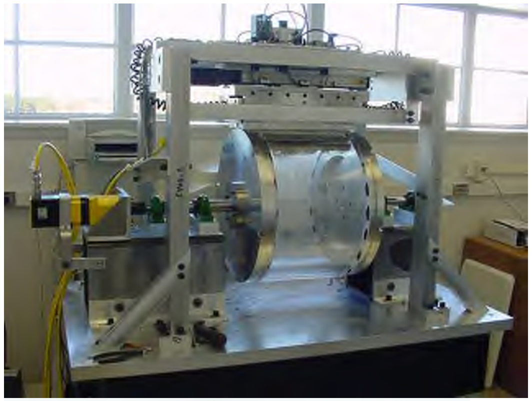


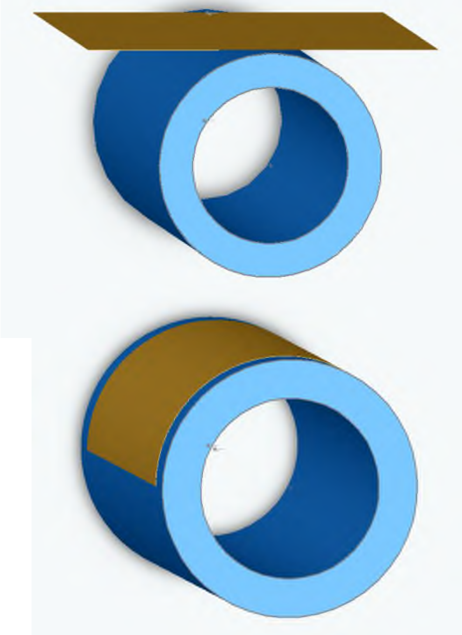
One or several mirror assemblies!

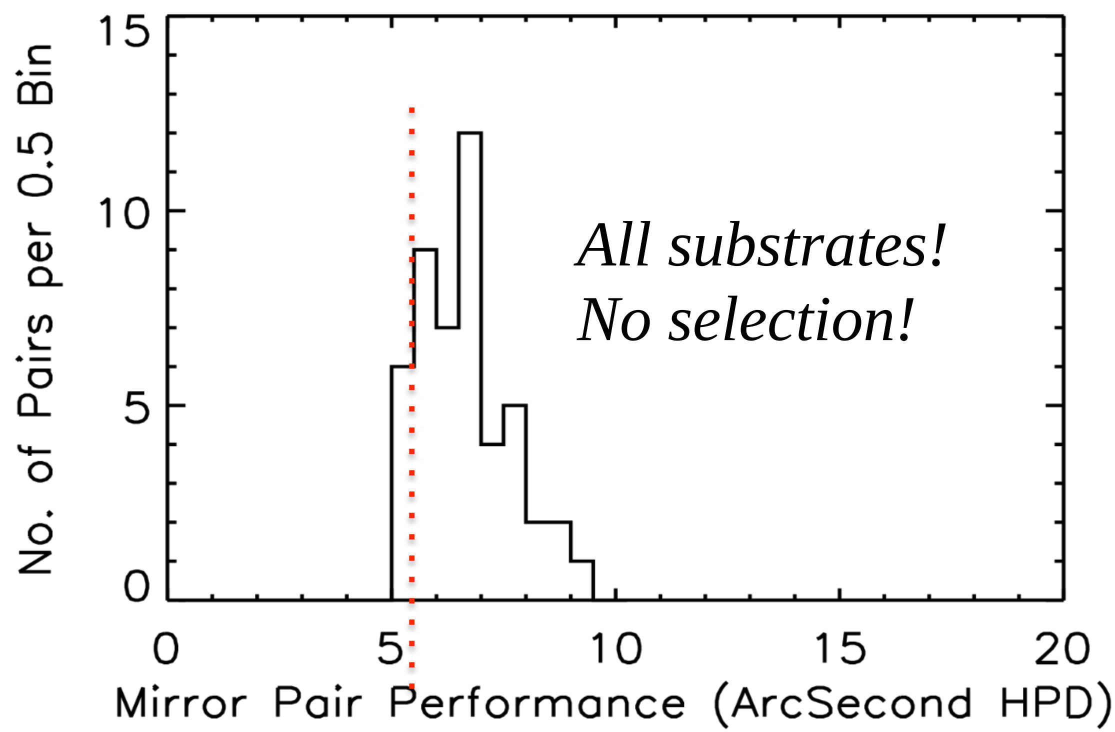
Will Zhang / GSFC

Glass Slumping

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



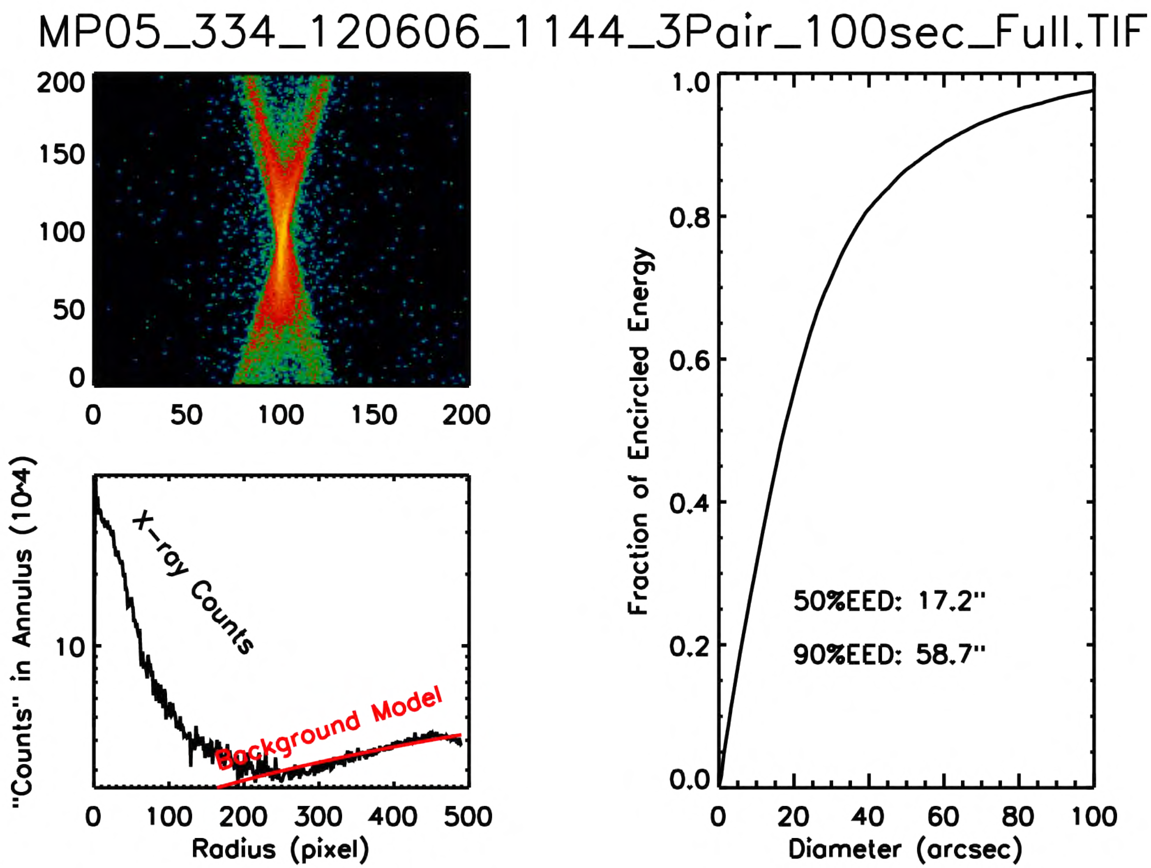




Will Zhang / GSFC

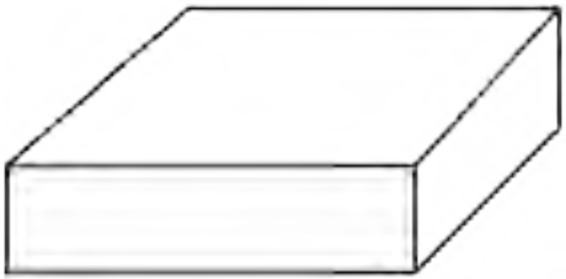
Technology Development Module
(X-ray Performance Test)

3 Pairs
Co-aligned
Bonded

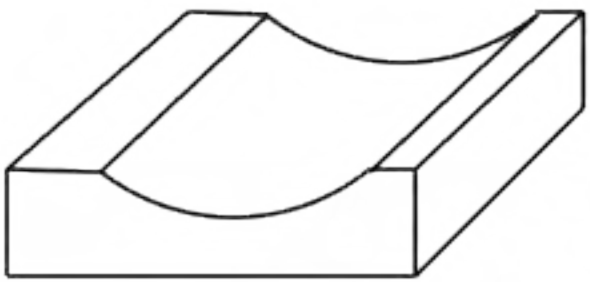


Will Zhang / GSFC

New Method for Fabricating Mirror Segment

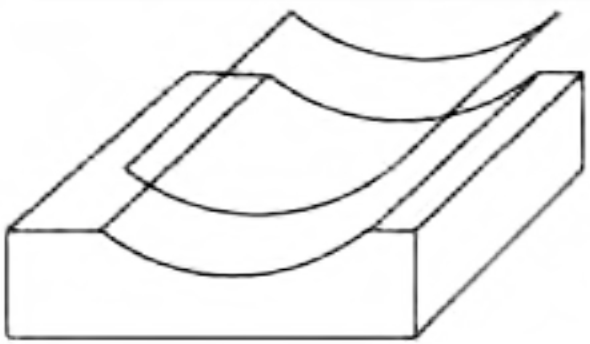


1. Procure mono-crystalline silicon: ***easy and cheaply*** *available.*
2. *Apply heat and chemical treatments to remove all surface/subsurface damage (**fast & cheap**)*



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**)*

!

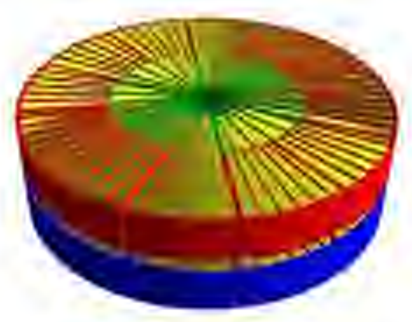


1. *Slice off (using W-EDM) the thin mirror segment (**fast & cheap**)*
2. *Apply heat and chemical treatment to remove all damage from back and edges (**fast & cheap**)*

Will Zhang / GSFC

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 $A_{ap} \approx 2.4\ m^2 \Rightarrow A_{surf} \approx 500\ m^2$.



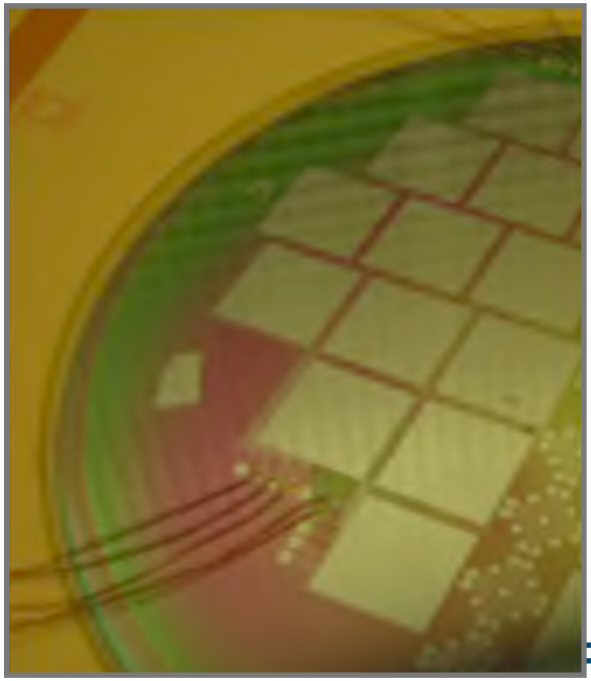
- **Launch considerations limit mass and volume.**
  - Mass constraints $\Rightarrow$ very lightweight mirrors.
  - Volume constraints $\Rightarrow$ many hundreds of highly nested (few mm), thin mirrors (0.4 mm).
- **Other considerations**
  - Very large number of actuators to fit in and control (10^6)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

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

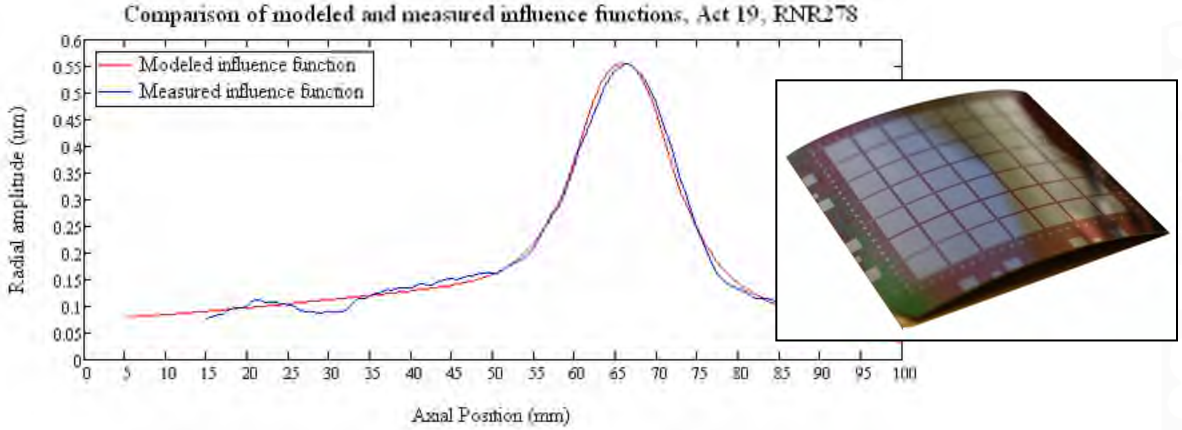


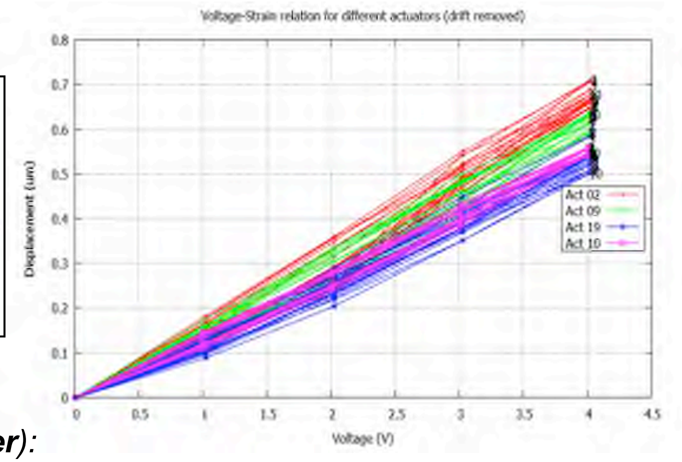
Flat test mirror – 100 mm diameter !
0.4 mm Corning Eagle glass with !
1.6 "m PZT and 1 cm^2 electrodes!
Also shows pattern of strain gauges!
(lower right) deposited on PZT.!

Paul Reid / SAO

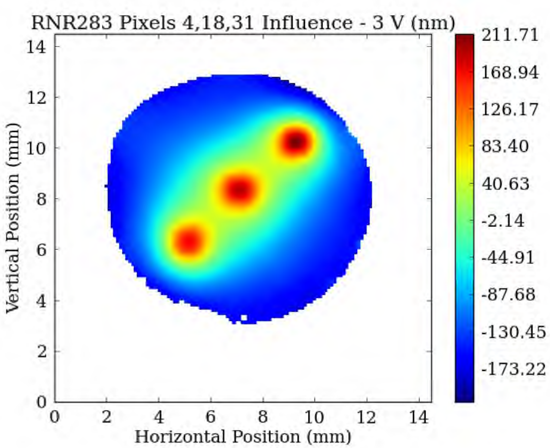
Adjustable X-ray Optics: recent progress

Conical mirror segments being produced with piezoelectric cells in place. Measured influence functions match modeled predictions well, and performance is stable and repeatable to within current metrology noise. Yield on flat test mirrors improved to consistently 97–100 per cent. !



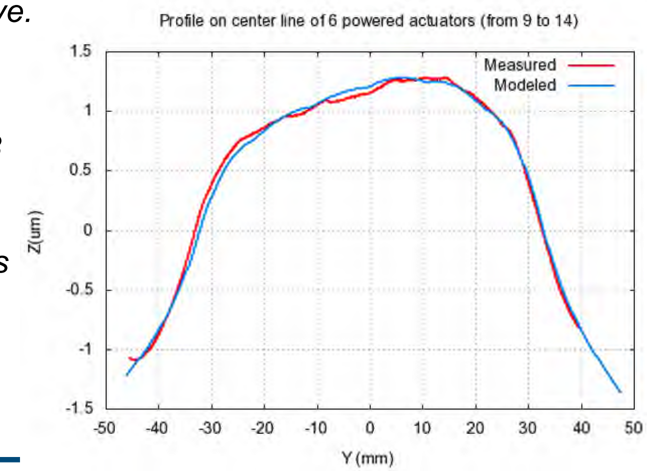


Cylindrical mirror**, 10cm x 10cm with 49 1cm x 1cm actuators (**top, center**):* ***Top Left: *Profile through modeled and measured influence function – agree to better than metrology noise.* ***Top Right**: Hysteresis curves for 4 piezo cells. 10 repeats of each curve.*



Flat test mirror (10 cm diam.):
Left: *Measured influence functions (3 piezo cells), measured with new Shack-Hartmann wavefront sensor.*
***Right**: Line scan through 6 piezo cells at 10V (using optical profilo-meter)*

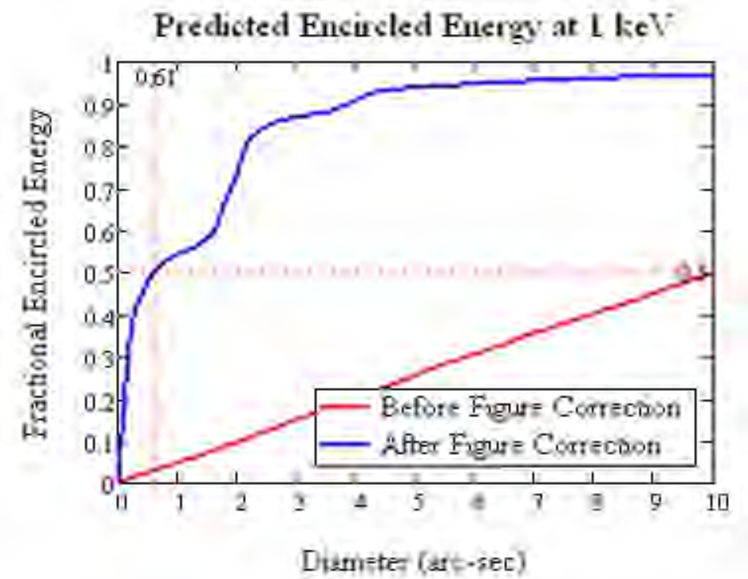
Paul Reid / SAO

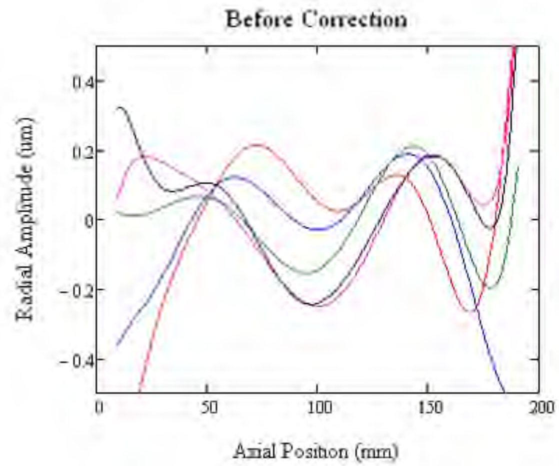


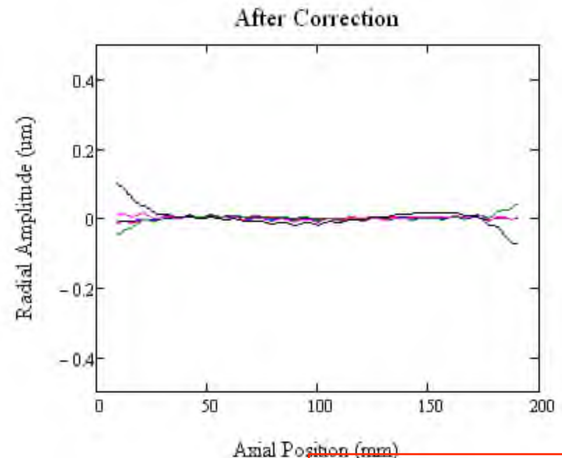
Simulated correction of measured data yields 0.6 arc sec HPD for initial 10 arc sec mirror pair

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:







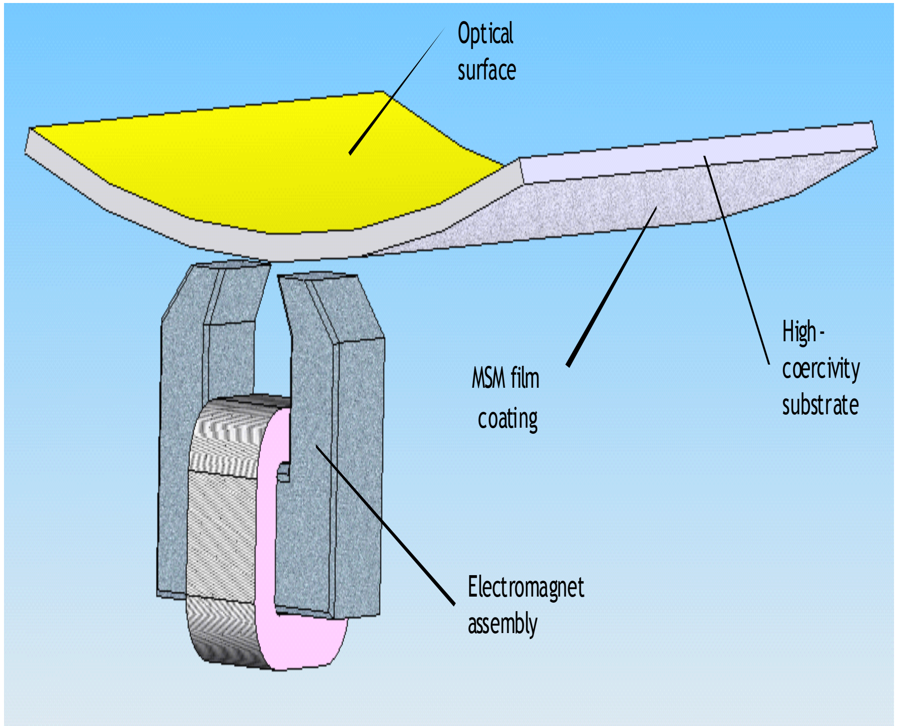
Paul Reid / SAO

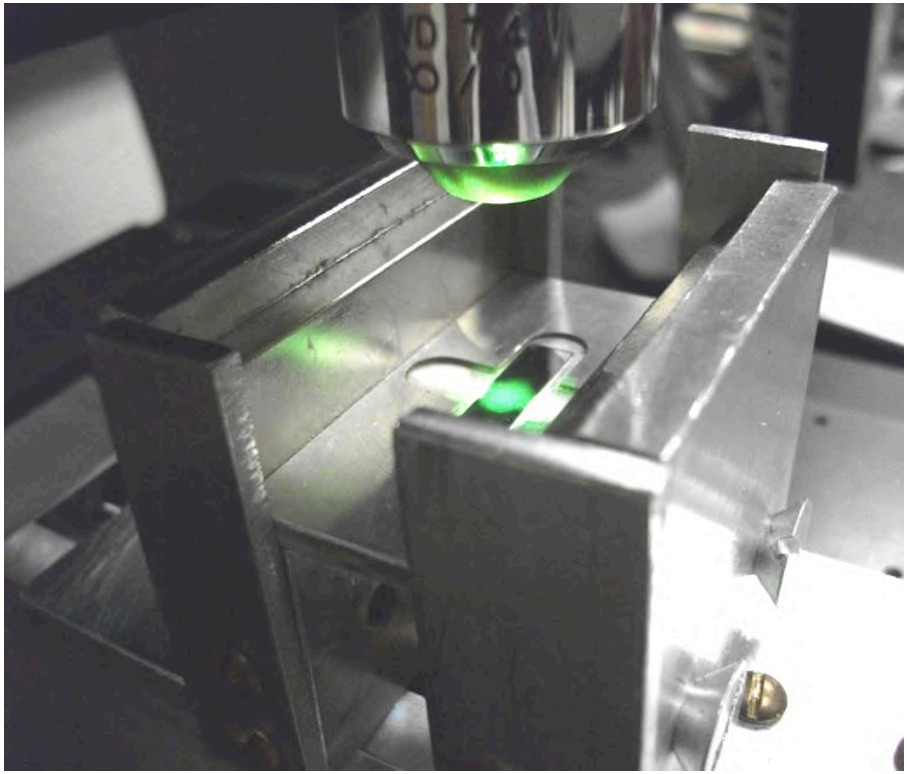
Adjustable X-ray Optics: recent progress

- **Simulations and modeling**
  - Used measured mounted mirror segment data scaled to the SMART-X mirror point design, with modeled influence functions
  - Optimize piezoelectric adjuster voltages using bounded, constrained least squares optimization, and apply simulated correction
  - Results in 0.4 arcsec rms diam. image from initial 16 arcsec rms diam.
- **Accelerated lifetime testing**
  - Consistent with > 10^2 years
- **Integrated on-piezo-cell control electronics (work in progress)**
  - ZnO thin film transistors deposited on piezo cells
  - Piezo electrical properties unchanged
  - Will enables row-column addressing of piezo cells (as in in LC displays)
- **Improving metrology accuracy**
- **Developing mirror segment alignment capability for sub-arcsec imaging.**

Paul Reid / SAO

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





Form substrate with 10” resolution.

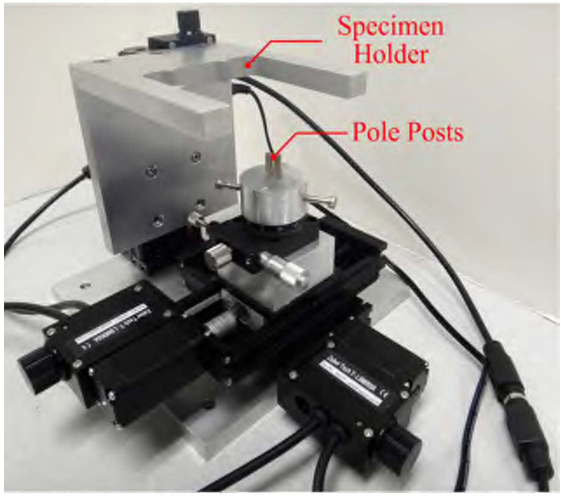
Use a magnetically hard substrate or coated layer on substrate.

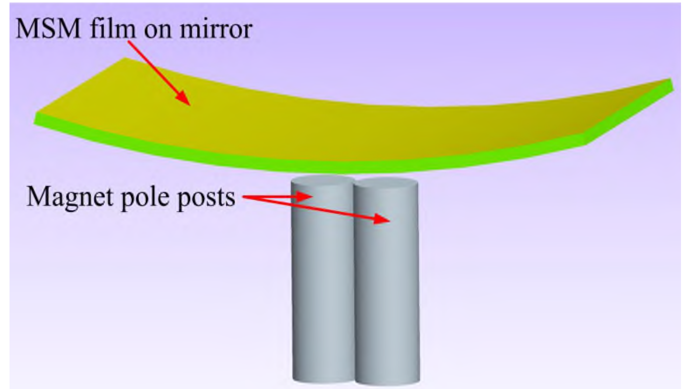
Deposit MSM thin film on back.

Measure magnetically written deformation with interferometer.

Mel Ulmer / NWU

Future work





Device set up

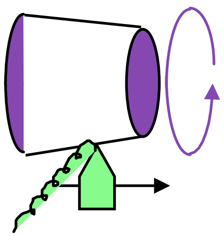
The motion stage with two permanent rare earth post magnetics that will allow us to write using up to about 0.1 T (1000 G) onto the piece being held in on a stage in the open U-shaped area. The travel ranges are 50 mm in x and y directions and 25 mm in the z direction.

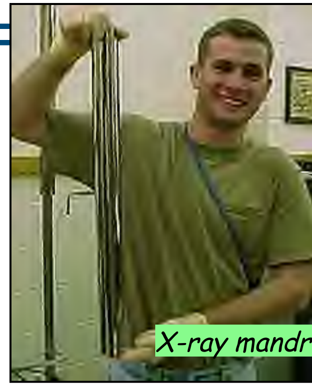
Active Control - Summary

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 ?**

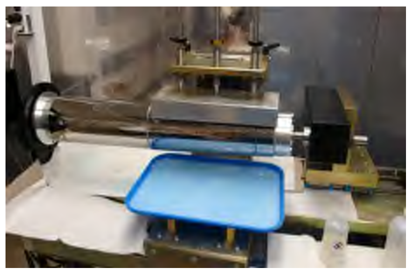
MSFC Developments : Electroformed Nickel Replication

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



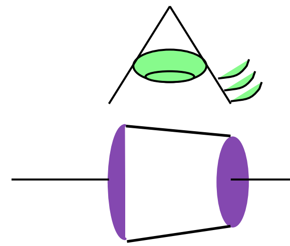


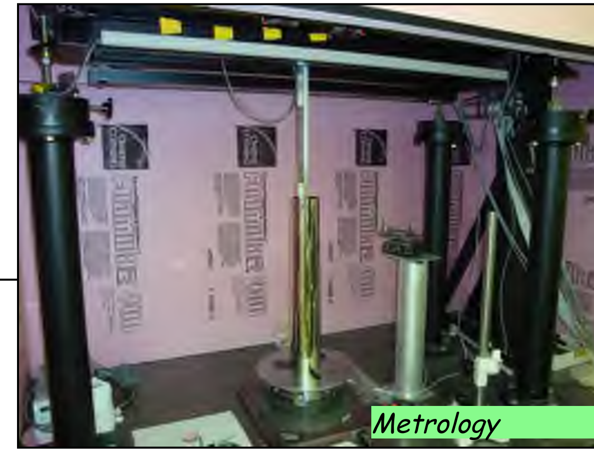
X-ray mandrel



Mandrel polishing

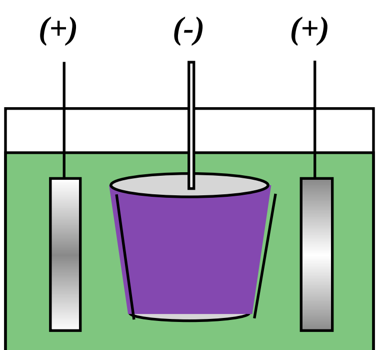
Metrology on mandrel





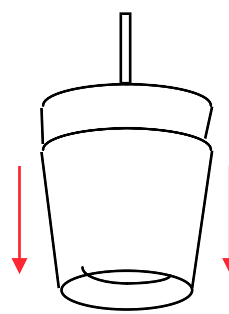
Metrology

Electroform Ni/Co shell onto mandrel



X-ray shell electroforming

Separate optic from mandrel in cold water bath

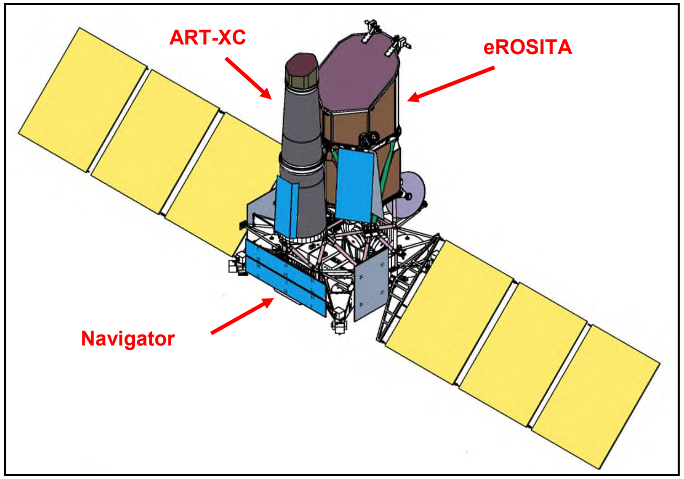


Replicated X-ray shells

Replicated X-ray optic projects at MSFC

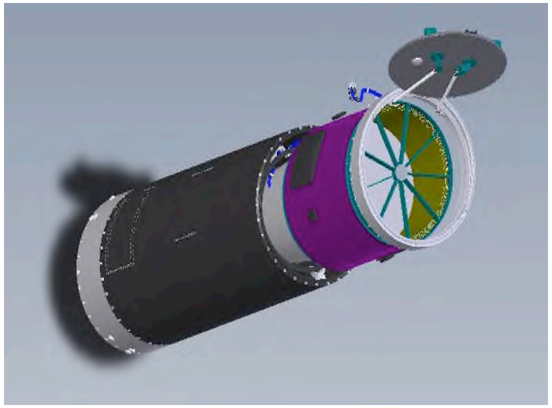
Astronomical applications

ART-XC



FOXSI

MicroX

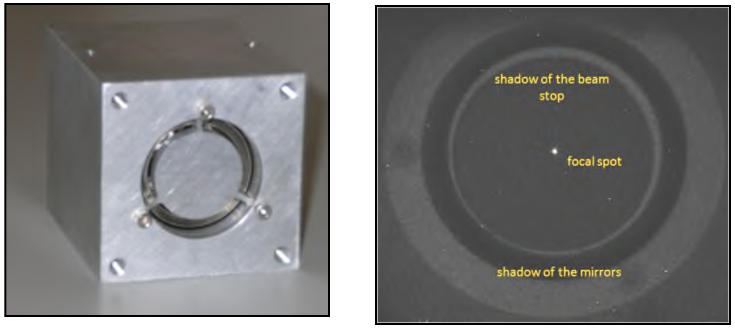


HEROES

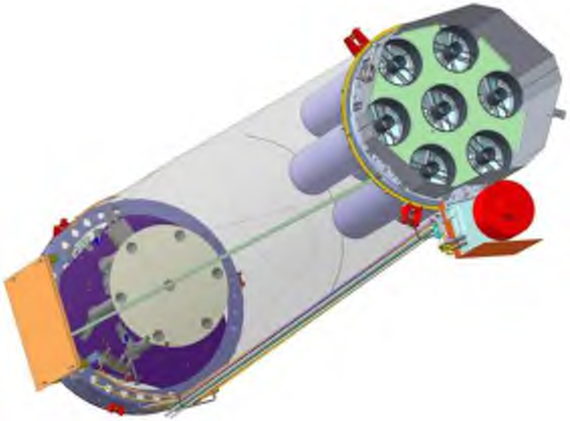
Non-astronomical applications

Medical imaging

Neutron imaging



ART-XC



Description:

ART-XC is a medium energy x-ray telescope that will fly aboard the Russian Spectrum-Rontgen-Gamma Mission.

ART-XC will fly in 2016 and during its 7-year mission will conduct a 4-year survey of the sky, with an additional 3 years for follow-on studies

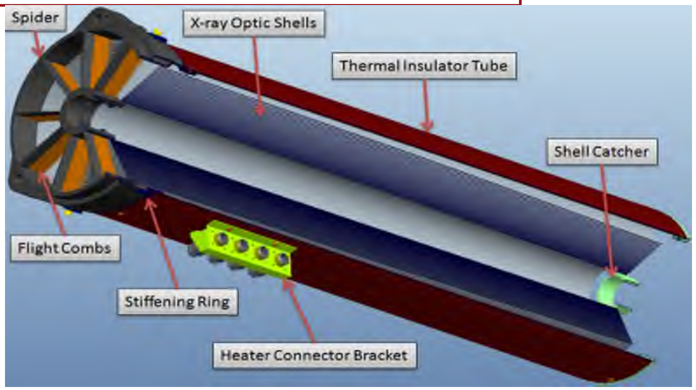
MSFC will provide x-ray optics modules for the ART-XC instrument.

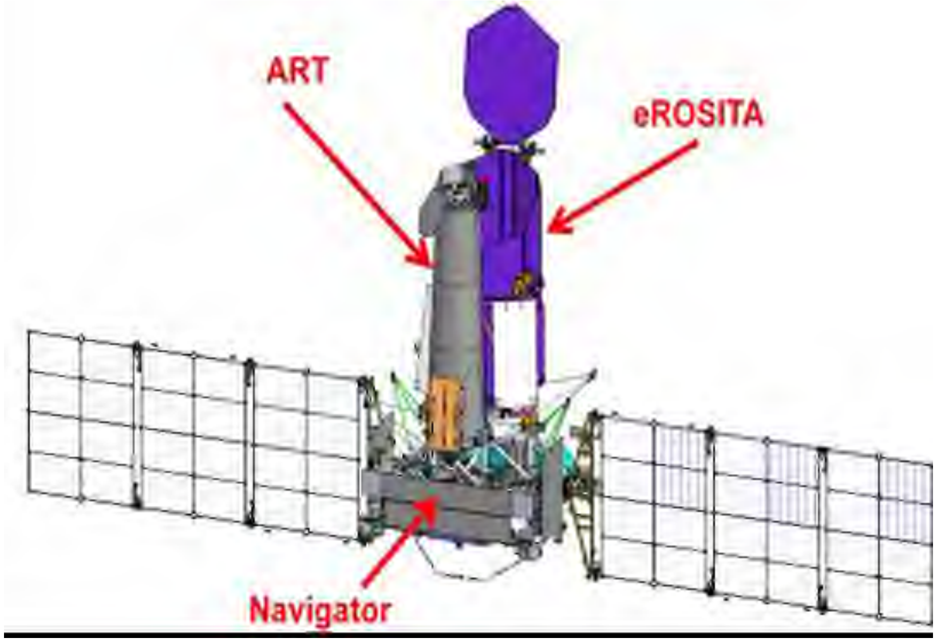
Delivery of the optics is scheduled for late Summer 2014

Customer:

Space Research Institute of the Russian Academy of Sciences (IKI)

Funded under an International Reimbursable Agreement between NASA and IKI



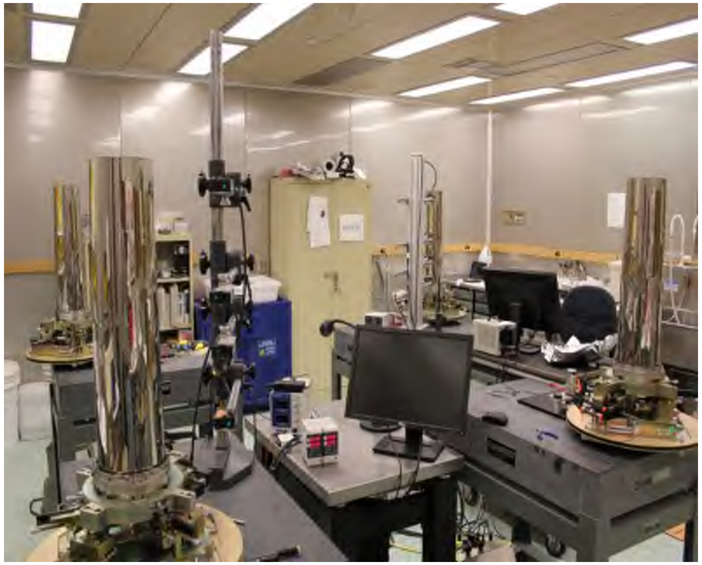


ART-XC Optics Configuration

MSFC has designed and is fabricating

- ***four** ART x-ray optics modules under an International Reimbursable Agreement between NASA and with IKI (delivery – August 2014)*
- ***three + one spare** ART modules under Agreement regarding Cooperation on the ART-XC Instrument onboard the SRG Mission between NASA and IKI (delivery – October 2014)*

Parameter	Value
Number of Mirror Modules	7=4+3 (plus 1 spare)
Number of Shells per Module	28
Shell Coating	> 10 nm of iridium (> 90% bulk density)
Shell Total Length, inner and outer diameters	580 mm, 50 mm, 150 mm
Encircled Half Energy Width	25 arcsec HPD on axis (measured)
Mirror Module Effective Area	≥ 65 cm^2 at 8 keV (on axis)
Module Focal Length	2700±1 mm



Focusing Optics X-ray Solar Imager (FOXSI)

Description:

FOXSI is a sounding rocket based payload consisting of x-ray optics (provided by MSFC) and focal plane detectors provided by ISAS/ Japan.

FOXSI has 7 mirror modules each with 7 (10 Foxsi-2) nested shells. Measured FWHM = 6-7 arcsec (with 5 arcsec detector).

FOXSI designed to make hard-x-ray observations (5-15 keV) of solar nanoflares, thought to play an important role in heating the corona to millions of degrees.

FOXSI was launched from White Sands missile range on 2 Nov, 2012, for a ~ 6 min flight.

FOXSI-2 version had successful flight from White Sands on 11 Dec, 2014!

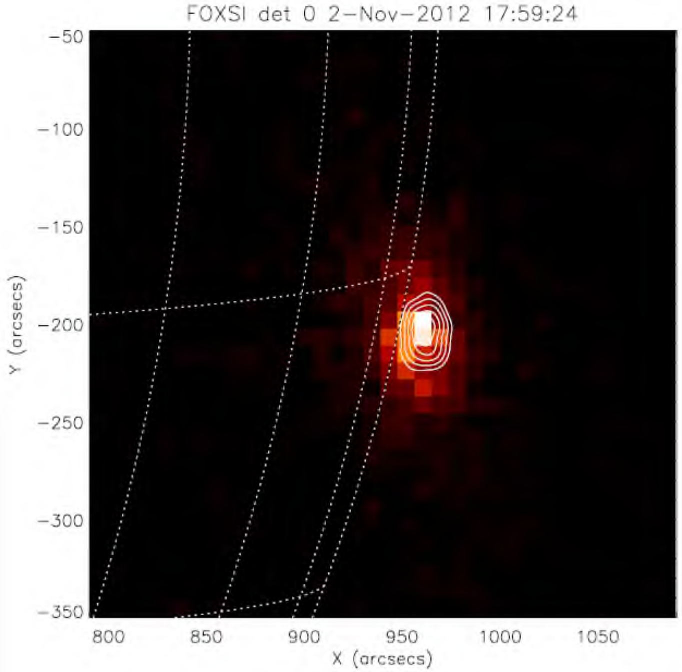
!

Customer:

University of California, Berkeley

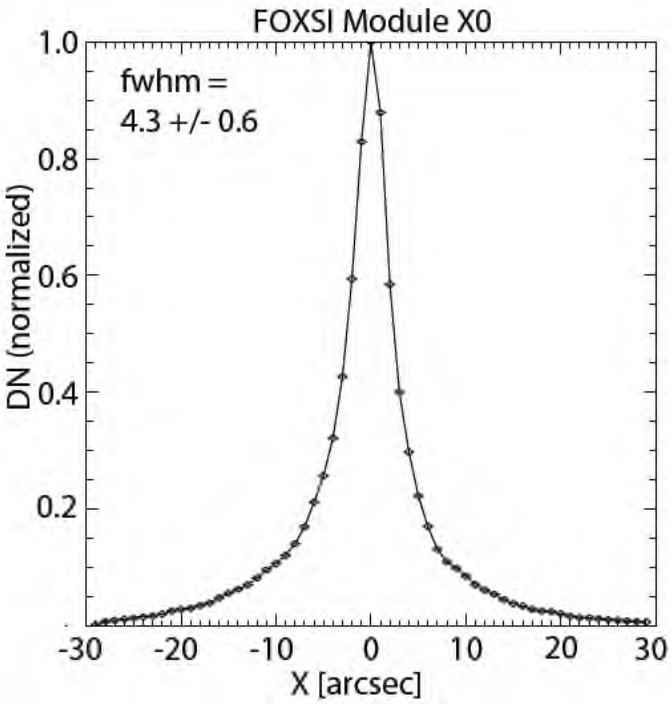
P.I. Sam Krucker

Funded by the Science Mission Directorate, through the low-cost access to space program.



FOXSI

Mirror shell alignment and installation station



Module net angular resolution after detector resolution removed

Micro-X

Description:

Micro-X is a sounding rocket based payload consisting of x-ray optics (provided by MSFC) and a calorimeter detector led by MIT

Micro-X will fly in early 2017 and make high-spectral-resolution images of supernova remnants Puppis A and Cas A.

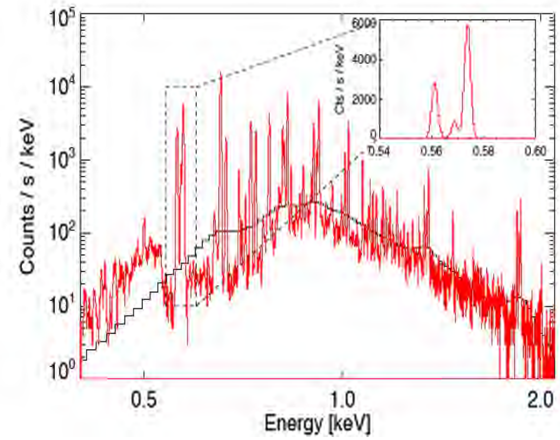
The 0.5m diameter optics are under construction at MSFC. Completion schedule for 2016.!

!

Customer:

Massachusetts Institute of Technology / Tali Figueroa

Funded by the Science Mission Directorate, through the low-cost access to space program.



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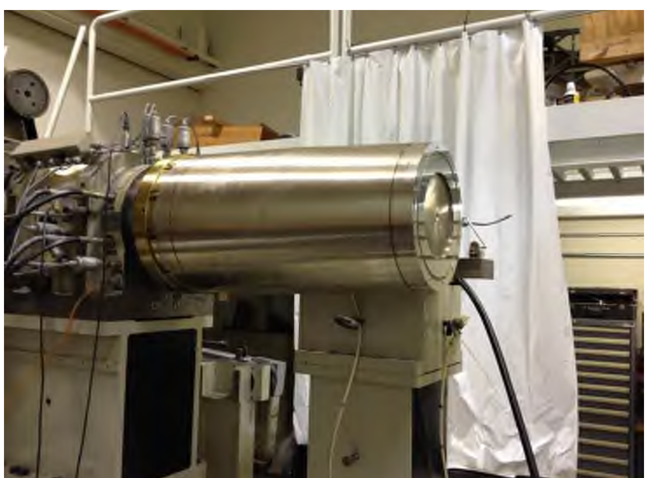
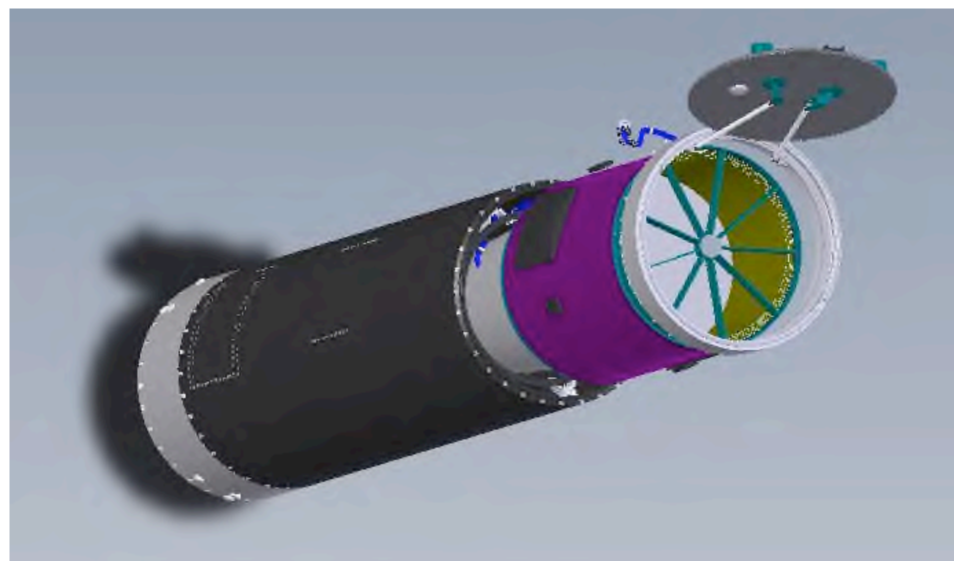


Micro-X mandrel on diamond turning machine



High Energy Replicated Optics to Explore The Sun

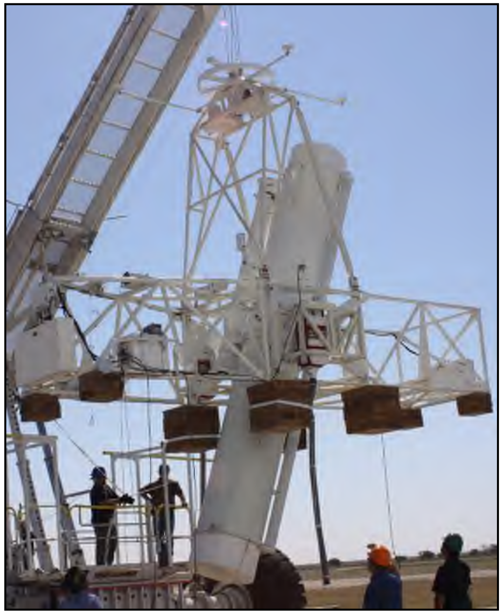
HEROES mission, a collaboration with GSFC, was part of the Hands On Project Experience (HOPE), with the primary goal of training NASA scientists and engineers to fly a hard x-ray (20-75 keV) telescope on a balloon platform.

Heliophysics

- Investigate electron acceleration in the non-flaring solar corona by searching for the hard X-ray signature of energetic electrons.
- Investigate the acceleration and transport of energetic electrons in solar flares.

Astrophysics

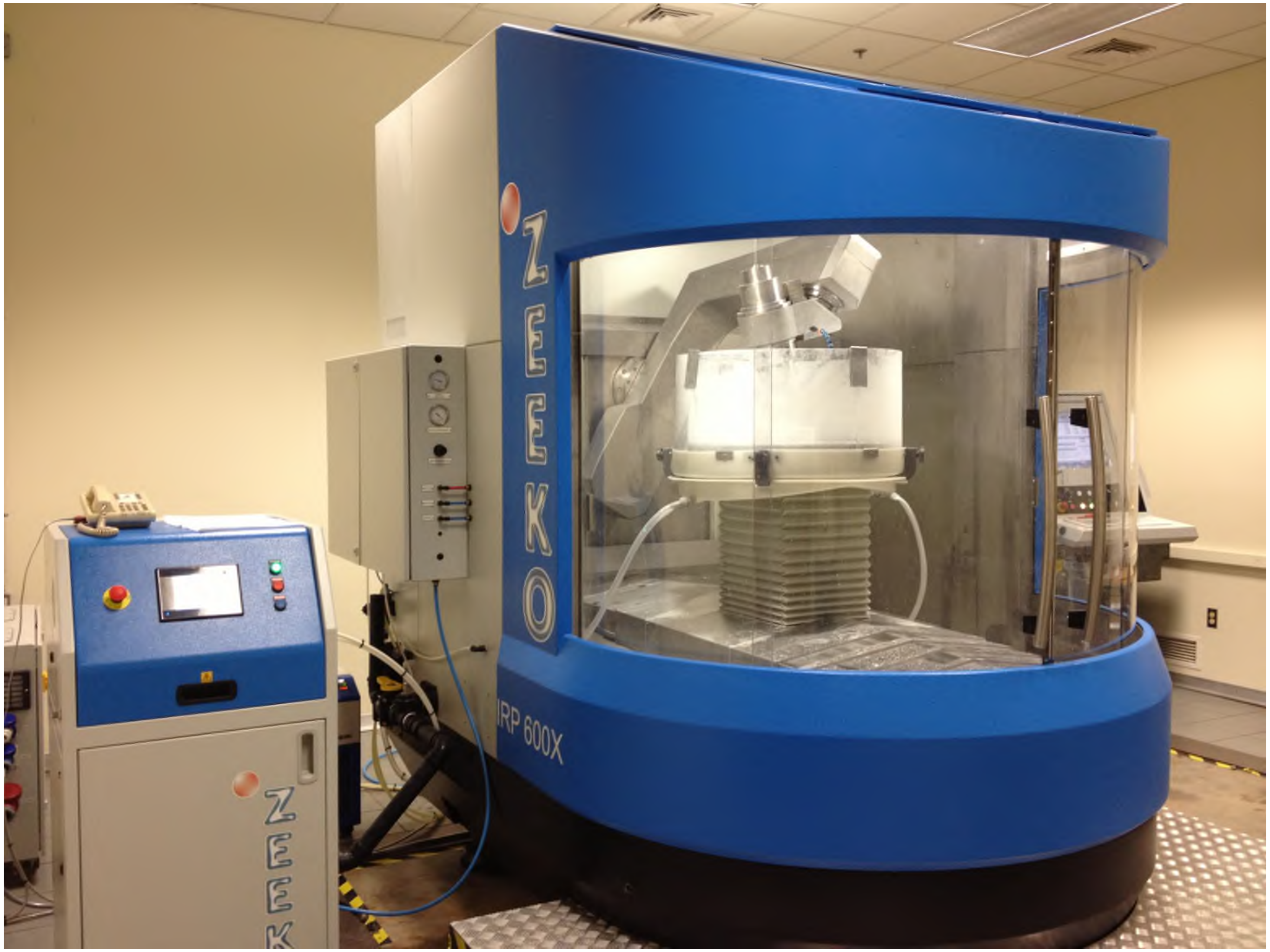
- Investigate the scale of high energy processes in a pulsar wind nebula.
- Investigate the hard X-ray properties of astrophysical targets such as X-ray binaries and active galactic nuclei.



Launch (9/21/2013)!

Flight!

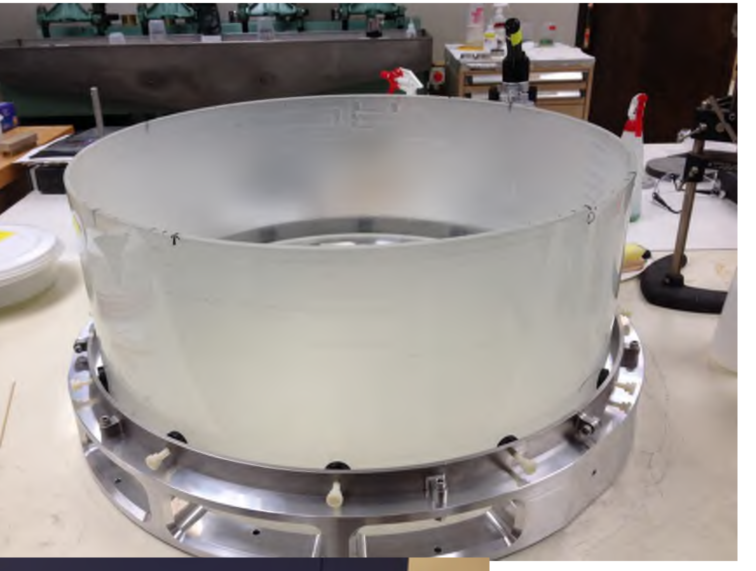
Other developments: Full-Shell Direct Fabrication

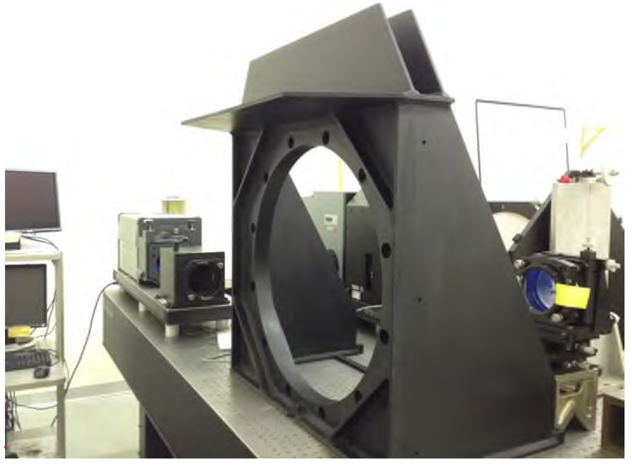


Full-*Shell* Direct *F*abrication

PLAN

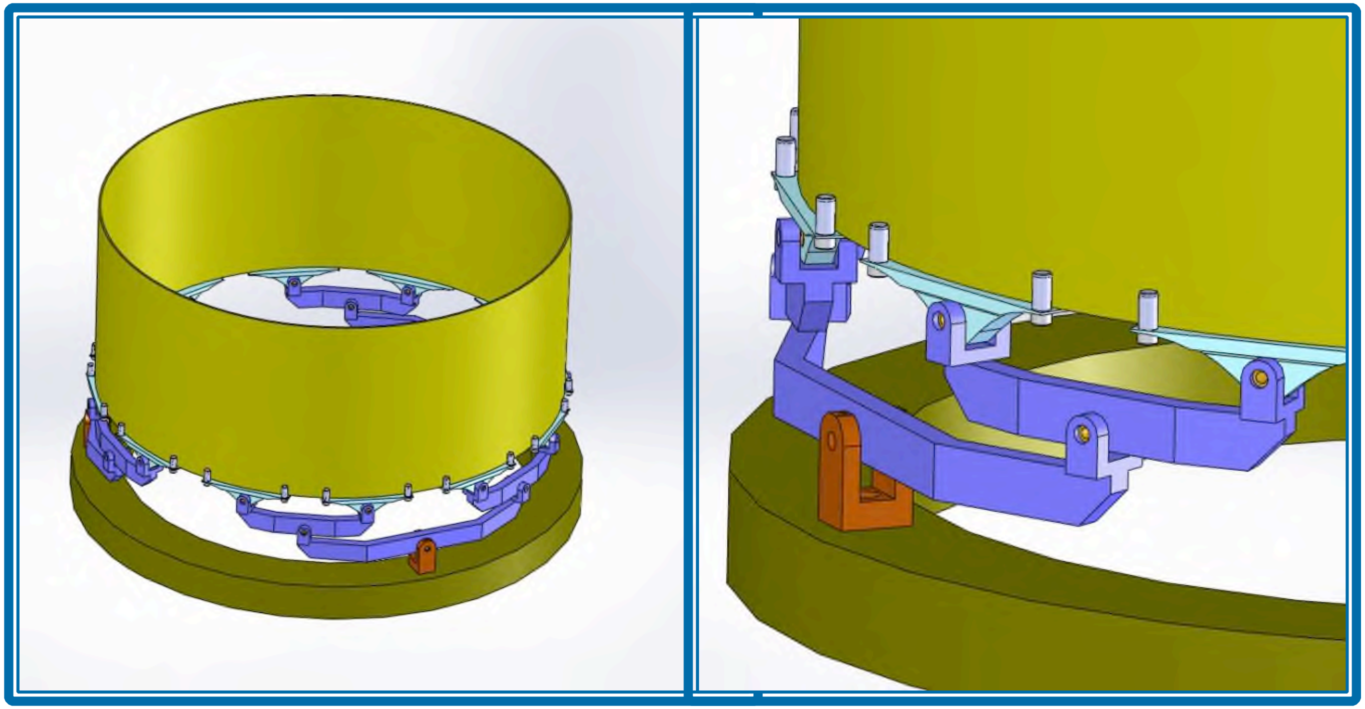
- *Demonstrate capability with 'thick' (~ 6 mm) shell first*
  - *Gain experience with ZEEKO machine (in process)*
  - *Grind glass shell ready for ZEEKO machine* 👍
  - *Fabricate fixturing for polishing shell* 👍
  - *Fabricate fixturing for metrology of shell* 👍
- *Move to thin shells (2-3 mm)*
  - *Develop polishing fixtures (in process)*
  - *Develop metrology fixtures (in process)*
- *Candidate materials*
  - *Start with glass (pyrex, fused silica)*
  - *Also investigate Be and AlSi alloys*





Full-Shell Direct Fabrication

Challenge: *Supporting glass during metrology*
Need to know the true figure of the shell. Polishing fixture will distort shell at some level. ***Solution:*** *to use a metrology mount that preserves the native shell figure (mount is termed a 'whiffle tree').*
!



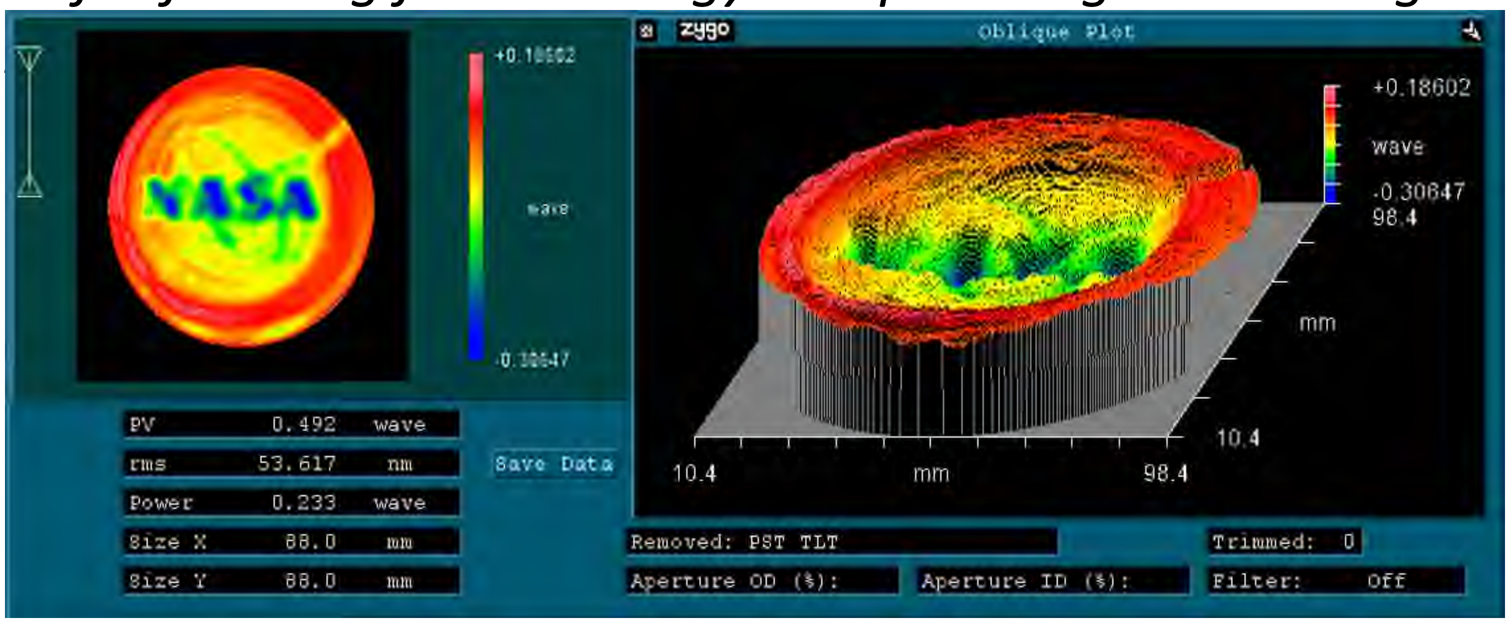
Direct Fabrication – Current Status

Thick Shell

- *All fixturing has been completed and we are ready to start thick shell fabrication*

Thin shell

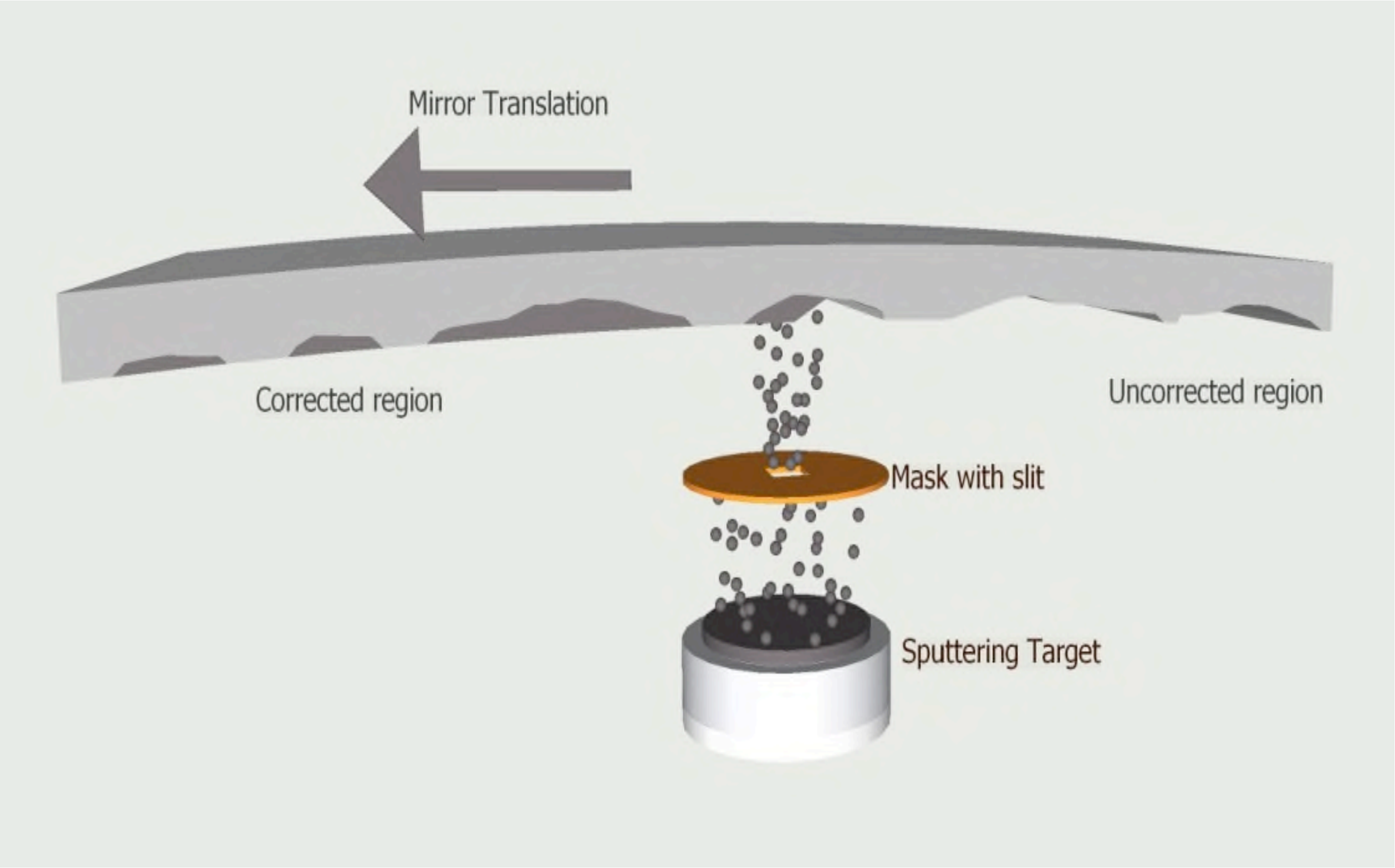
- *Designs for fixturing for metrology and polishing are nearing comp*



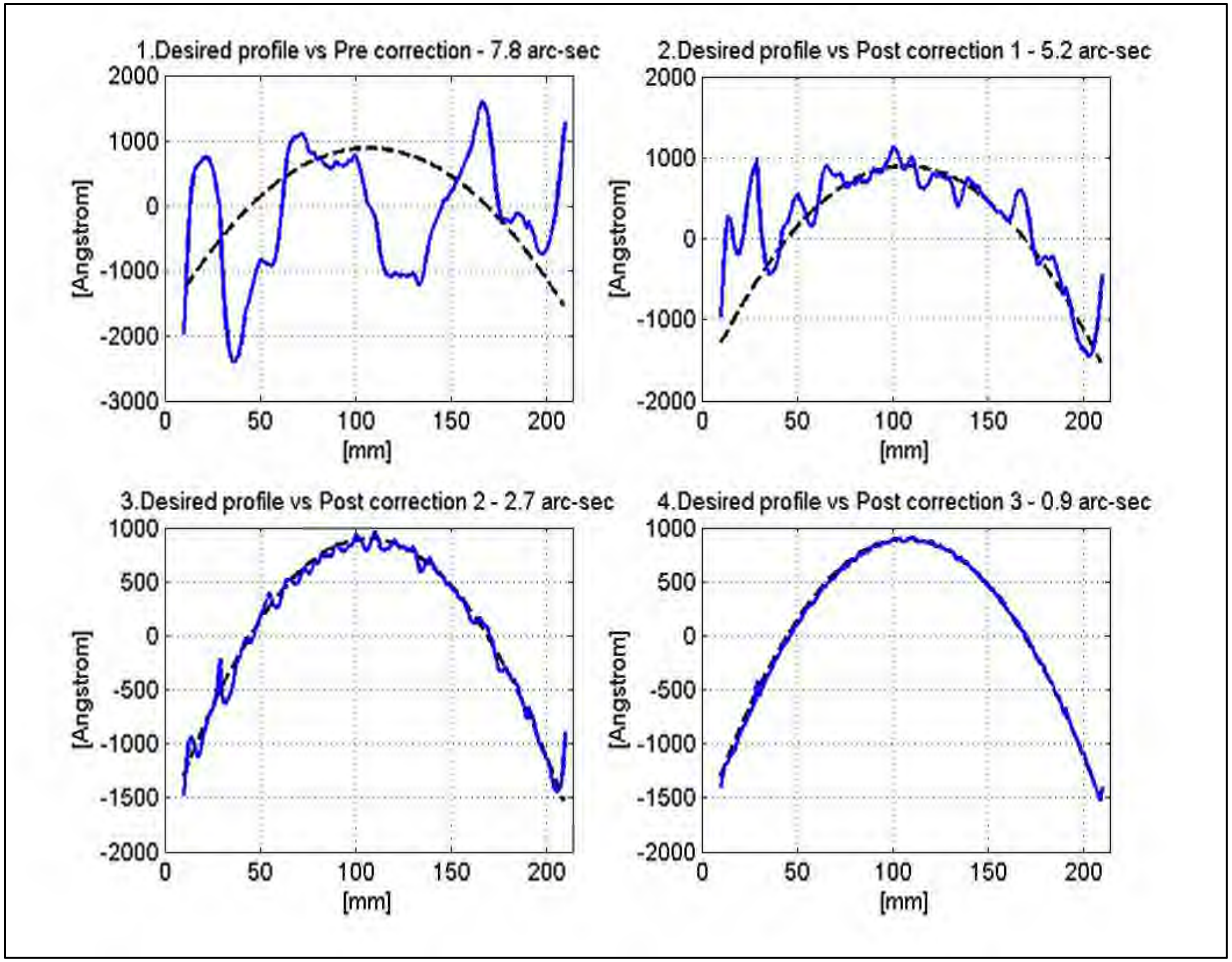
New Developments: Differential Deposition

- ***What***
  - *Differential deposition is a technique for correcting figure errors in optics*
- ***How***
  - *Use physical vapor deposition to selectively deposit material on the mirror surface to smooth out figure imperfections*
- ***Why***
  - *Can be used on **any type** of optic, full-shell or segmented, mounted or unmounted*
  - *Can be used to correct a wide range of spatial errors. Could be used in conjunction with other techniques… e.g. active optics.*
  - *Technique has been used by various groups working on synchrotron optics to achieve sub-µradian-level slope errors*

Coating Configuration

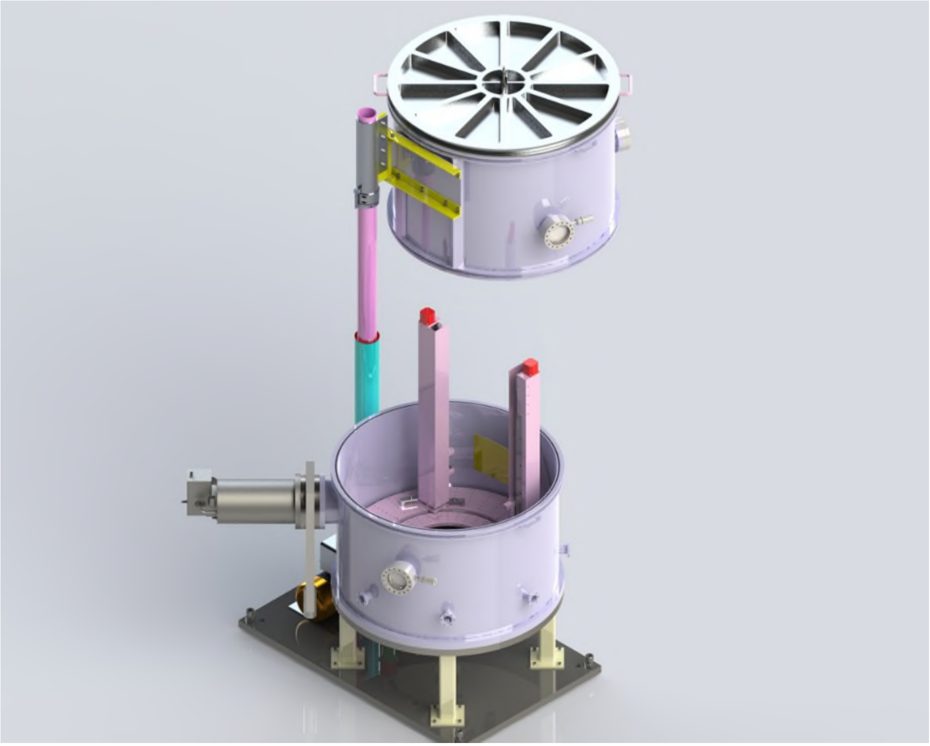


Process Sequence – Differential Deposition

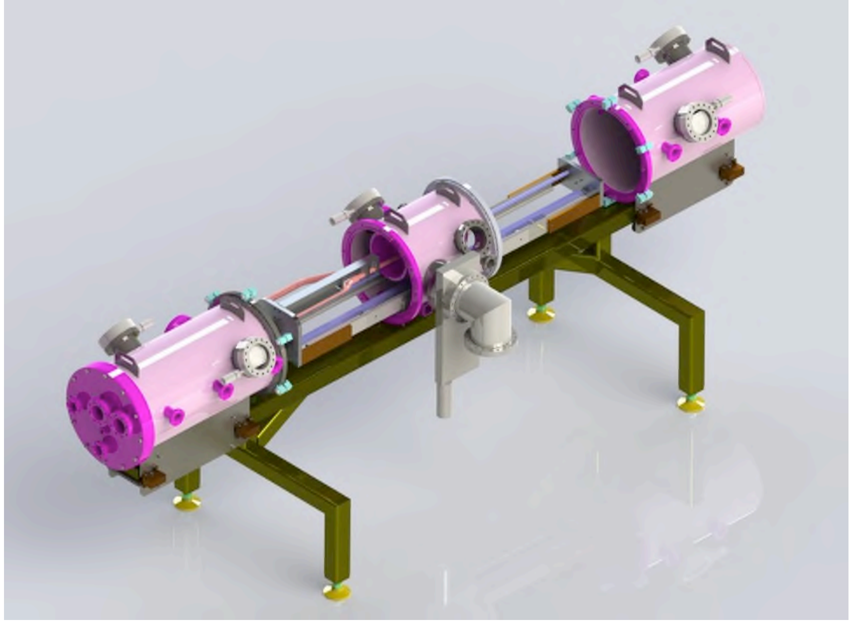


Simulated correction sequence showing parabolic axial figure profile before (top left) and after 3 stages of correction using a beam of FWHM = 14mm, 5.2 mm and 1.7 mm respectively. The dotted line gives the desired figure and the solid line gives the figure obtained at each stage. Overall, resolution improved from 7.8 arcsec to 0.9 arcsec HEW (2 bounce equivalent).!

New coating systems

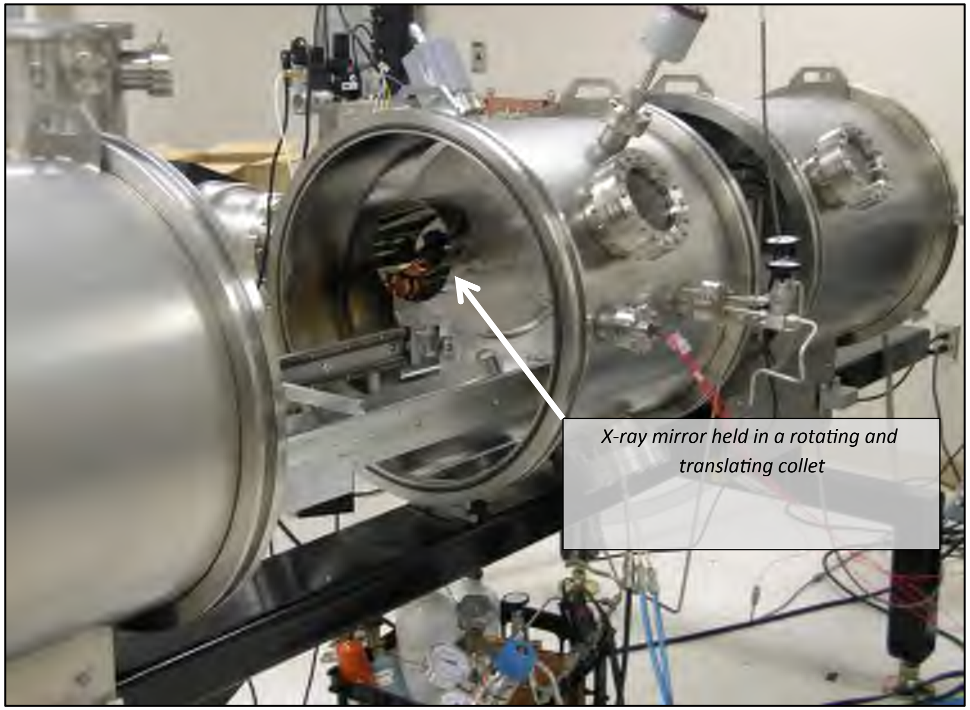


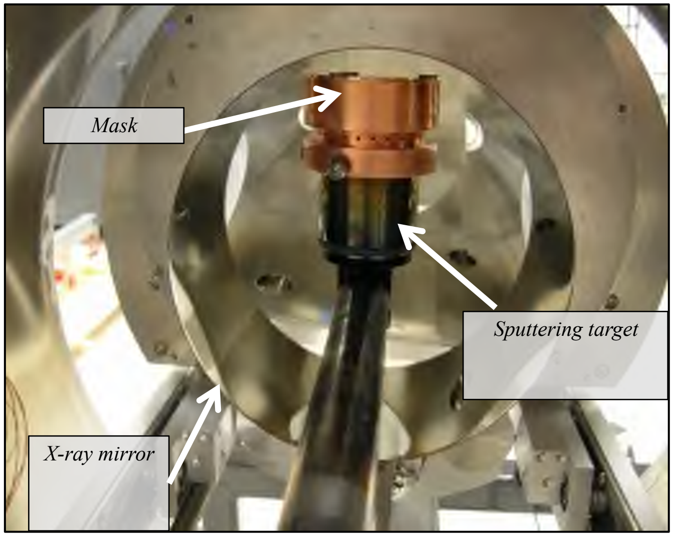
Vertical chamber for segmented optics



Horizontal chamber for 0.25-m-scale full shell optics

Coating Systems

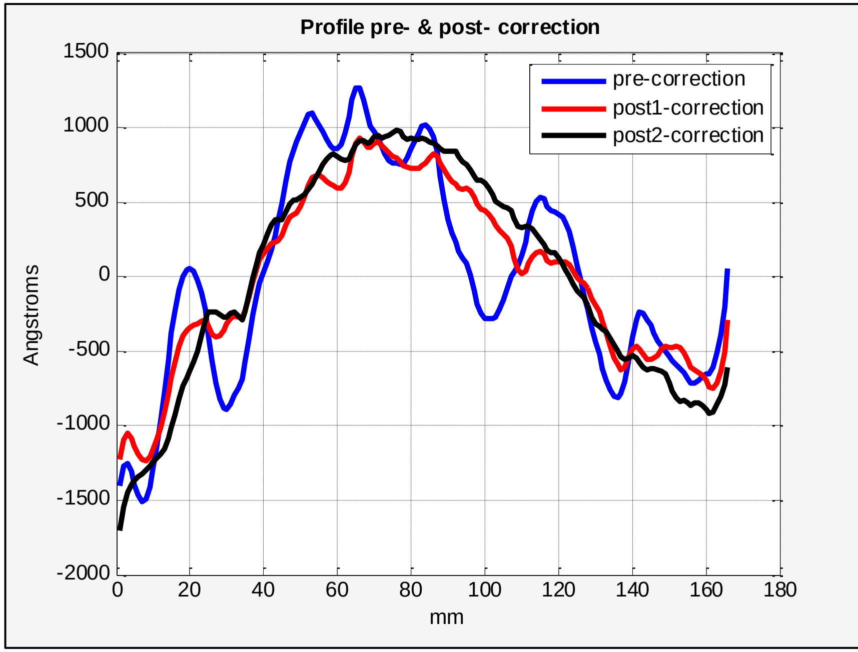


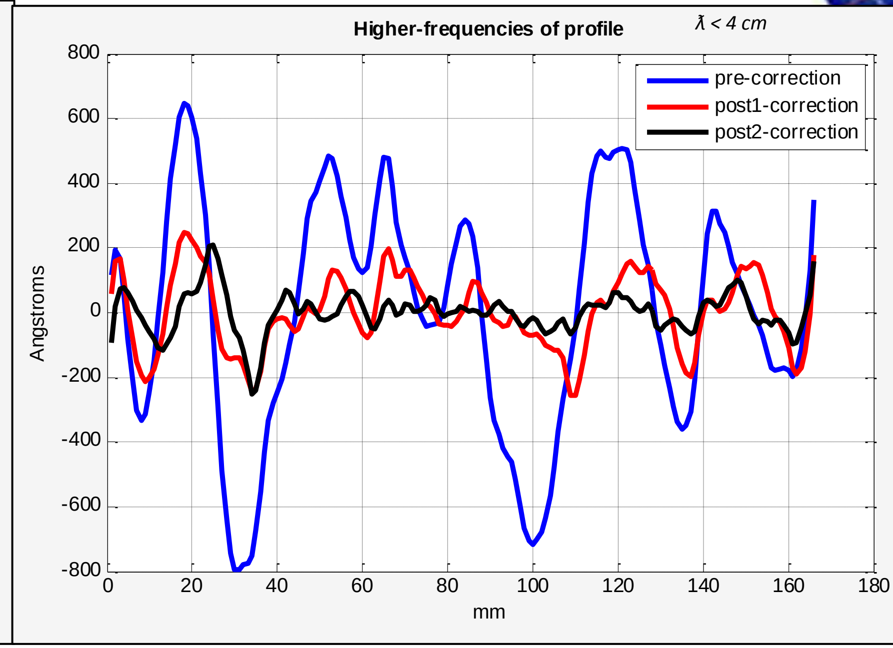


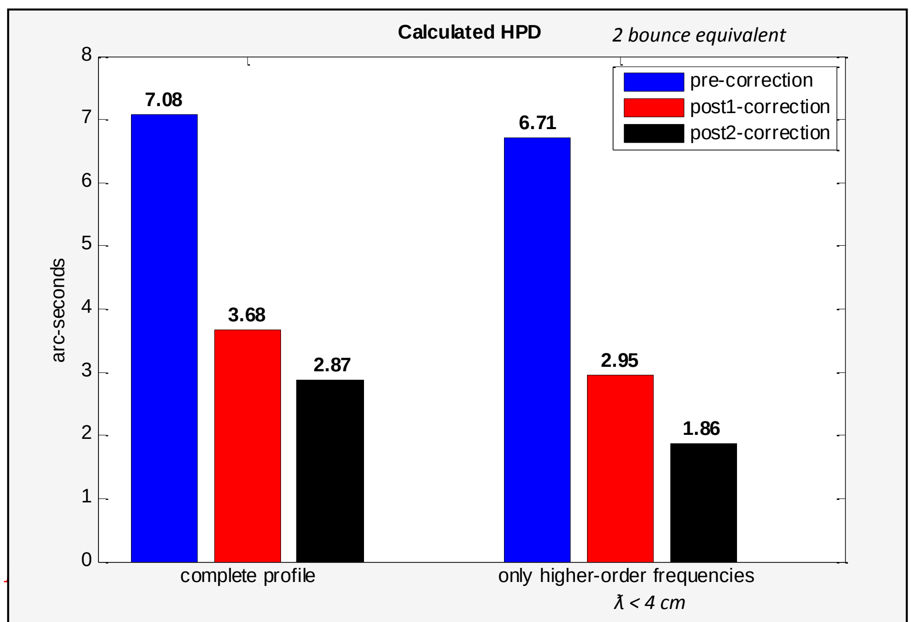
Sputtering head with copper mask positioned inside shell

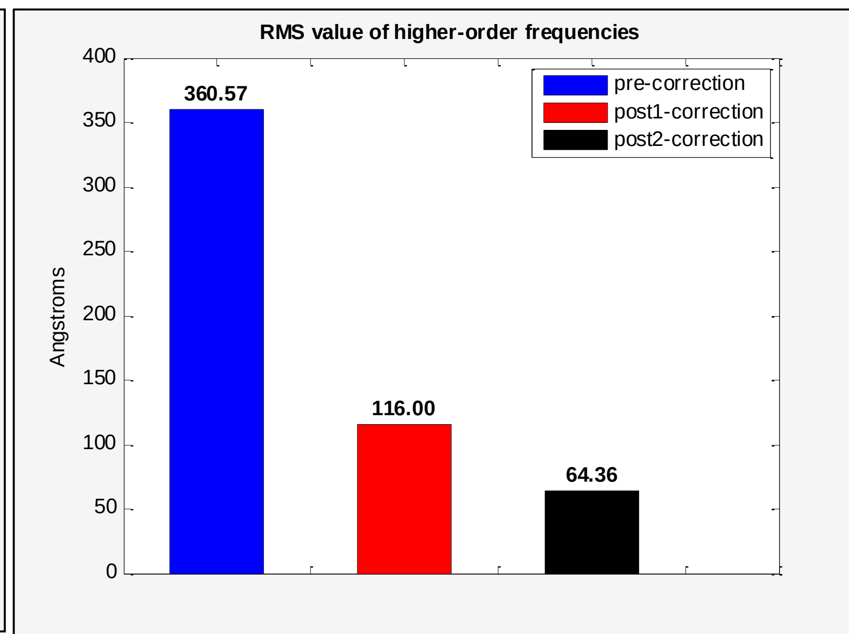
Horizontal differential-deposition chamber

Test # 1: 150 mm diameter shell P-end, 2 stages of correction









Differential Deposition – Top Challenges

• Metrology on the inside of the thin shells is very challenging. For 2 stages of correction need to get reliable and repeatable metrology to 10's Angstrom. Removing and mounting the thin shells for metrology is a tricky business. In-situ metrology, currently under development, should significantly improve matters.

• Stress control is also a challenge. We believe we can demonstrate very-low-stress coatings, but have to investigate the relationship between the properties of coatings in the differential deposition chambers and those in the stress characterization chamber. As an interesting aside it may be possible to use a thin layer of a stressed coating to change the figure instead of filling it in. We are also investigating this.