X-ray Optics at NASA/MSFC

Brian Ramsey

X-ray Astronomy Group

Astrophysics Office

NASA / Marshall Space Flight Center

X-Ray Astronomy

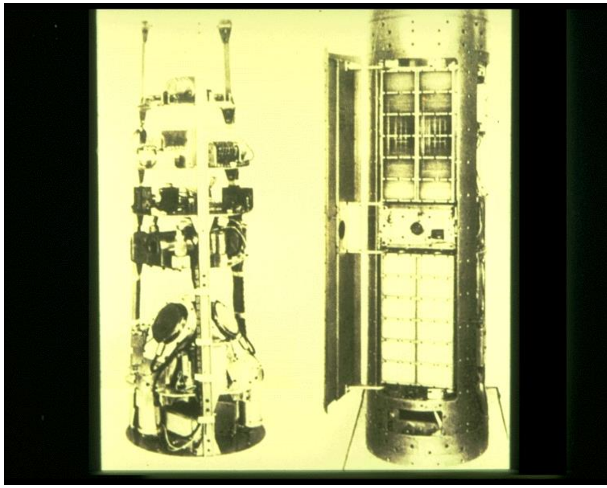
<u>Birth of X-Ray Astronomy</u>

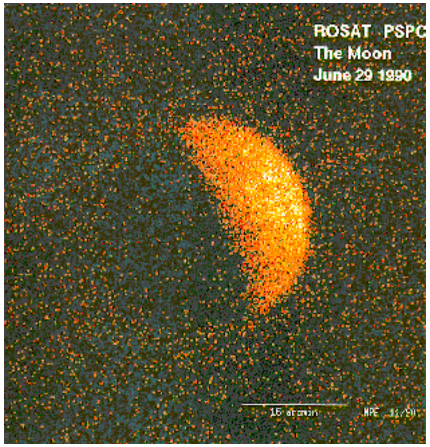
- In 1962, Riccardo Giacconi and colleagues at AS&E flew sounding rocket to look at x-ray fluorescence from the moon

- Lunar signal was overshadowed by very strong emission from the Scorpious region

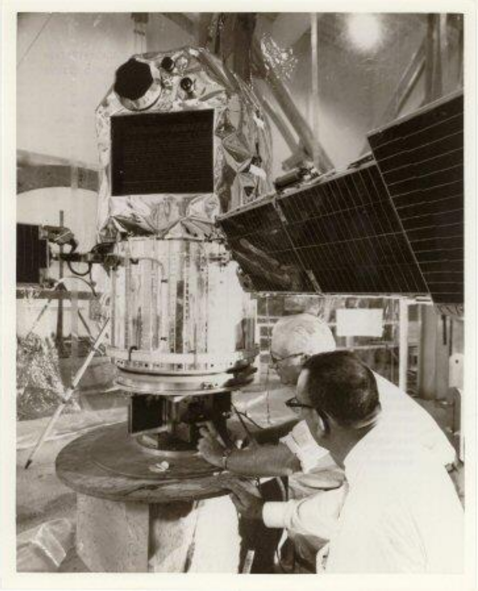
- Discovered the first extra-solar x-ray source, Sco X-1, and pervasive x-ray background

- This was the effective birth of x-ray astronomy





X-Ray Astronomy

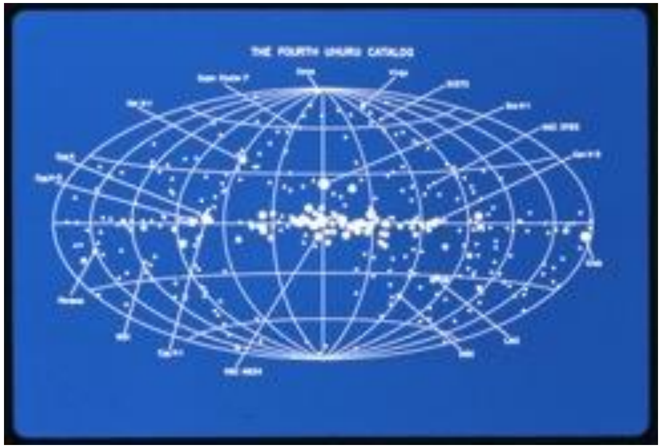


First X-Ray Satellite

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

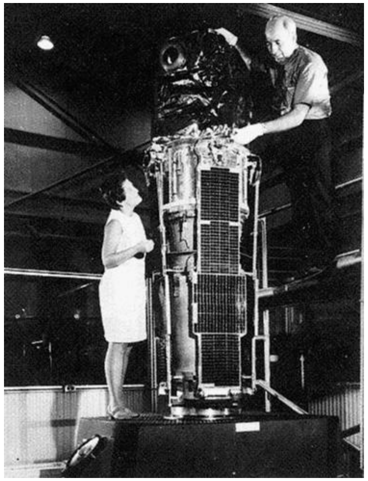
2) Background reduction

- 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

$\Rightarrow$ *enormous increase in sensitivity*

First dedicated x-ray astronomy satellite – UHURU →

mapped 340 sources with large area detector (no optics)

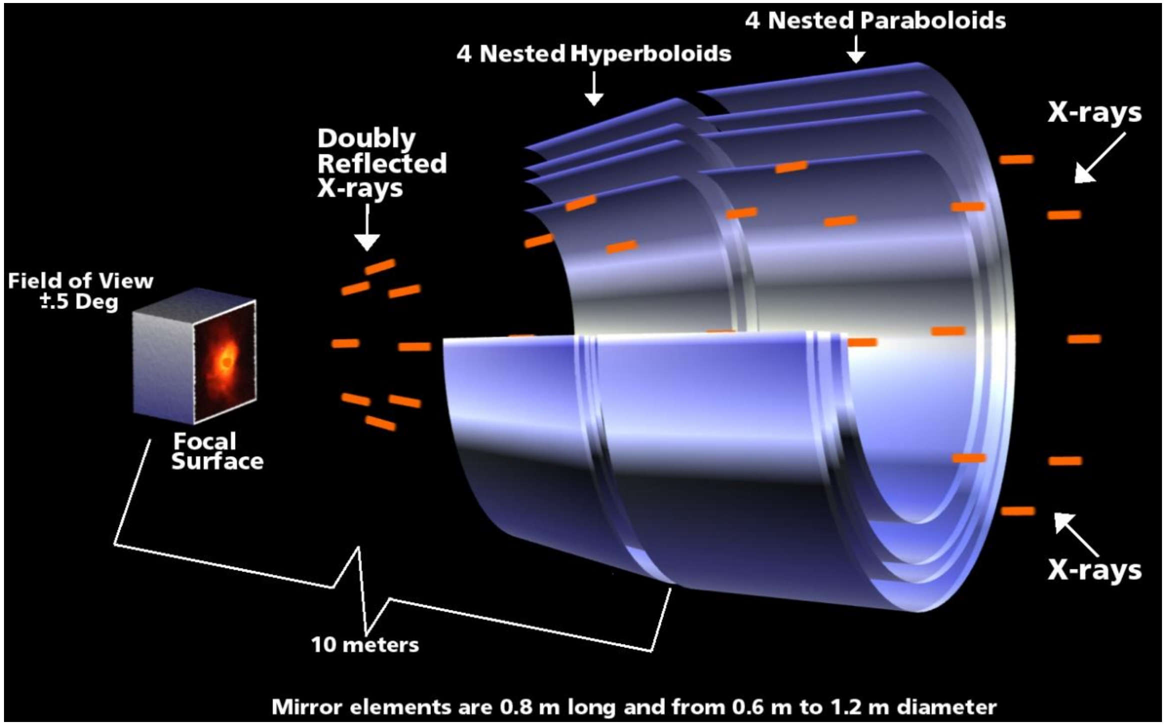


Chandra observatory - ~ same collecting area as UHURU

- *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

X-ray Optics



4 Nested Paraboloids
4 Nested Hyperboloids
X-rays
Doubly Reflected X-rays
Field of View ±.5 Deg
Focal Surface
X-rays
10 meters
Mirror elements are 0.8 m long and from 0.6 m to 1.2 m diameter

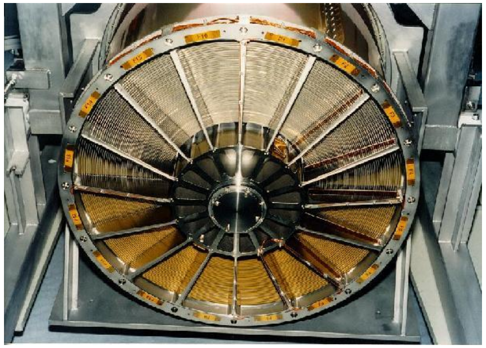
Approaches (flown so far [Soft X Ray])

Classical Optical Grinding and Polishing

Chandra, Rosat, Einstein

Advantage: Superb angular resolution

Disadvantage: High cost, large mass, difficult to nest

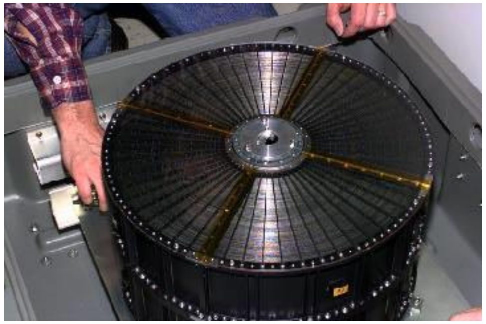


Electroformed Nickel Replication *

XMM, JETX/Swift, SAX

Advantage: High nesting factor, good resolution

Disadvantage: Significant mass (high density of nickel)



Segmented foil

ASTRO-E, ASCA, BBXRT

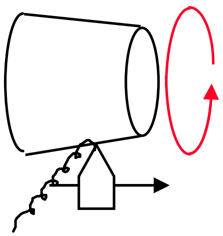
Advantage: Light weight, low cost

Disadvantage: Relatively poor angular resolution (few-arc-minute-level)

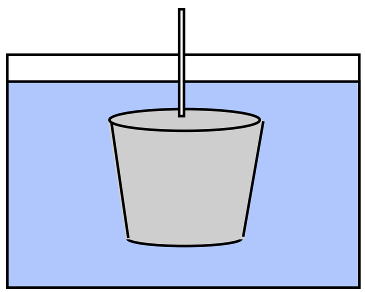
Electroformed Nickel Replication

Mandrel Preparation

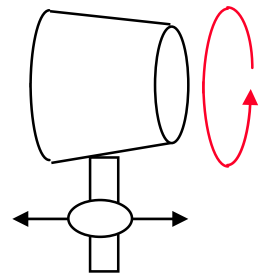
1. CNC machine mandrel from aluminum bar



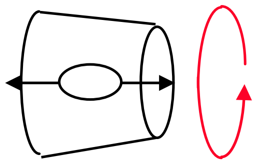
2. Chemical clean and activation & electroless nickel (EN) plate



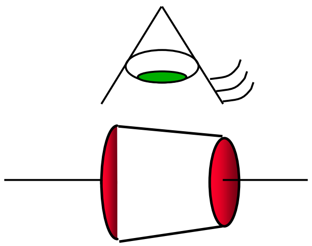
3. Diamond-turn to ~ 600Å, sub-micron figure accuracy



4.Superpolish to 3 - 4Å rms finish

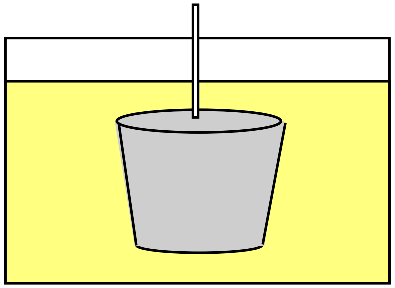


5. Metrology on mandrel

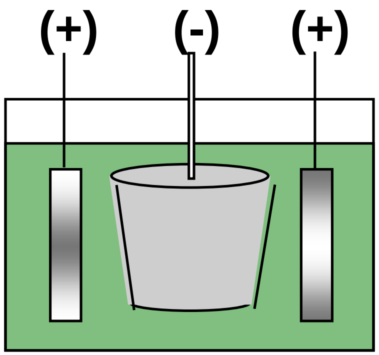


Shell Fabrication

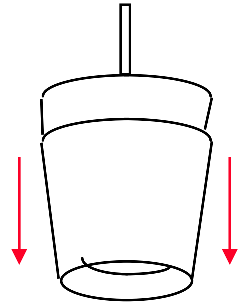
6. Ultrasonic clean and passivation



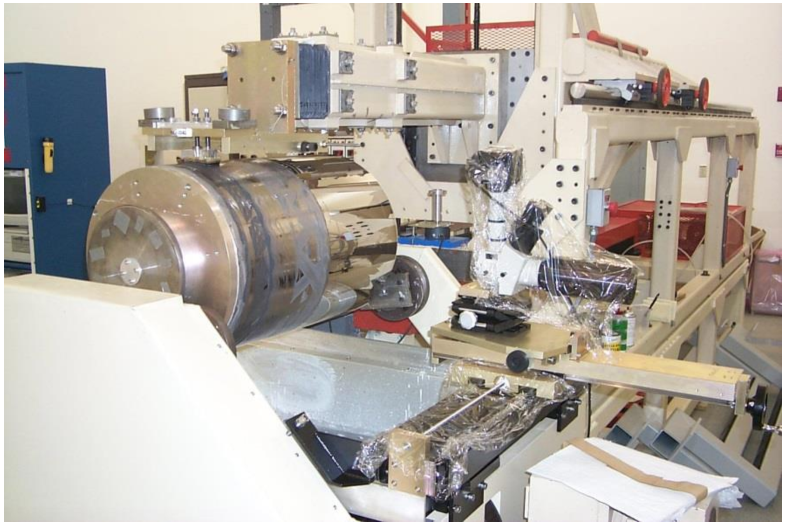
7. Electroform NiCo shell onto mandrel



8. Separate optic from mandrel in cold water bath



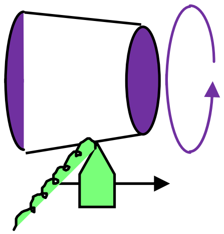
MSFC Infrastructure

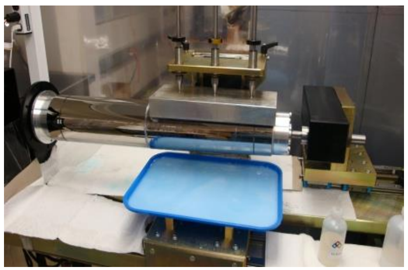


MSFC Developments : Electroformed Nickel Replication

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

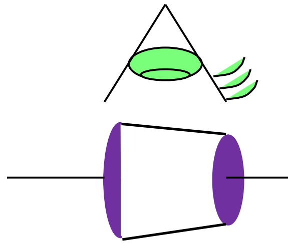
X-ray mandrel





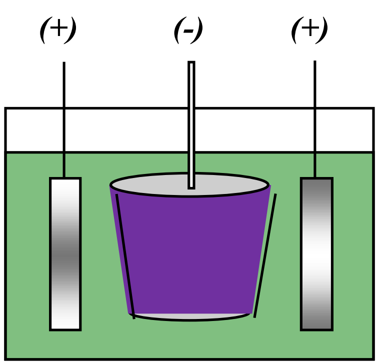
Mandrel polishing

Metrology on mandrel

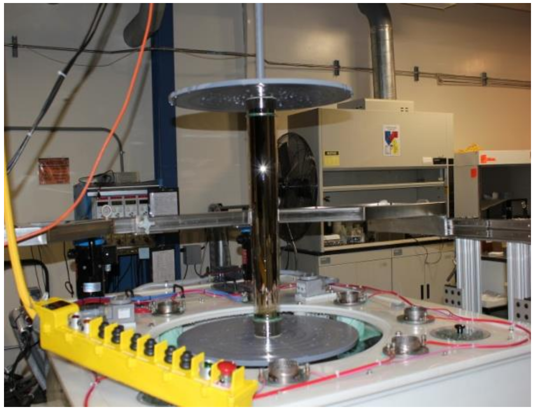


Metrology

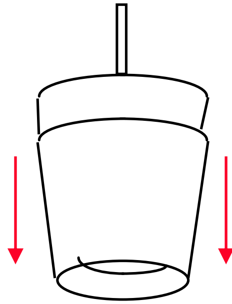
Electroform Ni/Co shell onto mandrel



X-ray shell electroforming



Separate optic from mandrel in cold water bath



Replicated X-ray shells

Sandia Apr 2015

ENR Development at MSFC

Nickel is a heavy material (9 g / cm^3). For light-weight optics, shells must be very thin (~ 0.1 mm [0.004"] at ~0.25-m diameter to meet Con X HXT weight budget) yet strong enough to withstand the stresses of fabrication and subsequent handling without being permanently deformed at the micron level.

Adhesion / Release

- Reduce adhesion of plated shell to mandrel so that shell can release easily

Material Properties

- Develop nickel alloy with much higher strength than pure nickel

Stress Control

- Small amount of stress distorts thin-shell optics
  - Fine tune plating bath chemistry and keep electric fields uniform

ENR Development

- **Release Coatings**

  - Electroplating must adhere to mandrel so that shell will grow, but must be loose enough to separate easily

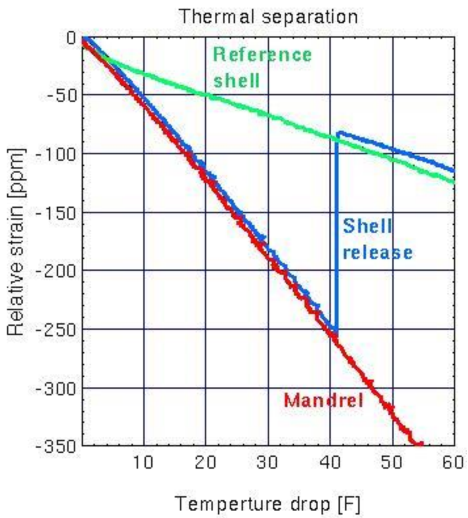
  - Have developed mandrel-surface treatments that give very low adhesion and do not significantly degrade surface with multiple replications.

  - All involve generating an oxide on the surface of the mandrel

    > Typically give ~ 7.10^5 Pa (100 psi) adhesion

      – This is a minimum to support the electroforming

ENR Development



Thin shells can experience large strain stresses under separation from a mandrel

Stress =(CTE $_{al}$-CTE$_{ni}$).Δ T.Youngs mod

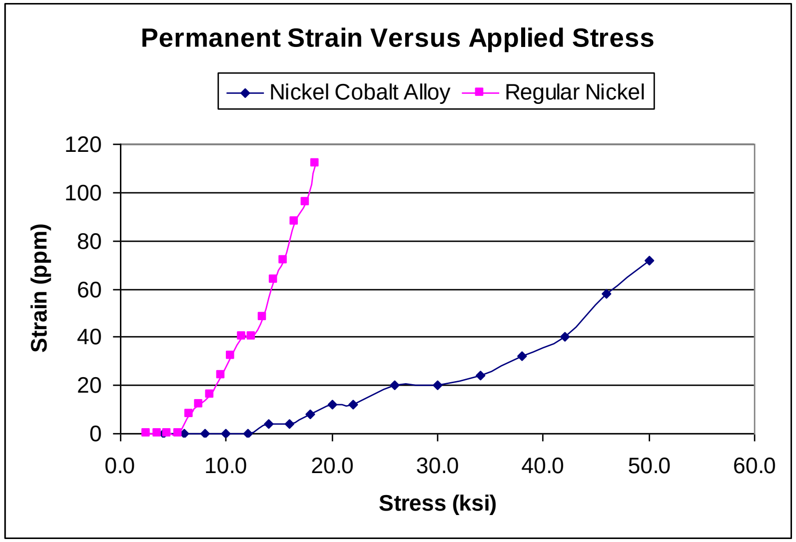
Example at right, show 0.25-mm-thick shell released from treated mandrel .. Stress ~ 35 MPa (5 ksi)

A shell 0.12-mm thick would experience twice this stress

Small stresses, well below the yield stress of a material can cause microyielding, of importance to high-resolution optics

We have developed alloys with higher yield strengths than pure nickel

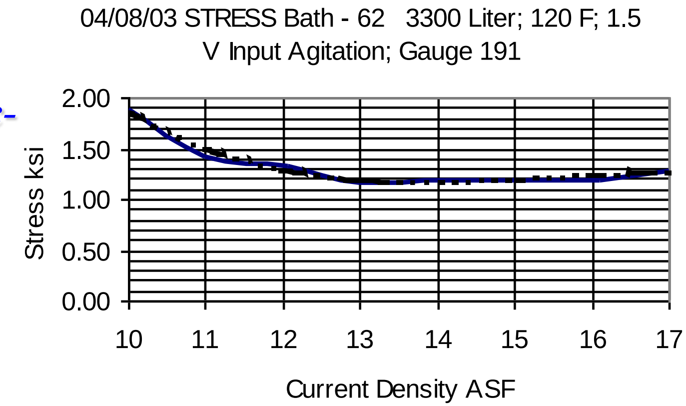
Have made shells from this alloy, just 0.075-mm-thick (0.003")



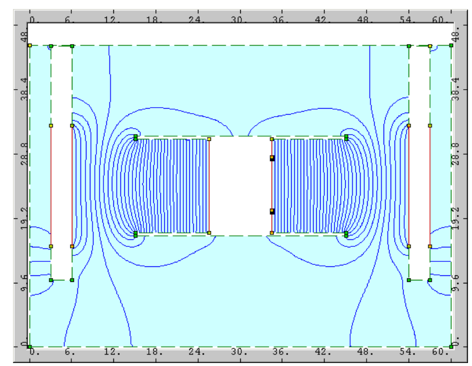
ENR Development

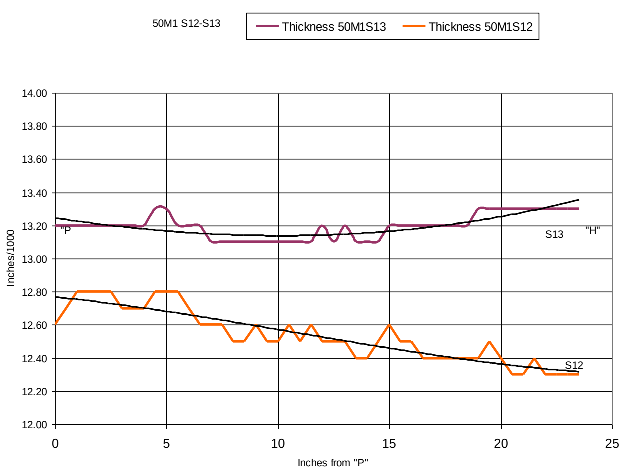
Plating stress control

Need to control the stress to ~ 10's psi to maintain 10-arcsec-level figure …adjust chemistry of bath to give flat uniform stress



Stress still varies with plating current density, so in turn need to control field … use models of plating bath to fine-tune layout of shields which modify field ⇒





Resulting deposit is very uniform,

⇐

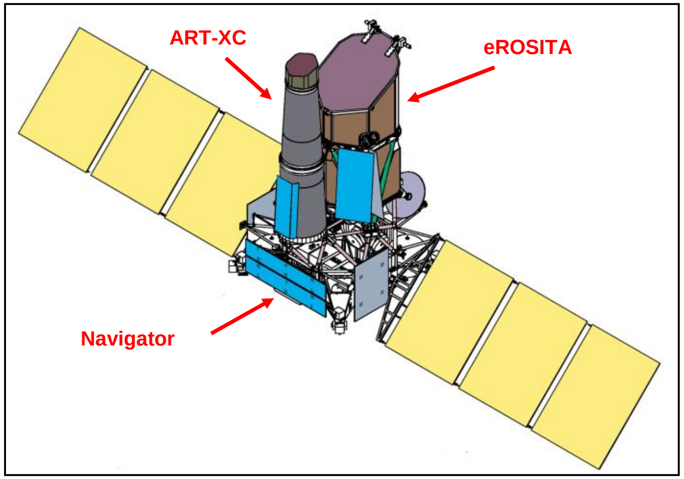
so stress variations are very low

ENR Development

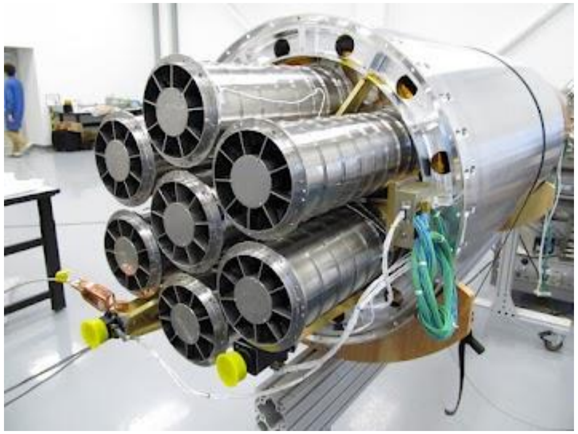
Replicated X-ray optic projects at MSFC

Astronomical applications

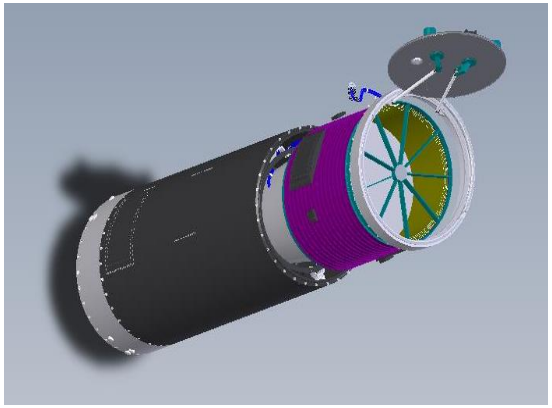
ART-XC



FOXSI



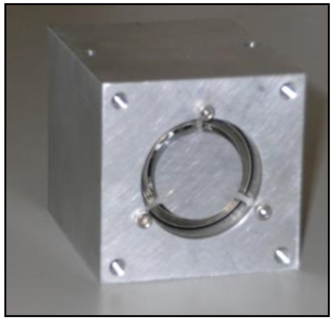
MicroX



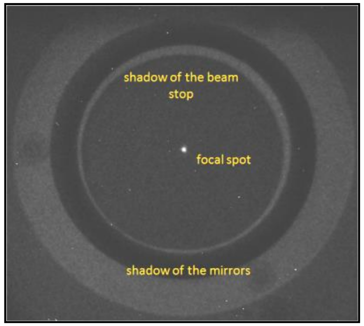
HEROES

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

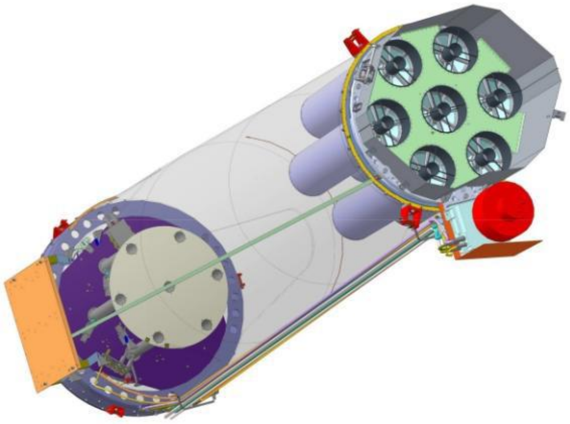
MSFC will provide x-ray optics modules for the ART-XC instrument.

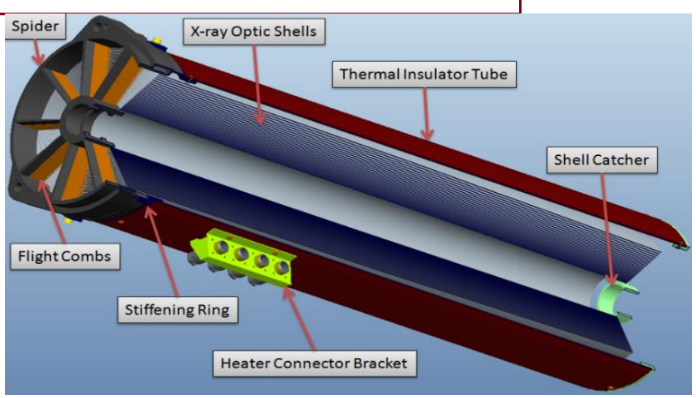
Delivery of the optics is scheduled for late Summer 2014

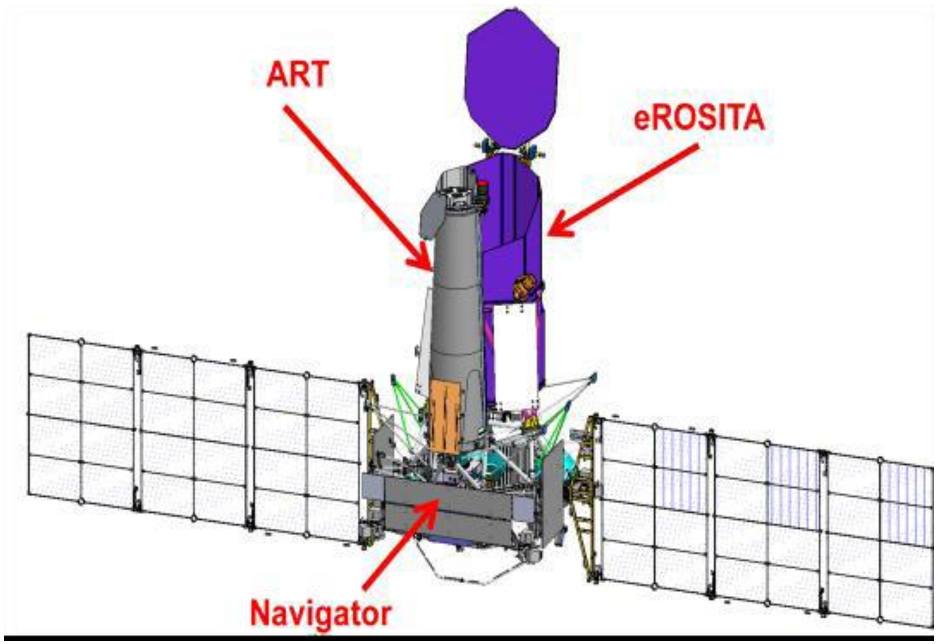
Customer:

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

Funded under an International Reimbursable Agreement between NASA and IKI





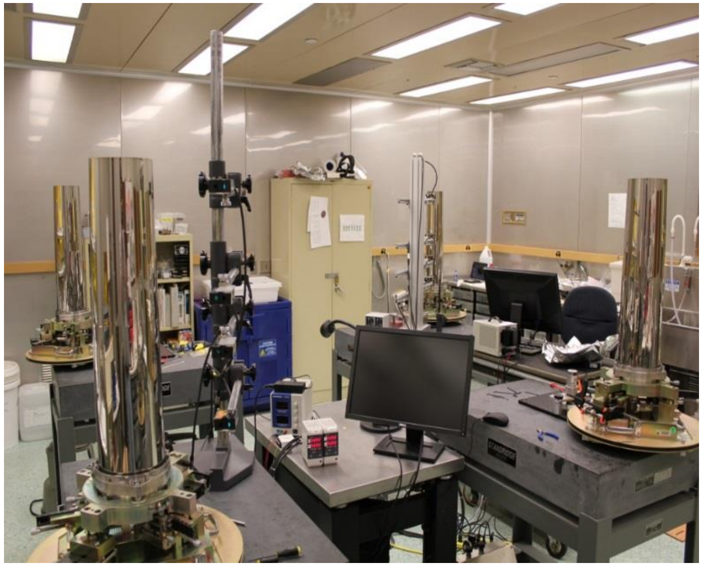


ART-XC Optics Configuration

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.

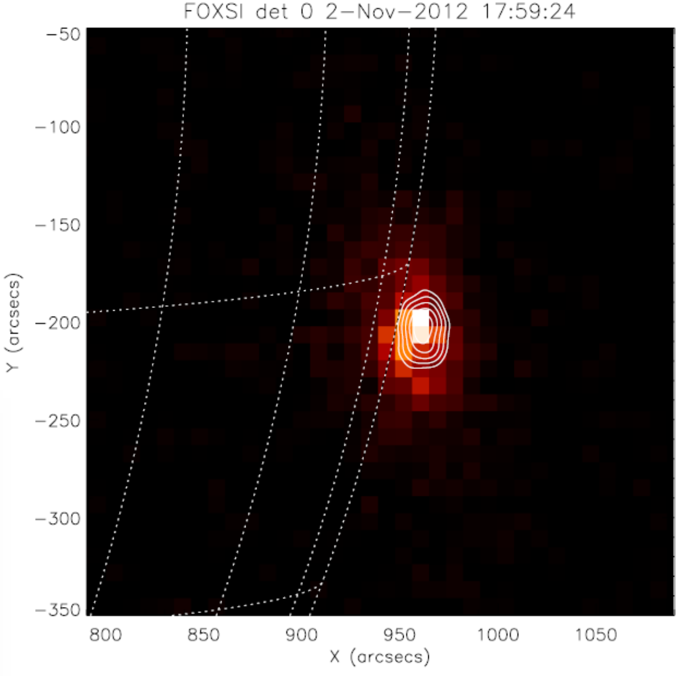
FOXSI-2 version had successful flight from White Sands on 11 Dec, 2014

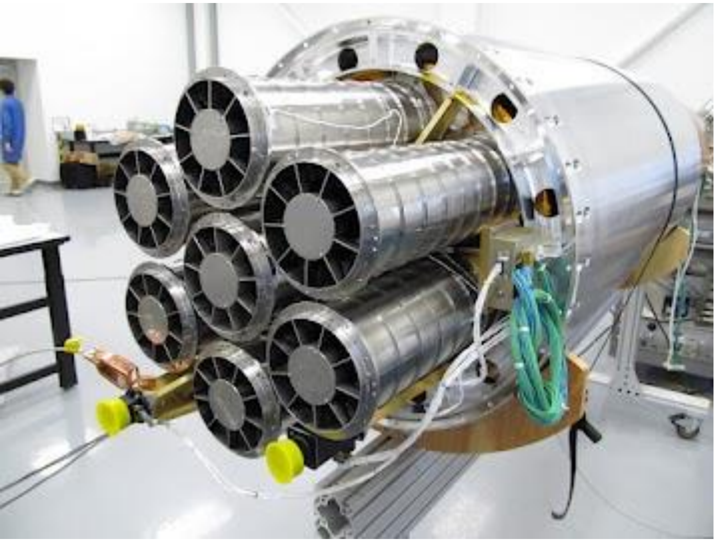
Customer:

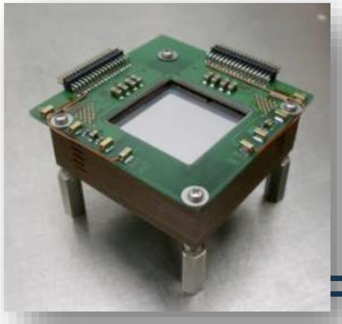
University of California, Berkeley

P.I. Sam Krucker

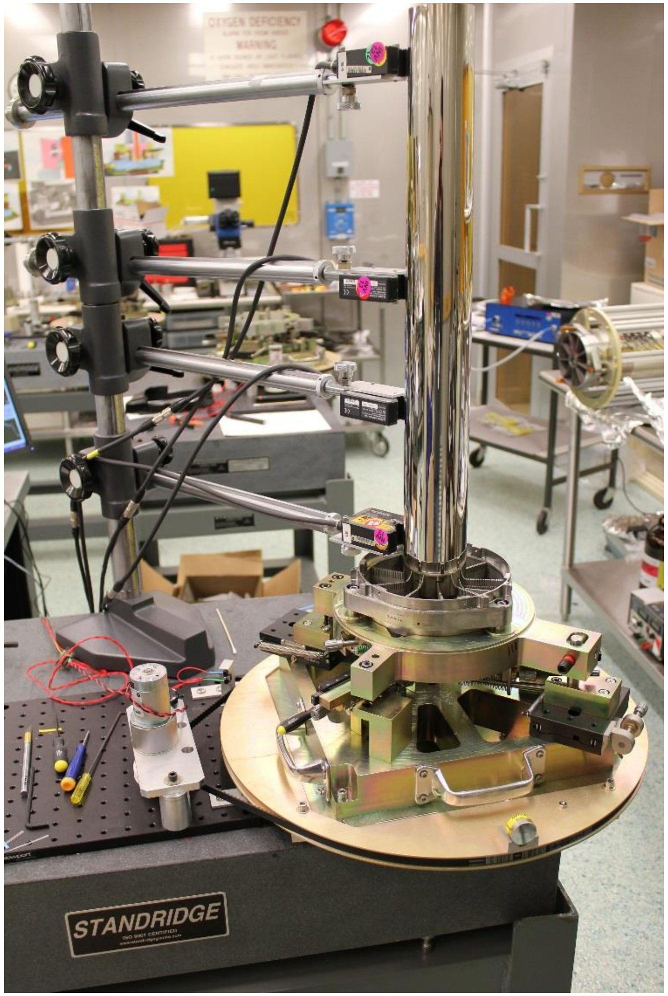
Funded by the Science Mission Directorate, through the low-cost access to space program.



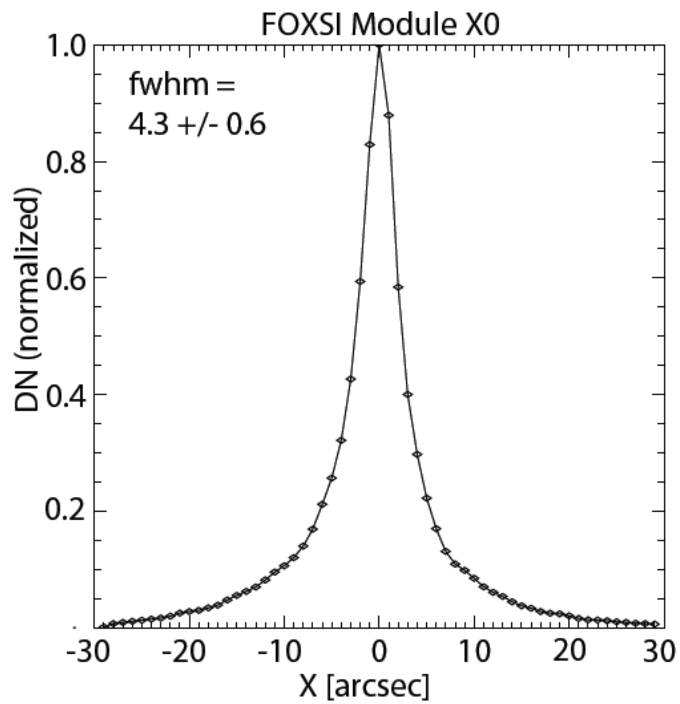




FOXSI



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

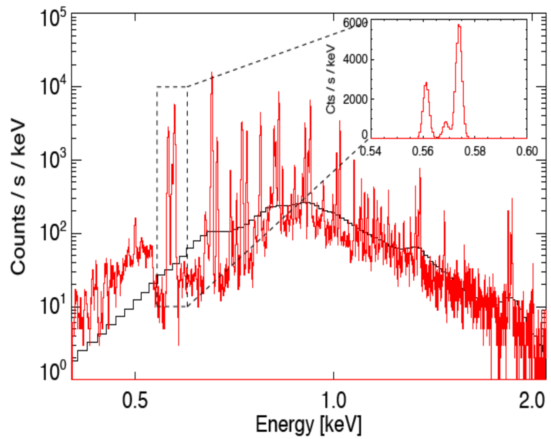
Micro-X will fly in early 2017 and make high-spectral-resolution images of supernova remnants Puppis A and Cas A.

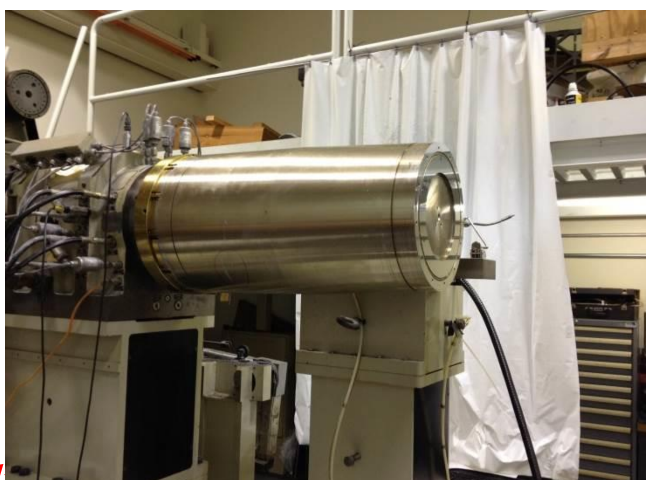
The 0.5m diameter optics are under construction at MSFC. Completion schedule for 2016.

Customer:

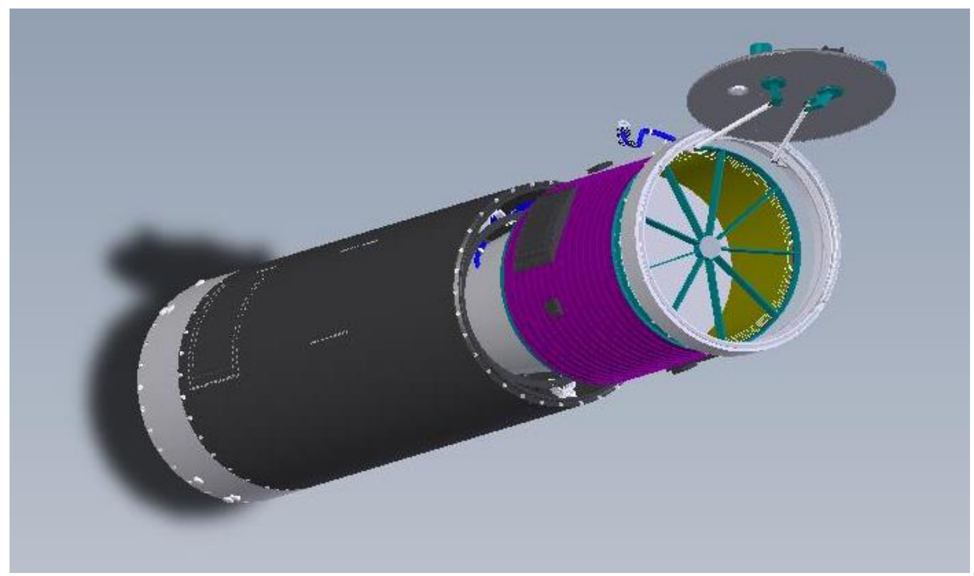
Massachusetts Institute of Technology / Tali Figueroa

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



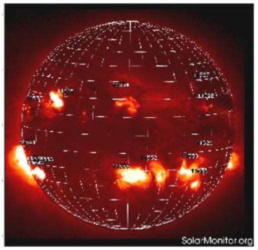


Micro-X mandrel on diamond turning machine



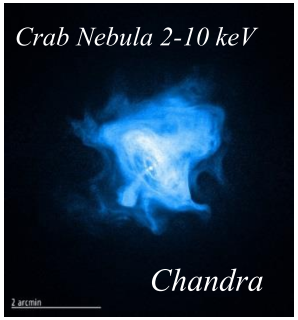
High Energy Replicated Optics to Explore The Sun

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.



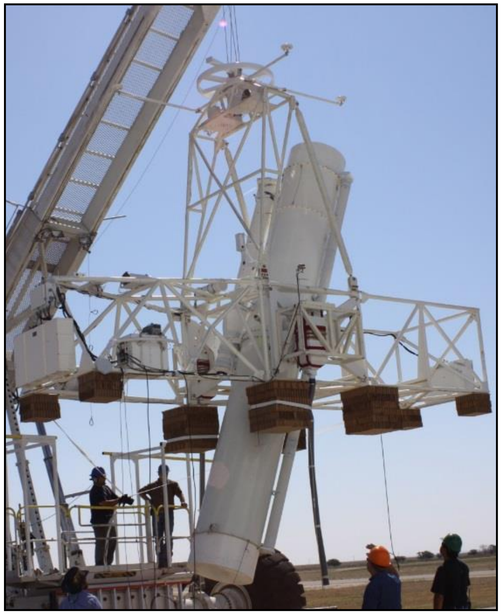
Heliophysics

- 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

Sandia Apr 2015

HEROES Optics

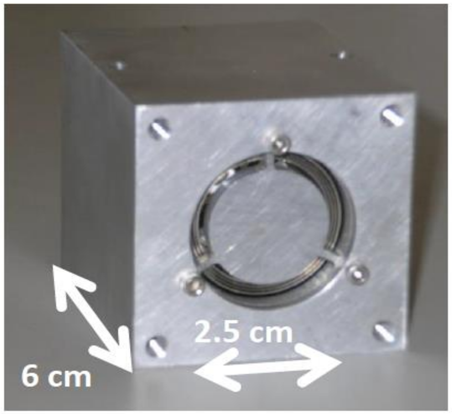
Mirror shells per module	14 (6 mod), 13 (2 mod)
Inner, outer shell diameters	50, 94 mm
Total shell length	610 mm
Focal length	6 m
Coating	Sputtered iridium, ~ 20 nm thick
Number of mirror modules	8
Effective area	~ 85 cm^2 at 40 keV, ~ 40 cm^2 at 60 keV
Angular resolution (module)	~25 arcsec FWHM
Field of View	9 arcmin at 40 keV 5 arcmin at 60 keV

Spinoff Application: Neutron Microscopy

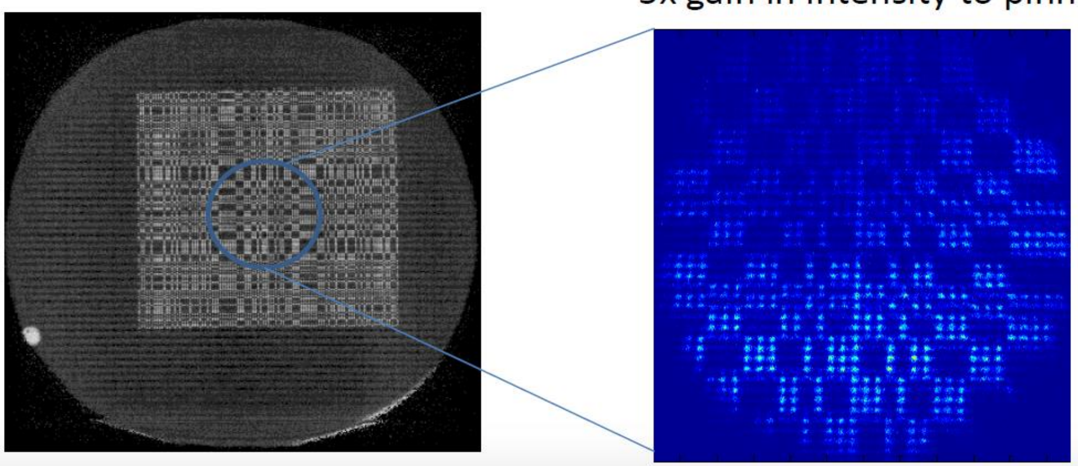
NIST

A Neutron Microscope for Energy and Materials Research

Demonstration with small prototype microscope

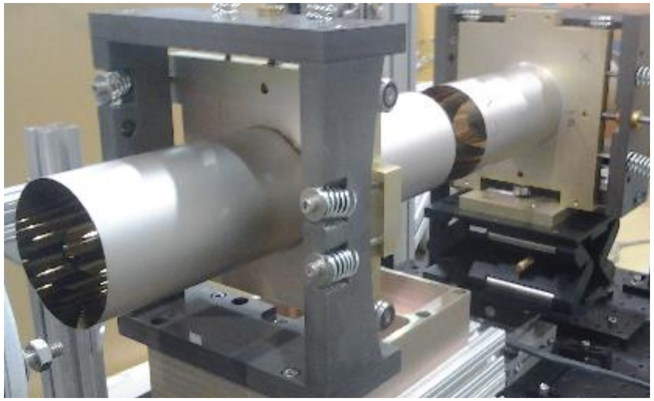


- Built for small mammal x-ray imaging
- Lens composed of ellipsoid and hyperboloid sections
- 3 nested Ni mirrors (nesting increases flux collection)
- Observed Performance:
  - 75 µm spatial resolution
  - 1 cm FOV & 4x magnification
  - 5 mm depth of focus
  - 5x gain in intensity to pinhole



- 2cm x 2cm Pinhole mask, with 0.1 mm diameters on 0.2 mm centers
- Left: Contact Image; Right: Lens Image

Optics for new cold neutron imaging instrument at NIST



Neutron microscope prototype

NIST Beamline Hall

Future home for our optics

Applications:
- *Fuel cell development (resolving concentration gradients in electrodes requires the highest possible spatial resolution)*
- *Lithium-air batteries development (lithium-air batteries have 10x storage capacity of commercial lithium-ion batteries)*
- *Non-destructive evaluation of nuclear fuel rods life cycle*

Also:

–Understand targeted drug delivery
–Advance oil and gas recovery
–Improve the safety of nuclear fuel cladding by imaging the grain structure of ZrH
–Develop additive manufacturing of metal alloys
–Reveal solar cell morphologies to reduce the cost of large area solar arrays
–Enhance efficiency of room temp. magnetic refrigeration by imaging 3D magnetic structures
–Solve protein structures in solution, 2/3 of all proteins can't be crystallized
–Understand polymer and block copolymer self-assembly and hydrogels
–Distinguish internal structure and morphology of graded nanoparticles
–Understand magnetic nanoparticles for hyperthermic cancer treatment, MRI contrast agents
-And more …

Source for funding – NIST director's fund

- *Task 1 (Demonstration of high resolution neutron optics)*
- *Task 2 (Neutron optics with magnification 1)*
- *Task 3 (Neutron optics with large magnification)*

Status – Negotiations on an Interagency Agreement for Task 1

Spinoff Application – Small Animal Radionuclide Imaging

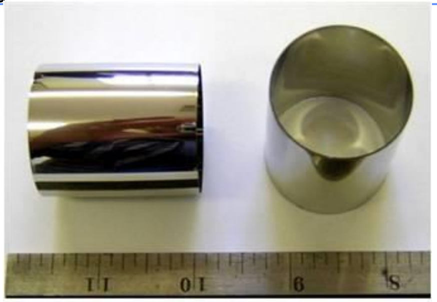
Development a grazing incidence optics for medical applications – radionuclide imaging in small animals to perform functional analysis

Optics

Novel use of reflective optics

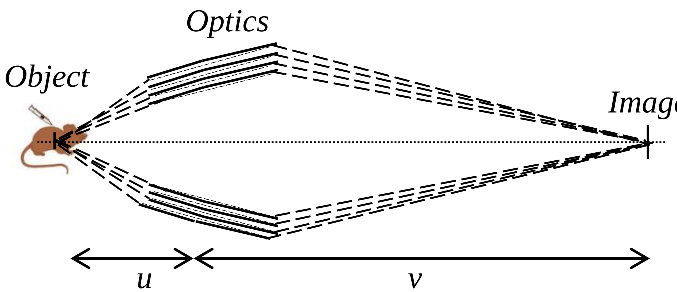
Can provide 100 µm spatial resolution which is 10 fold better resolution compared to existing techniques in the field

~60 mm in length and ~30 mm in diameter; much smaller in size compared to the astronomical optics regularly fabricated at MSFC



Radionuclide imaging X-ray optics

Geometry details
Total length = 3 m
Object distance (u) = 0.6 m
Image distance (v) = 2.4 m
Magnification = 4
Reflection angle = 0.5 deg



Nested shells - Confocal hyperbola and ellipse geometry

Collaborators

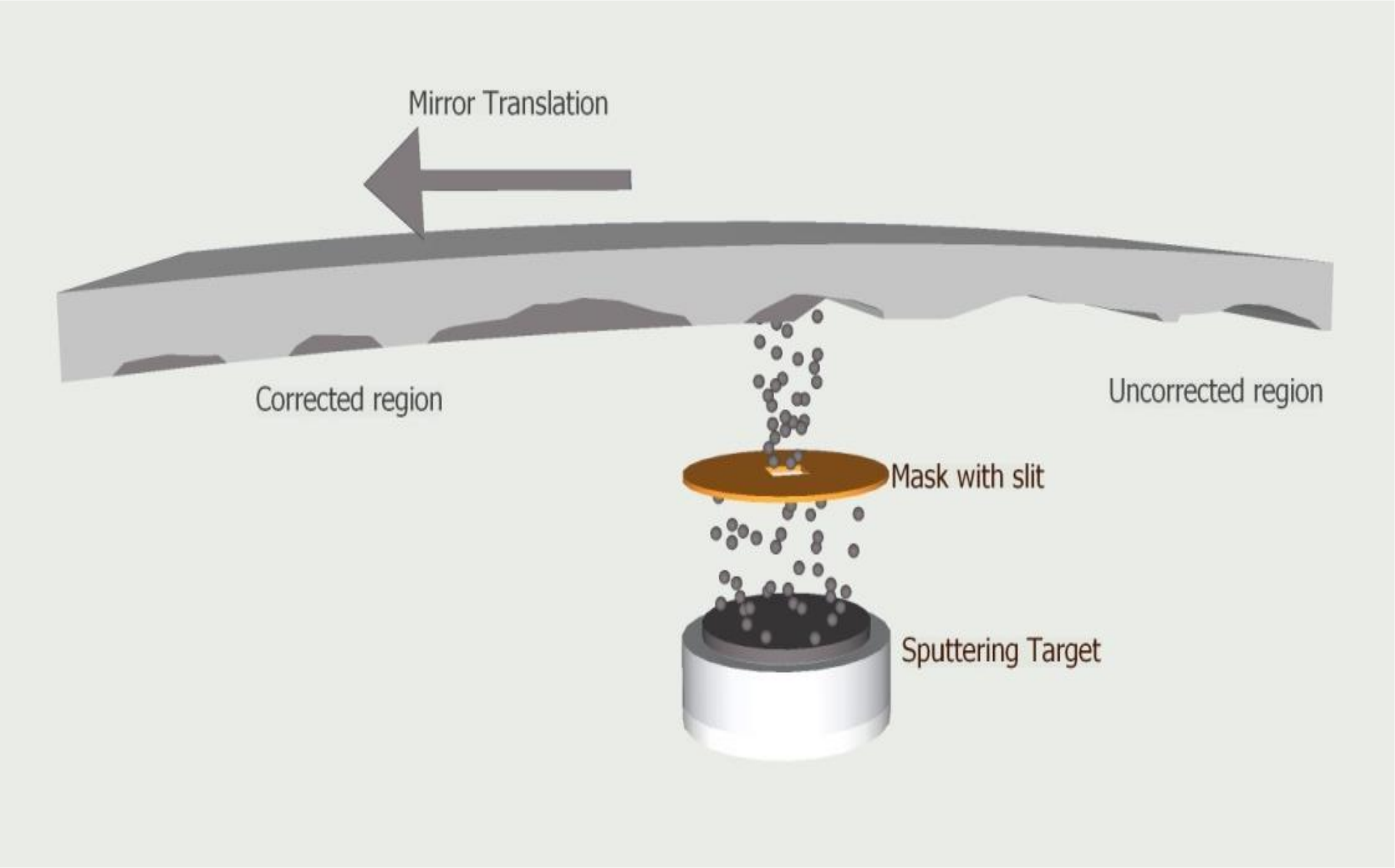
Lawrence Livermore National Laboratories
Harvard-Smithsonian Center for Astrophysics
University of California @ San Franciso

Funded by – National Institute of Health

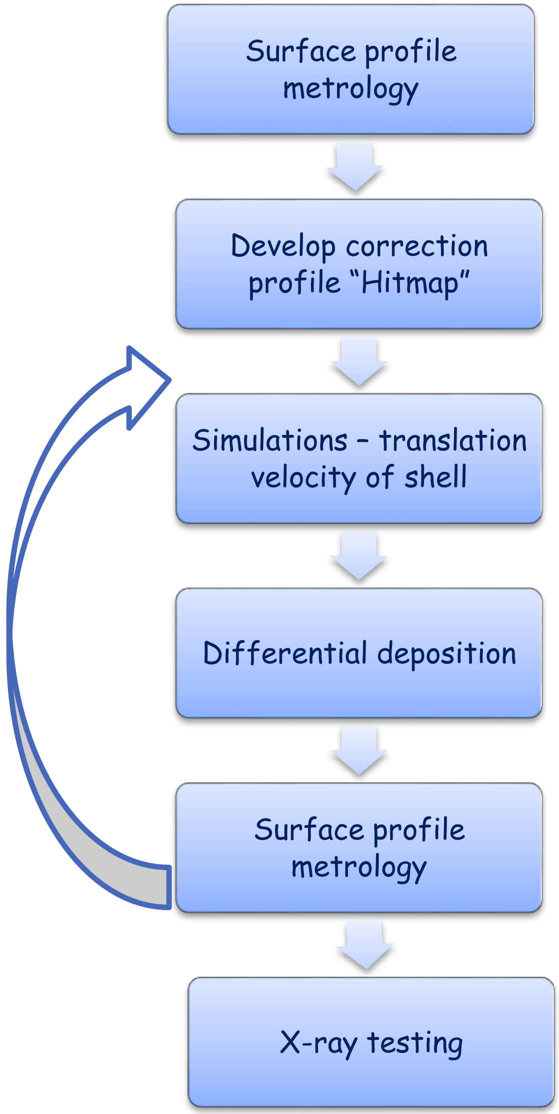
New Developments: Differential Deposition

- ***<u>What</u>***
  - *Differential deposition is a technique for correcting figure errors in optics*
- ***<u>How</u>***
  - *Use physical vapor deposition to selectively deposit material on the mirror surface to smooth out figure imperfections*
- ***<u>Why</u>***
  - *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*

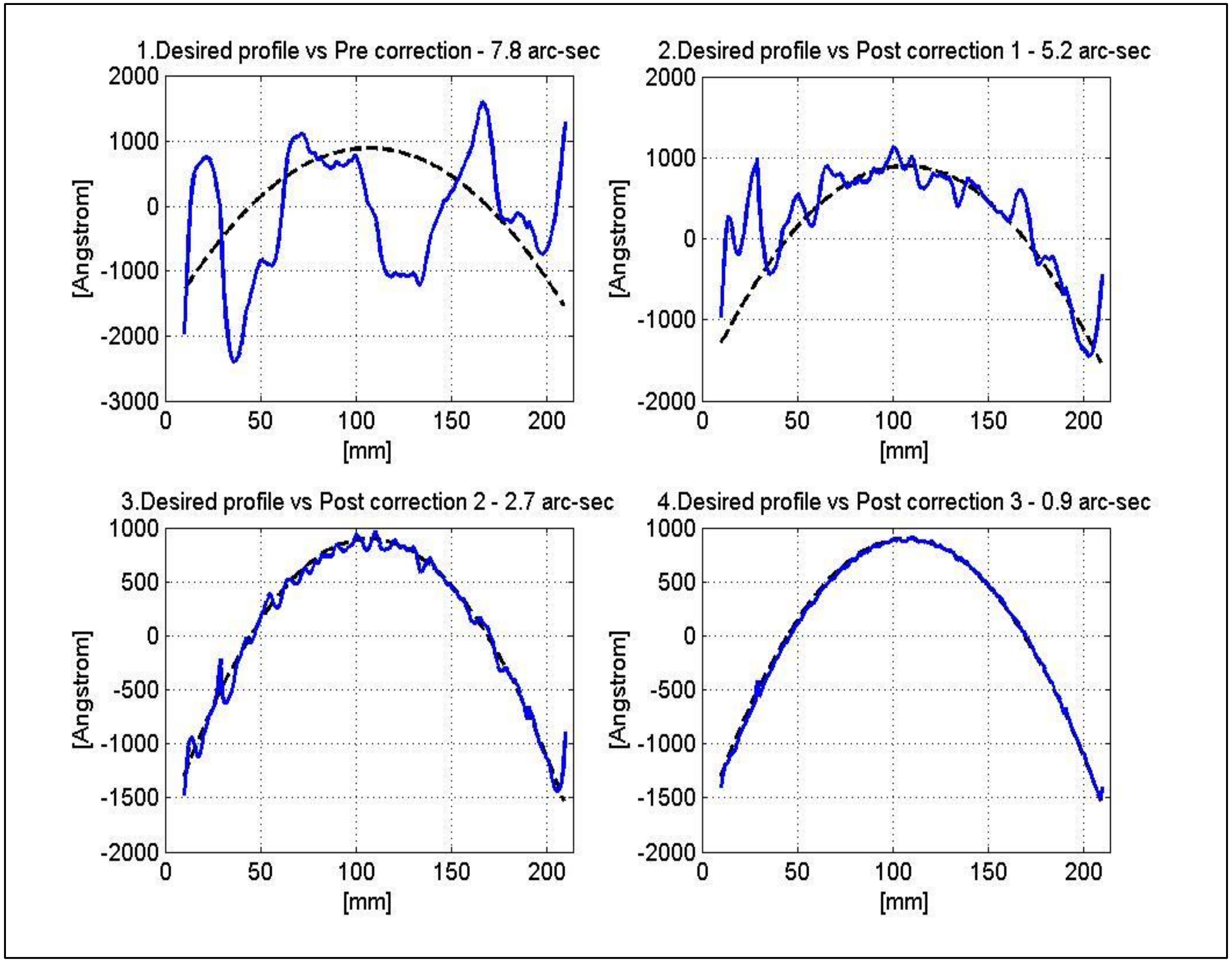
Coating Configuration



Process Sequence - Differential Deposition



Process Sequence – Differential Deposition

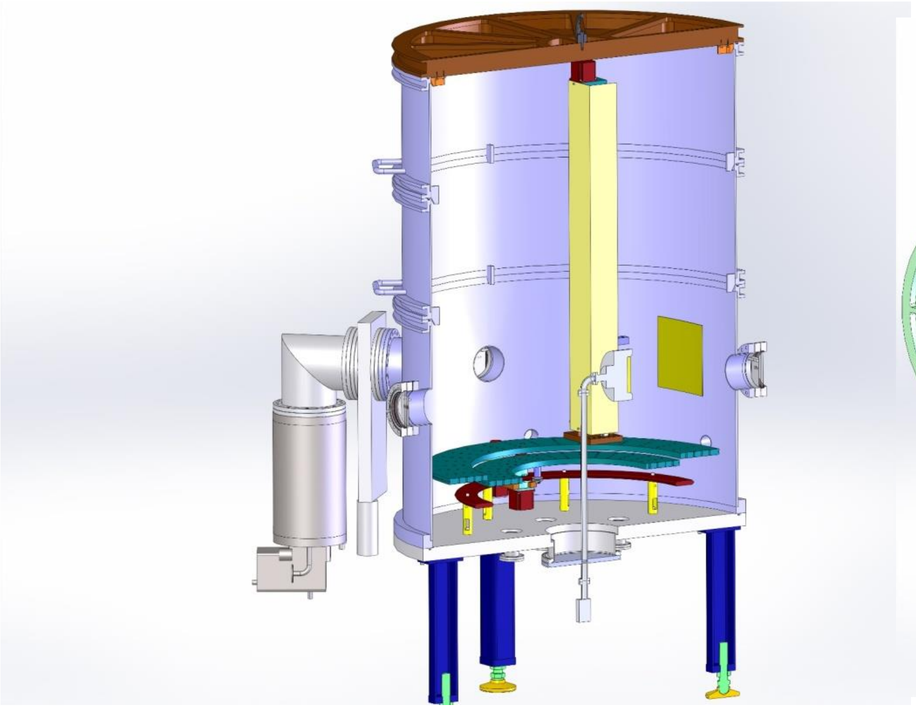


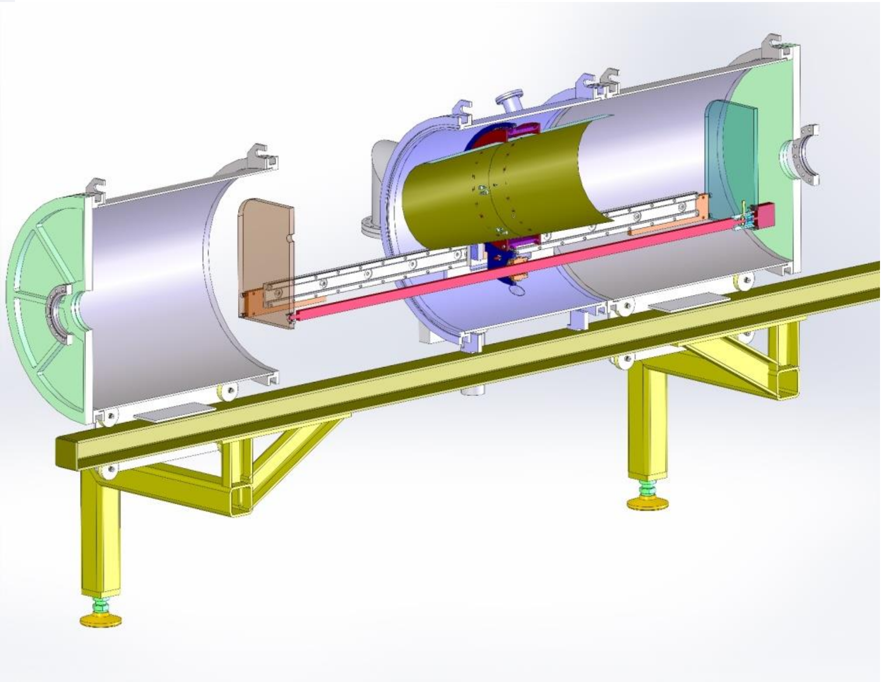
Simulated correction sequence showing parabolic axial figure profile before (top left) and after 3 stages of correction using a beam of FWHM = 14mm, 5.2 mm and 1.7 mm respectively. The dotted line gives the desired figure and the solid line gives the figure obtained at each stage. Overall, resolution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

Possible Practical Limitations We Are Addressing

- ***Variation of sputtered beam profile along the length of mirror – particularly for short focal length mirrors – Model and correct***
- ***Deviation in the simulated sputtered beam profile from actual profile, beam non-uniformities, etc. – Quantify and correct***
- ***Positional inaccuracy of the slit with respect to mirror – Model effects to derive requirements***
- ***Metrology uncertainty – Upgrade metrology system***
- ***Stress effects – Quantify and control stress***

Coating Systems (DC magnetron)

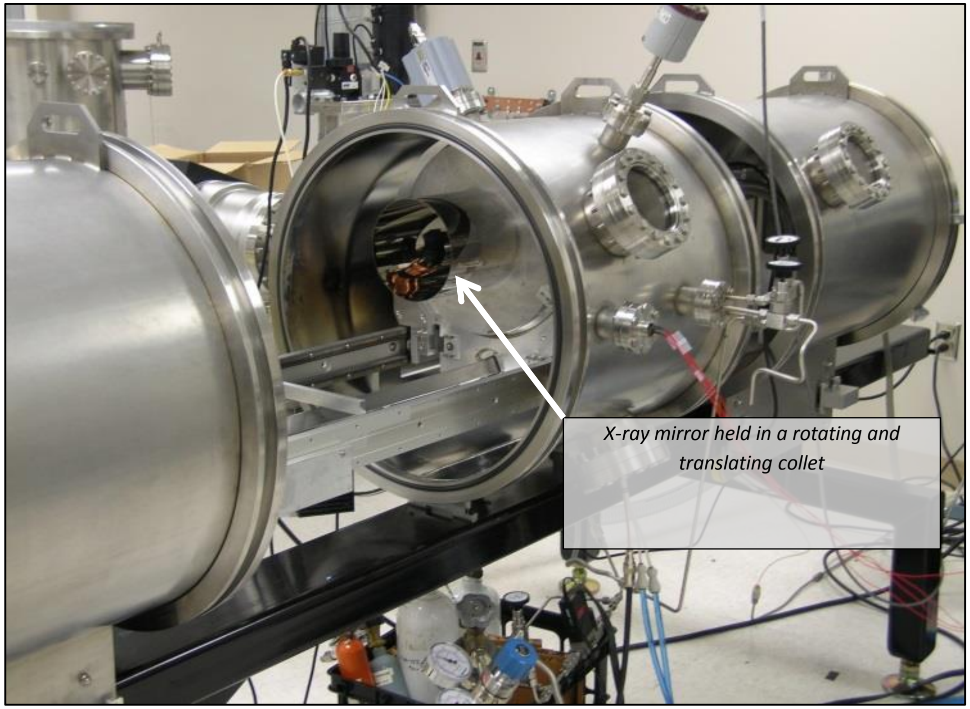


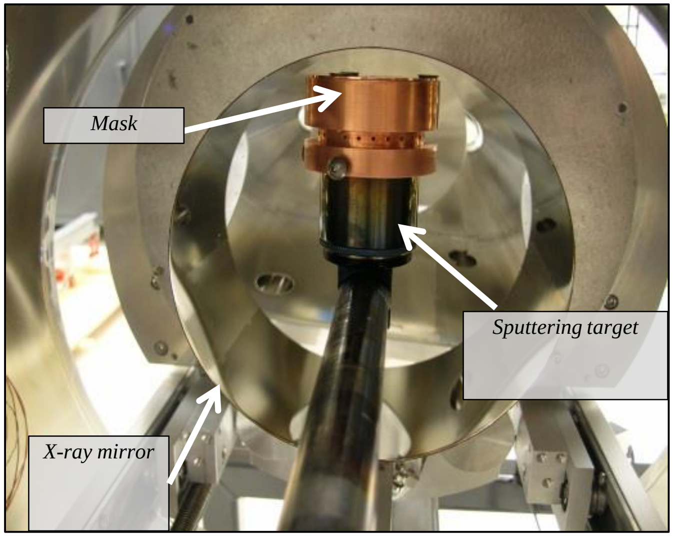


Vertical chamber for segmented optics

Horizontal chamber for 0.25-m-scale full shell optics

Coating Systems

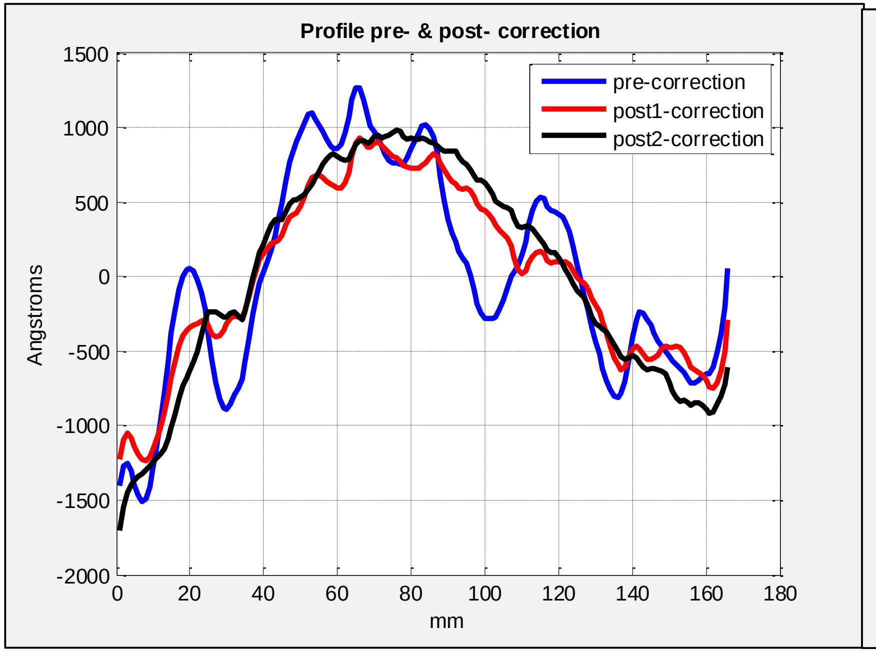


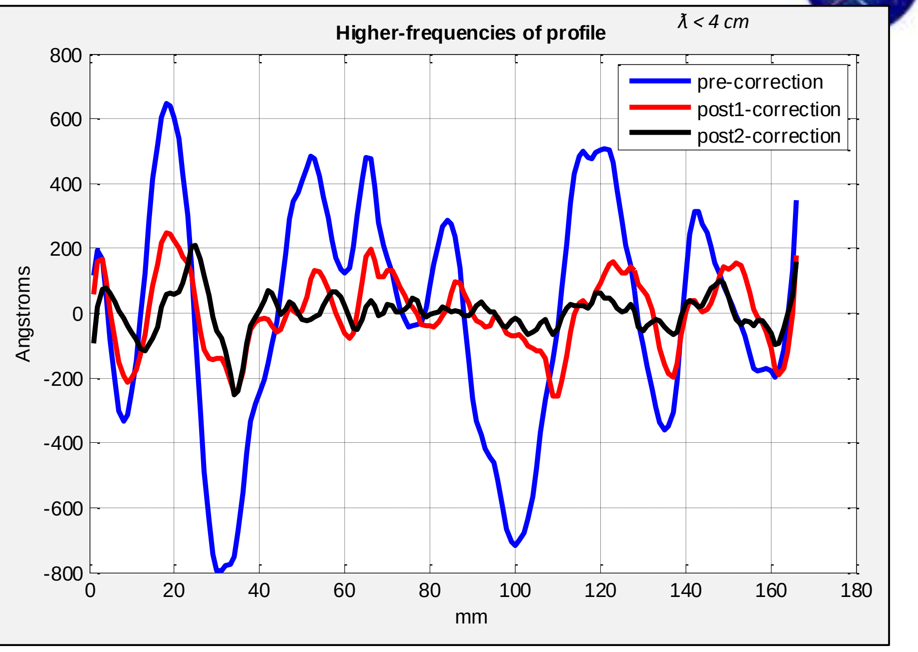


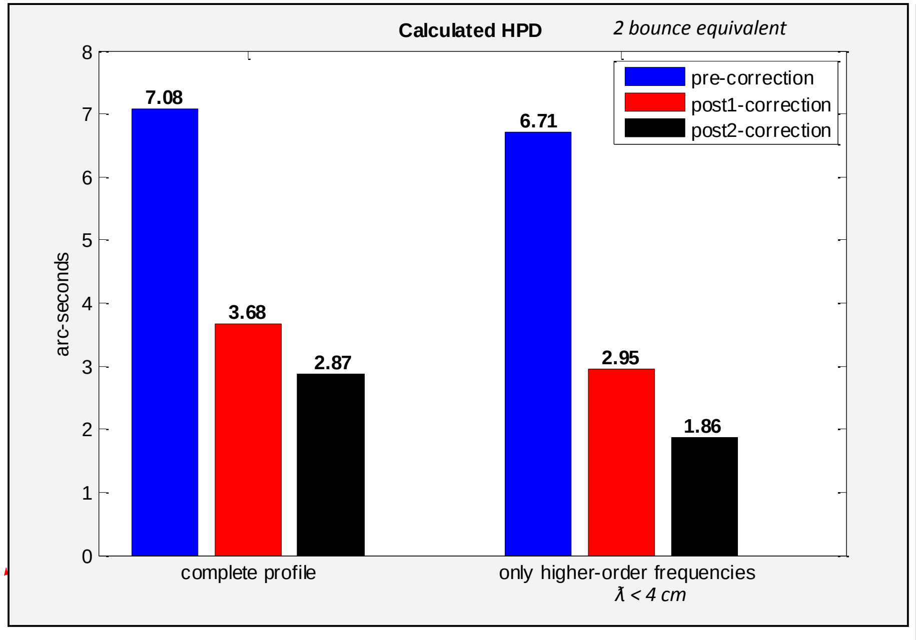
Sputtering head with copper mask positioned inside shell

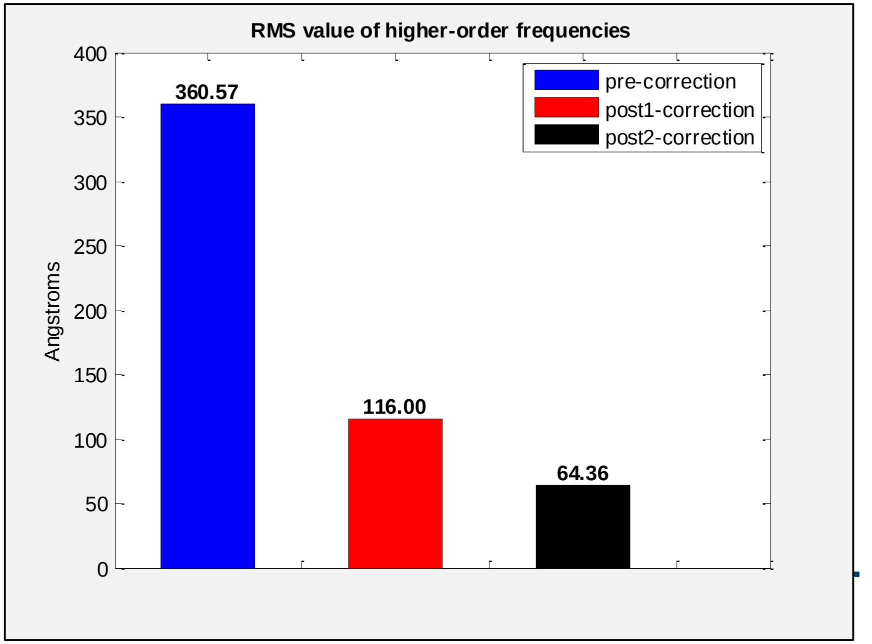
Horizontal differential-deposition chamber

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

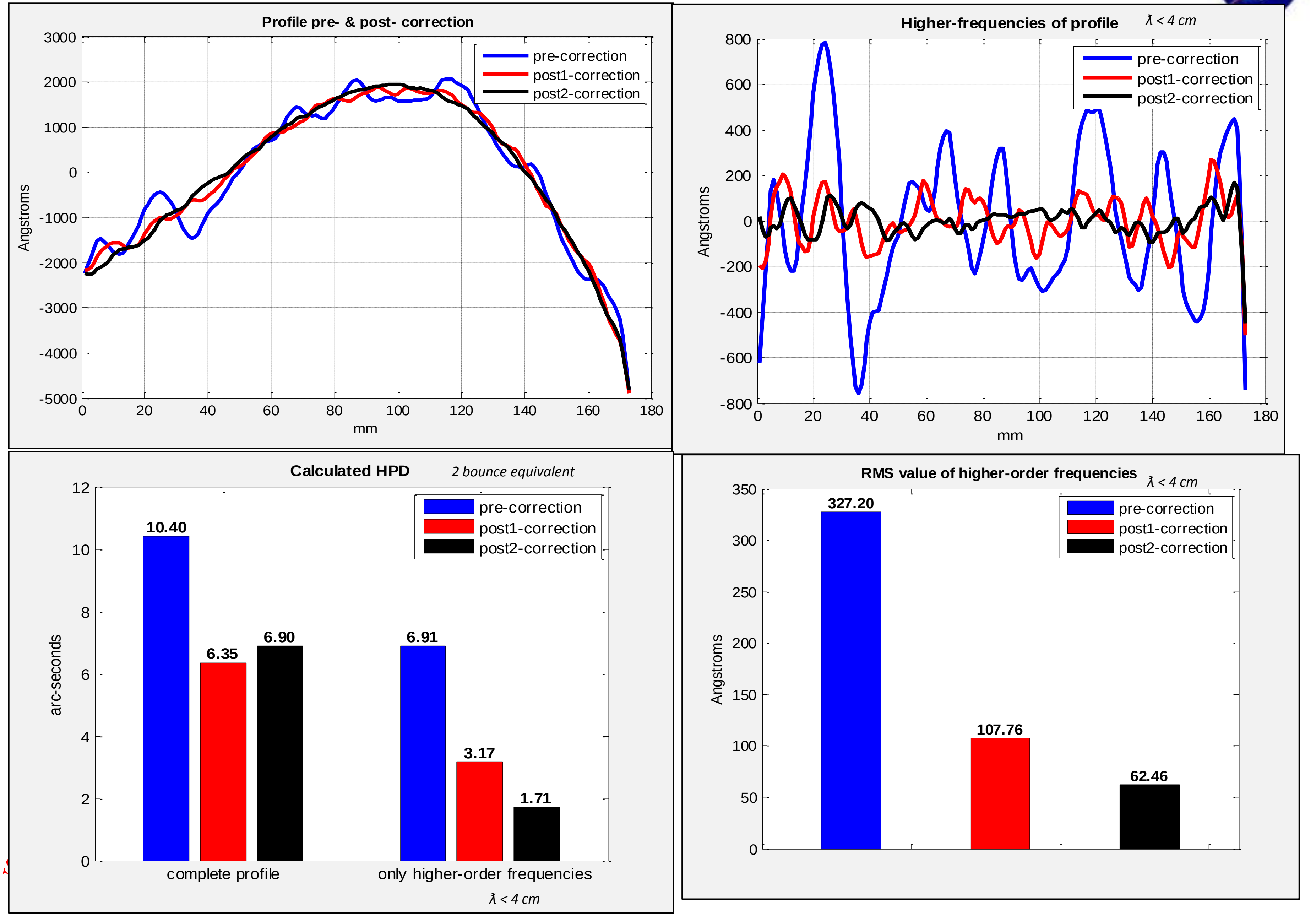








Test # 2: 150 mm diameter shell - 2 stages of correction



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, planned in current APRA proposal, would 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.