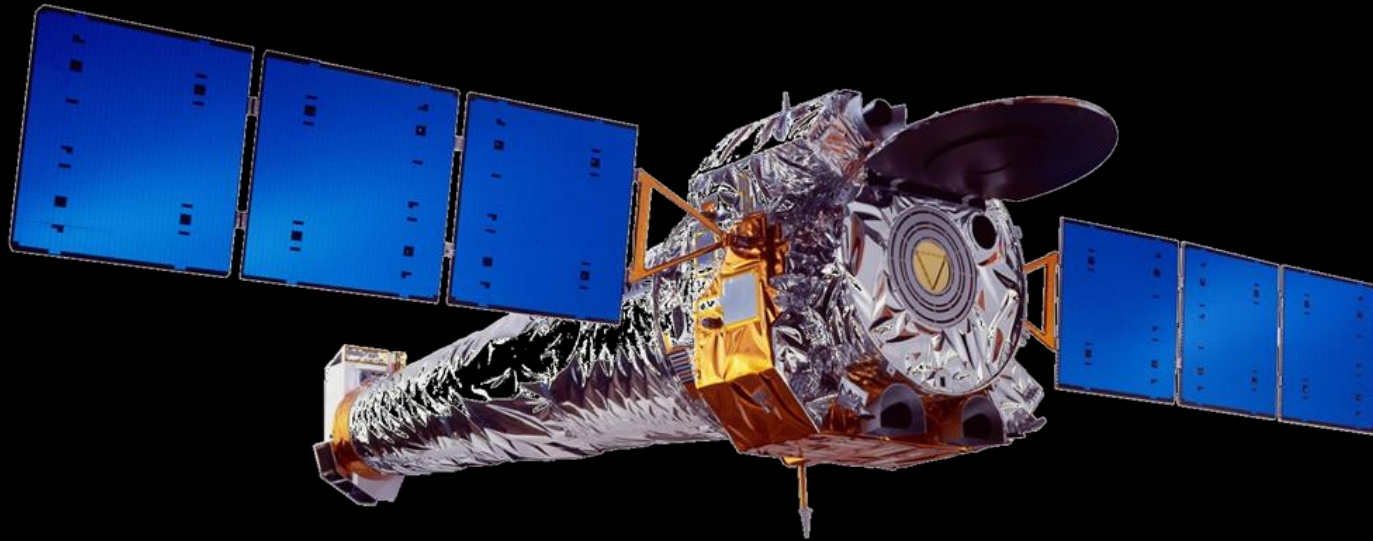


EUV and X-ray Optics: Synergy between Laboratory and Space (SPIE 9510)
2015 April 13-14; Prague (Czech Republic)

X-ray optics at NASA Marshall Space Flight Center



Steve O'Dell

NASA Marshall Space Flight Center
on behalf of the MSFC X-ray Astronomy Group



NASA Marshall Space Flight Center X-ray Astronomy Group

Steve O'Dell ^a, Carolyn Atkins ^b, David Broadway ^a,
Ron Elsner ^a, Jessica Gaskin ^a, Mikhail Gubarev ^a,
Kiran Kilaru ^c, Jeff Kolodziejczak ^a, Brian Ramsey ^a,
Jackie Roche ^a, Doug Swartz ^c, Allyn Tennant ^a,
Martin Weisskopf ^a, Vyacheslav Zavlin ^c

^a NASA Marshall Space Flight Center (USA)

^b University of Alabama in Huntsville (USA)

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Papers at Conference 9510: #1 (Martin Weisskopf),
#2 (Steve O'Dell), & #28 (David Broadway)



Outline

- Electroformed-nickel replication (ENR)
- Production of ENR x-ray optics
- Research toward high-resolution x-ray optics

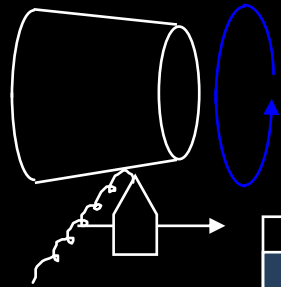


Outline

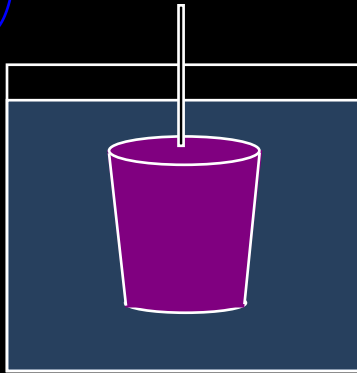
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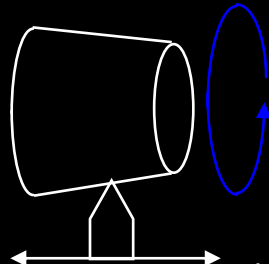
Electroformed Nickel Replication: Mandrel preparation



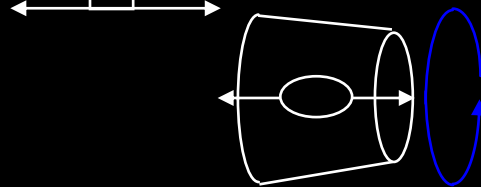
CNC machine the aluminum blank to (slightly undersized) near-net-shape mandrel.



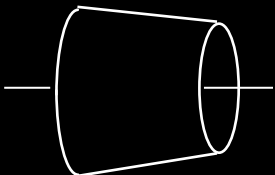
Chemically clean, activate, and deposit electroless nickel onto the machined aluminum mandrel.



Diamond turn electroless nickel to figure precisely the mandrel to its prescription.



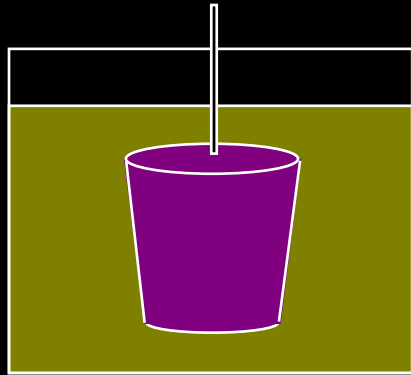
Lap and polish the mandrel to make final figure corrections, smooth, and superpolish surface.



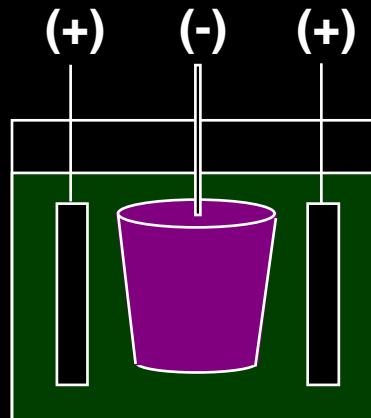
Perform in-process and final metrology to ensure that the mandrel satisfies precision requirements for surface figure and finish.



Electroformed Nickel Replication: Shell fabrication

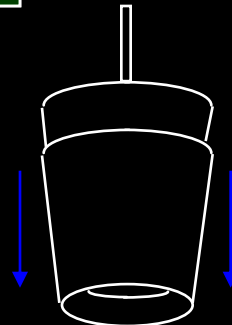


Ultrasonically clean and chemically passivate the electroless-nickel surface of the precision mandrel.



Electroform nickel or nickel-alloy shell onto the mandrel, with minimal uniform plating stress.

MSFC advances in controlling adhesion, plating stress, and alloy strength have enabled replication of very thin ($\sim 100\text{-}\mu\text{m}$) shells.



Separate the shell from the mandrel in a cold-water bath; clean mandrel for additional replications.



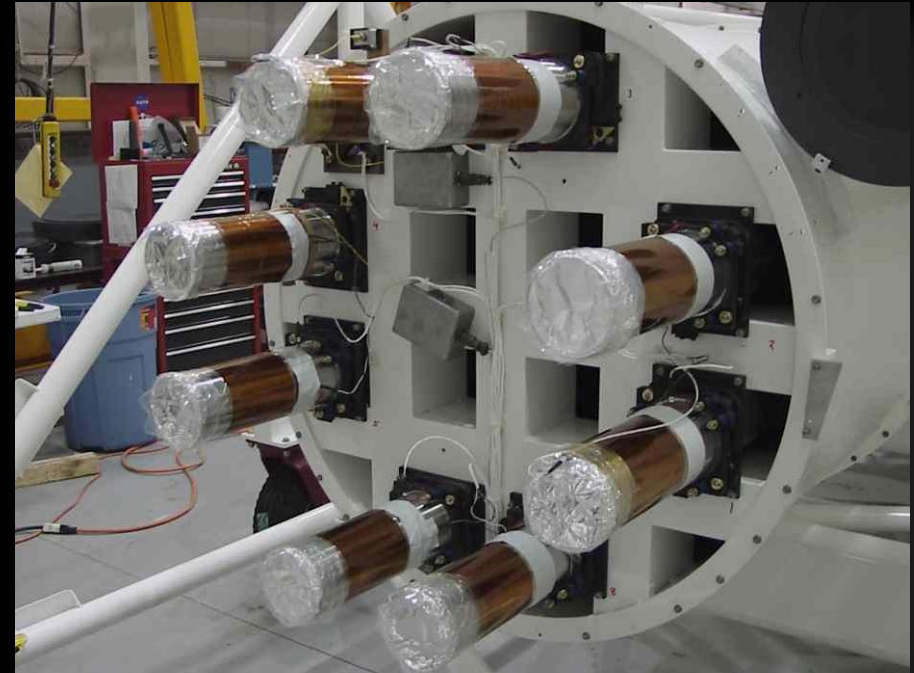
Outline

- Electroformed-nickel replication (ENR)
- **Production of ENR x-ray optics**
- Research toward high-resolution x-ray optics



High-Energy Replicated Optics to Explore the Sun (HEROES)

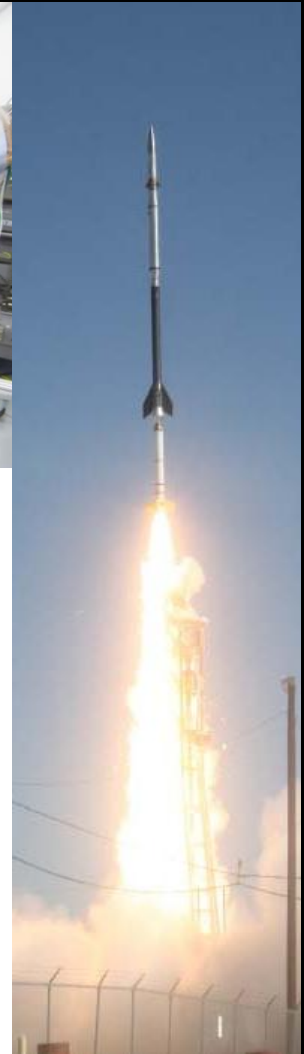
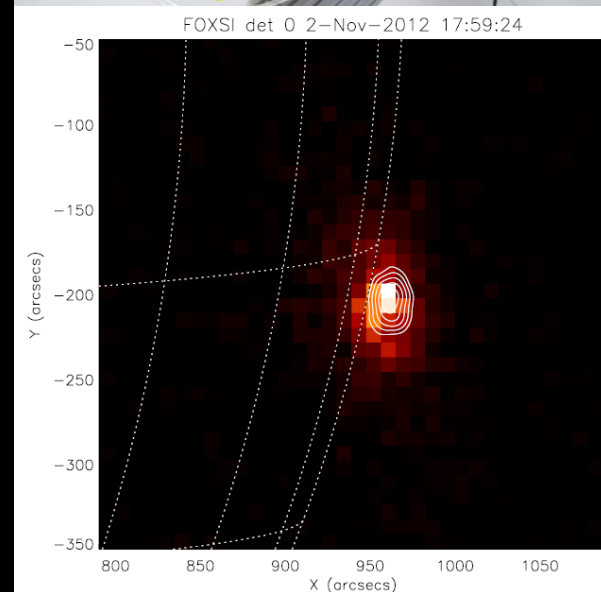
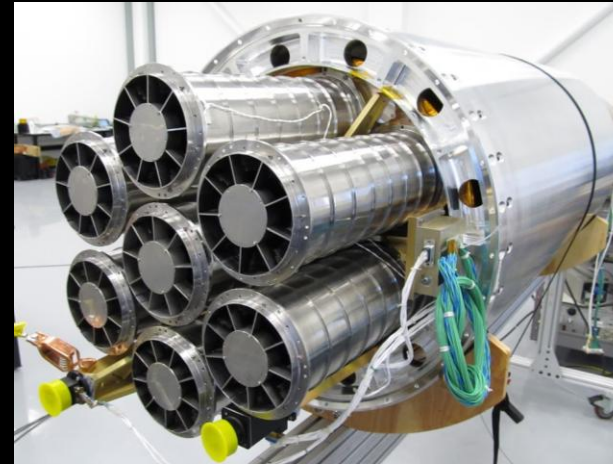
- High-energy x-ray telescope array for MSFC & GSFC balloon payload
 - ❑ Update to MSFC HERO
 - First focused image (2001)
 - ❑ Launched 2013
 - ❑ Heliophysics/Astrophysics
- 8 flight mirror modules
 - ❑ 6000-mm focal length
 - ❑ 14 shells per module
 - 610-mm long (P+S)
 - 50:94-mm diameters
 - Iridium optical coating
 - ❑ 25" half-energy width





Focusing Optics X-ray Solar Imager (FOXSI)

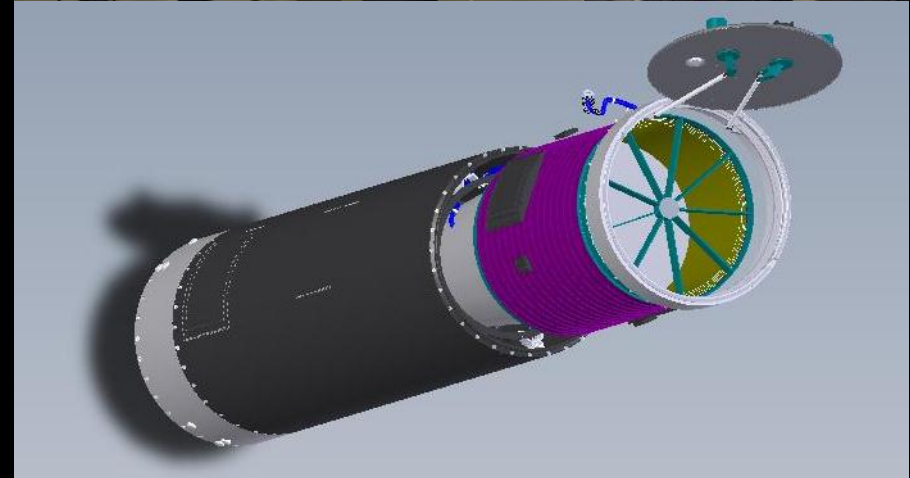
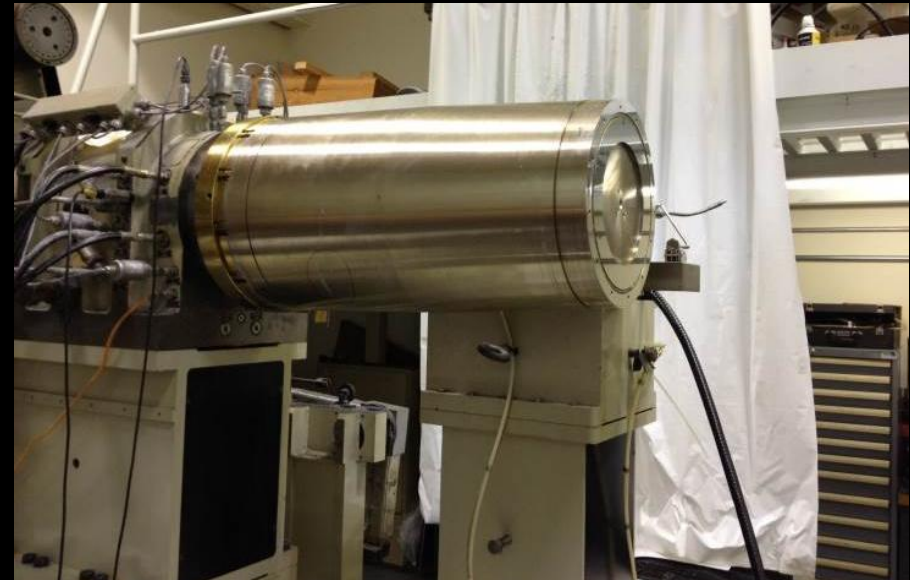
- Medium-energy x-ray telescope array for UC Berkeley's rocket payload
 - ❑ Launched 2012 (FOXSI-1)
 - ❑ Launched 2014 (FOXSI-2)
 - ❑ Study solar nanoflares
- 7 flight mirror modules
 - ❑ 2000-mm focal length
 - ❑ 7|10 shells per module
 - 600-mm long (P+S)
 - 76|63:103-mm diameters
 - Iridium optical coating
 - ❑ 5" full width half max





Micro-X

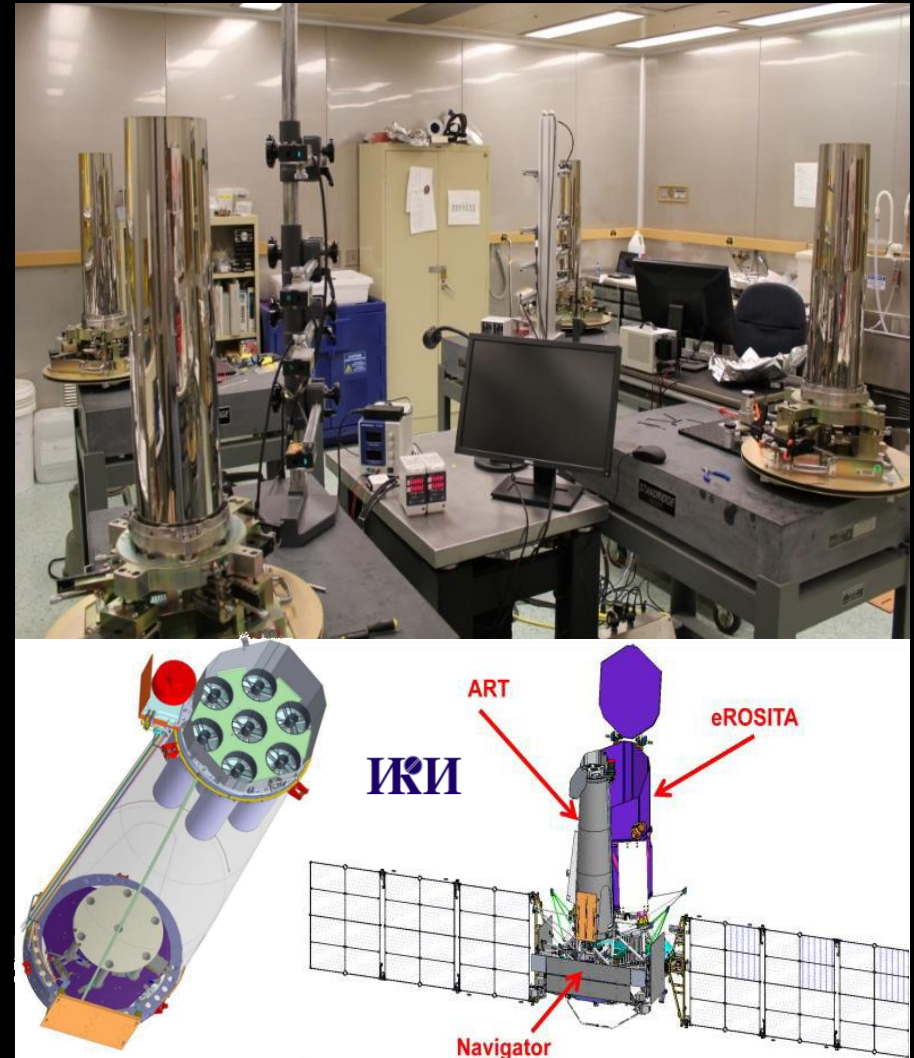
- Low-energy x-ray telescope for MIT's rocket payload
 - ❑ To be launched in 2017
 - ❑ High-spectral-resolution micro-calorimeter images of supernova remnants
- 1 flight mirror module
 - ❑ 2500-mm focal length
 - ❑ 5 shells per module
 - 600-mm long (P+S)
 - 383:444-mm diameter
 - Rhodium optical coating
 - ❑ <30" half-energy width





Astronomical Röntgen Telescope (ART) on Spectrum-Röntgen-Gamma (SRG)

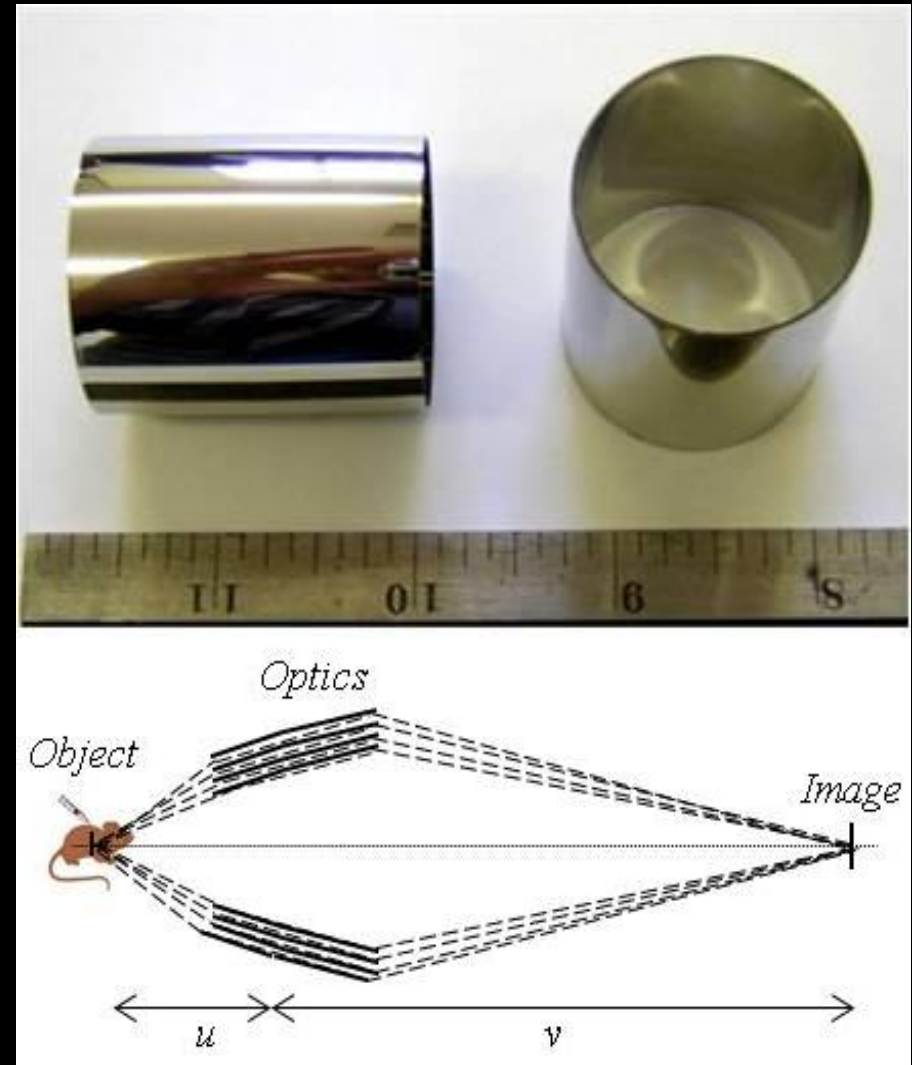
- Medium-energy x-ray telescope array onboard Russian SRG satellite
 - ❑ To be launched in 2016
 - ❑ Complements German low-energy eROSITA
- 7 flight mirror modules
 - ❑ 2700-mm focal length
 - ❑ 28 shells per module
 - 580-mm long (P+S)
 - 50:150-mm diameters
 - Iridium optical coating
 - ❑ 25" half-energy width





Medical applications: Small-animal radionuclide imaging

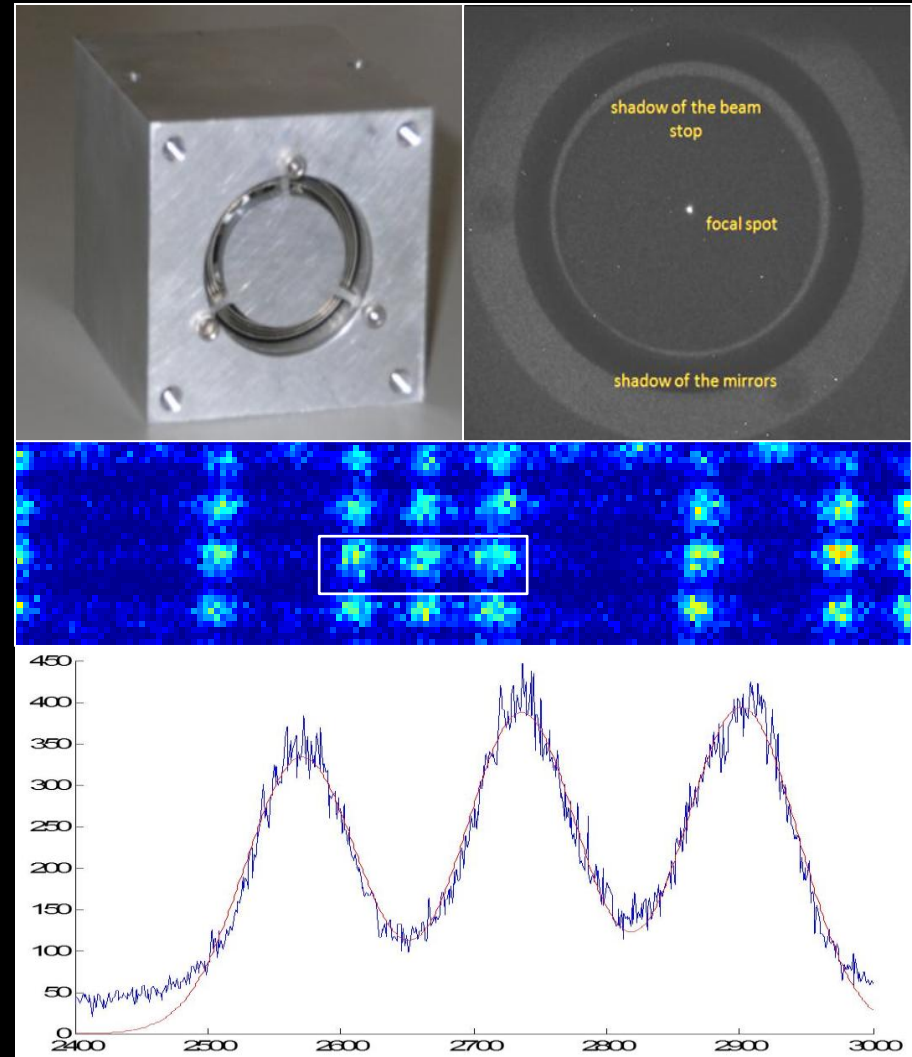
- Funded by US National Institutes of Health (NIH)
 - ❑ NASA MSFC
 - ❑ Lawrence Livermore
 - ❑ Harvard-Smithsonian Center for Astrophysics
 - ❑ UC San Francisco
- X-ray microscope
 - ❑ Nested hyperboloid-ellipsoid geometry
 - 600-mm object distance
 - 2400-mm image distance
 - ❑ 100- μm resolution





Cold-neutron imaging: Demonstration neutron microscope

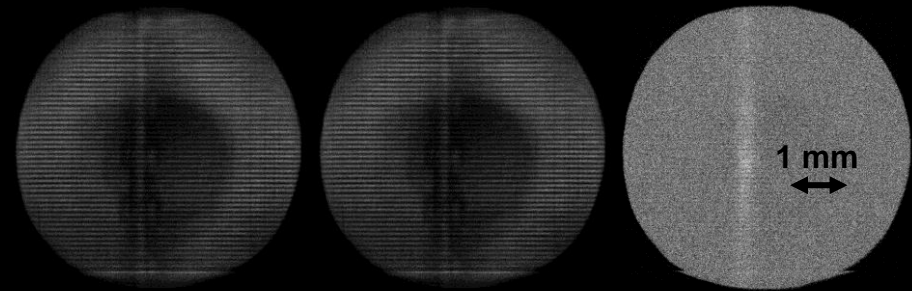
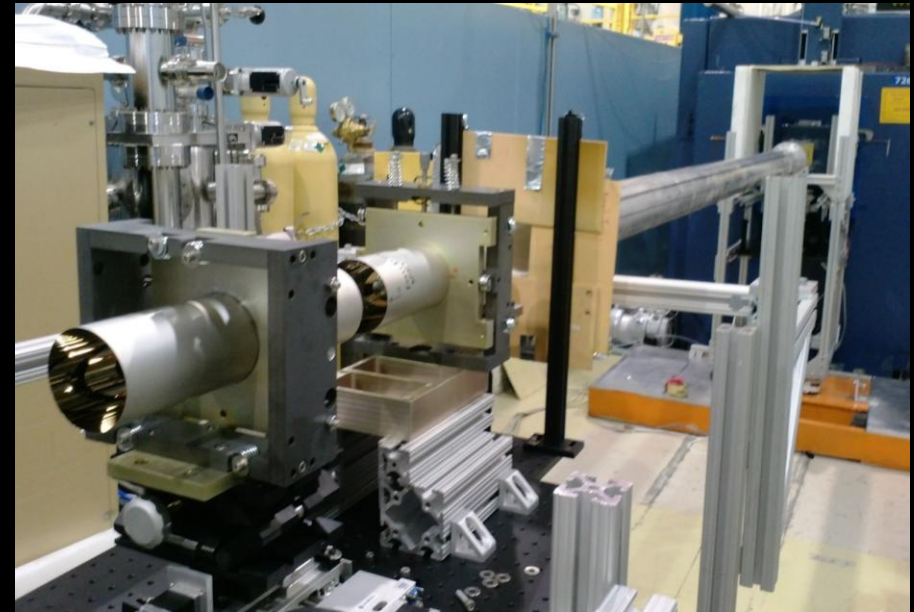
- Collaboration
 - ❑ NASA MSFC
 - ❑ Oak Ridge National Lab
 - ❑ MIT
- Cold-neutron microscope
 - ❑ Pure nickel for neutron reflectance ($K_n \approx 1$ meV)
 - ❑ Otherwise identical to the x-ray microscope
- Advantages over non-focusing methods
 - ❑ 70- μm resolution (FWHM)
 - ❑ 50–100 times intensity





Cold-neutron imaging: Development for NIST beamline

- Funded by US National Institute of Standards and Technology (NIST)
- Multi-step demonstration
 - ❑ High-resolution optics
 - ❑ 1X magnification imaging
 - ❑ Large-magnification imaging
- Applications
 - ❑ Fuel-cell development
 - ❑ Lithium-air batteries
 - ❑ Metallurgy and Chemistry
 - ❑ Medicine and Biology



Characterize water accumulation in fuel cell by differencing images before/after operation.

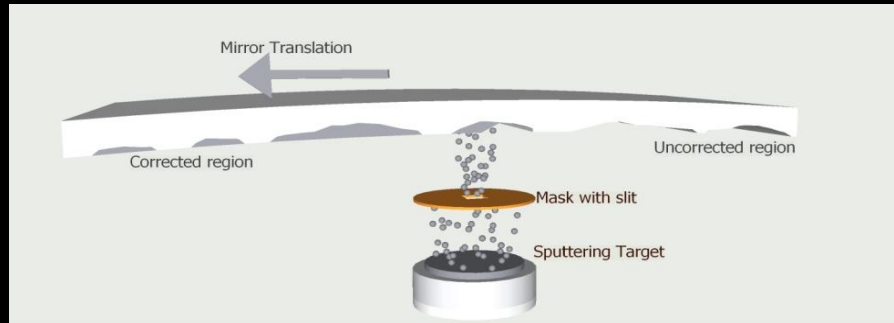


Outline

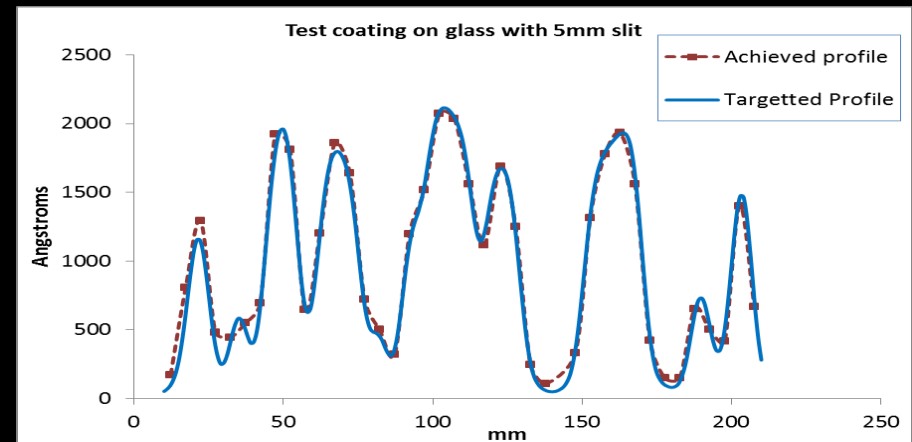
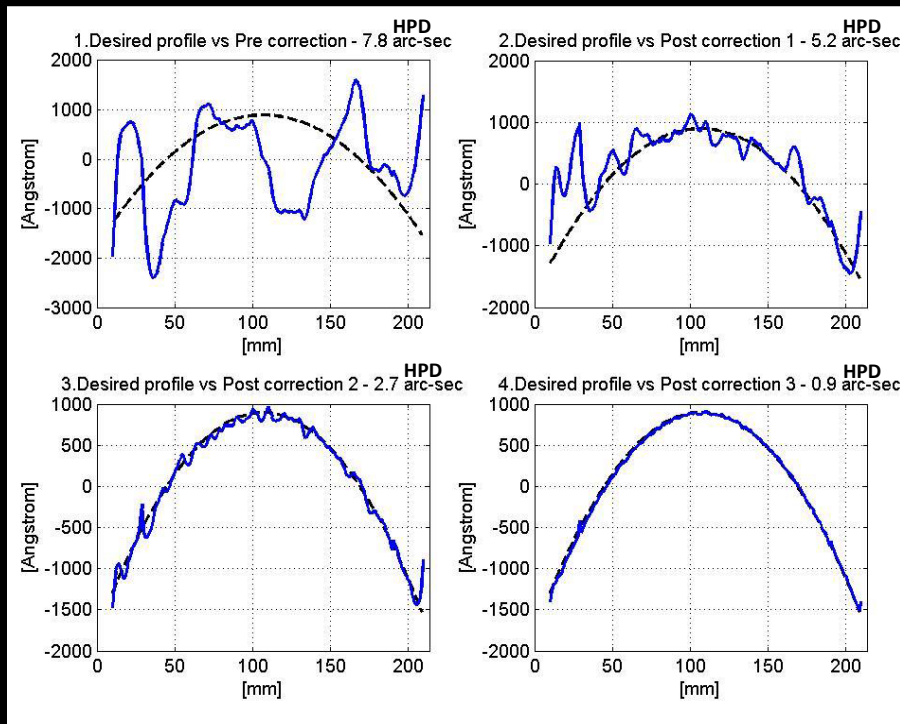
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- **Research toward high-resolution x-ray optics**



Differential deposition allows static correction of figure errors.

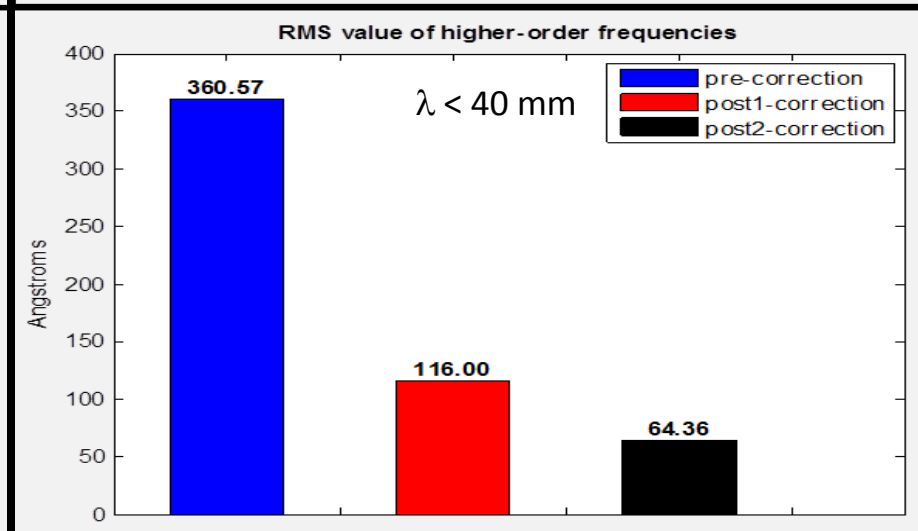
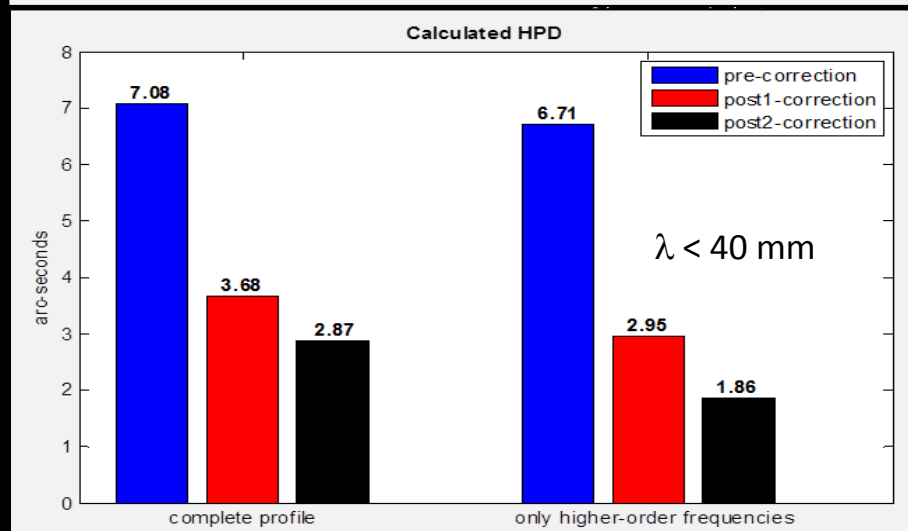
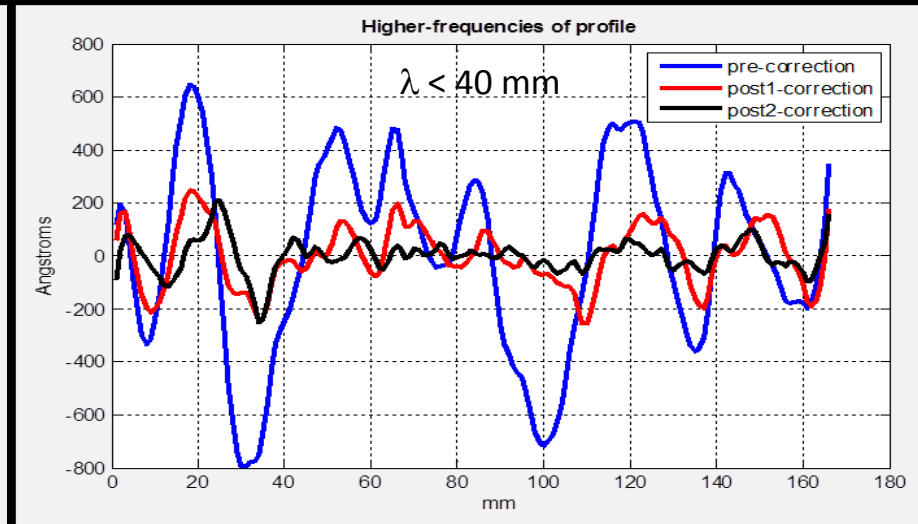
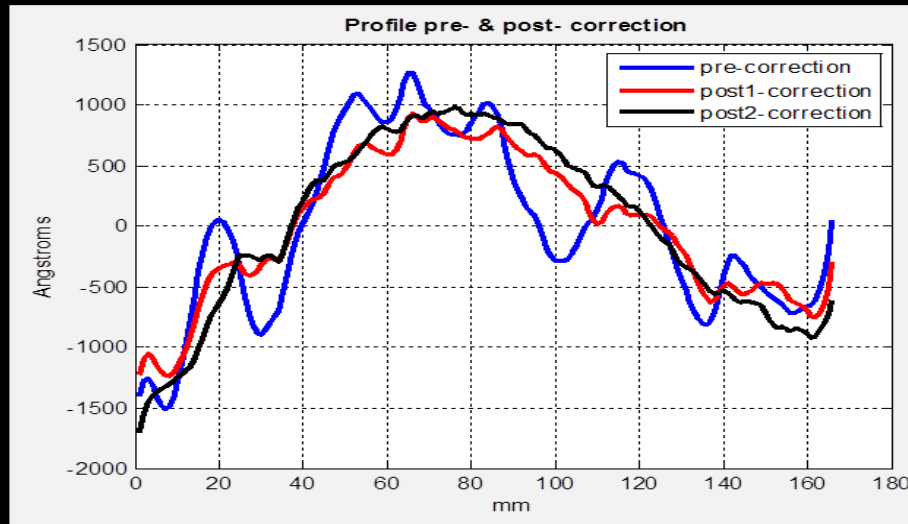


- MSFC is applying this technology.
 - ❑ Simulations show potential capability.
 - ❑ Initial tests are promising.
 - ❑ Need to control coating stress and deformation.
 - See David Broadway's talk.



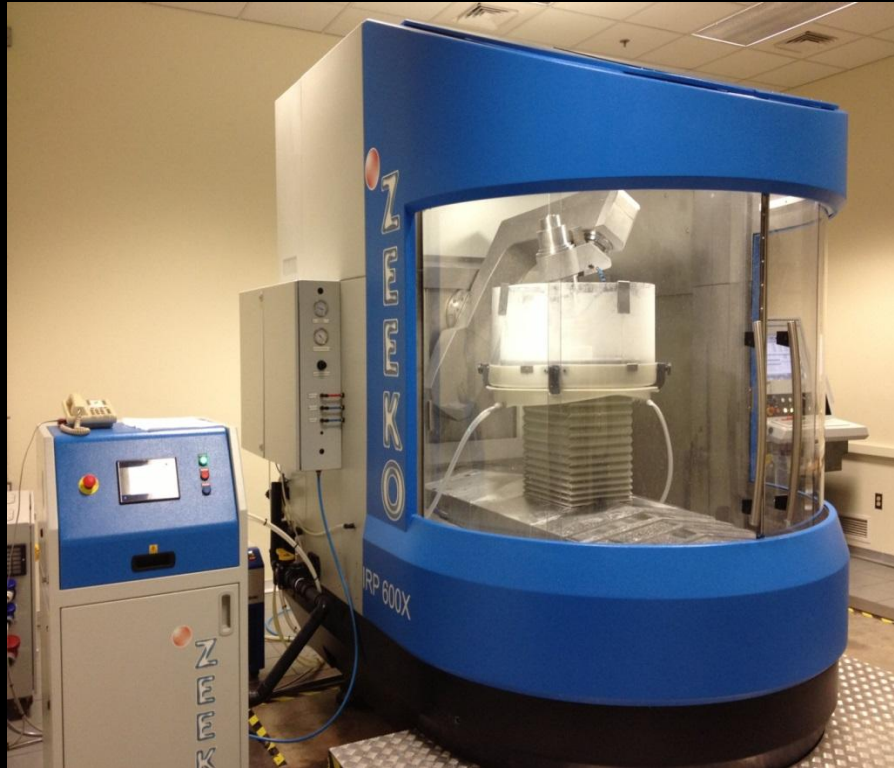


Demonstrated rapid correction of mid-to-upper-mid frequency errors

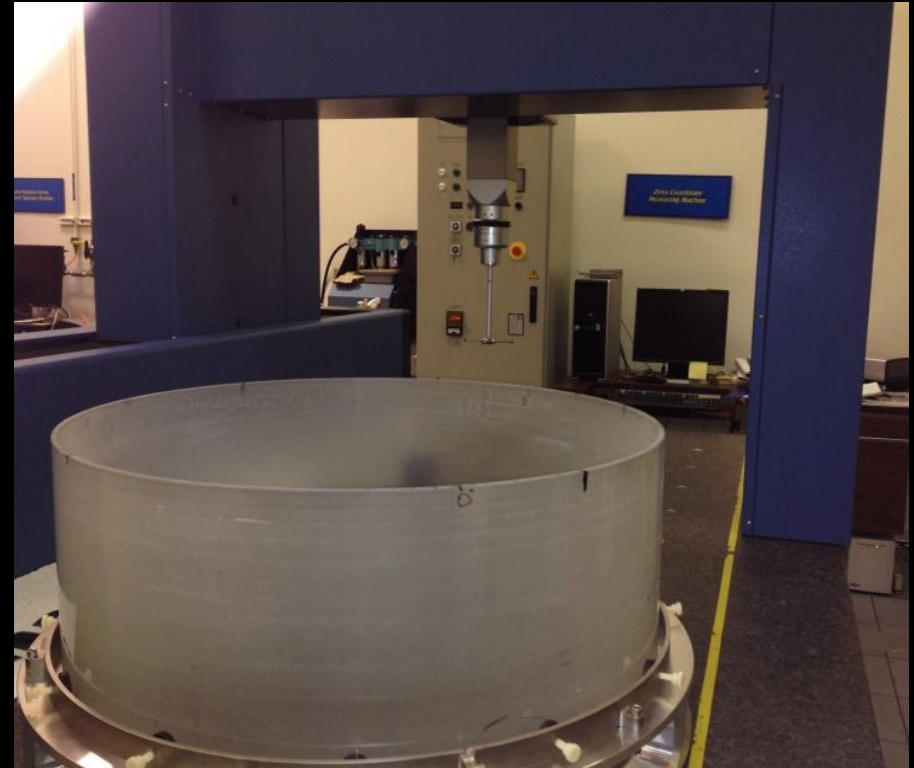




Direct fabrication of thin-walled full-shell grazing-incidence optics



Research in direct fabrication of thin-walled full-cylinder grazing-incidence optics utilizes a free-form robotic polisher.



Precision measurements with metrology instruments—including a Coordinate Measuring Machine—are essential during fabrication.