MSFC Advanced X-Ray Optics: Formulation to Flight

PI: Jessica Gaskin / MSFC

Objectives and Key Challenges:

- Enable the regular realization of thin (~1-mm) , sub-arcsec full-shell X-ray mirrors and mirror modules and enhance the performance of segmented optics for the Astronomy community
- The primary challenge is to produce full-shell Chandra-like mirrors, but with a much thinner mirror shell thickness; requiring reevaluation of our current replication process

Significance of Work:

- Provide a comprehensive capability to design and deliver *flight* mirrors that meets multiple missions' requirements, including those of the Next X-ray Great Observatory

Approach:

- Systematic analysis of our existing process steps to identify and correct for errors generated during fabrication, assembly, and test
- Generate a detailed error budget to inform us of where our dominant issues are, and to determine which process steps need to be modified or alternate solutions pursued
- Continue to supply world-class X-ray test and calibration facilities

Key Personnel & Collaborators:

- J. Kolodziejczak, S. Bongiorno, J. Davis, W. Baumgartner, N. Thomas, and B. Ramsey (MSFC X-Ray Astronomy Group, ST12)
- P. Champey and C. Speegle (MSFC Optics Fabrication Group, ES23)
- D. Gurgew (USRA Science and Technology Institute, ST12)
- S. Singam (ORAU NPP, ST12)
- J. Kegley (MSFC Science Test Branch, ST15)
- Collaborators include SAO, UMN, MSFC, NIF, NIST, Sandia, etc.

Current Funded Period of Performance:

Oct 2022 – Sep 2025

Recent Accomplishments (subset):

- ✓ X-ray testing of 125-mm L shell showed 2.1" FWHM
- ✓ Shell replication modeling and validation for predictable performance
- ✓ Upgraded alignment station design and fabrication
- ✓ Completed concept for high-resolution metrology for inner optical surface of full-shells

Next Milestones (subset):

- High-level error budget populated with expected/typical values (12/23)
- Improve mandrel polishing to achieve < 2" (12/2023)
- Replicate mirror shells with matched mandrel performance (12/24)
- Continue mounting/alignment station and epoxy studies (06/24)

Applications:

- Astrophysics missions (all mission classes)
- Heliophysics, Planetary, and OGAs

$TRL_{In} = 3$ $TRL_{Current} = 3$ $TRL_{Target} = 3\text{-}4$

Electroforming Replication

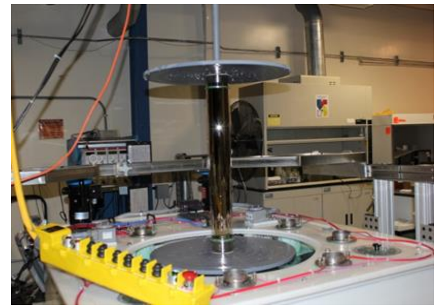
Panini Singam / MSFC NPP(ST-12)

Objectives and Key Challenges:

- Improve the electro-forming replication process in order to reduce figure errors and improve imaging quality of X-ray optics
- Challenges include deposition nonuniformity and deposition stress

Significance of Work:

- Electroforming technique fabricates full-shell X-ray optics from super-polished mandrel. Potential sources of errors like thickness nonuniformity and deposition stress induce figure errors that affect the optical performance.
- We have carried out in-depth study of the process to reduce the replication errors.



Electro depositing optics on mandrel

Replicated X-ray optics

Approach:

- Understand the electric field distribution (thickness) in the deposition tank
- Modify plating geometry to increase uniformity of field distribution
- Custom design gaskets and shields for a particular mandrel for optimized performance
- Improve shell separation for reducing separation stress

Key Personnel & Collaborators:

- ST-12 X-ray astronomy group
- ES-23 X-ray optics team
- Collaborators include SAO, UMN, MSFC, NIF, NIST, Sandia, etc.

Current Funded Period of Performance:

FY 2023-2025

Recent Accomplishments:

- ✓ Fabrication of < 5" HPD optics
- ✓ Better understanding of modelling the whole process

Next Milestones:

- Study newer alloy composition for polishability studies
- Reduce near-edge deformations of the optics
- (separation)

Applications:

- Grazing-incidence full-shell optics for astrophysics, Heliophysics, NIST, and NIF

$TRL_{In} = 3$ $TRL_{Current} = 3$ $TRL_{Target} = 4$

Advanced X-ray Optics: Mirror Fabrication (Mandrel and Direct Polishing)

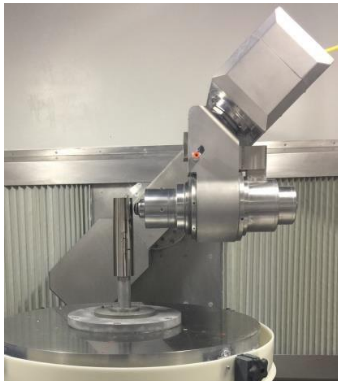
Jeff Kolodziejczak / MSFC ST12

Objectives and Key Challenges:

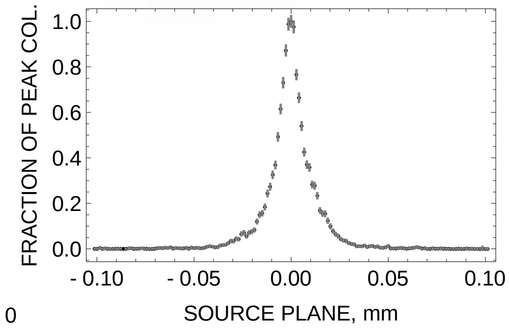
- Enhance mandrel polishing process to include CNC polishing to achieve sub-arcsec angular resolution
- Direct polish thin full-shell X-ray optics to produce shells with sub-arcsec angular resolution
- Design and demonstrate fixtures for holding thin, full-shell metal optics during direct polishing

Significance of Work:

- Enable probing the limits of replicated optics resolution
- Can't have high resolution shells without high-resolution mandrels
- Thin X-ray optics with sub-arcsec angular resolution are required for flagship-class X-ray astrophysics missions like Lynx



Deterministic polishing of a NIF mandrel in the Zeeko CNC polishing machine



Measured X-ray Performance: 2.3±0.3 (1σ) arcsec FWHM

Approach:

- Deterministic polishing of mandrels
  - Start with small mandrel 54-mm D × 125-mm L
  - Apply lessons learned to longer mandrels, 600-mm L
  - With success, extend to larger-diameter mandrels, 500-mm D
- Deterministic polishing of replicated thin shells

Key Personnel & Collaborators:

- J. Kolodziejczak, W. Baumgartner, J. Davis, G. Davis, B. Ramsey, O. Roberts, P. Singham, and N. Thomas (ST12)
- P. Champey, C. Speegle, J. Sanchez, T. Kester, A. Meekham, M. Stahl, and M. Young (ES23)
- Collaborators include SAO, UMN, MSFC, NIF, NIST, Sandia, etc.

Current Funded Period of Performance:

Oct 2022 – Sep 2023

Recent Accomplishments:

- ✓ X-ray testing of 125-mm L shell showed 2.1” FWHM
- ✓ First round of CNC Polishing of 600-mm L mandrels completed showing 50% reduction in predicted HPD
- ✓ Designed and parts procured for shell polishing development testbed

Next Milestones:

- Second pass on 600-mm L mandrels to achieve <2”
- Assembly and check-out of shell-polishing development testbed

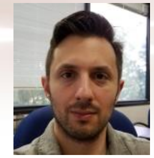
Applications:

- Grazing-incidence optics for astrophysics, heliophysics, NIST, and NIF

TRL $_{In}$ = 2 *TRL $_{PI\text{-}Asserted}$ = 3* *TRL $_{Target}$ = 4*

Advanced X-ray Optics: Mounting and alignment

Stephen Bongiorno / MSFC ST12

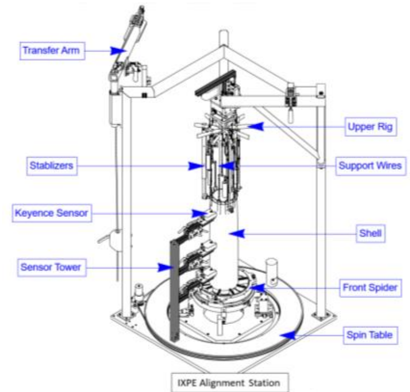


Objectives and Key Challenges:

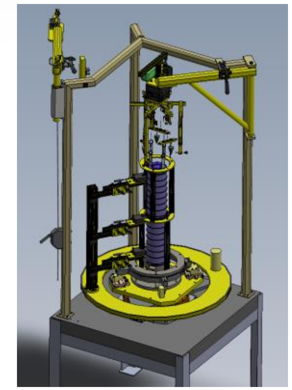
- To design and demonstrate an apparatus for supporting and aligning sub-arcsec full-shell optics during metrology and integration with mirror module assemblies
- Challenges include stability of materials and high-precision motion

Significance of Work:

- Thin optics are inherently compliant and distort significantly under self-gravity. During metrology and while being attached to permanent mounting structures, full-shell optics must be supported without imparting significant distortion. Mounting and alignment techniques must improve as we create thin-shell X-ray optics with progressively better angular resolution



IXPE flight alignment station



Upgraded alignment station

Approach:

- **Characterize epoxy shrinkage**
- **Improve alignment station suspension stability** – IXPE assembly noted shell tilt and center drift of approx. 5”/hr and 20 µm/hr; identify and eliminate source(s) of drift
- **Improve precision of alignment station bearing** – Current bearing has ~30” wobble. Procured high-precision air bearing will reduce wobble of metrology reference to ~0.2”
- **Improve alignment station stability** – Granite base will become monolithic platform for bearing, module, and upper rig
- **Shell circularity adjustment with piezo actuators**

Key Personnel & Collaborators:

- W. Baumgartner (ST12) , B. Weddendorf (Weddendorf Design)
- Collaborators include SAO, UMN, MSFC, NIF, NIST, Sandia, etc.

Current Funded Period of Performance:

Oct 2022 – Sep 2023

Recent Accomplishments:

- ✓ High-precision air bearing procured
- ✓ Upgraded alignment station design and fabrication complete

Next Milestones:

- Upgraded alignment station assembly and commissioning
- Perform suspension stability experiments
- Design closed-loop radial-shell shape-adjustment technique

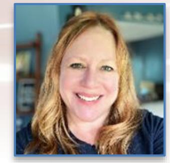
Applications:

- Grazing incidence full-shell optics for astrophysics, heliophysics, NIST, and NIF

TRL $_{In}$ = 2   *TRL $_{PI\text{-}Asserted}$ = 2*   *TRL $_{Target}$ = 4*

Metrology Development

Jacqueline Davis / MSFC ST12

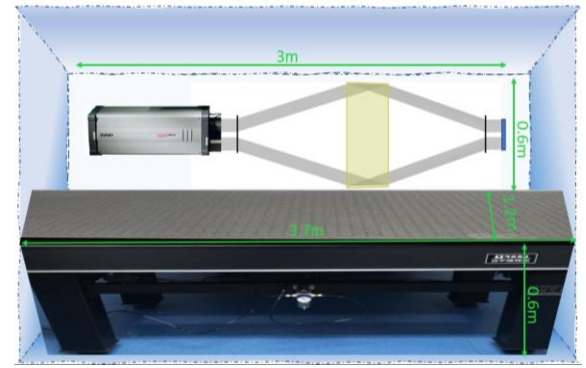


Objectives and Key Challenges:

- Reduce measurement error
- Quantify magnitude
- Determine source of error

Significance of Work:

- Approaching sub-arcsec X-ray optics necessitates more accurate measurements of the optical error
- Quantifying the source of the error creates a possibility for improving the optical surface



High-resolution instrumentation concept with controlled environment

Approach:

- Create an approach to predict scaled-up error from prototype metrology measurements
- Provide error for each manufacturing process, its spatial frequency and its predicted scaled-up optical error
- Determine path towards reducing overall optical error utilizing the Δerror of each manufacturing process
- Develop high-resolution metrology instrumentation for the optical surface on the inside surface of shell
- Train dedicated metrology technician
- Define detailed metrology methodology
- Create repository to store and organize metrology data

Key Personnel & Collaborators:

- J. Davis, P. Singam, S. Bongiorno, and J. Kolodziejczak (ST12)
- P. Champey and C. Speegle (ES23)
- C. DeRoo (University of Iowa)
- C. Zhao (Arizona Optical Metrology)

Current Funded Period of Performance:

Oct 2022 – Sep 2025

Recent Accomplishments:

- ✓ Concept study of high-resolution metrology for inner optical surface of full-shell X-ray optics
- ✓ Purchased components for high-resolution instrumentation
- ✓ Collaborated with ES23 on creating common metrology lab space

Next Milestones:

- Install high-resolution interferometer (Jan 2023)
- Align CGH for HR metrology instrumentation after interferometer installation
- Analyze past data to document current error in relation to error budget
- Develop method to predict error of a 3-m Lynx shell based on current metrology data
- Calculate scaled optical error of ConX shell
- Build environment-controlled space for a single metrology station
- Collaborate with ES23 to develop space for dedicated metrology lab
- Create job listing for metrology technician
- Investigate software options for storing and organizing metrology data

Applications:

- Future missions in X-ray Astronomy

TRL_{In} = **3** $TRL_{Current}$ = **3** TRL_{Target} = **3-4**

X-ray Optic Thin Film Coatings

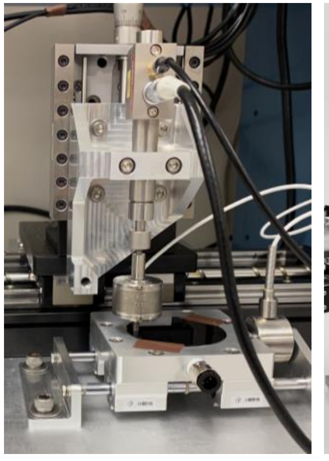
Danielle Gurgew USRA/ST12

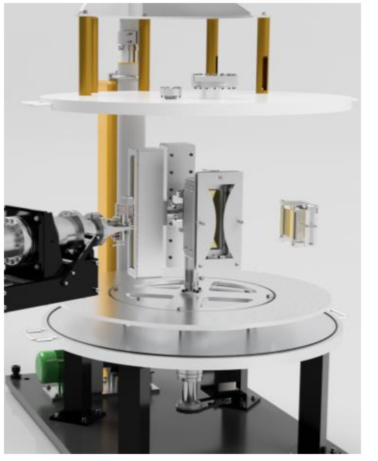
Objectives and Key Challenges:

- Develop low-stress, high-throughput reflective coatings that will enable future missions such as Lynx and HEX-P
- Key Challenge: Produce high-reflectance, smooth, low-stress coatings that preserve substrate figure post-coat

Significance of Work:

- Addresses key technological challenges identified by NASA's 2022 Astrophysics Strategic Technology Gaps
- Great Observatory and Probe-class missions will require large collecting areas and several-arcsec to sub-arcsec resolution that can't be achieved without addressing coating stress and improving quality





Left: Adhesion test system with coated wafer **Right:** Upgraded multilayer coating chamber design with three linear cathodes

Approach:

- The design and implementation of a novel coating scheme for achieving inherently uniform coatings on curved segments
- The use of a proven novel method of in-situ stress measurement that will be adapted to curved substrates
- Investigation of deposition parameter variation to achieve optimized multilayer coating performance including reactive sputtering applicable to current and future mission concepts

Key Personnel & Collaborators:

- P. Singam (NPP/USRA/ST12), O. Roberts and D. Swartz (USRA/ST12), B. Ramsey (Emeritus/ST12)
- Collaborators include CalTech/JPL, GSFC, SAO, UMN, MSFC, etc.

Current Funded Period of Performance:

Oct 2022 – Sep 2025

Recent Accomplishments:

- ✓ Adhesion test system completed and verified
- ✓ Procured linear cathodes for upgraded multilayer coating chamber optimized for segmented optics
- ✓ New X-ray source procured for upgraded X-ray reflectometer

Next Milestones:

- Identify practicality of Ni-based multilayer coating design for HEX-P Probe mission concept (2023)
- Install and commission upgraded multilayer coating chamber with linear cathodes (Jan 2024)
- Upgrade existing XRR system with new source and re-locate to coating lab (Jan 2024)

Applications:

- Explorers, Probe (e.g., HEX-P), Flagship missions (e.g., Lynx)

$TRL_{In} = 3$ $TRL_{Current} = 3$ $TRL_{Target} = 4$

X-ray Testing and Calibration

Jeff Kegley, Wayne Baumgartner, Nick Thomas / MSFC

J. Kegley

W. Baumgartner

N. Thomas

Objectives and Key Challenges:

- Primary objective is to provide facilities and support for X-ray optics and instrumentation testing within NASA research programs

Significance of Work:

- Facilities include the 500-m X-ray and Cryogenic Facility (XRCF) and the 100-m Stray Light Test Facility (SLTF), also known as the Marshall 100-m X-ray Beamline
- The Marshall 100 m is well equipped for quick turnaround tests of X-ray optics and optical components. The facility features a variety of X-ray sources from soft (e.g., < 1 keV)) through to hard (> 100 keV) energies (including polarized sources) and a variety of X-ray detectors for low-energy imaging (X-ray CCDs and CMOS cameras) and higher-energy detection (e.g., silicon drift and CdTe)
- The XRCF provides space simulation environments from 20K to +200F for optical, X-Ray, and structural testing

Marshall 100 Meter X-ray Beamline: left: beamline; right: instrument chamber with bell housing

MSFC XRCF Beam-line & chamber

Approach:

- Instructions currently in NSPIRES: *"The X-ray optics facilities maintained by MSFC include the X-ray and Cryogenic Facility and Stray Light Facilities as Agency Capabilities. In the past, PIs wishing to make use of the MSFC SLF and/or the XRCF included Co-I funding to MSFC in order to fund this usage. These facilities are now supported for some of this work by directed work packages under the NASA ISFM, so proposers planning to request use of the MSFC facilities should contact nicholas.e.thomas@nasa.gov and wayne.baumgartner@nasa.gov to discuss what portion of the request can be covered by current support and what portion needs to be included in the APRA proposal budget"*
- In practice, MSFC supplies a letter of agreement to researchers wishing to use the facilities to include in their proposals

Key Personnel & Collaborators:

- Stephen Cheney (ES23)
- Multiple universities and government institutions/organizations

Current Funded Period of Performance:

Oct 2022 – Sep 2025

Recent Accomplishments:

- ✓ Over the previous year, the Marshall 100 Meter Beamline successfully calibrated five programs
- ✓ Continued outreach to attract new collaborators
- ✓ During this year at XRCF: X-ray system updates and operations in preparation for ATHENA and UV-IR mirror evaluations for COR

Next Milestones:

- SLTF: Complete calibration efforts on: FOXSI-4, SSAXI, MaGIXS-2, Lobster-eye Optic Test Bed, NIST Neutron Optic (Jul 2023)
- SLTF: Begin calibration efforts on: Aligning high-resolution X-ray telescope mirrors using adjustable-height spacers, GOSoX (TBD)
- XRCF: Continue developing X-ray-test capability for future large-diameter optics and end-to-end calibration; perform COR SAT mirror testing

Applications:

- R&D of high-energy and IR optics and instrumentation
- Assembly, test, and calibration of flight hardware

TRL: N/A