MSFC Advanced X-Ray Optics: Formulation to Flight

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Task 1 Summary

The Advanced X-ray Optics effort at NASA MSFC takes a comprehensive approach towards advancing high-angular-resolution (sub-arcsec) full-shell mirror assemblies, while continuing to supply the community with low-cost, moderate-resolution flight mirrors and world-class calibration capabilities. This effort builds on our existing end-to-end capability to design, manufacture, coat, align, mount, test, calibrate, and fly full-shell X-ray mirror assembles. The MSFC X-ray Optics Team consists of scientists within the X-Ray Astronomy Group (ST12), optical engineers and scientists within the Optics Manufacturing Group (ES23), a USRA Visiting Scientist, an NPP postdoc, and a UAH graduate student.

This effort is responsive to the 2020 Astro Decadal recommendations for a New Great Observatory program, Probe-class missions, and multi-messenger/multi-wavelength efforts. MSFC optics are also relevant to Heliophysics and Planetary missions (collaborations with UMN, SAO, and many others), and we currently support other government entities such as the National Ignition Facility (NIF), National Institute of Standards and Technology (NIST), and Sandia National Laboratory.

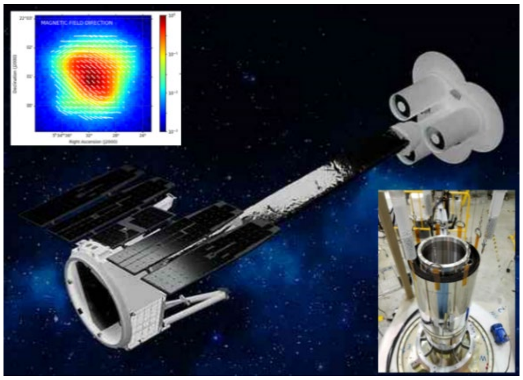

***Fig. 1**. Rendering of the IXPE Observatory.* Upper Left: *image of the Crab pulsar wind nebula taken by IXPE with measured magnetic fields superimposed.* Lower right: *IXPE optics during alignment and mounting.*

The previous generation of high-angular-resolution X-ray optics, flown on Chandra, achieved sub-arcsec resolution with thick (~16-24-mm), full-shell mirror assemblies, while the current generation requires thinner mirrors (~1-mm) for significantly increased effective area. Due to a variety of challenges, mirror assemblies with thinner mirrors have yet to achieve sub-arcsec resolution. MSFC's years of development has advanced low-cost, relatively thin full-shell *mirror assemblies* to the regular realization of <20" Half Power Diameter (HPD), which meets many current and proposed mission requirements – most recently SRG-ART-XC and IXPE (Fig. 1). While the current generation of medium-resolution X-ray mirrors is still in high demand, research and development toward low-cost high-resolution sub-arcsec mirrors is also a priority. The ISFM funding has allowed us to make significant improvements in our fabrication process, resulting in single mirror shells that are better than 5" HPD, and we have a clear path forward for making further improvements. As we are still in work to achieve sub-arcsec resolution mirror assemblies, TRL remains at a 3.

Background

Pathways to Discovery in Astronomy and Astrophysics for the 2020s [1] strongly endorses the need for high-resolution X-ray imaging and spectroscopy, as this capability enables all three high-priority science areas highlighted in the report.

Pathways to Habitable Worlds: “A high spatial and spectral resolution X-ray observatory to probe stellar activity across the range of stellar types, including host stars of potentially life-sustaining exoplanets.” [1]. The Lynx Concept Study Report (CSR) details the advantages of high-throughput, high-resolution spectroscopic capabilities to: “(1) characterize by proxy the crucial and difficult-to-observe EUV [extreme ultraviolet] stellar flux, as well as its history for planet hosting stars; (2) observe the stellar wind; and (3) detect the Doppler signatures of coronal mass ejections.” One example is the study of solar system objects (Fig. 2) [2].

***Fig. 2**.”* Left: *Chandra image of X-ray emission from the northern Jovian aurora, superimposed on a Juno image.* Right: *Comet C/2012 S1 (ISON) optical and X-ray emission in [2]. The X rays were detected with Chandra during the comet’s closest approach with Earth. The increase in soft-X-ray effective area of Lynx …and advances in spatial resolution will provide details at resolution of 1,000 km.” (Left credit: NASA JPL Caltech/SwRI/MSSS; Right credit: X-ray: NASA/CXC/Univ. of CT/B. Snios et al, Optical: DSS, Damian Peach)*

New Windows on the Dynamic Universe: “—the study of neutron stars, white dwarfs, collisions of black holes, and stellar explosions using the complementary perspectives provided by the wide range of messengers from light in all its forms from radio to gamma rays, gravitational waves, neutrinos, and high-energy particles” [1]. These studies are enhanced when complementary resolution capabilities are used, as is evidenced by Rosat and Chandra observations of the Crab Nebula (Fig. 3).

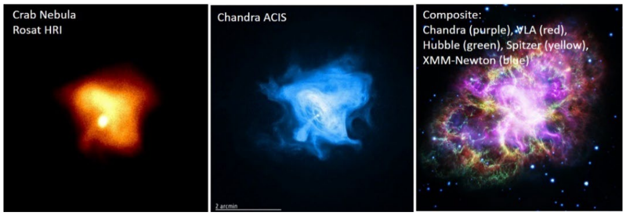

Fig. 3. Left: *ROSAT Crab image in X-rays from 0.1 - 2.0 keV;* Center: *Chandra image 0.5 - 8.5 keV.* Right: *Composite image using Chandra, VLA, Hubble, Spitzer, and XMM-Newton. (ROSAT Credit: S.L. Snowden; NASA/GSFC. X-ray: NASA/CXC/SAO; Optical: NASA/STScI; IR: NASA/JPL/Caltech; Radio: NSF/NRAO/VLA; UV: ESA/XMM-Newton).*

Unveiling the Drivers of Galaxy Growth: “To complement these capabilities (from UV/O/IR and ground-based observatories) a capable far-IR and/or X-ray mission will further transform these views by peering into the dusty hearts of galaxies to reveal enshrouded accreting black holes, or tracing the hottest phases of gas driven outward by this same accretion, with the spatial and spectral resolution needed to isolate critical physical quantities in massive galaxies.”[1] The *Lynx* CSR requires high angular resolution to discern black hole seeds in the first generations of galaxies (z=10) that will be detected by *JWST*, to trace black hole evolution over cosmic time, and to expose the essential drivers of galaxy evolution that extend into the circumgalactic medium [2].

Project Technology Summary: Fabricate and test thin (~1-mm) sub-arcsec full-shell X-ray mirror assemblies (with multiple mounted mirrors) for future Astrophysics missions (from suborbital to New Great Observatory).

Current SOTA & High-Level Development Plan: The state of the art (SOTA) for a full-shell X-ray mirror assembly with sub-arcsec angular resolution is that of Chandra. The Chandra mirror assembly has a maximum diameter of 1.2 m and the mirror thickness ranges from 16 to 24 mm. Much thinner (~1-mm) and smaller-diameter nickel replicated mirrors developed at MSFC have achieved ~5” HPD, while the mandrels they are replicated from are <2.5” HPD. Our development plan is to systematically identify and correct sources of error in each step of our process, with the goal of significantly improving our mandrel polishing, replication, mounting and alignment, coating, and testing (optical and X-ray) in order to realize high-throughput sub-arcsec full-shell X-ray mirror modules.

Objectives and Milestones

The project objectives under the previous package were identical to those going forward and are described in the above text. The primary difference between the previous and current package is the approach we are taking toward achieving sub-arcsec mirror assemblies. The path going forward is a systematic analysis of our existing process steps to identify and correct for errors generated during fabrication, assembly, and test. A detailed error budget is being generated as part of this process to inform us where our dominant issues are, and to determine which process steps need to be modified or alternate solutions pursued.

A top-level error budget architecture has been developed and initial allocations are informed estimates that will be refined as research progresses. Allocation uncertainties, sensitivities, and typical and best values achieved to date for a range of full-shell mirrors and assemblies will be recorded along with test validation method for all mirror shells.

Overarching goals for FY 2023-2025 are to design, fabricate, coat, assemble, and test a two-shell mirror module using thin (~1-mm) full-shell optics (with ~72-mm outer diameter and ~600-mm long) that achieves < 2” HPD, and establish a working error budget and roadmap to achieve < 1” HPD mirror-module performance.

Key Milestones:

- Replication Studies (mirror shell thickness is varied)
    - Develop a model of the electric field distribution in the deposition tank and implement (**completed – FY 2022**)
    - Develop a model of the plating geometry to increase the uniformity of field distribution and implement (**completed-FY 2022**)
    - Design end-gaskets and shields for a particular mandrel to reduce plating stress (**proof-of-concept completed – FY 2022, completion in FY 2023**)
    - Determine errors produced during shell separation process for reducing the separation stress (**on-going FY 2023**)
    - Reduce errors produced during shell separation process (**on-going FY 2023-2024**)
    - Determine the best alloy for direct mirror polishing, fabricate coupons for testing (**on-going FY 2023**)
- Mandrel and Mirror Polishing
    - Improve mandrel figure via deterministic polishing (**FY 2023-2024**)
    - Second pass on ~50-mm-diameter, 600-mm long mandrels to achieve <2” (**FY 2023-2024**)
    - Design and procure components for a custom full-shell mirror polishing development testbed (**completed FY 2022-2023**)
    - Assembly and check-out of shell-polishing development testbed (**FY 2023**)
    - Deterministic polishing of replicated thin shells (**FY 2024-2025**)
- Mounting and Alignment
    - Fully characterize existing epoxy shrinkage (**FY 2023**)
    - Identify and test UV-curing epoxies for improved performance (**FY 2023-2024**)
    - Identify alignment station suspension stability over that of IXPE (**completed – FY 2022**)
    - Identify precision of alignment station bearing (**completed – FY 2022**)
    - Identify alignment station base stability (**completed – FY 2022**)
    - Upgraded alignment station assembly and commissioning (**FY 2023**)
    - Perform suspension stability experiments (**FY 2023**)

    - Design closed-loop radial-shell shape-adjustment technique (with piezo actuators) (**FY 2023-2025**)
- Thin-Film Coatings
    - Apply in-situ stress measurement as part of a low-stress coating process that will be adapted to curved substrates, including full-shell mirrors (**on-going FY 2021-2023**)
    - Investigate deposition-parameter variation and reactive sputtering to achieve optimized multilayer coating performance (**FY 2023-2024**)
    - Identify practicality of Ni-based multilayer coating design for HEX-P probe mission concept (should we tie it to HEX-P or make it more general like 'for broad-energy-band coverage) (**FY 2023-2024**)
    - Install and commission upgraded multilayer coating chamber with linear cathodes (**FY 2024**)
    - Upgrade existing XRR system with new source and re-locate to coating lab (**FY 2023**)
    - Characterize low-stress bilayer and multilayer coatings on figured, segmented optics in the MSFC 100-m X-ray beamline. Finalize and test a magnetron sputtering cathode design for full shell optics (**FY 2025**)
- Metrology, X-Ray Test, and Calibration
    - Provide error values for each manufacturing process, its spatial frequency and its predicted scaled-up optical error as part of the overall error budget effort (**FY 2023-2024**)
    - Determine path toward reducing errors induced via current MSFC metrology techniques and processes (**FY 2023-2024**)
    - Develop high-resolution metrology instrumentation and processes for the optical surface on the inside surface of full-shells (**FY 2022-2024**)
    - Create repository to store and organize metrology data (**completed FY 2022**)
    - Continue to support the community needs for X-ray test and calibration through the APRA program (XRCF and MSFC-100m beamlines) (**on-going**)

Progress and Accomplishments

Task 1 – X-Ray Optics Development

Mirror Replication Studies (Includes Mandrel Polishing)*:* Our group is working on a project to build a high-resolution X-ray microscope for NIF, the goals of which strongly overlap with that of the full-shell optics ISFM directed work tasks. This effort, which acted in concert with work done under the ISFM X-ray optics package, demonstrated 2.3"±0.3" FWHM angular resolution from a 56-mm-diameter, ellipsoid (E) hyperboloid (H) mirror prescription, 1-mm-thick replicated nickel-cobalt (NiCo) shell. This result was enabled primarily by two research efforts: improving mandrel figure via deterministic polishing and improving shell shape by applying changes to the electroforming process used for mirror replication. Deterministic polishing of the mandrel was carried out on our Zeeko IRP 600X CNC polishing machine and resulted in improving the mandrel figure from 50-nm RMS surface error to 2-nm RMS surface error, the latter corresponding to an estimated performance of 2.3" FWHM. The shell replication process was improved by simulating the electroforming bath in COMSOL multi-physics software and optimizing the replication hardware to minimize electric field non-uniformity along the mandrel in the electroforming bath. The most important outcome of this modeling effort was the new understanding that the diameters of the gaskets that define the ends of the shell have a significant influence on the bath electric field, with large-diameter gaskets providing greater field uniformity. Using larger gaskets and the improved mandrel resulted in an X-ray shell with a measured FWHM focal spot width in the source plane of 8.1±1 μm, corresponding to a FWHM angular resolution of just 2.3"±0.3" at 3.5-5 keV (Fig. 4) [3].

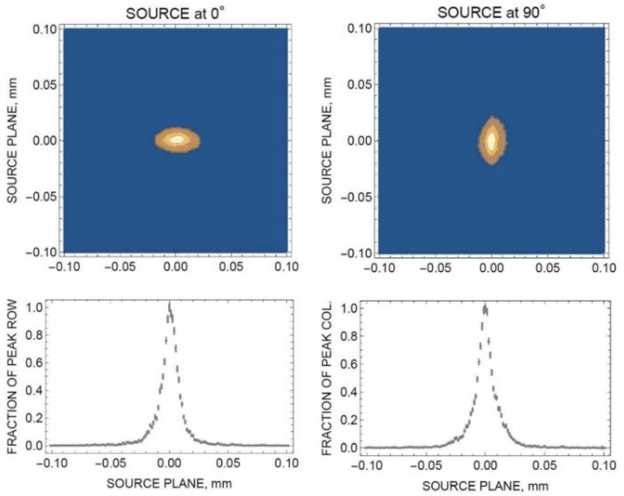

Fig. 4. *X-ray image of NIF/ISFM replicated optic with (Left) the source at 0° orientation, where the narrow source direction is aligned with the vertical CCD readout and (Right) source oriented 90° to the CCD readout direction. The spot width in the source plane is 8.1±1 µm FWHM, which corresponds to 2.3"±0.3" FWHM angular resolution [3].*

A second, competed, project that has overlapping goals with the X-ray ISFM is the Focusing Optics X-ray Solar Imager (FOXSI) sounding rocket. Under this project and in conjunction with the ISFM package, replication studies have been carried out to improve the process on larger-diameter mirror shells. As with the NIF program, studies included improved mandrel figuring, NiCo electroforming bath simulations, gasket modeling, and shell-thickness uniformity measurements.

Direct Polishing: Direct polishing of full shells to further improve their figures after replication offers a potential path to sub-arcsec angular resolution. Toward this end we have been developing the capability to produce mirror shells from electrolytic NiP (eNiP), a glassy-metal material that is already used (via an electroless process) to coat the surface of our mandrels for precise figuring and polishing. Patented by Ramsey and Engelhaupt at MSFC, the low-stress eNiP process will produce shells with high hardness that can be polished directly and, with the addition of cobalt, will have tunable stress-current density curves, a property needed for producing electroformed shells with accurate figure. We have built a new 35-liter plating bath for this. With coupons and polishing pucks made in this bath, as a function of bath chemistry and temperature, we will perform mechanical-property testing and, through detailed polishing tests, will assess suitability for figuring and polishing. In parallel, the plating-stress characteristics will be investigated. When optimum bath chemistry is determined, a larger bath, suitable for electroforming full shells, will be commissioned.

Polishing the inside of these shells requires a custom polishing machine to deterministically remove material directly from the optical surface. Given our group's experience with pitch-lap polishing and deterministic polishing on the Zeeko machine, we identified two areas where polishing could be improved; simplified machine design that can reach inside long, narrow X-ray shells and force control of the polishing head. The pathfinder design (Fig. 5) will meet these requirements with a long vertical arm that will be able to reach into a variety of X-ray shells and with a passive force feedback system that will mechanically control the force that the polishing head exerts on the optical surface. The pathfinder design has been completed and all components have been procured.

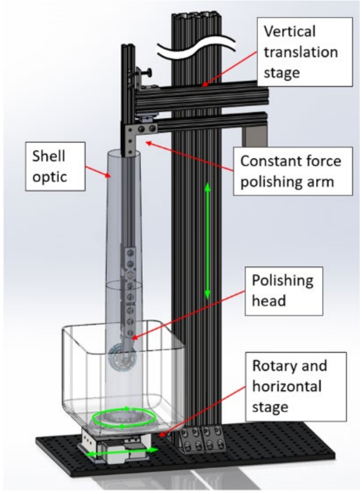

Fig. 5. *Custom pathfinder polisher design of for full-shell optics.*

Mounting and Alignment: We have designed and are assembling a high-precision shell-alignment station based on those used for IXPE flight optic assembly (Fig. 6). This updated design improves the stiffness and stability of the shell suspension truss structure by mounting directly to a granite surface plate. As in the previous design, the shell shape and position are measured by three laser displacement sensors that rotate around the outside of the shell [5, 6]. In the updated design, these sensors rotate on an ultra-precision air bearing with a manufacturer-reported <0.2" of wobble. Compared to the previous design, which had ~30" of wobble, the high motion stability of the new design will enable a more accurate measurement of shell shape. The air bearing was procured and components are being assembled.

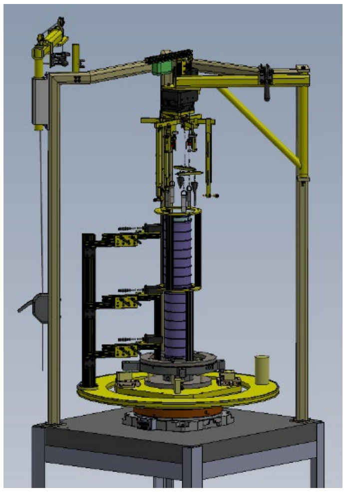

Fig. 6. *Diagram of high-precision mirror-shell alignment station in development.*

Improving shell mounting also requires research into improved epoxies used to attach the mirror shells. Data acquired during IXPE and FOXSI flight optics assembly showed that epoxy shrinkage degrades the optical performance of the assembled module by approximately 3" HPD. While not dominant in 20"-HPD optics such as these, glue-shrinkage-induced error at this level would quickly become the limiting factor in achieving a sub-arcsec optical module. To reduce this error, we are collaborating with the Aerospace Corporation Space Materials Laboratory to develop low-shrinkage UV-cure epoxies for bonding X-ray optics to mounting structures. Initial testing indicates that one of Aerospace's epoxies exhibits a factor-of-14 reduction in cure-induced shrinkage compared to MSFC's flight-heritage epoxy. We are working toward tests that will determine whether this UV-cure epoxy may work with the bond geometries germane to X-ray optics mounting structures.

Post-Fabrication Figure Correction: Post-fabrication figure correction addresses residual figure errors from the fabrication process. In the past, this research focused on the use of differential deposition to correct mid-spatial frequency deviations resulting from the mandrel polishing process and active optics to correct for low-spatial-frequency deviations that result from the replication and/or mirror separation process. While differential deposition has shown some promising results [7], we have decided to prioritize improving the mandrel-polishing process (which may negate the need for post-figure correction) and on the application of active full-shell optics, which leverages an internal MSFC investment. The latter effort involves bonding electrostrictive, surface-parallel actuators directly to a replicated full-shell. Intensive modeling and initial prototyping indicate promising results [8, 9].

Thin Film Coatings: This work focuses on optimizing reflective thin-film coatings for relatively thin X-ray mirror shells and segments. Improved deposition techniques for single-layer and multilayer coatings are under development and can be used on multiple existing and future missions not only for the X-ray band, but also for applications from the IR to EUV regimes as well as other diagnostic processes.

Four on-going coatings research areas are: low-stress coatings; development of advanced multilayer coatings; DC-magnetron sputtering of full-shell optics; and mandrel release layers for low-stress shell replication. Completed work includes the development of an improved high-sensitivity in-situ stress-measurement device, recommissioning of an X-ray reflectometer for high-precision coating qualification, a thin-film adhesion test system for coating integrity and release studies, and upgrades to an existing multilayer coating chamber to include reactive sputtering capability for enhanced coating quality and production of thin-film compounds.

Metrology Development: Achieving sub-arcsec-resolution optics and optical assemblies requires the ability to measure and analyze optical surfaces throughout the fabrication and mounting process. This research focuses on 1) capturing current metrological capabilities and applications; 2) co-developing an error budget with the process step leads; 3) establishing metrics that contextualize different metrology techniques; and 4) identifying and addressing gaps or deficiencies in existing metrology. Previous work pertains to overcoming the challenge of accurately measuring the internal optical surface of a full-shell mirror. The metrology system (Fig. 7) was designed to accomplish this. The Zygo Verifire HDX interferometer and the Zeiss optical flats have been purchased and delivered. The aspheric Computer Generated Hologram (CGH) optics were purchased and construction is underway.

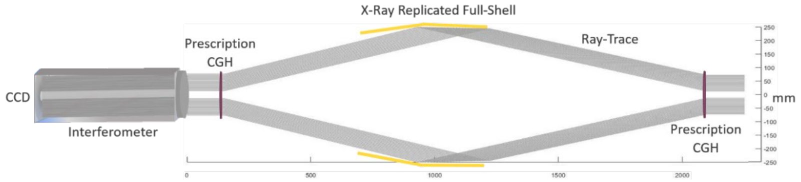

Fig. 7. Metrology testbed for full-shell X-ray optical testing that uses an interferometer to capture high-resolution data of the internal optical surface.

Task 2 – Astronomical Mirror & Instrumentation Test and Calibration

MSFC's 100-m (aka Stray Light Test Facility) and X-ray & Cryogenic Facility (XRCF) are internationally recognized as premier facilities for test and calibration of developmental and flight hardware.

MSFC 100-m: This facility is just over 100-m long and features a 1.3-m diameter beamline and large, 3-m-diameter and 8-m-long instrument chamber that is uniquely suited for single optics, optical assemblies, and instrumentation [10]. The facility is integrated into a building that houses the Optics Group and includes multiple metrology labs, polishing machines, and machining capability. ISFM funding has provided and continues to provide access to scientists for testing through the APRA and other programs. Planned and proposed test and calibration activities are listed in Table 1.

Table 1. *Example of recent and near-term test activities showing facility utility. MSFC provides a service to the community to support X-ray optics and instrumentation testing for existing and future X-ray missions.*

Project Name	Institution	Dates
The Lunar Environment Heliospheric X-ray Imager (LEXI)	BU & GSFC	05/05/22 – 05/27/22
Miniature X-ray Optics (MiXO)	SAO	07/05/22 – 01/23
Focusing Optics X-ray Solar Imager (FOXSI-4*)* Nagoya University optic	Nagoya University	07/25/22 – 08/05/22
SmallSat Solar Activity X-ray Imager (SSAXI) 62-mm X-ray Optic	SAO	08/08/22 – 08/17/22
FOXSI-4 MSFC Single Shell Test	UMN & MSFC	08/18/22 – 12/23
SSAXI mounted shell	SAO	10/10/22 – 10/28/22
X-Ray Lobster Eye-Optic Test Bed	MSFC	01/23 (TBC)
FOXSI-4 Flight Module	UMN & MSFC	02/23 (TBC)
Neutron Microscope single shell Concentrator optic	NIST & MSFC	04/23, 06/23

X-ray and Cryogenic Facility (XRCF): XRCF is an adaptable space-environment-simulation facility that has enabled science missions since 1991. As the world's largest X-ray optical test facility, the XRCF enables development, performance, and calibration testing of grazing- and normal-incidence optics, detectors, and assemblies. As NASA's premier cryogenic optical test facility, the XRCF facilitates the development and pre-flight evaluation of large systems and structures in relevant thermal environments to 20°K. This facility, like the MSFC-100m, supports the community through APRA and other proposals at reduced cost. The previous ISFM funding was used to help restore many of the Chandra-era X-ray test systems to an operational state. The 500-m-long beamline and supporting systems, electron impact point source, X-ray filter wheels, X-ray beam monitors, focal-plane motion stages, and test-article alignment systems have all been reactivated. Initial X-ray beam characterization testing including flux measurements, size and uniformity maps, and temporal stability assessments have been completed.

Path Forward

Task 1 – X-Ray Optics Development

The recently selected work package supports work done in FY 2023-2025. The goal of achieving a sub-arcsec X-ray mirror module over this decade is a lofty one that will require multiple sources of funding. Forward work will be funded through a combination of continued ISFM support, competitive proposal efforts (technology-development APRAs, suborbital, Pioneers, Explorer, and Probe-class), directed work from other government entities (NIST, Sandia), and internal MSFC efforts (e.g., Technology Investment Program).

Replication Studies: Building on the group's recent significant progress, forward work will focus on improvements to the mandrel and gasket design, mandrel polishing, plating-bath modeling, shell replication, and shell-separation studies. Effort will be on achieving similar results to those obtained for the smaller-diameter NIF optic on larger-diameter full-shell optics.

FY 2023: Optimize plating bath and carry out shell-mandrel separation studies to minimize release stresses for large shells. Refine modeling of plating bath and gasket geometry to characterize effects on the replication process.

FY 2024: Continue polishing FOXSI or similar mandrel on Zeeko to achieve ~2" FWHM on a larger-diameter optic. Complete optic-separation studies and mandrel and gasket designs. Determine optimal mirror thickness needed to compensate for plating and separation stresses for large-diameter optics.

FY 2025: The replication process will be further optimized (with a view to flight-type production) for mandrel polishing, replication, and mirror-shell separation.

Mandrel polishing and Direct-Polished Full Shell: This research includes continuing deterministic polishing of existing mandrels and assembly and checkout of a direct mirror shell polishing development testbed. For the latter, electroforming a glassy-nickel alloy shell using an existing mandrel and performing deterministic figure correction on that shell is the goal. As a prelude to this, optimize the electroforming bath chemistry to give deposits with good mechanical properties, good polishability, and low stress characteristics.

FY 2023 – Continue polishing 600-mm-long mandrel to achieve < 2" and complete polishing machine pathfinder and perform polishing studies on coupons from eNiP. Determine bath chemistry and electroforming conditions to give high-strength deposits that support polishing and figuring and have low inherent plating-bath stress. Lower bath temperature to minimize thermal distortions of mandrels at electroforming temperatures.

FY 2024 – Fully characterize the custom polisher demonstrator on full shells of various compositions (NiCo, eNiP, etc.). Complete COMSOL optimizations of electroforming configuration to assess size of gaskets and shields necessary for the planned IXPE mandrel. Construct a full-size eNiP bath to give good field uniformity in this electroforming configuration (from the COMSOL studies) with chemistry derived from smaller-bath tests.

FY 2025 – Plate eNiP shell on the largest IXPE mandrel, direct-polish resulting shell as appropriate, coat and mount the resulting mirror shell to support structure on high-precision shell alignment station, perform metrology, and X-ray test.

X-ray Shell Alignment Station: Forward work is the development and construction of an alignment station with performance that exceeds the current SOTA (i.e., that used for IXPE). This will allow us to offload the mass of the mirror shell and then align it, bond it in place, and characterize the circularity and slope errors at the sub-arcsec level. The ensuing effort will focus on assembly optimization and incorporation of Aerospace Corp. epoxy tests into our existing process.

FY 2023 – Final assembly and commissioning of high-precision alignment station. Characterize shell stability and validate shape-measurement accuracy. Build epoxy-shrinkage-characterization apparatus and perform shrinkage comparison. Select epoxy and application/cure process.

FY 2024 – implement a closed-loop shell-circularity optimization with pico-motors. Upgrade and commission high-precision alignment station to ultimately accommodate 0.5-m-diameter shells.

FY 2025 – Carry out further optimization as needed for mirror shell assemblies.

Thin-Film Coatings: Forward work includes optimizing existing processes, initiating new processes (e.g. multilayers), and completing the fabrication of diagnostic test instrumentation.

FY 2023: Studies to optimize the DC magnetron and reactive-sputtering processes for low-stress coatings on flat test samples will be conducted for both single-layer (Ir) and multilayer designs (Ni-based). An adhesion test system developed to assist in film stress and release studies will be optimized for continuous monitoring. A comparative study of Au-release layers deposited onto test substrates will be conducted. Upgrades to the X-ray reflectometer will be implemented.

FY 2024: Low-stress bilayer and multilayer coatings will be demonstrated (relevant to mission concepts such as Lynx and HEX-P) on test flats and curved substrates. Upgrades to an existing multilayer coating chamber with linear-cathode geometry (cathodes already procured) for coating segmented mirrors will be completed. Work will begin on development of full-shell DC-magnetron sputtering system. Full-scale testing of a release layer process will be conducted on full-shell optics.

FY 2025: Low-stress bilayer and multilayer coatings on figured, segmented optics will be characterized in the MSFC 100-m X-ray beamline. A magnetron-sputtering cathode design for full-shell optics will be finalized and tested.

Metrology Development: This research includes contributing to an error budget that will be used to identify limiting metrology capabilities as a function of the fabrication and mounting at each step in our process and subsequently determining a metrology solution. A repository has been created to systematically track each mirror shell's metrology history, from mandrel fabrication through module assembly and coating. A dedicated, environmentally controlled laboratory space will be established appropriate for sub-arcsec metrology, along with configuration-controlled procedures and software and staff training.

FY 2023: Complete the fabrication of the high-resolution metrology system for measuring the figure on the internal, reflecting surface of a full-shell and set up a dedicated metrology lab.

FY 2024: Fully implement the internal-shell metrology system. Determine metrology requirements for all spatial frequencies necessary to achieve our desired angular resolution. Construct a database for past and future optics metrology. Finalize procedures for existing metrology equipment.

FY 2025: Continue the work from the previous year. Train operating staff.

Task 2 – Astronomical Mirror & Instrumentation Test and Calibration

MSFC-100-m Beamline: The MSFC-100 m team is committed to providing world class X-ray calibration, partnering, and creating an inclusive environment for the development of young scientists. The MSFC 100-m scientists and support team will continue to provide access to visiting scientists for testing through the APRA program and to support facility upkeep. It is expected that as technology maturation ramps up in preparation for the Great Observatory Maturation Program (GOMaP) and the Probe AO, this facility will be even more essential.

MSFC XRCF: While XRCF currently supports ATHENA, the schedule also accommodates other, short-term projects. The ISFM has permitted MSFC personnel to maintain XRCF capabilities, provide the availability to APRA proposers, and deliver flexibility for facility support to community users across multiple wavebands.

During the FY 2023-2025 timeframe, XRCF X-ray test systems will continue to be updated and improved; alignment and metrology techniques necessary to calibrate large X-ray optics via partial illumination in a diverging beam will be investigated (relevant to multiple future NASA Probe and Flagship missions); and test article and focal plane positioning systems will be characterized. The XRCF is also planning to test UVO-FIR Mirrors for future strategic missions as well.

Summary

The ISFM package, together with funding from multiple other sources (competitively obtained or direct) has allowed us to make significant progress over the past several years. We now regularly produce <20” HPD full-shell mirror assemblies for flight, meeting many current and proposed mission requirements, and single full-shell mirrors to better than 5” HPD. Further progress will be made through a systematic analysis of, and subsequent improvement in, all of our process steps – from fabrication to coating, mounting, and test.

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Publications Related to this Effort

1. P.R. Champey, J. Kolodziejczak, B. Kozioziemski, J. Davis, C. Griffith, T. Kester, et al., "*Toward the fabrication of a 5-μ m-resolution Wolter microscope for the National Ignition Facility*,". Review of Scientific Instruments, **93(11)**, 113504 (2022)
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3. B. Salmaso, A. Moretti, and J. Gaskin, "*Facilities for X-ray Optics Calibration*," In: C. Bambi and A. Santangelo (eds) Handbook of X-ray and Gamma-ray Astrophysics; Springer, Singapore https://doi.org/10.1007/978-981-16-4544-0_14-1 (2022)
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9. L. Glesener, J.C. Buitrago-Casas, J. Vievering, A. Pantazides, S. Musset, AS.A. Panchapakesan, et al., "*The FOXSI-4 Sounding Rocket: High Resolution Focused X-ray Observations of the Sun*," in AGU Fall Meeting Abstracts, Vol. **2021**, pp. SH55B-1831 (2021, December)

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