

Metrology advancements for X-ray optics: Lynx and beyond

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ABSTRACT

Next-generation X-ray telescopes require mirrors with surface height errors of a few nanometers. Traditional Fizeau interferometry is limited as measurements include surface errors on the surface under test (SUT) as well as the reference. Axial shift mapping (ASM) is a self-referencing interferometric method for near-cylinders that can separate the reference surface from the SUT. ASM recovers the absolute figure of the reference and SUT in lines along the axial direction. However, it does not recover the axial slope of the lines. Incorporating shifting in the azimuthal direction recovers the axial slope of each line as well as axial slope variation across the optic. This paper discusses progress towards adding azimuthal shifting to the ASM technique. Additionally, this paper outlines upgrades to the MIT soft X-ray beamline to allow for mirror testing. X-ray testing will be used to verify the accuracy of ASM with at-wavelength measurements.

Keywords: X-ray optics, shear interferometry, at-wavelength metrology, grazing-incidence mirrors

1. INTRODUCTION

The 2020 Astrophysics Decadal Survey recommended development of a high angular resolution X-ray mission, based off the Lynx Observatory mission concept, as part of the Great Observatories Mission and Technology Maturation Program.¹ *Lynx* requires well-figured and lightweight optics to achieve the angular resolution and sensitivity required to study supermassive black hole growth, map hot gas around galaxies and in the Cosmic Web, and investigate high-energy processes related to stellar evolution and ecosystems.² *Lynx* maintains the 0.5 arcsecond half-power diameter (HPD) achieved by the Chandra X-ray Observatory, but improves the sensitivity by up to two orders of magnitude through increasing the effective area from 0.08 m² to 2 m² at 1 keV. The increase in mirror area is enabled by the shift from full-shell, 20-mm-thick mirrors to 0.5-mm-thick mirror segments that can be tightly nested together. The *Lynx* Design Reference Mission utilizes the silicon meta-shell optics technology which requires around 40,000 silicon mirror segments, around 100 mm by 100 mm in length and width, and less than 1 mm thick. Each mirror pair, comprised of a primary and secondary mirror with a Wolter-Schwarzschild prescription, a highly-off axis conic, must achieve better than 0.2 arcsec HPD.³ The figure accuracy of these mirrors must be only a few nanometers root mean-square (RMS) and the metrology used to guide their polishing must be a fraction of this.⁴ Fizeau interferometry is mature and scalable for high-volume manufacturing. However, Fizeau interferometry is limited by the quality of the reference and null surfaces that the SUT is compared to.

To overcome the limitations created by the quality of the reference surfaces, we have previously introduced Axial Shift Mapping (ASM), a self-referencing interferometry technique for near-cylindrical mirrors where the SUT is shifted between measurements.⁵ Figure 1 shows the experimental setup and coordinate frame. The cylindrical wavefront is created by a computer generated hologram (CGH). Two planar mirrors, called known artifact mirrors (KAMs), measure two rigid body rotations, e_{θ_x} and e_{θ_z} , during shifting so that the absolute axial

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figure of the SUT and reference can be unambiguously separated. If rigid body errors are not accounted for during measurement, they creating an ambiguity in the quadratic term of the extracted surfaces. Detailed information about the experiment and mathematical derivation of the rigid body error removal and surface extraction can be found in Wisniewski et al.⁵ ASM alone gives the profile along each axial trace of the mirror. Their tilt about x , or the local axial slope, is unknown. Adding in an azimuthal shift, realized as a small rotation about the center of curvature, extracts the axial slope of each axial trace.⁶ Section 2 discusses adding in azimuthal shifting, which is essential for determining the axial slope.

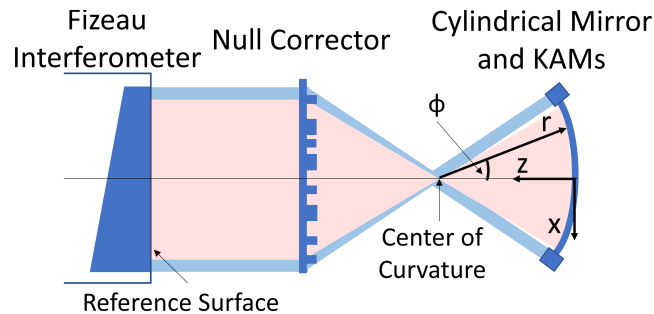


Figure 1. Fizeau interferometry setup for Axial Shift Mapping. A computer generated hologram acts as the null corrector for the cylindrical mirror. Two planar mirrors, called known artifact mirrors (KAMs), are characterized using a three-flat test and are used to measure rigid body errors in e_{θ_x} and e_{θ_z} during shifting. The cylindrical wavefront is shown in red and the collimated wavefronts for the KAMs are shown in blue.

1.1 State of the art for segmented X-ray mirrors

The Next Generation X-ray Optics (NGXO) group at NASA Goddard Space Flight Center (GSFC) has developed segmented X-ray optics. The NGXO manufacturing process has demonstrated a 0.5 arcsec HPD (two reflection equivalent) mirror with a 5 nm height error after removal of sagittal depth.³ The NGXO uses ion beam figuring (IBF), a deterministic figuring method, for final figure correction of their mirrors. The NGXO group states that the final mirror quality is metrology limited; their Fizeau metrology of the individual mirror segments limits the ability of IBF to correct figure errors.⁷ The goal of ASM is to improve the Fizeau metrology used to guide the IBF of mirrors so that their angular resolutions meet the requirements of future X-ray telescopes.

1.2 Why not use other metrology techniques?

ASM should be compared to metrology for other X-ray optics, such as techniques used to figure synchrotron mirrors. While synchrotron mirrors have superior figure, the methods used to guide their figuring are impractical for the manufacturing scale required for next-generation X-ray telescopes. Synchrotron mirrors are long and thin, 100–1000 mm long with sagittal lengths of only a few millimeters, and require sub-nanometer RMS height error. As each beamline requires only a few optics to function, synchrotron facilities can spend weeks to months measuring and figuring their mirrors. The rigid body errors that ASM measures and corrects for and the surface shape ambiguities they create are well known in the synchrotron mirror metrology community. The mirrors are too long to measure with traditional Fizeau apertures and require moving the mirror during measurement. Additionally, like astronomical X-ray mirrors, synchrotron mirrors require better figure than what the reference optics can typically provide. Techniques such as profilometry and stitching interferometry track rigid body errors from motion stages during measurement. Stitching interferometers also actively null the mirror between measurements.^{8–13} Relative-angle determinable stitching interferometry (RADSI) has provided the metrology for elastic emission machining to achieve 0.1 nm RMS surface error (more than 10 times better surface figure than what mirrors for *Lynx* require).¹⁴ RADSI systems are custom built at synchrotrons and require extensive environmental controls and superb angle measurement accuracy.¹⁵ While scaling the synchrotron mirror metrology model to next-generation X-ray telescopes is currently infeasible, it is clear that more capable Fizeau techniques eliminate the errors present in reference optics and actively null the optic through tracking rigid body errors from motion. ASM bridges the gap between traditional Fizeau techniques and the ultra-precise

synchrotron metrology stitching techniques. The hexapod, CGH, and commercial Fizeau interferometer that ASM uses can be produced at scale.

2. IMPROVEMENTS TO AXIAL SHIFT MAPPING

Previously, we transferred the ASM setup from the University of Arizona to MIT and replicated the results.⁴ As shown in Figure 2, we have replaced the motion stage stack with a much stiffer Symetrie PUNA hexapod. We have also included active nulling of e_{θ_z} rotations instead of measuring the clocking angle and removing the misalignment from the measured data. Figure 3 shows the average extracted SUT and reference surface. Over 5 measurement campaigns, the repeatability of the SUT extraction was improved to 1.6 nm RMS. We are now investigating the effects of environmental noise, such as temperature fluctuations and vibrations, on the measurement repeatability.

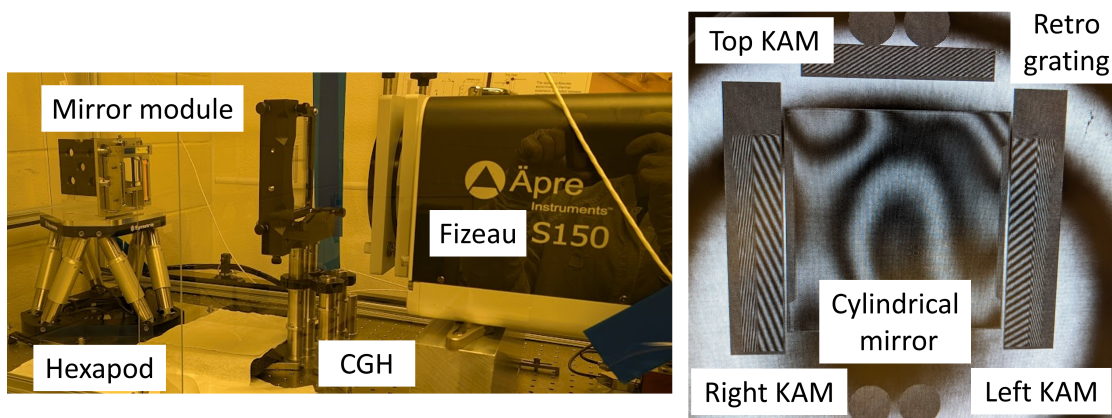


Figure 2. (Left) ASM setup at MIT showing the mirror module on the hexapod, the CGH, and the interferometer. (Right) Interferogram of the CGH showing tilt fringes on left, right, and top KAMs, the cylinder, and the retroreflection grating for alignment of the CGH to the interferometer.

We have also begun preliminary measurements using azimuthal shifting. Ultimately, the axial and azimuthal shifts will be combined so that the absolute figure and axial slope of each line (relative to the other lines on the surface) can be extracted. Currently, only RBEs in e_{θ_x} and e_{θ_z} are corrected for between azimuthal shifts. Figure 4 shows the associated interferograms, optical path length differences, and extracted traces along the axial and azimuthal directions for each RBE (except for translations in y , which are invariant for a perfect cylinder). Fringes on the horizontal KAM can be used to track e_{θ_y} . Adding a fiducial to the horizontal KAM will allow tracking of translation in x and in y . Translation errors in z require an additional measurement of the distance between the mirror and CGH. Alignment errors between the center of curvature of the mirror and the virtual coordinate system origin of the hexapod cause RBEs during shifting as the mirror is rotating and translating instead of purely rotating along its axis. Figure 5 shows the extracted SUT and reference for azimuthal only shifting. Each horizontal line is its own system. The best fit quadratic was removed from each azimuthal profile. As defocus errors, which are unmeasurable with a Fizeau alone, other RBEs that are currently uncorrected, and true surface errors can cause a quadratic, it is unclear if we have removed surface figure errors. Additionally, it appears that higher order terms which may be from uncorrected RBEs are present on both extracted surfaces. Before the azimuthal shift measurements can be combined with the axial shift ones, the ambiguities from RBEs during measurement need to be accounted for. Once two-dimensional shifting of cylinders is accomplished, we will progress to an ellipsoid of revolution, which has axial curvature.

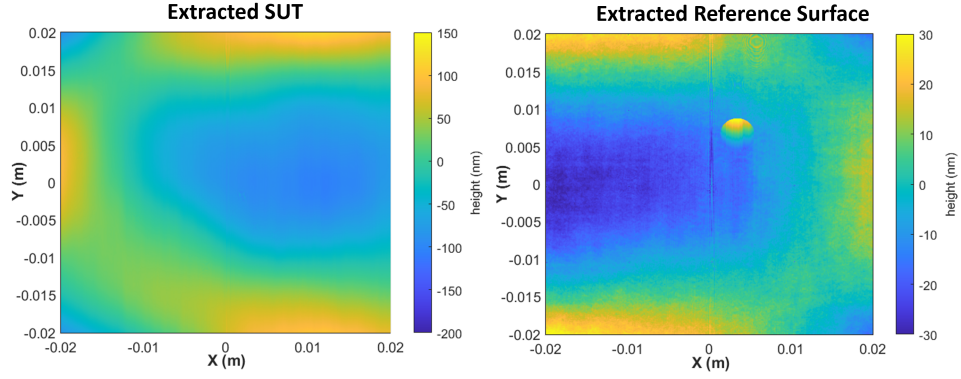


Figure 3. Average extracted SUT and reference from five measurement campaigns of ASM using the hexapod and active clocking correction. The repeatability of the extracted SUT is 1.6 nm RMS and the repeatability of the extracted reference is 2.0 nm RMS. The circular artifact is caused by removal of an interferometer reflection issue and seen more clearly in the extracted reference surface.

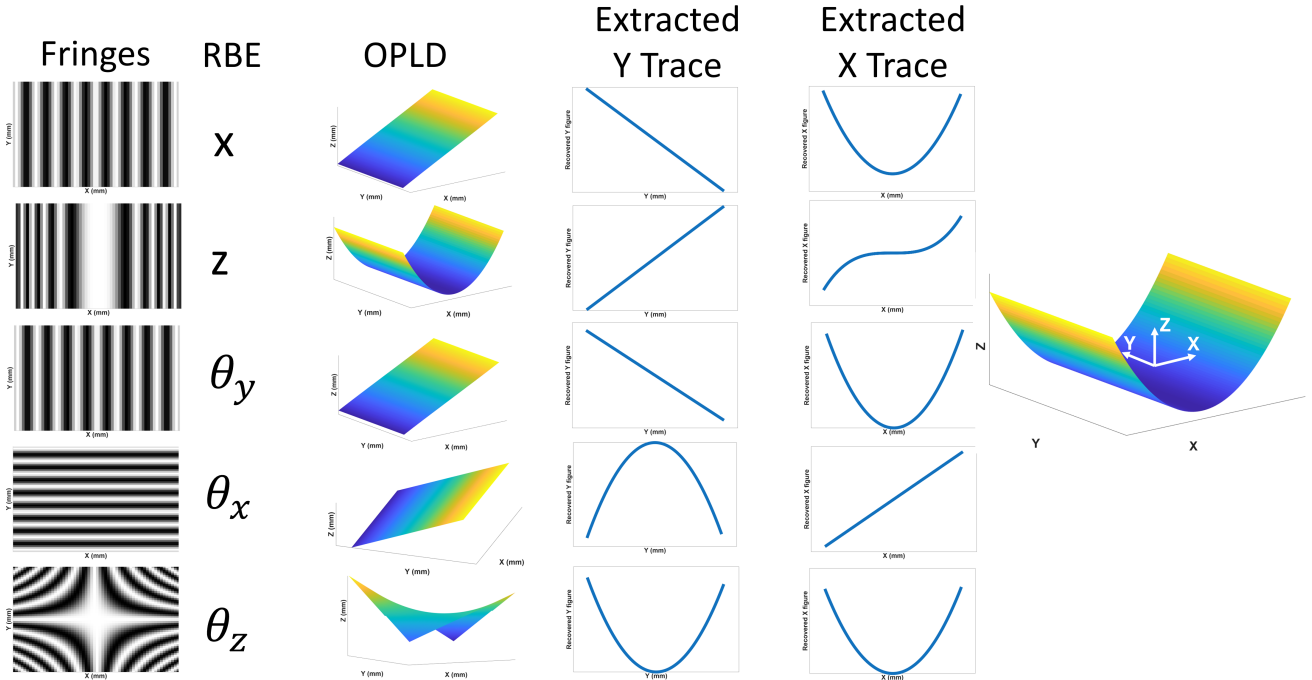


Figure 4. Fringes produced for each rigid body movement of the SUT with the resulting measured optical path length difference (OPLD). The OPLD is integrated by the figure extraction process. The resulting extracted figure in the y and x direction for the RBEs are shown. Extracted surfaces from RBEs that are quadratic or higher order are degenerate with true surface errors. For shifting in the axial direction, e_{θ_x} and e_{θ_z} result in degenerate profiles along the shift direction. For azimuthal shifting, all RBEs except for e_{θ_x} result in degenerate profiles along the shift direction.

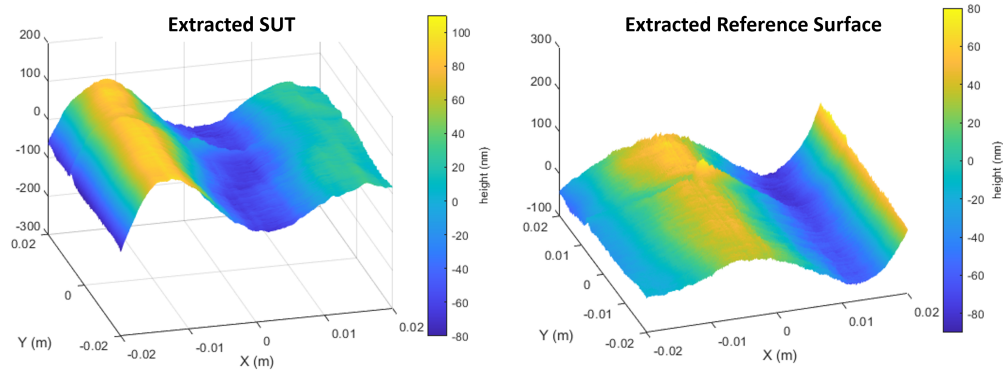


Figure 5. Preliminary extracted SUT and reference for azimuthal only shearing. The best fit quadratic was removed from each horizontal line, which may remove true surface error. Additional RBE tracking using the KAMs to null the mirror between shifts is needed.

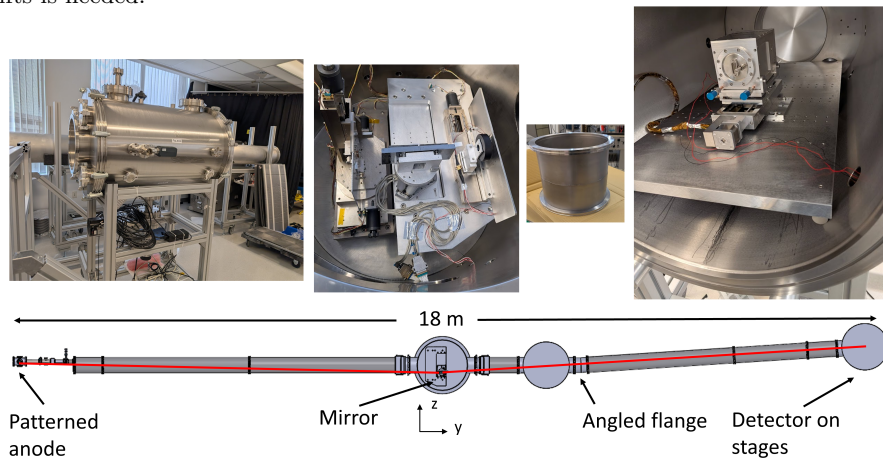


Figure 6. (Top, left to right) Metrology chamber that will house in-vacuum sCMOS, Hartman grid, and grating. OGRE optics mounted on hexapod.¹⁶ The OGRE optics will be replaced with a rotated ellipsoidal mirror. Angled flange. In-vacuum sCMOS using the EUV-Enhanced GSENSE2020 BSI sensor with $6.5 \mu\text{m}$ pixels in the metrology chamber. (Bottom) Layout of beamline.

3. PROGRESS TOWARD AT-WAVELENGTH MEASUREMENTS

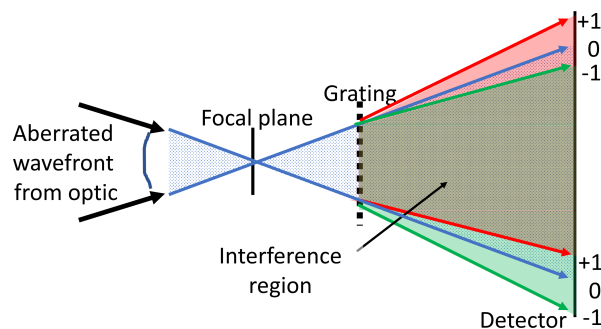


Figure 7. Layout of lateral shear interferometry (LSI) for at-wavelength metrology of X-ray mirrors. The $30 \mu\text{m}$ pitch grating is placed 1.5 m downstream of the focus and the detector is in the first Talbot plane, 146 mm downstream of the grating. A high contrast self-image of the grating is created by interference of the diffracted orders. LSI can be used to help with mirror alignment as well as measure wavefront slope.

The MIT polarimetry beamline is being adapted to allow for testing of ~ 9 m focal length X-ray mirrors. Figure 6 shows the layout for mirror testing as well as the new hardware. Focal spot testing, Hartmann testing using a pinhole array, and wavefront testing using lateral shear interferometry (LSI) is planned. Figure 7 shows the basic layout of LSI. LSI uses a grating to create sheared orders that interfere with each other. The wavefront slope can be extracted from the interference pattern.¹⁷ The low flux and spatial incoherence of the source, a Manson model 5, are the largest barrier to wavefront measurements. The low flux coupled with mirror reflectivity, absorption from the SiC support membrane on the grating, and multi-layer mirror efficiency, requires integration times to be on the order of 25 minutes to have the minimal acceptable signal-to-noise ratio. Additionally, the incoherent source reduces the visibility of the X-ray fringe due to low mutual coherence. The spatial coherence at the grating plane can be taken as the Fourier transform of the focal spot intensity distribution by the van Cittert–Zernike theorem. The size of the focal spot is limited by the size of the source. We are experimenting with lithographically patterned sputtered B4C to create a $40\text{ }\mu\text{m}$ diameter source to increase spatial coherence.

4. CONCLUSION

We are expanding Axial Shift Mapping to include an azimuthal shift so that the axial slope variation of X-ray mirrors can be measured in addition to the absolute axial surface profile. Additionally, we are updating the MIT X-ray beamline to accommodate testing of ellipsoids of revolution. At-wavelength measurements will verify the capability of our Fizeau technique for guiding ion beam figuring of mirrors.

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