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# Fabrication of the Advanced X-ray Astrophysics Facility (AXAF) optics : a deterministic, precision engineering approach to optical fabrication

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The AXAF observatory is the third of NASA's "Great Observatories", designed to image cosmic x-rays in the energy regime of 0.1 to 10 keV (124 - 1.24 Å).[1] The mirror assembly consists of four concentric, confocal, Wolter type I telescopes. Each telescope includes two conical grazing incidence mirrors, a paraboloid followed by a hyperboloid. Fabrication of these state-of-the-art optics is now complete, with predicted performance that surpasses the goals of the program.

The fabrication of the these optics, whose size and requirements exceed those of any previous x-ray mirrors, presented a challenging task requiring the use of precision engineering in many different forms. Hughes Danbury Optical Systems (HDOS) used an integrated metrology/fabrication system consisting of various high precision metrology stations, a sophisticated metrology analysis and fabrication strategy software system, and computer-controlled grind/polish fabrication stations[2,3,4]. In keeping with the philosophy of a true metrology/fabrication system, the same team of engineers performed both the metrology analysis and the generation of subsequent fabrication runs. This analysis and strategy development relied heavily on modeling and frequency domain analysis. In fact, the program schedule was planned based on the modeling of figure convergence. Another critical component of the system was the process study effort, where tools and slurries are calibrated, new tool designs evaluated, and models validated with experimental data. The final cornerstone of the philosophy was the use of metrology cross-checks within and between systems, with an insistence on consistency in order to protect against systematic errors.

Virtually all of the equipment used for this effort required precision engineering. In order to characterize these unique mirrors, whose optical surfaces resemble the insides of large barrels, 2 classes of metrology were used. Axial metrology, corresponding to the staves of the barrel, was acquired at many azimuthal positions. This data was then combined with circularity data at each end of the cone, corresponding to the hoops of the barrel, to form a surface map. Inner diameter measurements supplied information about the absolute size and cone angle of the piece.

Accurate metrology required deterministic support of the mirrors in order to model the gravity distortions which will not be present on orbit. This was a particularly difficult problem due to the flexibility of the mirrors, which have wall thicknesses of less than 25 mm. To this end, a Precision Metrology Mount (PMM)[5] was designed to support the elements with the optical axis parallel to gravity. Interface pads, which were carefully aligned and bonded to the endfaces of the mirrors, mate with a series of support points. Three of these were fixed axial 'hard points' instrumented to monitor axial loads. Depending on the size of the mirror, there were then between 6 and 15 'off-loaders' evenly spaced around the circumference, each of which was capable of supplying an adjustable load to the mirror. The system was modeled in software, and the offloaders adjusted until the optimum load was supplied at each support point. The end result was a system which imparted axial load errors of less than 0.03 lbs, tangential load errors of less than 0.05 lbs, and radial load errors of less than 0.05 lbs. After subtraction of the systematic distortions, this system contributed less than 600 Å rms circumferential error and less than 16 Å rms axial error, both of which were localized at the supported end and faded away exponentially.

Circumferential figure and inner diameter were measured in 2 metrology enclosures known as the Circularity and Inner Diameter Stations (CIDS)[6], one for use with the larger elements and one for use with the smaller ones. These stations used a combination of calibrated zerodur reference standards, laser gauge interferometers and precision rotary air bearings. Using a variety of calibration techniques, from the well-known Donaldson reversal for spindle error analysis to more subtle, system specific tests, the CIDS routinely measured diameters of ~1.2 meters to accuracies of better than 2 µm. Circumferential figure measurements, which were dominated by the random metrology mount induced errors, were routinely acquired with a 2 sigma accuracy of better than 400Å rms over circumferences of greater than 3.5 meters. This performance was achieved by measuring an optic in 2 orientations, thus minimizing the previously mentioned metrology mount effects.

The primary axial instrument, known as the Precision Metrology Station (PMS)[7], was a unique scanning Fizeau interferometer. A highly calibrated reference cylinder was placed in close proximity to the optical surface forming an interference cavity which was scanned with an argon laser source. The resulting fringe pattern was monitored and converted into optical path difference through specially designed algorithms. The known errors of the reference optic were then removed, along with the gravity distortion calibration and the prescription of the AXAF optic, resulting in an error profile. The most impressive of the AXAF metrology instruments, the PMS measured the sag of the optics (approximately 1/2 cycle per aperture) with a 2 sigma accuracy of less than 150 Å over a length of 840 mm. The rest of the PMS bandwidth, from spatial periods of over 800 mm down to periods of 1 mm, had an uncertainty of less than 15 Å rms. The repeatability of the measurements was routinely less than 5 Å rms over the full bandwidth.

Microroughness (the bandwidth between $1mm^{-1}$ and $1000mm^{-1}$) was only measured after the final cycle. This took place on the Micro-Phase Measuring Interferometer (MPMI), which was a WYKO Topo-2d profilometer modified for use with the AXAF mirrors.

One of the cornerstones of the program philosophy was the use of various metrology cross-checks. These cross-checks, which were performed periodically between and within the metrology stations, confirmed that data acquired on different systems were consistent within the accuracies of the instruments.[8] Careful attention was paid to the error budgets for these tests, and any unexpected result was investigated until understood.

After metrology was complete, the optics were placed in specially designed Glass Support Fixtures (GSFs) for installation on the Automated Cylindrical Grinder/Polishers (ACG/Ps). The GSF's were custom molded for each mirror element to match the shape of the outer surface. This minimized distortions of the inner surface, which otherwise could have introduced errors during polishing with full length laps. The ACG/Ps were computer controlled fabrication machines which used precision encoders and high accuracy control servo's in order to maintain positional control of the polishing tools. These tools ranged in size from 50 mm to less than 10 mm in axial extent, and material removal was varied by modulating the amount of time the tool dwelled over a given location on the glass. The ACG/Ps were also operated in a manual mode using full length laps. These laps were used for correction of errors with spatial periods less than about 20 mm, where small, computer controlled tools were less efficient. For both types of runs, the optic was rotated approximately about its optical axis while the tool was stroked in the axial direction.

Another important aspect of the philosophy involved post-run analysis in order to understand the process more completely. By comparing the actual fabrication results with those that had been predicted before the run, consistencies and inconsistencies provided valuable clues about which parts of the process were limiting performance. This feedback was then used to provide more accurate pre-run analysis for subsequent cycles as well as fine tuning of models. This process uncovered several significant error sources which were then addressed in order to improve the performance of the system.

The end result was a process which continued to improve throughout the program. The final optics had the advantage of earlier learning, and so enjoyed the fastest rates of convergence. H4, one of the last optics through the system, had a figure error of over 6 µm peak-peak (~1.8 µm rms) at the beginning of polishing. After only three metrology/fabrication cycles, it was brought to a final figure of less than 0.02 µm peak to peak (less than 50 Å rms). Likewise, the process of using full length laps to achieve super smooth microroughness was refined after the first few trials, with the surface finish of the final optic (H3) measured at less than 2.1 Å rms over the bandwidth from 1 to 1000 $mm^{-1}$. These values were typical for all eight mirrors, a total of 19 square meters of optical surface, where the primary difference was the number of cycles required to achieve them.

The final performance of the telescope is expected to far exceed the original goals and expectations of the program. The increased rates of convergence saved about four months of schedule when compared to expectations going into the polishing phase. Likewise, the low microroughness surfaces achieved significantly boosted performance of the telescope for high energy x-rays where scattering becomes one of the dominant loss mechanisms. These successes are due in large part to the philosophy which demands close attention to every segment of the system, as well as a continuing commitment to gain improved understanding of the process.

## References


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