High angular resolution and lightweight x-ray optics for astronomical missions

W. W. Zhang[1], M.P. Biskach[2], P.N. Blake[1], K.W. Chan[3], T.C. Evans[2], M. Hong[2], W.D. Jones[4], L.D. Kolos, J.M. Mazzarella[2], R.S. McClelland[2], S.L. O'Dell[4], T.T. Saha[1], and M.V. Sharpe[2]
[1] NASA Goddard Space Flight Center, Greenbelt, MD 20771
[2] Stinger Ghaffarian Technologies, Inc., Greenbelt, MD 20770
[3] University of Maryland, Blatimore County, Catonsville, MD 21228
[4] NASA Marshall Space Flight Center, Huntsville, AL 35805

Abstract

X-ray optics with both high angular resolution and lightweight is essential for further progress in x-ray astronomy. High angular resolution is important in avoiding source confusion and reducing background to enable the observation of the most distant objects of the early Universe. It is also important in enabling the use of gratings to achieve high spectral resolution to study, among other things, the myriad plasmas that exist in planetary, stellar, galactic environments, as well as inter-planetary, inter-stellar, and inter-galactic media. Lightweight is important for further increase in effective photon collection area, because x-ray observations must take place on space platforms and the amount of mass that can be launched into space has always been very limited and is expected to continue to be very limited. This paper describes an x-ray optics development program and reports on its status that meets these two requirements. The objective of this program is to enable Explorer type missions in the near term and to enable flagship missions in the long term.

Introduction

By any measure x-ray astronomy is enjoying its golden age. The three currently operating observatories, Chandra, XMM-Newton, and Suzaku, have advanced our understanding of the Universe to an unprecedented level. In the meantime they have also raised questions that can only be answered by future x-ray telescopes with one better angular resolution, larger photon collection area, higher energy spectral resolution.

This x-ray optics technology development program was initiated in 2001 (Zhang et al. 2003) in direct support of the Constellation-X mission development (White & Tananbaum 2003). The Constellation-X mission, which later became the International X-ray Observatory (IXO), was designed to be the successor to the Chandra x-ray observatory. With its priority set on spectroscopic studies, IXO required a moderate angular resolution of ~5" HPD (half-power diameter) and a large photon collection area of >1 m^2. Figure 1 places these requirements and the achievements of this program as of August 2011 in the context of the technologies that built the three telescopes: ground and polished Zerodur shells for Chandra (Gordon & Catching, 1994), electroformed nickel shells for XMM-Newton (Gondoin et al. 1994), and epoxy replicated aluminum foils for Suzaku (Serlemistsos et al. 2007).

In general, four parameters characterize an x-ray optics technology: (1) angular resolution, (2) effective are per unit mass, (3) production cost per unit effective area, and (4) production rate or schedule. Figure 1 use the first two variables to show that the three current missions form more or less a line that demarcates the past and future of x-ray telescope making. Above and to the left of the line is the region representing the past and telescopes that are easy to build and less powerful, and therefore is of no interest for now. Below and to the right of the line is the region representing the future. Any telescope in this region requires technology development.

This technology development program is based on the segmented approach to building x-ray telescopes, as shown in Figure 2. It is hierarchical and suited to building both small and large telescopes, which differ mainly in the number of modules that need to be built and assembled. In either case, the dimensions of the module and the number of mirror segments contained therein are substantially similar. The objective of this technology program is to develop all necessary techniques to construct mirror modules that meet x-ray performance requirements in angular resolution and effective area, and environment requirements.

The process and components of building a module are illustrated in Figure 3. It consists of three main steps: (1) forming mandrel fabrication, (2) mirror segment fabrication, and (3) installation of mirror segments into module housing. Each of these main steps in turn consists of one or more smaller steps. This technology program's objective is to develop and perfect each of these steps so that they can be engineered to become highly accurate to meet x-ray optical requirements and highly reliable and efficient to minimize both cost and schedule. The totality of this process's qualification lies in the successful and repeated construction of modules that meet those requirements. The rest of this paper describes the requirements and status of each of these steps as of August 2011.

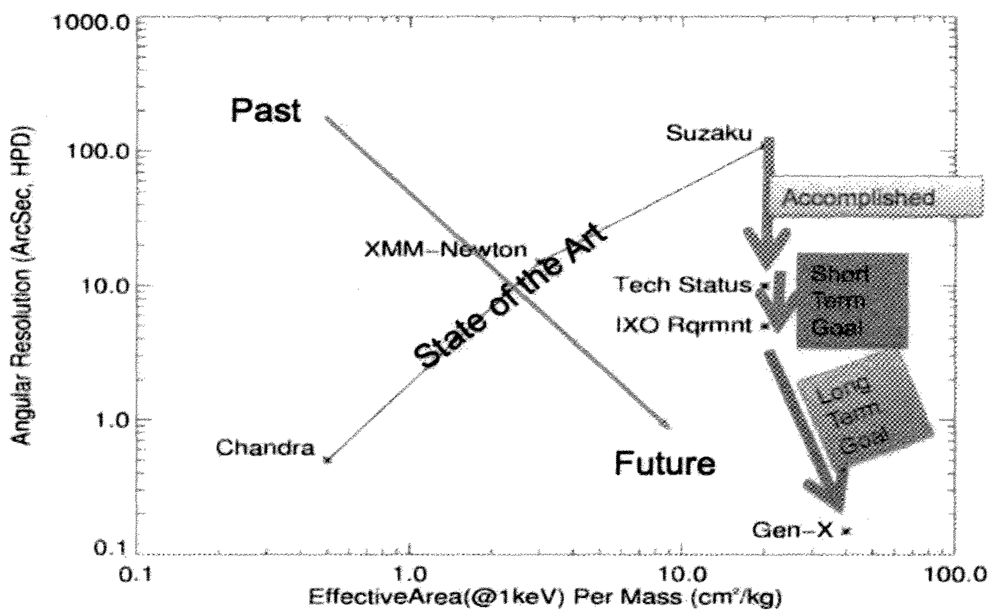

Figure 1. The three currently operating telescopes represented by their angular resolution and effective area per unit mass. This technology program starts with Suzaku's effective area per unit mass and tries to improve its angular resolution. The short-term goal is to achieve 5" HPD (half-power diameter) required by the IXO mission concept. The long-term goal is to meet the requirements set out by the Generation-X mission (Zhang et al. 2001 and Windhorst et al. 2006).

Forming mandrel fabrication

Forming mandrels provide the optical figure to the mirror segments that eventually determine the imaging performance of the telescope. As such each forming mandrel must meet figure quality requirements. For the purpose of this technology development, a total of 2.5" HPD (two reflection equivalent) has been allocated for the forming mandrel figure shared among a primary and its conjugate secondary. In addition to optical figure requirement, the forming mandrel must also be able to maintain its figure against repeated thermal cycling. It has to be thermally cycled between room temperature and ~600°C hundreds of times in the course of developing the slumping technique and for producing flight mirror segments (Blake et al. 2011).

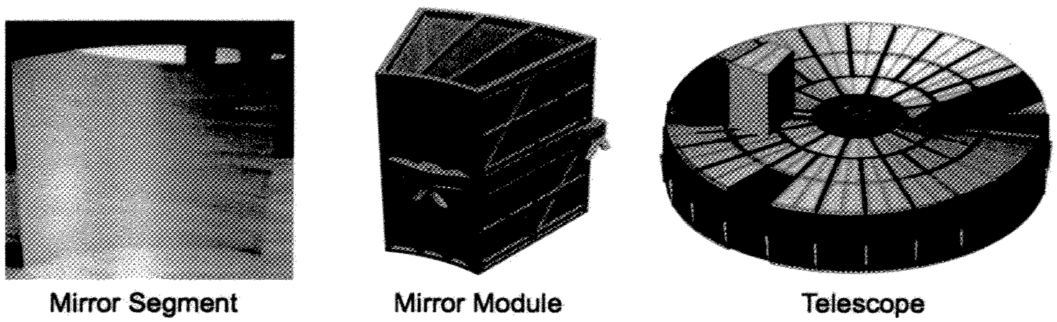

Figure 2. Hierrachical structure of a segmented design: mirror segment, mirror module, and telescope. The typical mirror segment is 200mm by 200mm. The typical mirror module has ~100 pairs (parabola and hyperbola) of mirror segments. The typical telescope has ~100 or more mirror modules aligned and integrated onto a superstructure.

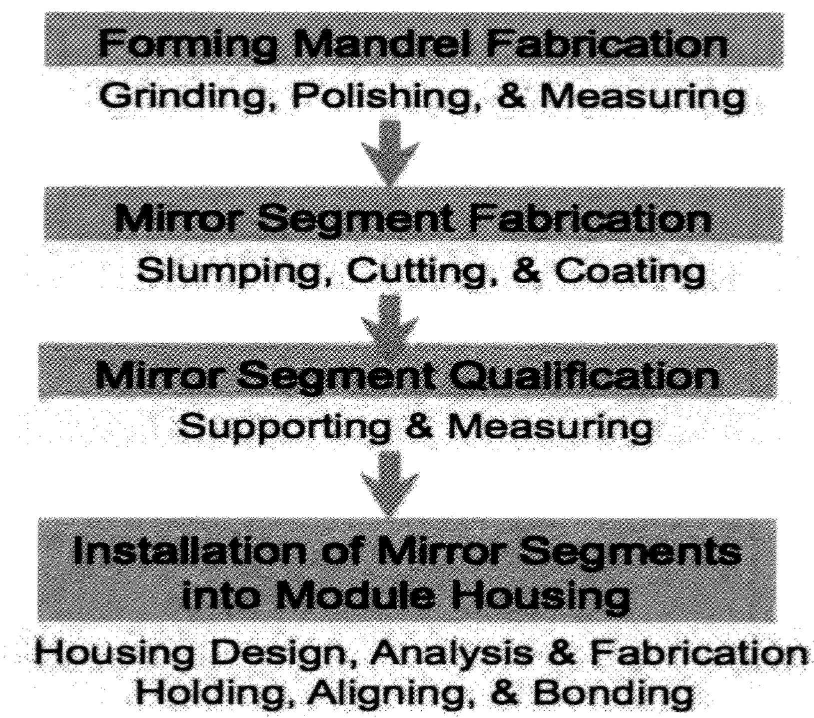

Figure 3. Flow chart of the module construction process. The objective of this development program is to develop and perfect each of these steps into reliable and efficient procedures to meet technical requirements and minimize cost and schedule.

For the purpose of this technology development, industrial quality fused quartz was chosen as the forming mandrel material. It is inexpensive and abundantly available. Many optical fabrication houses have had experience in grinding and polishing it. Three pairs of full shell mandrels, designated 485P/S, 489P/S, and 494P/S using their diameters in mm, have been successfully fabricated and qualified. The fused quartz material was procured from Technical Glass Products, Inc. of Painesville, OH in roughly ground nominal cylindrical shapes. They were then fine-ground and polished into conical shapes by Rodriguez Precision Optics, Inc. of Gonzales, LA. Finally they were precision-polished to meet the 2.5" HPD requirement at the Optical Fabrication Shop of Goddard Space Flight Center, as shown in Figure 4 (left).

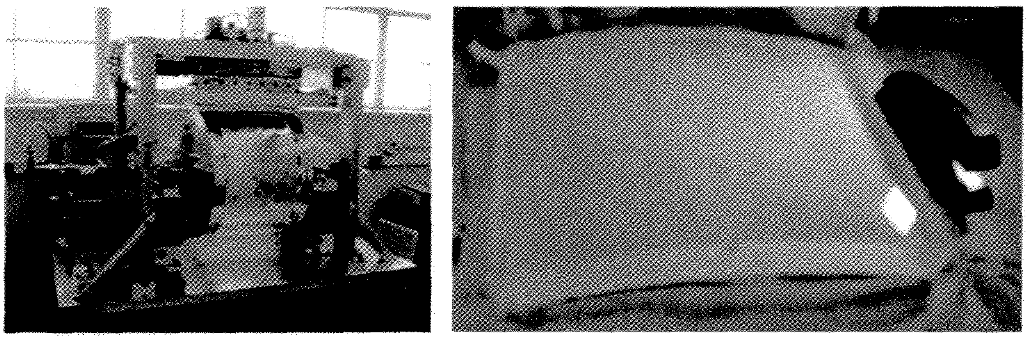

Figure 4. A 500mm in diameter mandrel is being precision-polished at Goddard's Optics Fabrication Shop (left). A segment mandrel blank waits to be fine-ground and precision-polished (right).

These mandrels were then measured on a Zygo 24-in aperture Fizeau interferometer for their axial figures and a coordinate measuring machine for their diameters and cone angles. Since the Zygo interferometer is susceptible to noise in the mid-spatial frequency band (10mm to 0.5mm spatial periods), these mandrels were shipped to Marshall Space Flight Center and measured for their axial figures on a slope-measuring profilometer which does not suffer from any mid-frequency noise. Once the Zygo data are properly filtered with a low-pass filter, its results agree well with those of the profilometer. As of August 2011, all three pairs of mandrels have been proven by this measurement process to meet the 2.5" HPD requirement.

The experience from fabricating and measuring these three pairs of forming mandrels demonstrate that full shell mandrels of their quality can be made quickly at a modest cost. Work is underway to implement a similar process for polishing segmented mandrels that can have an average radius of curvature as large as 750mm, as shown in Figure 4 (right). Meanwhile mono-crystalline silicon is being investigated for its suitability as an alternative mandrel material. Its main advantage is its purity, homogeneity, and high thermal conductivity in comparison with fused quartz. These advantages may enable the slumping process to produce substrates of higher figure quality.

Mirror segment fabrication

The mirror segment fabrication process starts with a qualified forming mandrel and ends with a finished mirror segment. Its purpose is to replicate the figure of the forming mandrel to a thin (0.4mm) sheet of float glass while preserving the naturally excellent microroughness of the float glass. The slumping process, illustrated in Figure 5, is a simple and straightforward process of heating a glass sheet placed atop the forming mandrel to ~600°C so that the glass sheet, being a viscous liquid, becomes soft and slumps under its own weight to conform to the figure of the mandrel. After cooling gradually to room temperature, the glass sheet hardens and becomes a replica of the mandrel.

Since the slumping process is a gravity-assisted thermal process, the areas of the glass sheet near its edges never accurately conform to the mandrel. These areas need to be cut off. Cutting is also necessary to create a substrate that has the correct dimensions for installation into modules. Before the glass is removed from the mandrel, a precision-machined template is used to mark the glass for cutting. The template uses the end surfaces of the mandrel as references so that the resulting circular edges are as perpendicular to the optical axis as required. Two independent methods have been used to cut the marked glass replicas. The first one is a hot-wire technique that has been developed in-house and second one is a carbide wheel procured on the open market. Although the hot-wire cutting creates smooth and fracture-free edges, it has been abandoned because recent experiences have shown that it creates permanent stress near the cut edges, resulting in permanent distortion. The carbide wheel creates edges that probably need treatment to prevent fracture propagation. This question is under investigation.

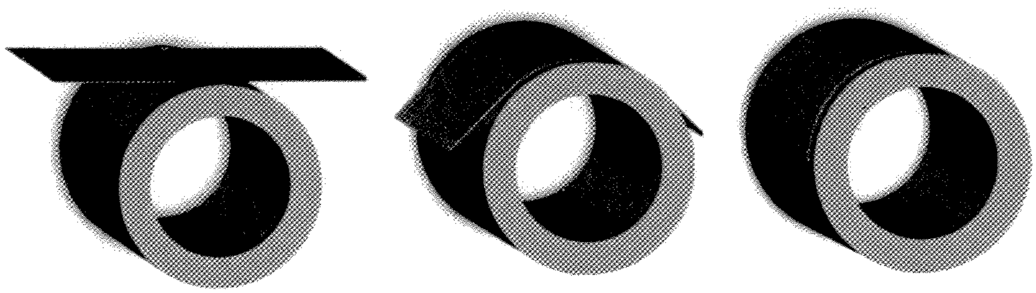

Figure 5. Illustration of the glass slumping process. A thin float glass sheet is placed atop of a mandrel inside an electric oven. When the oven temperature is raised gradually to approximately 600°C, the glass sheet slumps under its own weight and wraps itself around the mandrel, taking on the mandrel's precise figure.

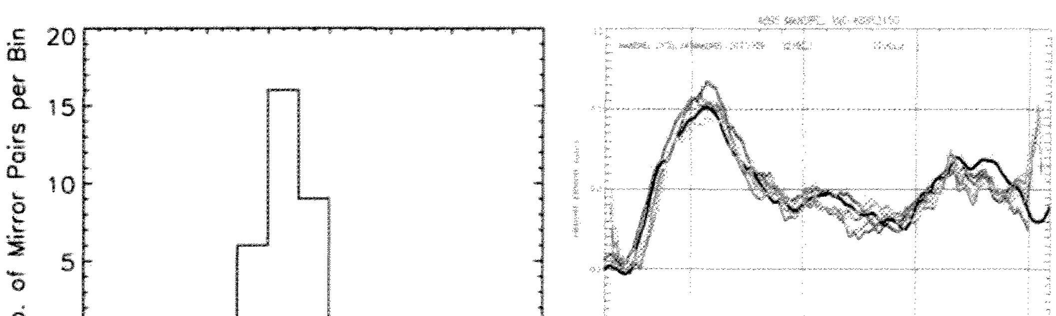

Figure 6. A histogram of the predicted performance of 31 pairs of recently produced mirror substrates (left). These 31 pairs came from consecutive cycles, demonstrating excellent yield and consistency in quality. The panel on the right shows comparisons of axial figures of the mandrel (black and red) and a typical substrate (other colors), demonstrating the high replication fidelity of the glass slumping process.

Once it is slumped and cut, each substrate is measured for its figure on a Fizeau interferometer with a relatively incoherent light source (see next section on mirror segment fabrication). Data from the interferometer allow accurate prediction of the imaging performance of the substrate as well as detailed comparison between mandrel figure and substrate figure. Figure 6 (left) shows a histogram of the HPD of 31 consecutively produced primary (parabolic) and secondary (hyperbolic) pairs, showing that the average HPD of these substrate pairs is about 6.5", well suited for making a 10" telescope. Figure 6 (right) shows a comparison of mandrel axial figures and the resulting substrate figures, proving that at low spatial frequencies the substrate replicates the mandrel with high fidelity. In the mid-frequency domain, the substrate has more small wiggles, which are the reason why the substrates' 6.5" HPD is worse than the mandrels' 2.5" HPD. Work continues to reducing these mid-frequency errors.

After measurement, the substrate needs to be coated with iridium to maximize its reflectivity of x-rays. Being only 0.4mm in thickness, the glass substrate can be deformed by even a very thin layer of sputtered iridium coating, shown in Figure 7 (left). In order to reduce or eliminate the deformation caused by the iridium coating, two methods have been investigated. The first one is to use a chromium undercoating which also stresses the glass but with the opposite sign. Figure 7 (right, courtesy D. Windt, Reflective X-ray Optics, LLC, New York, New York) shows the effectiveness of a chromium undercoating. The stress of a given thickness of iridium top coating can be completely cancelled by an appropriately thick layer of chromium undercoating. Furthermore, numerous experiments have shown that the resulting Cr-Ir bi-layer coating has satisfactory micro-roughness. Work is underway to implement this Cr-Ir bi-layer recipe for coating full-size mirror substrates.

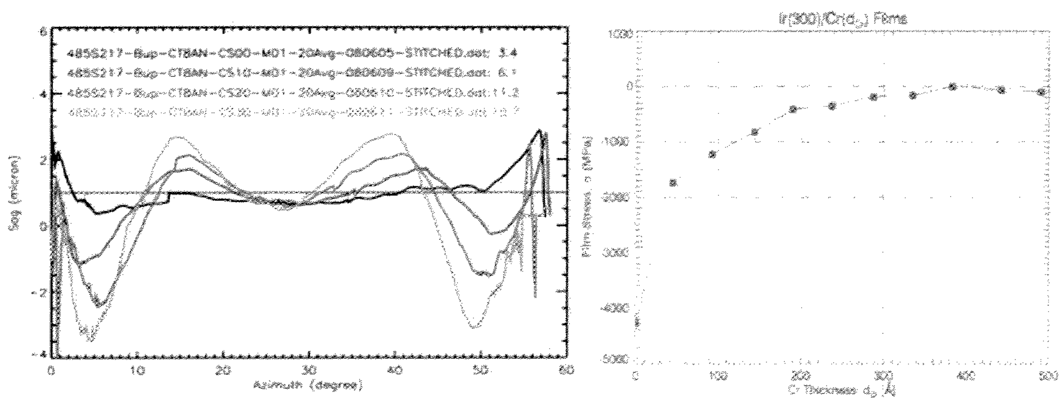

Figure 7. Sag measured at an azimuth as a function of azimuth angle (left). Different curves represent the substrate coated with different thicknesses of iridium. The red straight line represents the sag vs. azimuth of the substrate before any iridium was coated. The right panel (courtesy of D. Windt, RXO LLC, New York, New York) shows the results of a number of coating experiments performed with small glass coupons. Each coupon was coated with 300 Angstroms of iridium and measured for coating stress. Then each coupon was coated with a different thickness of chromium and measured for its net stress. This plot demonstrates that, under this specific circumstance, the stress of 300Å iridium can be completely cancelled by about 400Å of chromium.

The second method is to coat the concave and the convex sides of each mirror substrate with an iridium layer of equal thickness. The two layers of iridium cancel each other's stress, resulting in the preservation of the substrate's optical figure. Preliminary experiments show that this method is promising. This method has the added advantage of reducing the emissivity of the convex side from nearly 1 to nearly 0, resulting in a mirror segment less susceptible to radiative heating or cooling. This is important during the installation of the mirror segment into the module housing.

Mirror segment qualification

Now that the mirror segment fabrication is completed, it needs to be fully qualified before being installed into a module housing (Chan et al. 2011). The qualification has a mechanical aspect and an optical aspect. The mechanical aspect includes among other things, visual and other kind of inspection for defect that may cause facture of the mirror segment later, measurement of dimensional accuracy to assure proper clearance for installation in the module housing, etc. This aspect is not a major one as all of these factors can be adequately addressed with existing techniques that can be procured on open markets. The optical aspect includes the complete characterization of the optical surface to ensure that, once it is installed in the housing, it can give adequate optical performance. An equal importance of the optical aspect is that it provides feedback to the mirror segment fabrication process for improvement.

The complete characterization of the optical surface has two steps. The first step is that, being easily distorted by either gravity or other forces, the mirror segment must be properly supported such that any distortion to its intrinsic optical figure is reduced to an acceptable level. The second step is the actual measurement of the optical figure. Many trials and errors have led us to a simple and elegant way of supporting a mirror segment as shown in Figure 8 (left). The actual measurement is done with a Fizeau interferometer and a cylindrical lens that converts the parallel beam into a cylindrical beam which is then retro-reflected by the nearly cylindrical mirror segment.

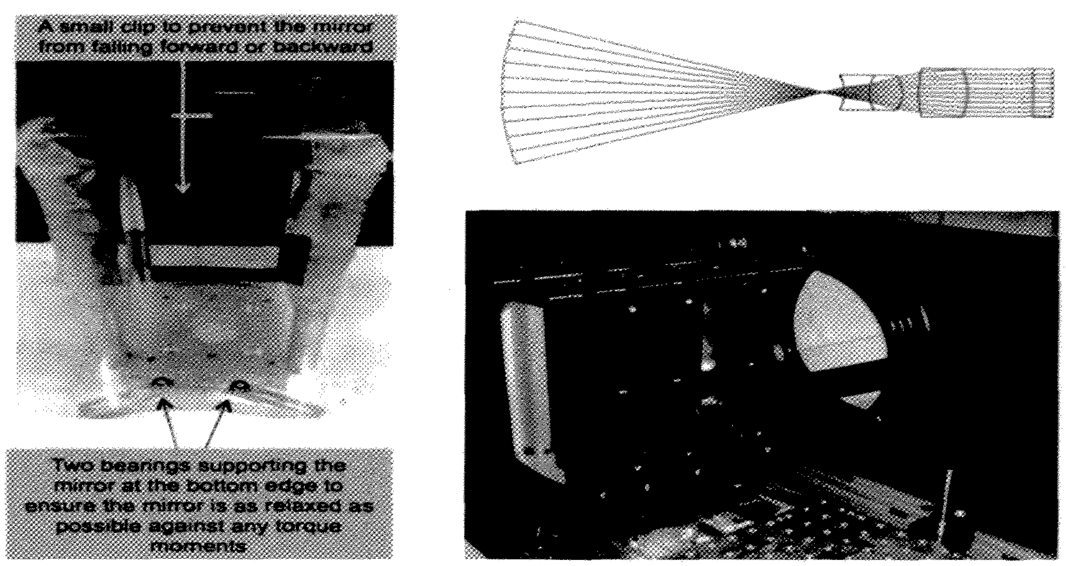

Figure 8. Normal incidence metrology of the mirror segment. The mirror segment is supported at three locations (left) such that its optical axis is nearly parallel to the local gravity vector. The figure of the mirror segment is captured with a Fizeau interferometer and a cylindrical null lens (lower right panel). The principle of the measurement process is illustrated (upper right panel).

Another significant factor is the thermal effect of the laboratory environment on the measurement result. The mirror segment, being very small in thermal mass, is susceptible to both convective and radiative heating. An appropriately designed and built thermal shield has been implemented as part of the measurement setup. As of August 2011, highly repeatable and consistent measurements have been achieved in measuring figure of mirror segments, sufficient to ensure that any performance prediction based on the acquired data has an uncertainty less than 0.5" HPD. This is good enough for enabling the building of a 5" HPD telescope.

Most of the measurement uncertainty comes from systematic errors associated with the placement of the mirror segment into the supporting structure. Further refinement is necessary to achieve better measurement repeatability. Another area of improvement is in the absolute measurement of the null lens wave front error. This error is mainly of second order in the axial direction, directly affecting the sag measurement of the mirror segment. More systematic calibration against certified flat mirrors is underway, expecting to arrive at an absolute calibration of the sag to better than 20nm which corresponds to an imaging performance error of less than 0.2" HPD.

Installation of mirror segments into a module housing

A module is a collection of a large number of primary (parabolic) and secondary (hyperbolic) mirror segments that are precisely aligned with each other and each permanently attached to a housing. These mirror segments are aligned such that they all have a common focus. The attachment is such that the mirror segments can maintain their alignment and preserve their optical figure over time, against temperature excursion, and being able to withstand launch vibration and acoustic loads. The entire design, analysis, construction, and testing of a module is an iterative process (McClelland et al. 2011).

The process starts with a preliminary design and finite analysis of a module. This design must meet several initial requirements imposed for practical reasons. The first requirement is that the completed module can be kinematically mounted at three locations for alignment and integration to make an entire telescope. Together with an overall mass allocation from the telescope level, this requirement determines approximate dimensions of the module in both radial and azimuthal directions. The second requirement is that the completed module must be testable in a horizontal x-ray beam that exists in several institutions including both Goddard and Marshall Space Flight Centers. This requirement determines the angular size of mirror segments and broadly how each mirror segment has to be attached so that, when its optical axis is in the horizontal direction, its deformation due to gravity is minimized and aceeptable. The third requirement is that each mirror segment must be able to survive launch loads with acceptable margins. This requirement determines the number of attachment points each mirror segment must have. The fourth requirement is that the mirror module must be able to maintain optical performance against small (~1°C) bulk temperature change. This requirement stipulates that the coefficient of thermal expansion (CTE) of the module housing must be fairly close to that of the mirror segments at room temperature, i.e., 6.3 ppm/K.

Taking into consideration of all those requirements and after extensive finite element analysis (Biskach et al. 2011), the azimuthal dimension of a typical module has been determined to be about 30° or about 150mm in arc length, whichever is smaller; the radial dimension has been determined to be approximately ~200mm. Figure 9 shows an illustration of the design (left) and a stress analysis result (right). The development of techniques for installing a mirror segment into the mirror housing proceeds with these basic parameters.

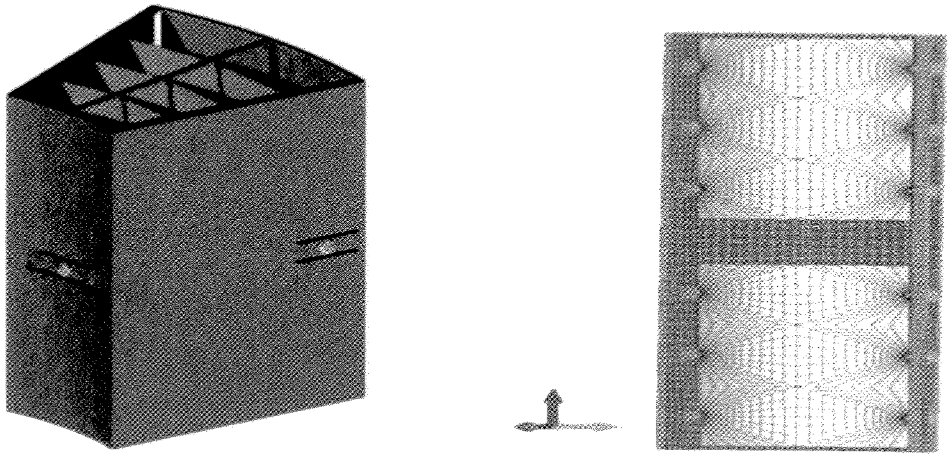

Figure 9. The conceptual design of a module with two of its three kinematic mounting points shown (left). Each mirror segment is bonded to the housing at six locations (right). Finite element analysis shows that the mirror segments can withstand launch loads with acceptable margins.

The installation of a mirror segment is conceptually divided into three steps. In the first step, the mirror segment is temporarily mounted to a stiff structure with little or no distortion to its intrinsic figure. The stiff structure serves as a support of the flexible mirror segment so that it can be moved and aligned as if it were a rigid body. Two independent methods are under development to accomplish this purpose. In the first method, shown in Figure 10 (left), the mirror segment is temporarily bonded to a stiff structure at three locations, two at the bottom edge and one at the top edge, when it is suspended from a gantry with two wires so that its optical axis is nearly in the vertical direction. Finite element analysis of the mirror segment in the suspended configuration has determined that the figure distortion is totally negligible for a 5" HPD telescope system. In the course of last year, the process of bonding the mirror segment at the three locations to a stiff structure has been perfected to be reliable and reproducible with distortion acceptable for a 5" HPD telescope system. After the epoxy bonds have cured, the suspension wires are cut. The mirror segment is ready to be measured and manipulated.

In the second method, shown in Figure 10 (right), the mirror segment is temporarily supported by a stiff structure via three balls, two of which are glued to the bottom edge and the third to the top edge. The bottom two balls sit in appropriately machined sockets to prevent the mirror from moving in one direction while allow it to be unconstrained in the orthogonal direction. The mirror leans against a flat surface via the top ball to prevent it from tipping forward or backward.

The two methods are similar in that they both constrain the mirror segment at three locations, which are the minimum number required. They differ in the level of these constraints. In the first method, each of the bottom two locations have 6 degrees of freedom (DOF) constraints while the top location is a 5-DOF constraint. In the second method, in principle, each of the three balls provides only 2-DOF constraints. Together they provide the 6-DOF constraints necessary to totally fix the mirror segment. Currently both methods are used to in the installation process. Many trials of alignment and permanent bonding in coming months will decide on an empirical basis which method is more appropriate.

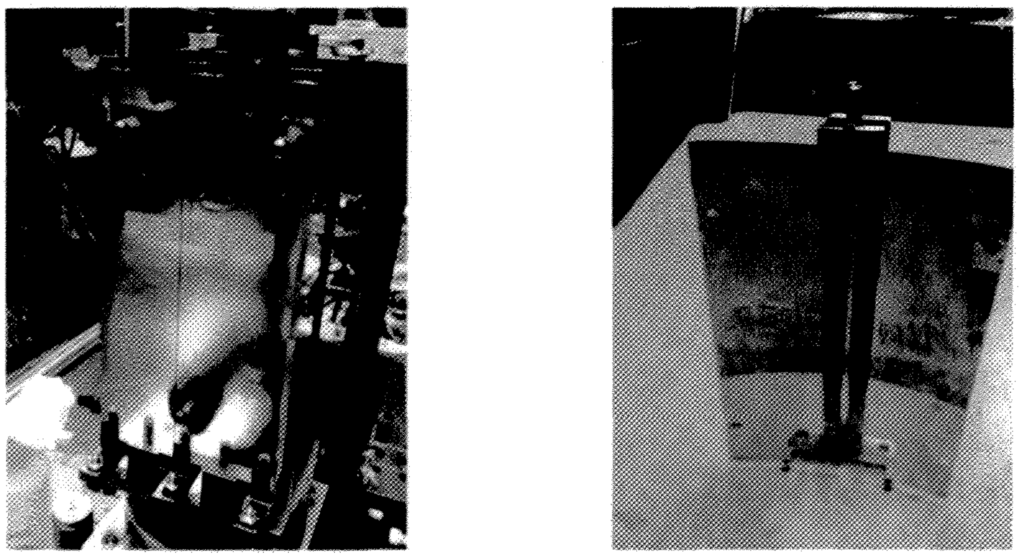

Figure 10. The two methods of temporarily holding a mirror segment for alignment and permanent bonding. The first method (left) temporarily attaches the segment at three locations, two at the bottom and one at the top. The second method (right) supports the segment with three balls that are bonded to the edges, two at the bottom and one at the top.

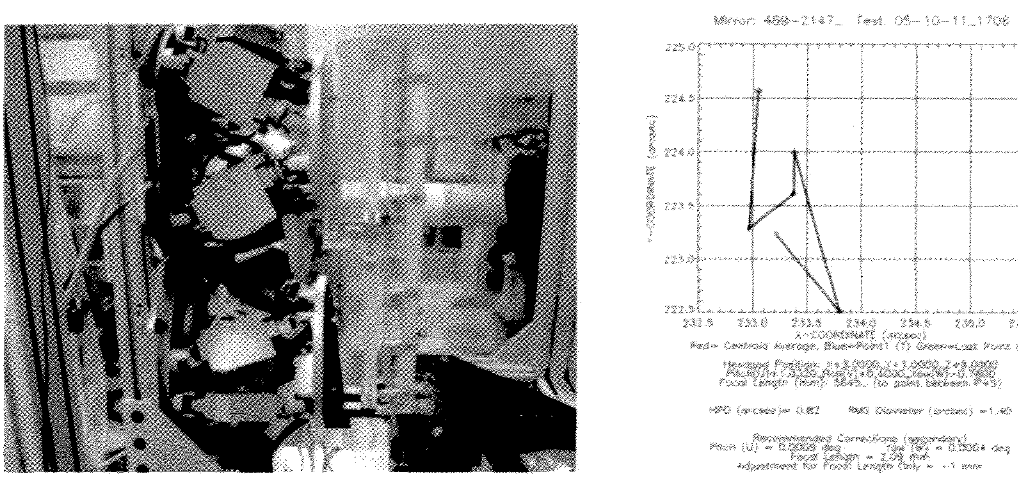

Figure 11. The two hexapods used for aligning a pair of mirror segments (left). A typical Hartmann map with several centroids obtained from different sectors of the mirror being aligned (right). Each division being 0.5", all the Hartmann centroids fall within 1" by 2" area, indicating good focus quality.

The alignment of the mirror segment with its conjugate segment and other mirror pairs in the module is achieved with a precision hexapod, shown in Figure 11 (left), under the guidance of a Hartmann test beam (Evans et al. 2011). The hexapod is controlled by a computer to adjust the mirror segment in all of its six degrees of freedom: x-, y-, z-translation, pitch, yaw, and roll. The effect of each adjustment is accurately measured by a set of Hartmann tests each of which interrogates a small sector (currently 2 degrees) of the mirror segment for the centroid of its focus. The totality of these Hartmann centroids from all the sectors determines the focus quality and determines the next adjustment (Saha et al. 2011), shown in Figure 11 (right). The entire adjustment and Hartmann test process has been engineered into a closed loop and automatic operation. Once a mirror segment in its temporary hold is place on the hexapod, optimal alignment can be achieved in a matter of minutes.

Once a mirror segment is brought into alignment, it is permanently bonded to the housing using epoxy. Two independent methods of permanent bonding are under investigation. In the first method, shown in Figure 12 (left), the bonding is in the azimuthal direction. Each of the six locations on the mirror segment edges is attached to the housing via a metal pin. The head of the metal pin is dabbed with a small bead of epoxy. The pin is guided by a small bushing that has been machined in the local azimuthal direction and pushed by an actuator until the bead of epoxy comes into contact with the mirror segment's edge. Then the epoxy is left to cure. During the cure process, as it shrinks, the epoxy pulls the pin along the direction determined by the bushing, thereby exerting little, if any, force to the mirror segment. After all epoxy on all six pins have fully cured, a small amount of anaerobic adhesive is injected into each bushing through the capillary effect to lock down the pins. After the anaerobic adhesive cures, the mirror segment is permanently bonded to the housing and the temporary holder is removed.

In the second method, shown in Figure 12 (right), the mirror segment is bonded on six spots on its x-ray reflective surface. In other words, the bonding takes place in the local radial direction. Six pads, whose positions are only accurate to mechanical precisions (~10 μm), are provided by the housing structure to which the mirror segment is bonded with epoxy. The gaps between the mirror surface and the pads are taken up by epoxy. As the epoxy cures, the radial locations of these six spots on the mirror segment are continuously monitored by a set of capacitance displacement sensors. These sensors provide real time input to a set of actuators that force the mirror segment to where it was before the epoxy was injected and started to cure. This cure-monitor-adjustment process is a closed-loop operation. In the end when the epoxy has cured, the mirror segment remains where it was and keeps it figure, within certain tolerance.

Both methods have successfully bonded mirror segments to housing simulators and achieved good x-ray images. They are complementary to each other in that they bond in two orthogonal directions. The plan is to continue to purse both approaches in coming months, each with many more trials, so that the advantages and disadvantages of each can experimentally manifest themselves. Once sufficient empirical evidence is gathered, they will be evaluated and the better one will be chosen.

As of August 2011, single pairs of mirror segments have been successfully aligned and bonded to housing simulators multiple times. They have been tested in an x-ray beam for the overall imaging quality. Figure 13 shows the result from the latest test.

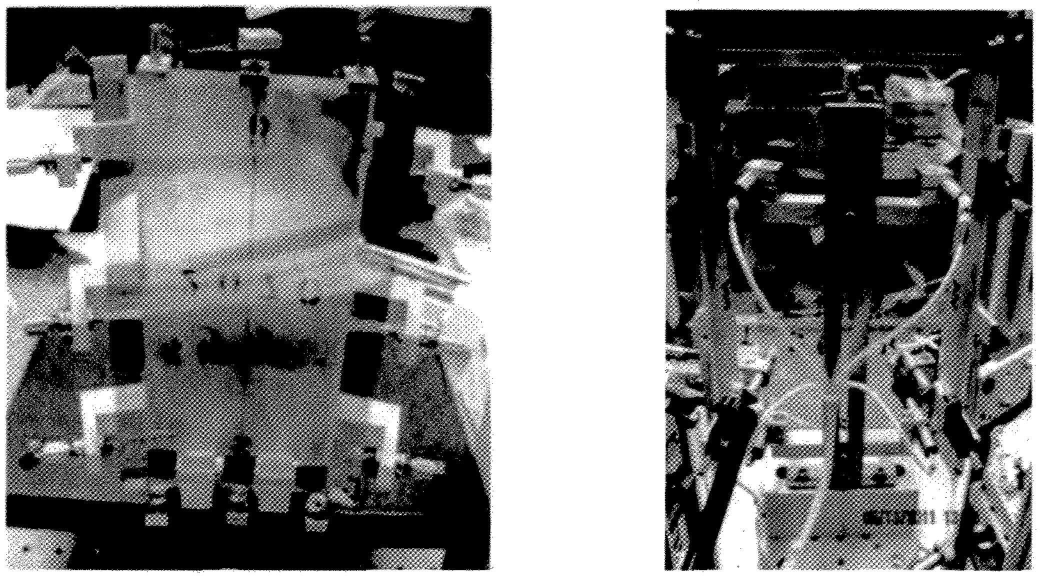

Figure 12. Development setups of the two methods of permanently bonding the mirror segment to module housing. In the first method (left), the bonding takes place in the local azimuthal directions, whereas in the second method (right), the bonding takes place in the radial directions.

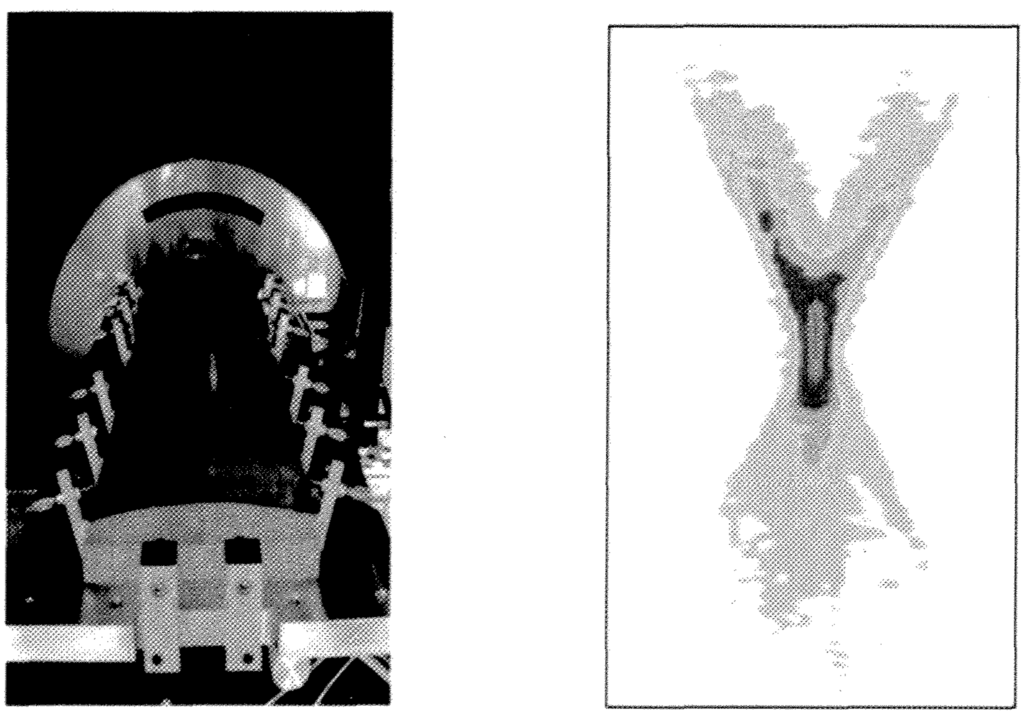

Figure 13. A fully aligned and bonded pair of mirrors in a vacuum chamber ready to be x-ray tested (left). The x-ray image obtained from this test has an HPD of 8.7".

Summary and Prospects

This paper has briefly described a complete process of making lightweight x-ray optics modules. Although much progress has been made toward readying this technology for spaceflight, much refinement needs to be done to improve both x-ray image quality and robustness of these techniques to minimize technical and budgetary risks when it is used for a spaceflight mission.

In coming years, forming mandrels of better figure will be fabricated, possibly using higher quality materials such as mon- or poly-crystalline silicon. The slumping process will be continually refined and updated to achieve higher fidelity in replication, especially in reducing mid-spatial-frequency errors. The mirror segment measurement process will be better calibrated to achieve the absolute measurement of parameters as well as better repeatability.

In the near term, the installation of mirror segments into module housing will be systematically perfected to achieve both x-ray imaging performance and pass all necessary environment tests. This progression is illustrated in Figure 14. In the first step, shown in Figure 14 (left), single pairs of mirrors are aligned and bonded to a structure that acts as a housing. It is open to facilitate access and development of alignment and bonding techniques. Once single pairs can be aligned and bonded repeatedly and accurately with long-term stability, the second step, shown in Figure 14 (middle), will be carried out, where three pairs of mirror segments are co-aligned and bonded into a housing that looks like a module housing except that it is smaller in the radial direction because it contains only three pairs of mirrors. This mini-module will be subjected both x-ray performance and environment tests. Once it is demonstrated that mini-modules can be repeatedly constructed and tested, the third step, shown in Figure 14 (right) will be carried out, where a high-fidelity mirror module with many pairs of mirror segments will be constructed and tested for both x-ray imaging performance and withstanding launch loads.

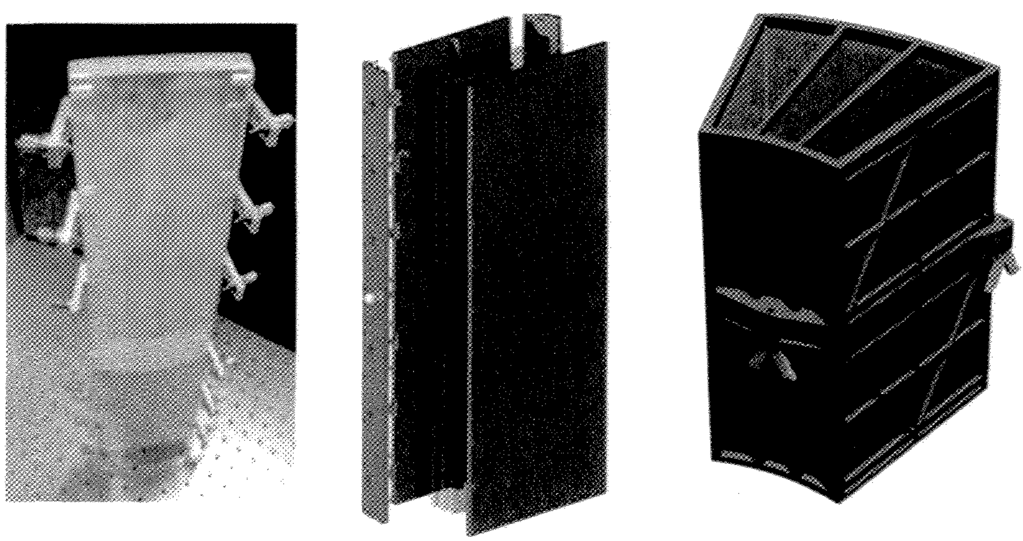

Figure 14. Progression toward complete demonstration of this x-ray optics technology. Initially single parabolic and hyperbolic pairs are repeatedly aligned and bonded to an open structure to develop the technique (left). Then the technique is used for construct a mini-module with three co-aligned pairs (middle). Finally a high-fidelity module with many pairs will be constructed and tested to meet mission angular resolution and environment requirements.

Acknowledgements

The work described in this paper represents the effort of many people over several years. The authors wish to acknowledge the support of the many scientists, engineers, and technicians at both Goddard and Marshall Space Flight Centers. The work has been financially supported by the National Aeronautic and Space Administration through the IXO Project Office at the Goddard Space Flight Center and a grant from the *Research Opportunities in Space and Earth Sciences* program.

References

1. Biskach, M. et al., "Size optimization for mirror segments for x-ray optics," in these proceedings (2011)
2. Blake, P.N., et al., "Forming mandrels for making lightweight x-ray mirrors," in these proceedings (2011)
3. Chan, K.W., et al., "Metrology of IXO mirror segments," in these proceedings (2011)
4. Evans, T. et al., "Alignment and integration of lightweight mirror segments," in these proceedings (2011)
5. Gondoin, P. et al., "X-ray multi-mirror (XMM) telescope," SPIE, Vol. 2279, pp. 86-100 (1994)
6. Gordon, T. E. & Catching, B. F., "Status of the Advanced X-Ray Astrophysics Facility (AXAF) optics production program," SPIE, Vol. 2263, pp. 233-242 (1994)
7. Lehan, J. P. et al., "Progress toward a complete metrology set for the International X-ray Observatory (IXO) soft x-ray mirrors, " SPIE, Vol. 7437, pp.74370R-74370R-9(2009)
8. McClelland, R. et al., "Design and analysis of mirror module for IXO and beyond," in these proceedings (2011)
9. Saha, T. et al., "Grazing incidence wavefront sensing and verification of x-ray optics performance," in these proceedings (2011)
10. Serlemitsos, P.J. et al., "The X-Ray Telescope onboard Suzaku," PASJ, Vol. 59, pp. 9-21 (2007)
11. White, N.E. & Tananbaum, H.D., "Constellation-X mission: science objectives and implementation plan," SPIE Proc., Vol. 4851, pp. 293-303 (2003)
12. Windhorst, R. A. et al., "Generation-X: An X-ray observatory designed to observe first light objects, " NewAR, Vol. 50, pp. 121-126 (2006)
13. Zhang,W.W. et al.,"Development of mirror segments for the Constellation-X observatory," SPIE Proc. Vol. 4851, p. 503 (2003)
14. Zhang, W., Petre, R., White, N. E., "Generation-X: a Large Aperture, High Angular Resolution X-ray Observatory for the 2010's," ASPC, Vol. 234, pp. 657-662(2001)
15. Zhang, W.W. et al., "Mirror technology development for the International X-ray Observatory mission (IXO), " SPIE, Vol. 7732, pp. 77321G-77321G-8 (2010)