The Astro-H Soft X-ray Mirror

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Abstract— The Astro-H is led by the Japanese Space Agency (JAXA) in collaboration with many other institutions including the NASA Goddard Space Flight Center. Goddard's contributions include two soft X-ray telescopes (SXTs). The telescopes have an effective area of 562 cm^2 at 1 keV and 425 cm^2 at 6 keV with an image quality requirement of 1.7 arc-minutes half power diameter (HPD). The engineering model has demonstrated 1.1 arc-minutes HPD error. The design of the SXT is based on the successful Suzaku mission mirrors with some enhancements to improve the image quality. Two major enhancements are bonding the X-ray mirror foils to alignment bars instead of allowing the mirrors to float, and fabricating alignment bars with grooves within 5 microns of accuracy. An engineering model SXT was recently built and subjected to several tests including vibration, thermal, and X-ray performance in a beamline. Several lessons were learned during this testing that will be incorporated in the flight design. Test results and optical performance are discussed, along with a description of the design of the SXT.

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1. INTRODUCTION

The Astro-H Soft X-ray Mirror (SXT) is a vital component of the X-ray observatory that is being built at NASA Goddard Space Flight Center. Astro-H is a joint project with the Japan Aerospace Exploration Agency (JAXA) in collaboration with NASA GSFC and other Japanese and European institutions. It will launch in 2014 as the latest in a line of facility-class X-ray observatories. Astro-H is the follow-on observatory to Suzaku that launched in 2005. Its purpose is to observe the spin of black holes, provide insights into the behavior of material in extreme gravitational fields, determine the equation of state of neutron stars, and study other interesting astronomical phenomena.

Two identical SXT mirrors are being built at GSFC to be installed on Astro-H. One mirror focuses X-rays for the X-ray Calorimeter Spectrometer (XCS), and the other mirror is paired with the Soft X-ray Imager. The design of the SXT includes 1624 precisely aligned mirror foils. This paper will discuss the mirror requirements, design, analysis, assembly and test challenges encountered so far.

2. X-RAY MIRRORS

The purpose of the SXT mirror is to focus X-rays onto a detector. Visible light can easily be reflected from a mirror at any incident angle, but X-rays can only glance off of a mirror at incident angles less than about 1 degree. X-ray mirrors are typically shaped as a shallow cone and oriented nearly "edge-on" to the incident photons. A single mirror will therefore have only a very small projected surface area, so the efficiency of a single X-ray mirror is quite low. Starting in the 1970s a new kind of X-ray mirror was built that consisted of a series of nested concentric shells [1]. Grazing incidence optics technology has been improved over the years and successfully flown many times on missions such as BBXRT, ASCA, XMM Newton, and Suzaku. Current missions in development include GEMS, Nustar, and Astro-H.

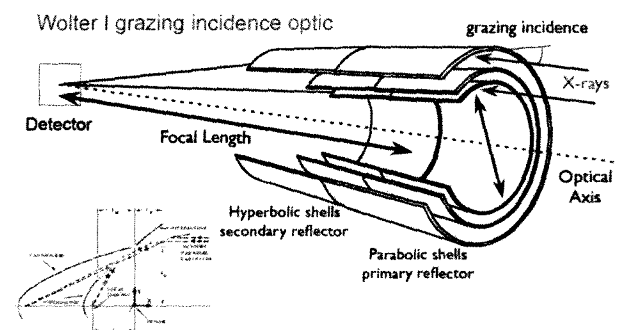

Figure 1 – Wolter-I Grazing Incidence Concept

The two most important performance parameters of X-ray mirrors are angular resolution and effective area. Science that requires high resolution imagery requires a telescope with high angular resolution. Spectroscopy, on the other hand, can tolerate poor angular resolution but needs a large effective area providing a flood of photons to create the spectral lines on the detectors. The Chandra mirror was optimized for angular resolution, and consists of four very thick and precisely ground shells that provide an angular resolution on the order of 0.5 arc-seconds. The disadvantage with this kind of mirror is the mass, volume, and cost required to get a modest effective area. Chandra has an effective area of about 400 cm^2 at 5.0 keV and the mirror assembly weighs over 900 kg. The Astro-H mirror was optimized for effective area and can gather as many photons as Chandra in a lightweight and small package, with angular resolution about 1.7 arc-minutes. The Astro-H mirror weighs only 44 kg. It also costs about two

[2] IEEEAC Paper #1565, Version 4, Uploaded 1/18/12.

orders of magnitude less than the Chandra mirror.

3. SXT Requirements

The requirements of the SXT are shown in Table 1:

Table 1 - SXT Requirements

Parameter	Requirement
Focal Length (M)	5.6m
Diameter (cm)	45
Mass (kg)	44
Max Launch Loads (G)	20 G's
Effective Area (cm^2@1 keV)	450
Effective Area (cm^2@6 keV)	390
Spatial Resolution	< 1.7' HPD
# Shells	203
# Forming Mandrels	71
Groove position accuracy	5 μm
Foil thicknesses (μm)	152, 229, 305

The curve in Figure 2 below shows the expected effective area up to 10 keV. The relationship is not linear because absorption and reflection of photons on the mirror surface is different depending on its energy. The chart in Figure 3 shows the effective area error budget. Various knock-down factors reduce the ideal clear aperture mirror area down to about 10-15%. In other words only about 10-15% of the photons that enter the mirror are received by the detectors.

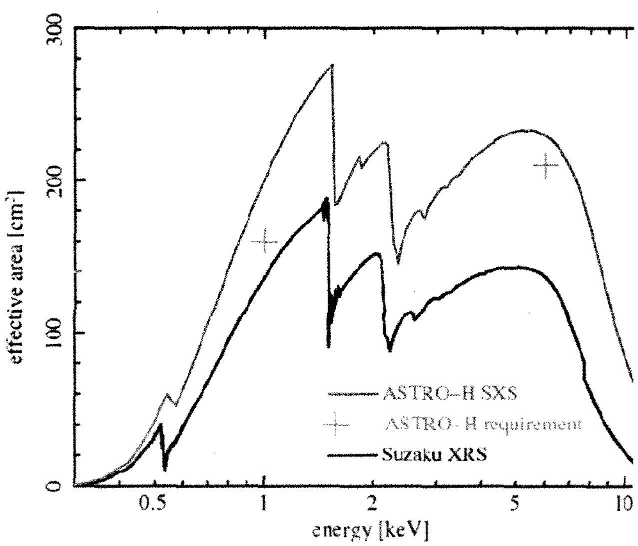

Figure 2 - Expected Effective Area vs. Energy

Table 2 – SXT Effective Area Error Budget

Item	1 keV		6 keV	
	fraction	cm^2	fraction	cm^2
Geometric area	1.00	1478	1.00	1478
Mirror structural/edge obs.	0.58	857	0.58	857
Mirror reflectivity	0.82	703	0.62	533
Reflector figure & alignment error	0.8	562	0.8	426
Mirror requirement		450		390
Thermal Shield	0.86	484	0.94	401
Possible alignment error	0.98	474	0.98	393
PSF (1.7 arcmin)	0.71	337	0.71	279
Filter (Si mesh)	0.62	209	0.89	248
Detector filling factor	0.96	200	0.96	238
Detector Q.E.	1.00	200	0.97	231
System requirement		160		210
Margin		20%		9%

4. Astro-H SXT Design

The SXT is based on designs flown on several earlier missions including Suzaku. Figure 4 shows an exploded view of the SXT assembly which consists of a cylinder of nested mirror foils that are divided into four quadrants and two stages. There is a primary mirror stage and a secondary mirror stage. Splitting the design into quadrants makes it easier to build up the mirror in small subassemblies that are easier to assemble, align and test. Mounted to the primary mirror stage is a stray light precollimator and thermal shield.

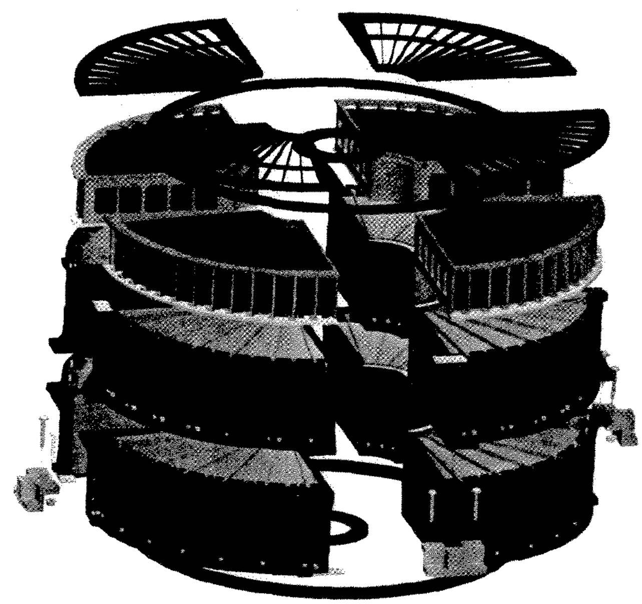

Figure 3 – Exploded view of the SXT Mirror Assembly

Thermal Shield and Pre-Collimator

The thermal shield is a thin sheet of aluminized polyimide that covers the aperture of the stray light pre-collimator. It permits soft X-rays from passing through but greatly reduces the radiation heat transfer into and out of the SXT.

The stray light pre-collimator is provided by Nagoya University in Japan. It is installed onto the entrance aperture end of the primary mirror quadrants. The purpose of the pre-collimator is to block photons from entering the mirror aperture at angles that permit a single bounce from either the primary or secondary mirrors, or a backside reflection from a mirror. These photons are not properly focused and are the largest contributor to noise in the image. The pre-collimator reduces stray light by several orders of magnitude at the expense of narrowing the field of view and reducing effective area off-axis slightly. The design of the Astro-H pre-collimator is similar to the one on Suzaku [5] and consists of 203 nested aluminum foils which are located above each primary mirror foil at the proper angle to block stray light.

Housings

The mirror housings are made from 7075-T7351 aluminum. They are the main structure elements in the mirror and their primary function is to hold the alignment bars and mirror foils in position. They have tight flatness control on their top, sides, and bottom to make a good interface and alignment with the other housings. The eight housings are connected together via a fairly simple arrangement of inner and outer rings and splice plates.

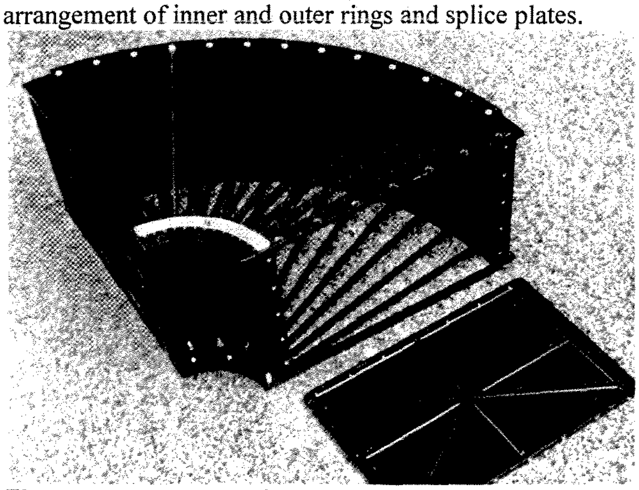

Figure 4 - Mirror Housing Quadrant

Positioning Bars

The mirror positioning bars are a key part of the mechanical assembly since it is their job is to hold the mirror foils in precise position. A series of 203 grooves are cut into the bars via a very accurate wire electric discharge machine (EDM). A table of over 400 unique dimensions for each alignment bar is uploaded into the wire EDM computer. Groove dimensional accuracy is within 5 microns (.0002"). There are three different widths to the grooves to correspond to the three different mirror foil thicknesses. The distance between the grooves are progressively larger from the inside to the outside of the mirror to correspond to the change of cone angle of the mirrors. Inner mirror foils have a smaller cone angle than the outer ones.

Positioning bars made for previous projects did not have the dimensional accuracy of the ones being made for Astro-H. Improvements in wire EDM technology in the last ten years has enabled the tolerances on the grooves to decrease by about an order of magnitude. This improvement is a major contributor of the reduction of Half Power Diameter (HPD) error compared to the Suzaku mirror. It is expected to reduce HPD error by 20 arc-seconds.

Figure 5 - Section of an alignment bar

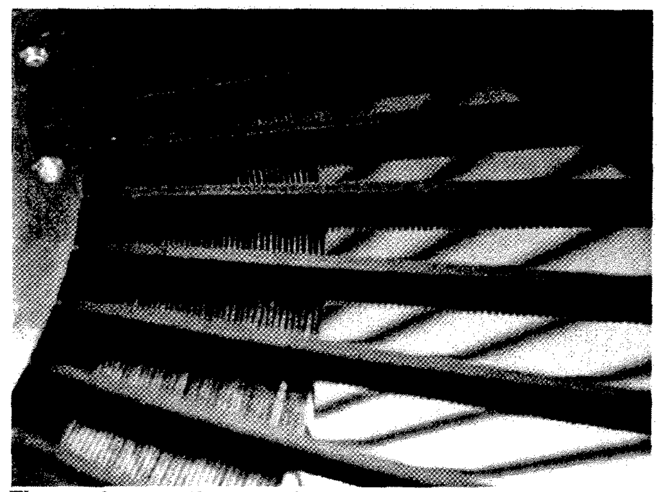

Figure 6 - Foils assembled to alignment bars. Gap between foils is about 1mm.

Mirror Foil Fabrication

There are 203 shells of nested mirror pairs. Considering the four primary and secondary mirror quadrants, the total number of mirror foils is 1624. Mirror foils are created one at a time in a process detailed in several excellent papers [2, 3, 4]. About 16 foils are prepared each day in an assembly line process. The mirrors are made of 5052 aluminum sheets that are cut into a fan shape and rolled into the approximate conical shape. The rolled aluminum pieces are placed onto a conical shaped mandrel and stress relieved at 200C. Then a thin layer of gold is sputtered onto a cylindrical glass mandrel, and a 12 micron thick layer of epoxy is applied to the aluminum piece. The aluminum piece is then placed onto gold-plated glass mandrel and cured at 40C for 16 hours. The aluminum foils take the conical shape of the mandrel based on a conical approximation the Wolter-I prescription. The gold surface serves as a release layer to the mandrel in addition to providing an efficient X-ray grazing incident surface.

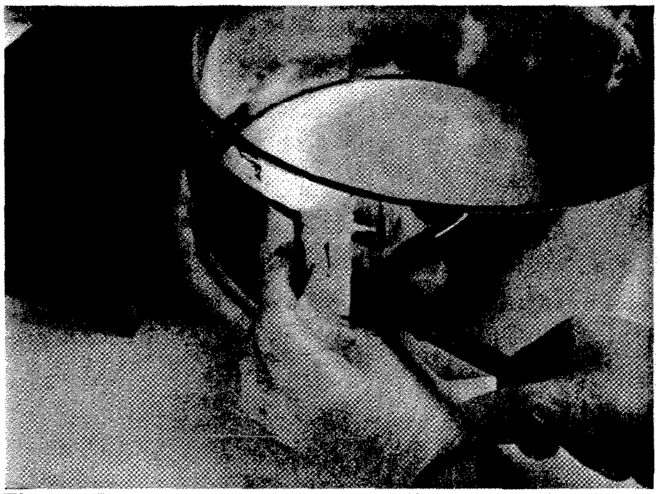

Figure 7 – Removing a mirror foil from its forming mandrel.

The conical approximation prescription requires that each mirror foil have a unique conical shape. For Astro-H, 71 mandrels have been fabricated, about three times the number used on the Suzaku (Astro-E2) mirror. An average of about three neighboring foils share the same forming mandrel as compared to eight for the Suzaku mirror. The optical quality has been improved by 10-20 arc-seconds from the Suzaku mirror as a result. Future gains will result from unique mandrels for each shell, but were beyond the resources of this project.

Assembly and Alignment Process

The assembly of a mirror starts with a mirror housing. Five support bars and eight alignment bars are installed onto the mirror housing. Then the work of installing mirror foils begins. Mirrors are installed through the side window in the quadrant housing. Installation is painstaking since there is a unique mirror for each groove on the support and alignment bars, and each foil must be slid in and rotated through thirteen grooves just 160 microns wider than the foils. A nudge or bump can cause mirrors to jump out of the grooves and the process must be started over. A quadrant alignment fixture is used during the foil loading process. This fixture holds the housing on a rotation stage and has microscopic video cameras and monitors which provide a close-up view of the mirror as it is slowly threaded through the gaps in the bars. After all the mirror foils are installed, six of the alignment bars are removed, as they were in place only to help in loading the mirrors. The side panel is installed to close out the side window of the quadrant where the mirrors were installed.

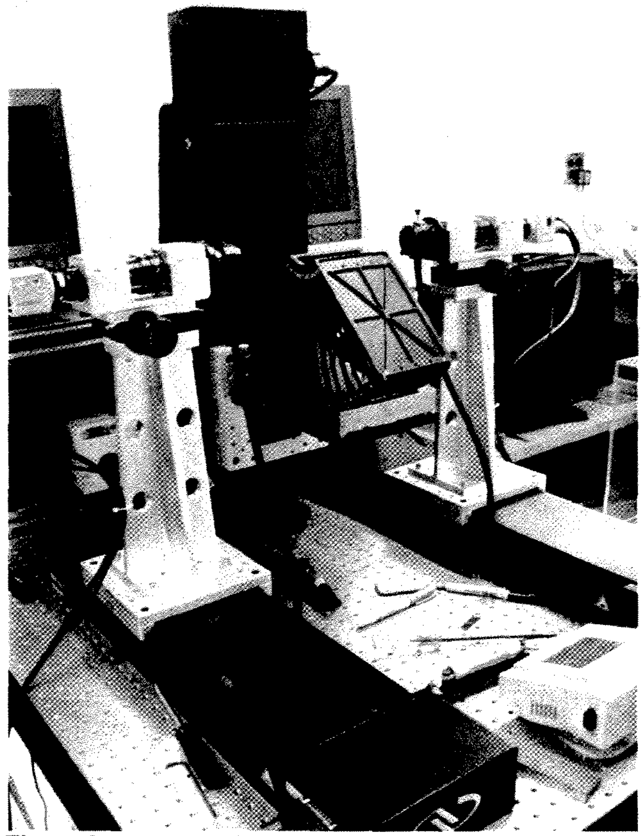

Figure 8 - Mirror Foil Loading Fixture

A new technique being introduced on the Astro-H SXT is that the foils will be epoxied to the positioning bars. Earlier generations of X-ray mirrors allowed the foils to float in the grooves. This usually worked but during vibration testing sometimes mirror foils could jump out of the grooves. Also the orientation of the mirrors was more random when they were floating in the gap. Astro-H's mirrors are biased to one side and then bonded with a soft epoxy such as Arathane 5753 so that optical alignment is locked in to the desired orientation. This is expected to improve the HPD error by about 15-30 arc-seconds, a large jump in performance.

An optical check is performed to verify that the focal length is correct. Collimated light is directed through the subassembly and focused onto a detector far downstream. There is not much that can be done to change the alignment of the foils relative to each other, but the positioning bars can be shifted radially tens of microns to adjust the focal length of the foils. Once the optical quality is verified at this subassembly level, primary and secondary quadrants are attached together. This process involves stacking them and co-aligning holes on the inner and outer diameters of the quadrant. Rotations between the two quadrants can be made with very thin shims. Lateral shifts are permitted within the tolerance of clearance holes. This process involves some trial and error while the quadrant is in a collimated beam.

For these alignments in visible collimated light, the quadrant is installed onto a table with its optical axis parallel to gravity. A light source projects down onto and through the quadrant and is turned 90 degrees with a large fold flat. The optical path runs horizontally to a light flux meter. The detector is able to determine the light flux and shape of the image. A perfectly focused image would appear as a single point on the detector, but because the angular resolution is on the order of one arc-minute, the image forms a characteristic bow-tie shape. Visible light is not suitable for obtaining HPD and effective area, but it is useful for determining the focal length and establishing the alignment between primary and secondary quadrants.

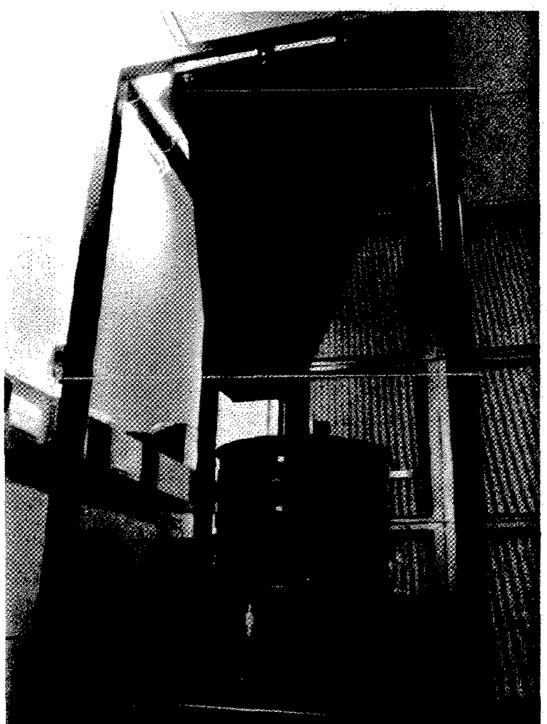

Figure 9 – Vertical Optical Facility

Focal length is adjusted by tilting the primary relative to the secondary. This is a very critical alignment as the focal point will shift about 1.7 millimeters for every arc-second of tilt. A 2.5 micron (.0001") shim between the hub flanges of the primary and secondary housings will shift the focal point about 5 millimeters. The requirement for the accuracy of the focal length is +/-5 millimeters from the nominal 5.600 meters, so the shims must be quite accurately measured and placed. Three shim locations are used, two on the outer rim and one on the hub. Lateral alignment between primary and secondary is accomplished by nudging the primary quadrant tenths of millimeters within the extent of the clearance in the holes until the maximum flux is obtained on the detector.

Tightening screws to secure the primary and secondary quadrants together causes elastic deformations on the micron level which disturb the alignment. At the micron level no machined parts are ever perfectly flat and two mating flanges are never perfectly coplanar, so there are places where small gaps are present. When the gaps are closed by the compression forces from the screws, small tilts between primary and secondary quadrants occur. To overcome this problem, liquid shims are used around the screw holes. Epoxy is applied in a ring around each fastener hole and the quadrants are mated together and the fasteners installed finger tight around the liquid shim holes and fully preloaded around the three metal shimmed holes. The epoxy flows into the gaps forming a kind of gasket seal. After the epoxy cures, the screws are torqued up and bear against the hardened epoxy. Distortion of the flanges is virtually eliminated and optical alignment is preserved.

After a quadrant pair is aligned in visible light and all the fasteners are properly preloaded using the liquid shim technique, the quadrant pair is taken to the NASA Goddard X-ray beamline where it is installed into a vacuum chamber. The quadrant pair is mounted on a stand with its optical axis oriented horizontally. The beamline operates at 4.5 keV and has a beam diameter of approximately 30 cm which illuminates most of the quadrant. This capability is sufficient for preliminary verification purposes. Using a CCD imager at the focal point, the HPD error of the mirror quadrant can be determined.

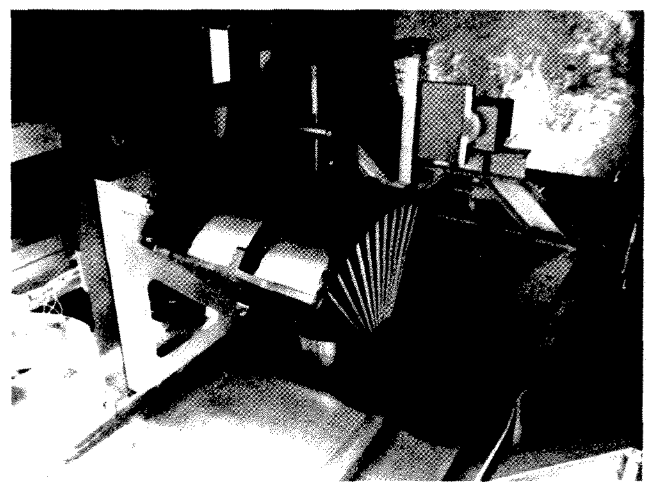

Figure 10 - An aligned quadrant pair in the Goddard X-ray facility being prepared for testing.

To complete the mirror assembly, a total of four quadrant pairs are assembled, aligned, and characterized independently. Then all four quadrant pairs are placed onto inner and outer (hub and rim) integration rings and connected together via splice plates on the rim and hub flanges. Alignment between quadrants is limited to slight lateral shifting and tilting. Initial alignment takes place in the visible light facility. The quadrants are nudged into place, shims are installed as necessary, and the hub and rim splice plate fasteners are loosened and tightened until the four images are co-aligned. Liquid shims of epoxy are installed in several points between neighboring quadrant pairs. After the epoxy cures the fasteners are given a final torque. The mounting feet are installed and the SXT is taken to the X-ray beamline to complete the optical characterization.

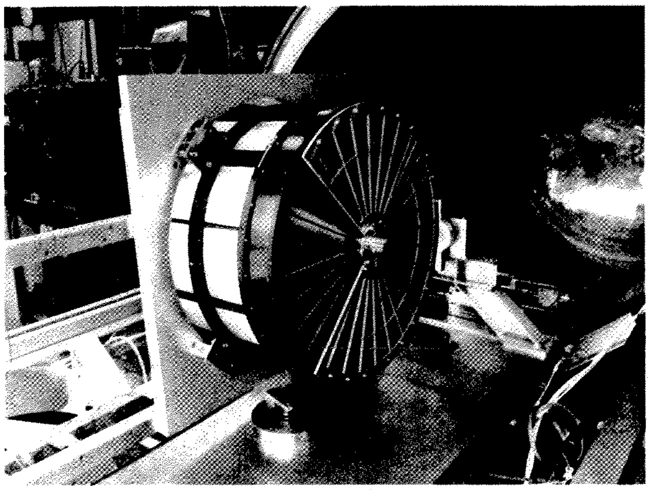

Figure 11 - Engineering Model SXT installed in the X-ray facility vacuum chamber

Spacecraft Interface and Mounting Feet

The interface to the spacecraft is a simple arrangement of four titanium brackets, or feet. The four pads of the feet must be coplanar within 50 microns and the bolt holes must have a position tolerance of about 150 microns. During integration with the spacecraft, the four feet of the mirror are set down onto the optical bench. If there is any gap between the ring and the feet, then when the mounting bolts are installed a small but significant bending may occur in the housing which will distort the SXT. The focal length could shift or some of the mirrors could become misaligned and the HPD could be degraded. Shifts on the order of a few microns can cause significant degradation in optical performance.

The mounting feet are also installed onto the housings so that they cannot induce any distortion. A 10 cm tall aluminum ring that is very flat and stiff is used as an assembly fixture to properly position the mounting feet and assist with drilling their interface holes onto the SXT. On its very flat top surface, a drill template jig was used to locate and drill the mounting holes simulating and precisely matching the interface to the spacecraft optical bench. The mounting feet are screwed to the assembly ring, and the assembly ring is placed on a granite surface plate. A small granite plate is placed at its center.

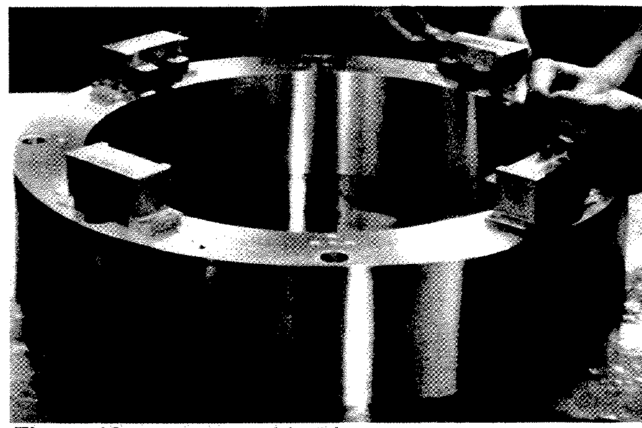

Figure 12 - SXT Assembly Ring

The SXT is brought in and lowered down onto the small block so that it rests on its inner alignment ring. Shims are installed under the aluminum ring to raise it up just enough to create a gap of about 0.1-0.3 mm between mounting feet and SXT housings. Shims fill in the gaps between the housings and the mating surface of the feet, and the mounting foot interface holes are drilled into the SXT housings via another drill template jig. The holes are drilled as a slip-fit to the housing to ensure that the SXT cannot shift alignment during launch. The SXT is lifted slightly and liquid shims are applied around each bolt hole location, and then the SXT is lowered back down, and the mounting bolts between housing and feet are installed. That completes the installation of the mounting feet to the SXT housings.

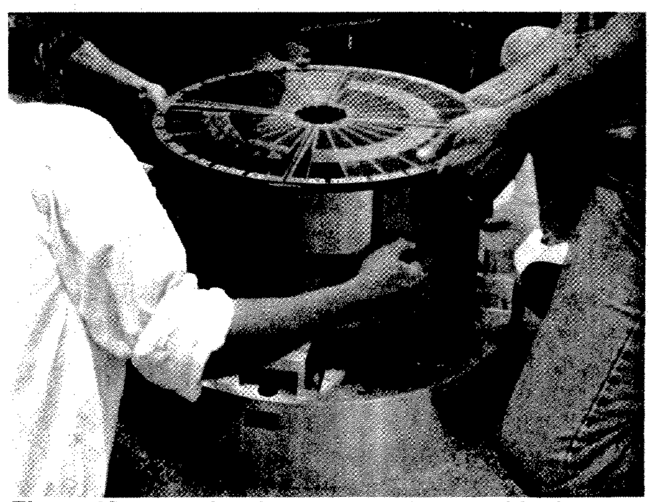

Figure 13 - Lowering the SXT onto the assembly ring.

5. ENGINEERING MODEL SXT TESTING

A full-scale engineering model (EM) SXT was built to be a pathfinder for several new aspects of the mirror design. These new aspects include:

- Bonding mirror foils to the positioning bars
- Reducing number of positioning bars from 13 to 7

- Locating mounting feet at the midplane between primary and secondary quadrants. Earlier mirrors were mounted at the aft end.
- Reducing foil epoxy replication layer thickness from 25 microns to 12 microns
- Increasing the number of forming mandrels from 20 to 71.

Due to resource constraints, only one of the four quadrants was fully populated with X-ray mirror foils. The other three quadrant pairs had mass simulators installed. The mass simulators were designed so that several properties including mass, center of gravity, and important vibration modes are the same as the flight mirror assembly. The mass of the EM SXT including pre-collimator and thermal shield was 42 kg.

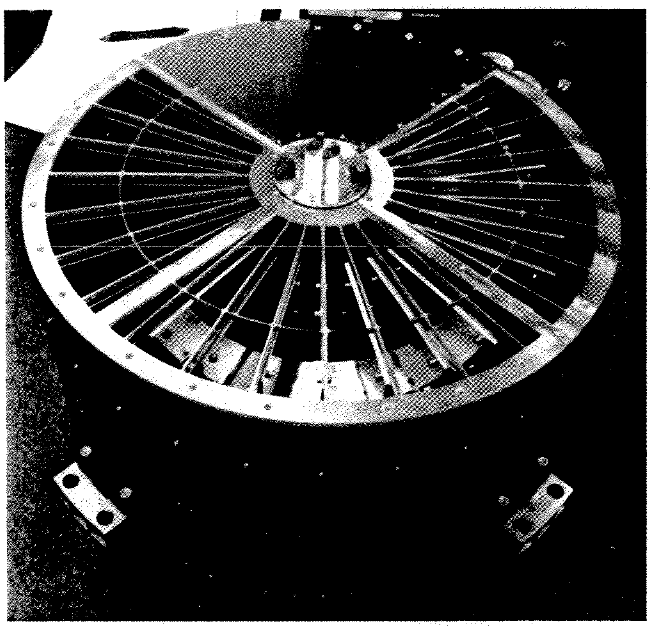

Figure 14 - Astro-H Engineering Model SXT.

A stray light pre-collimator and thermal shield was installed on top of the mirror to complete the assembly. Only one quadrant was fully populated with the vanes necessary for the thermal shield. The other three were mass simulators. A visitor to the EM SXT might be surprised to see that the thermal shield is not positioned over the populated mirror foils but clocked 90 degrees around. The reason is that the thermal shield was installed as a fit check and for vibration testing, and not for X-ray testing at this stage. It was more important to be able to see and inspect the populated mirror quadrant.

The fully assembled EM SXT was taken to the NASA Goddard X-ray facility and given a pre-test baseline of its optical performance. The measured HPD error was about 65 arc-seconds. Its performance is shown in Figure 15 compared to the ASCA and Suzaku mirrors.

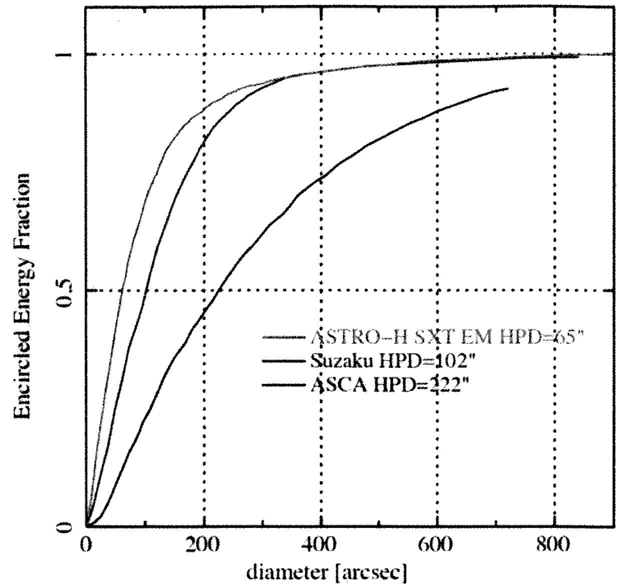

Figure 15: EM SXT compared to previous flight mirrors

The focal length was found to be about 50mm off nominal, indicating that the populated primary quadrant had become tilted from the secondary by about 30 arc-seconds during the assembly of the other mass simulator quadrants. After a little investigative work, this was easily remedied. The shim between the inner ring and the inner rim of the quadrants was not the proper thickness, being off by about 25 microns (.001"). After replacing the improper shim with one of the proper thickness, the focal length returned to its nominal 5.600 meters.

The SXT was vibration tested at NASA GSFC. It was subjected to sine vibration from 5-100 Hz at 10 G's, sine burst of 20 G's, and a standard random vibration spectrum of about 10 G-rms. Notching was used at several frequencies to avoid overtesting. After vibration testing, the EM SXT was taken back to the X-ray facility. The optical performance and focal length were found to be identical to the pre-test results, indicating that the SXT design is able to maintain alignment through the launch environment.

The EM SXT was disassembled into quadrants and the populated EM quadrant was readied for thermal performance testing. Heaters were installed on the quadrant and a sensitivity study was performed in the Goddard X-ray facility. Thermal gradients were applied between the inner hub and outer ring of the quadrant to characterize how thermal expansion causes a degradation of HPD error. The test showed that a gradient of 2 degrees Celsius between inner and outer diameters degrades the HPD error from 65 to 73 arc-seconds. The degradation primarily comes from tilts between primary and secondary mirrors caused by thermal expansion of the positioning bars as well as the housing and the mirrors themselves.

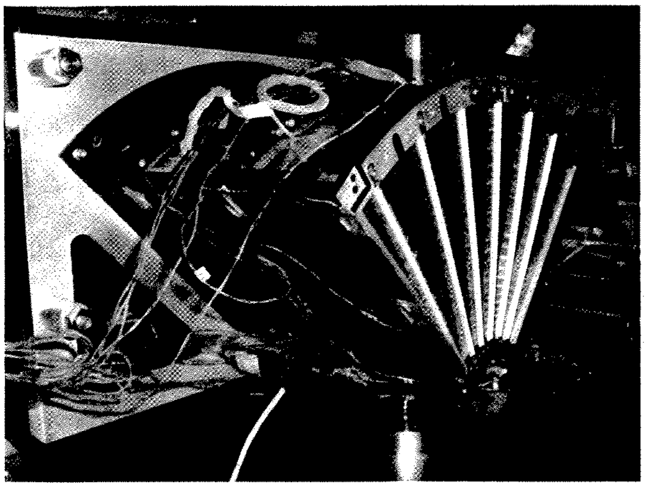

Figure 16 - EM SXT mirror quadrant pair in thermal testing in the X-ray facility.

Another thermal test was performed to determine the effect of bulk temperature increases between 5C and 35C in increments of 5 degrees. As shown in Figure 16 below, bulk temperature changes caused less than 10 arc seconds of HPD error. The SXT was not very sensitive to bulk temperature changes because all of its components are made of aluminum and so there is not much differential thermal expansion.

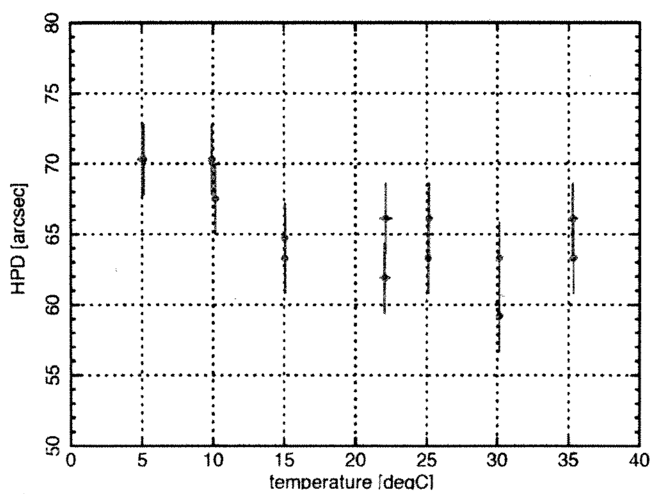

Figure 17: HPD error vs. Bulk Temperature Change

This information was given to the thermal analysis group to help them develop a heater scheme to control the SXT temperatures appropriately.

In October 2011, the EM SXT was shipped to Japan to serve as a fit check unit to the spacecraft and to be more fully characterized in a scanning X-ray beam. Pending successful results in Japan, the flight SXT mirrors will be fabricated, assembled, and tested in the same fashion as the EM.

6. SUMMARY

The Astro-H SXT mirror represents a major improvement in performance over previous foil X-ray mirrors flown in space. Design improvements and testing with the SXT engineering model have helped the team develop the process for assembly, alignment, and testing of the flight SXT. The team is looking forward to the launch in 2014!

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BIOGRAPHY

David Robinson is currently the Mechanical Systems engineer of the Astro-H project at the NASA Goddard Space Flight Center. He started his career with NASA Glenn Research Center in 1990 working on the International Space Station and several microgravity fluids space experiments for the space shuttle and the Russian Mir space station. While at Goddard, he has worked on JWST, Swift, Solar Dynamics Observatory, the TIRS instrument on LDCM, the International X-ray Observatory and many proposals along the way. He received a B.S in Aerospace Engineering from the University of Virginia, an M.S. in Mechanical engineering at Cleveland State University, and an M.S. in Space Studies at the International Space University in Strasbourg, France.

Dr. Takashi Okajima is a Research Astrophysicist at NASA's Goddard Space Flight Center, currently working on the ASTRO-H project as a SXT instrument scientist. He started his career at NASA Goddard as a postdoc of Japan Society for the Promotion of Science in 2002 working on developments of a depth-graded multilayer hard X-ray mirror and a CdZnTe hard X-ray detector for balloon-borne experiment. While at Goddard, he has worked on the Suzaku X-ray telescopes, the GEMS X-ray telescopes as well as study of active galactic nuclei and clusters of galaxies. He received a Ph.D. in Astrophysics from Nagoya University in Japan.