Development of segmented x-ray mirrors for Constellation-X

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ABSTRACT

We describe recent progress toward producing a segmented mirror that meets the mass and angular resolution requirements for the Constellation-X Spectroscopy X-ray Telescope (SXT). While the segmented approach has its heritage in conical thin foil X-ray mirrors pioneered at GSFC, the Constellation-X implementation introduces innovations in nearly all components. The baseline configuration uses thermally formed glass for reflector substrates; thermally formed Be is being investigated as an option. Alignment is performed using etched Si microstructures that locate reflectors to submicron accuracy. The only aspect preserved from previous mirrors is epoxy replication of the X-ray reflecting surface. Thus far, all developments have been at the component level. Nonetheless, we have made substantial progress toward meeting the Constellation-X SXT angular resolution goal.

Keywords: High throughput X-ray optics, grazing incidence mirrors, Constellation-X

1. INTRODUCTION

The 1.6 m diameter Spectroscopy X-ray Telescope (SXT) represents a significant technical challenge for the Constellation-X program. Its required combination of moderate spatial resolution (< 15" half power diameter, or HPD) and low mass (< 400 kg) require significant development of either a full shell[1] or a segmented approach.[2] In this paper, we describe our recent progress toward developing a segmented mirror that meets the SXT specifications.

Segmented mirrors offer several advantages over full shells. By virtue of its modular nature, a segmented design is more conducive to mass production. Modules within a telescope unit can be interchanged without significant complication, in the event a module is underperforming or damaged. There is no need to manufacture mandrels with full surfaces of revolution; this could be critically important as there currently is no facility capable of producing the largest diameter mandrels needed for Constellation-X. Finally, each reflector is physically smaller, and therefore can be thinner and still maintain its structural integrity. Though more support structure would be needed to assemble a mirror, the overall mass would be less than a mirror made of full shells.

2. HERITAGE

The X-ray group at GSFC has pioneered the use of thin, lightweight, segmented X-ray mirrors. Our efforts until recently have emphasized collecting area and low cost at the expense of angular resolution. Thus we have built mirrors with a conical approximation to the true paraboloid/hyperboloid (Wolter I) shape needed to form a perfect image. The fundamental innovation involves application of a microscopically smooth surface onto a thin substrate, initially (for BBXRT and ASCA) by controlled dipping into acrylic, and more recently (for ASTRO-E) by epoxy replication. The angular resolution of the conical mirrors we have delivered for flight have not been limited by the intrinsic resolution of the conical approximation (typically 10-20"), but by figure and alignment inaccuracies. Segmentation into quadrants facilitates handling and mass production.

Constructing a state-of-the-art segmented X-ray mirror entails the following steps (refs. 3 & 4):

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1. Forming a reflector substrate to approximately the correct shape.
2. Preparing a mandrel for replication by sputtering a thin layer of gold or platinum onto its surface.
3. Epoxy replication, by coating the substrate and mandrel simultaneously with a precise thickness of epoxy, bringing them into contact under vacuum, allowing the epoxy to cure, and separating the finished reflector from the mandrel.
4. Installing and aligning replicated reflectors in their housing.
5. Coaligning the segments comprising a complete mirror.

This straightforward approach yielded 40 cm diameter mirrors with angular resolution approaching 1.5' for ASTRO-E. Innovations being introduced for Constellation-X are expected to improve the resolution to 15" for a meter class mirror. While the steps are preserved (i.e., forming, mandrel preparation, replication, and mounting), virtually every component in the Constellation X segmented design is different from that used for ASTRO-E and its predcessor mirrors. We will use glass or Be instead of Al as substrate material, figured and polished quartz or metal replication mandrels instead of extruded pyrex cylinders, an alignment mechanism based on etched Si microstructures instead of precision machined aluminum alignment bars, and a Wolter I optical design instead of a conical approximation. These differences are tabulated in Table 1. In the sections below, we describe the new approach we are taking for each component.

Table 1
Comparison between ASTRO-E and Constellation-X components

Component	ASTRO-E	Constellation-X
Optical design	Conical	Wolter I
Mandrel	Extruded Pyrex pipe	Figured, polished metal or quartz mandrels
Substrate	Heat formed Al alloy	Thermally formed glass or Be
Surface deposition	Epoxy replication	Epoxy replication
Alignment bars	EDM cut Al	Etched Si
Alignment technique	Gang alignment by alignment bar translation	Separate mounting, alignment fixtures; position using Si bars and epoxy to structure

3. SUBSTRATES

Aluminum has been an easy substrate material with which to work. It is inexpensive, available in a variety of thicknesses and as alloys with a range of stiffness, and easy to form and cut into approximately the right shape. Unfortunately, global figure errors, especially edge distortions, both axial and azimuthal, that go unnoticed in an arc minute mirror and are difficult to avoid producing, dominate the figure, making the use of Al for a few arc second mirror problematic. We have performed an extensive search for alternative materials that form with fewer figure errors. We have found two promising candidates, glass and beryllium. Both are shaped by thermal forming.

Thin glass sheets manufactured by Schott for flat screen displays (Desag AF45 and D263) are both strong and exceedingly smooth on scales below a millimeter. The rms microroughness of the as-delivered stock is a few Ångstrom. The use of AF45 as an X-ray mirror substrate was pioneered by the group at Columbia University[5,6]. Our approach differs from theirs in two key respects, driven by our more stringent angular resolution requirement. The Columbia group adopted concave cylindrical mandrels for slumping. While this approach preserves the microscopically smooth surface of the Desag glass, it has the potential of leaving the axial and azimuthal edges curled, thereby degrading the overall figure. They subsequently stress the glass into an approximately conical shape as part of the mounting process, an approach that minimizes the influence of the edge effects on the overall performance. As our goal is to produce substrates whose global unstressed form is as close as possible to the ideal form, we need to accurately form the glass azimuthally and axially. With the availability of epoxy replication to restore a microscopically smooth surface, we can trade the substrate surface quality for a more accurate figure (as long as mid-frequency errors remain smaller than a few microns). We therefore form the glass using a accurately figured convex conical mandrel, adding a small amount of uniform pressure to induce the glass to conform to the mandrel shape. We subserquently produce the reflecting surface using epoxy replication. A less important difference is that we use Desag D263, which has a lower softening temperature than AF45. Figure 1 shows a formin mandrel in our laboratory oven; Figure 2 shows a finished glass segment.

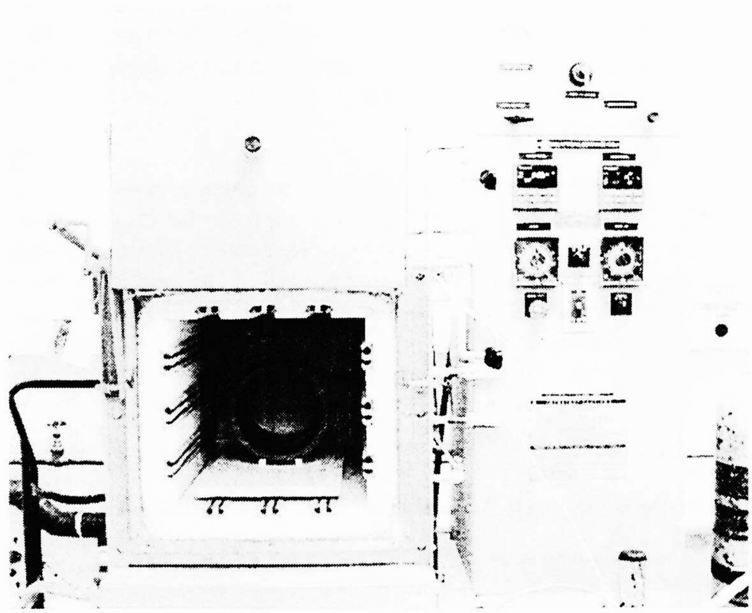

Figure 1: Glass forming mandrel in laboratory oven. Substrate is formed over the outside of the mandrel, which has been precisely figured to a conical shape, approximating the final Wolter element.

Our experiments thus far have concentrated on conical reflectors with $\sim$10 cm radius of curvature. For pieces this size, we can routinely produce replicated reflectors with better than 10" overall figure. Some fraction of the figure error arises from the replication, which up to now has been performed using an ASTRO-E cylindrical mandrel. The shape mismatch (conical substrate on cylindrical mandrel) and the macroscopically imperfect mandrel surface combine to dominate the overall figure error. We will quantify the true contribution of the substate later this year, when we replicate using a figured cylindrical mandrel.

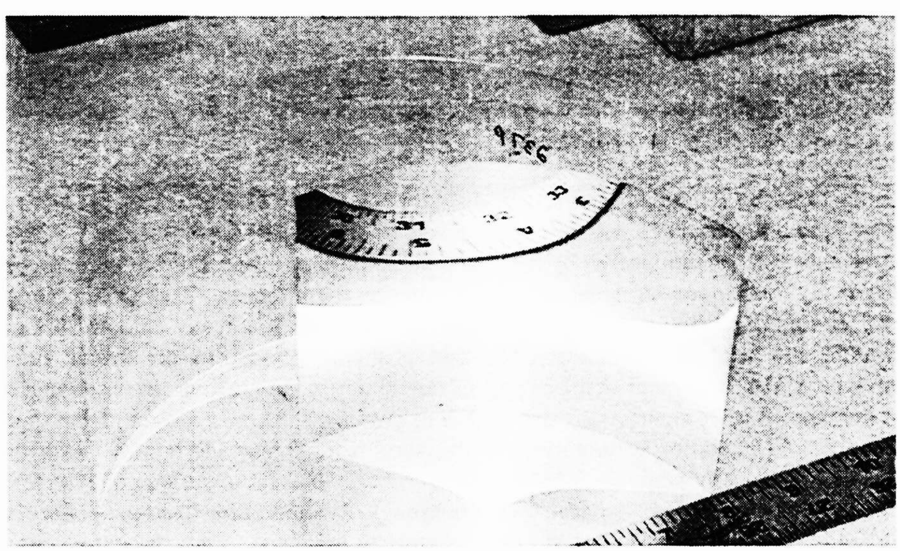

Figure 2: Thermally formed glass substrates. Examples of uncoated substrate and replicated reflector (substrate with gold surface epoxy replicated) are shown.

Further development of the glass process entails overcoming two formidable challenges: scaling our production to sizes appropriate for Constellation X, approximately 30 cm on a side; and determining how to introduce axial curvature into the final reflector. The options available are to produce axially curved substrates or introduce curvature in the epoxy layer. This latter approach is made feasible by the fact that the largest sagittal depth of a Constellation X mirror is on the order of 20 μm. Experiments in both these crucial areas will commence later this spring.

In parallel with the glass work we are investigating the use of thin Be sheets. The Be is also thermally formed, by being placed between two precisely shaped mandrels and squeezed into shape at high temperature. The resulting piece conforms to the shape of the mandrel to within 25 μm. The use of the thicker, stiffer Be facilitates a heavier epoxy coating, up to 100 μm, before concerns about deformations arise. We have made Be substrates that subtend a 30 degree arc of a 0.5 m diameter mirror. An example is shown in Figure 3. We are assembling the infrastructure to replicate onto two of these the surface of a Wolter I mandrel.

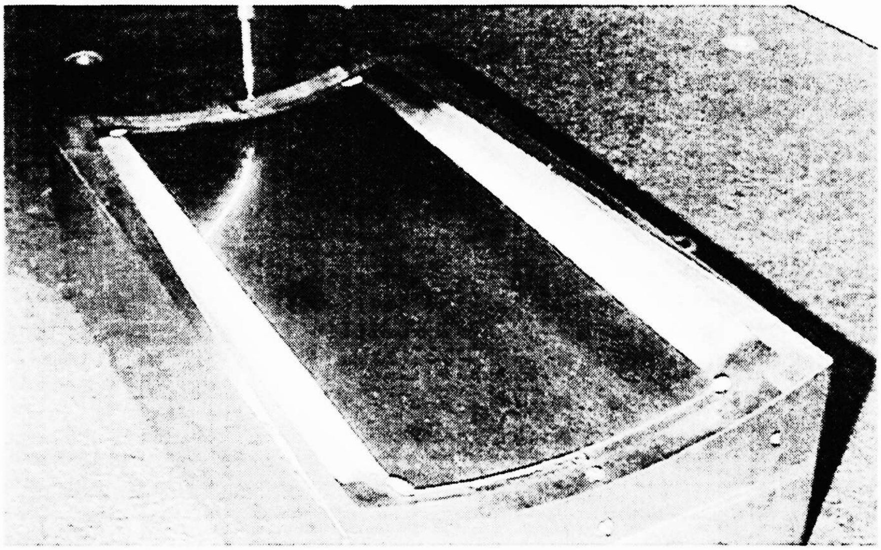

Figure 3: Be substrate resting in outer mandrel. The thickness of the Be is 500 μm; its surface is formed accurately to within 25 μm.

4. MANDRELS

Whether the Constellation X mirror consists of full shells or segments, accurately figured mandrels are required. The overall figure of each must be accurate to 5 arc seconds or better.[1,2] As long as it is possible to fabricate complete surfaces of revolution, the same mandrel can be used for either shells or segments. Mandrel development has thus far proceeded largely independently between the shell and segment efforts, primarily because the development paths had needs for different kinds of mandrels. The shell effort has used exclusively Wolter-type mandrels and is now concentrating on 50 cm mirrors. The segmented effort, in contrast, is building from its experience with conical mirrors. The initial precision mandrels are conical with approximate diameter of 20 cm. This allows direct comparison between the products of ASTRO-E fabrication techniques and the new ones being developed for Constellation X. Once the degree of improvement of using precise mandrels for conical mirrors is demonstrated, we will shift to replicating segments off identical Wolter I mandrels.

5. REPLICATION

Epoxy replication is the single remaining component in common between the previous generation segmented mirrors and Constellation X. It is a proven technique for low cost production (and mass production) of low scatter X-ray reflectors. Nevertheless, there are issues that must be resolved before we can confidently produce a mirror that meets the requirements.

The thickness of the epoxy layer is one issue. Every epoxy undergoes some amount of shrinkage as it cures. The shrinkage places mechanical stress on the substrate. The degree of stress is strongly related to the epoxy layer thickness, while the resistance of the substrate to deformation under its stress it related to its stiffness and thus its thickness. Thus the allowed epoxy thickness is intimately related to the composition and thickness of the substrate.

We have measured the stress introduced by the cure of the epoxy, by measuring the deformation of an optical flat introduced by a uniform epoxy layer of known thickness. The total stress is approximately 5 percent of that expected if one assumes that the epoxy shrinks homeogeneously as it cures. Moreover, the stress appears only in the late stages of the cure cycle. This implies that during most of the cure cycle, the epoxy flows to compensate for shrinkage-induced stress. Calculations based on these measurements indicate that the maximum allowable epoxy thickness for 300 μm glass is larger than the 25μm we are currently applying. For the 500 μm Be it is larger than 125 μm.

A second potential issue we have just begun to confront is the uniformity of the epoxy surface as it cures. This was not a problem in the previous generation of mirrors, but it becomes increasingly important as smaller figure error is tolerated or as thinner a epoxy layer is applied. It can become a major issue if we expect to introduce the axial curvature exclusively in the epoxy layer. We currently apply the epoxy to substrate and mandrel via computer controlled spraying. The epoxy is diluted with toluene to facilitate spraying. We anticipate that more precise control over the spraying (e.g., spray pattern and velocity; degree of dilution), nozzle can overcome any nonuniformities that are introduced.

5. HOUSINGS

A fundamental advantage of segmentation is that each reflector is small and easily manipulated. We have preserved that in the Constellation X design. Previous mirrors were segmented into quadrants.[3,4] The Constellation X mirror is substantially larger, so we have divided into a larger number of segments, 12 in all. The largest substrate is approximately 30 cm on a side. A sketch of the baseline design is shown in Figure 4.

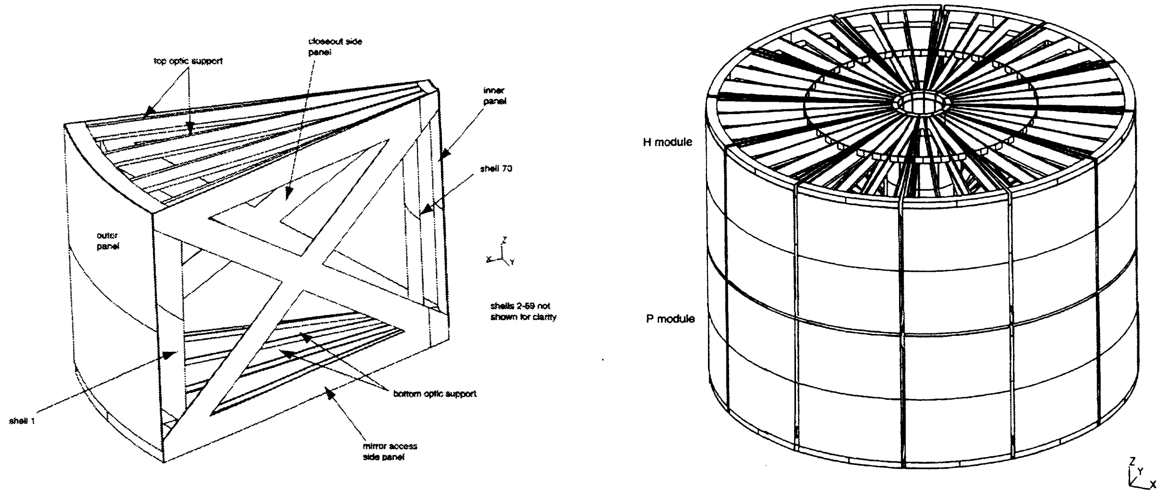

Figure 4: Schematic of housing for segmented Constellation-X SXT mirror. Left: Each module subtends a 30-degree arc. Each reflection stage is assembled separately. Four mounting bars at top and bottom keep reflectors fixed. The inner and outermost reflectors are shown installed in housing. All precision alignment derives from a removeable fixture containing the Si microstructures. Right: Fully assembled housing.

The most substantial departure from previous generation segmented mirrors is in mounting and alignment. For the ASTRO-E and other previous mirrors, mounting and alignment were performed using the same component. The foil reflectors were installed into a quadrant housing, each of which had 13 pairs of toothed bars, top and bottom, to hold the reflectors in place. The slots in the bars were machined via EDM. They were positioned precisely with respect to one another to a tolerance of 2.5 μm, but each slot was oversized by approximately 20 μm to permit sliding a foil through without binding. Once all reflectors were installed, they were gang-aligned by radial translation of the bars. Thus the overall reflector quality was dictated by the slope errors introduced by the clearance in the slots. Measurements of an ASTRO-E reflector show that half the blur is introduced in this way.

For Constellation X we are decoupling the mounting and the alignment. Like ASTRO-E, the mounting bars will be machined with clearance for allowing assembly. But unlike ASTRO-E they will be fixed, and serve only as a surface for an epoxy bond. Accuracy will be introduced using a removeable alignment apparatus. The heart of this apparatus will consist of two sets of etched Si alignment bars. One set provides fixed reference points for the surface of each reflector. The second set slides radially applying pressure against the back of reflector to force it up against the accurate references. Figure 5 shows examples of the two types of bars; Figure 6 shows the basic mounting scheme.

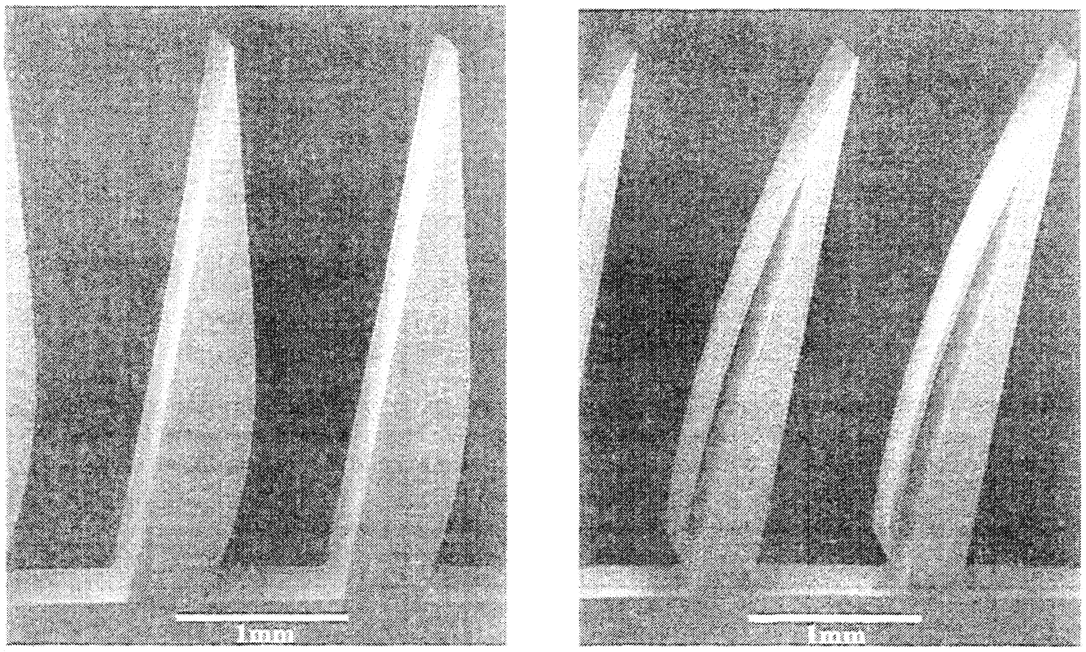

Figure 5: Photomicrographs of prototype etched Si alignment bars. On left is the bar containing the rigid reference surfaces. On the right is the bar containing the flexible surfaces with integral springs. A reflector is placed between a reference surface and a spring, and then aligned by pushing the reflector against the reference surface by moving the bar with flexible surfaces.

We have produced several sets of alignment bars, and in so doing, have refined the production process. The most recently produced set has been measured using a microscope on a precison stage. The alignment surfaces are located relative to one another to better than the 2.5 μm measurement limit of the device. We have also conducted an initial set experiments designed to determine the alignment accuracy these bars can provide. We have built a small test box with alignment bars mounted top and bottom, shown in Figure 7. The side of the box against which the alignment bars rest is a diamond-turned reference flat, whose surface is flat to 0.1 μm. In the initial test, a set of thick glass flat reflectors are mounted arc second, well within the alignment error budget.

Future tests using this fixture will repeat the parallelism measurements using thin glass plates. We also plan a full battery of mechanical tests to determine the amount of friction encountered when attempting to slide reflectors into position, the degree of wear on the alignment bars, and whether the general behavior of the bars is consistent with the predictions of our finite element analysis. Once we have developed confidence in this approach and understand its limitations, we will constuct a small flight prototype housing.

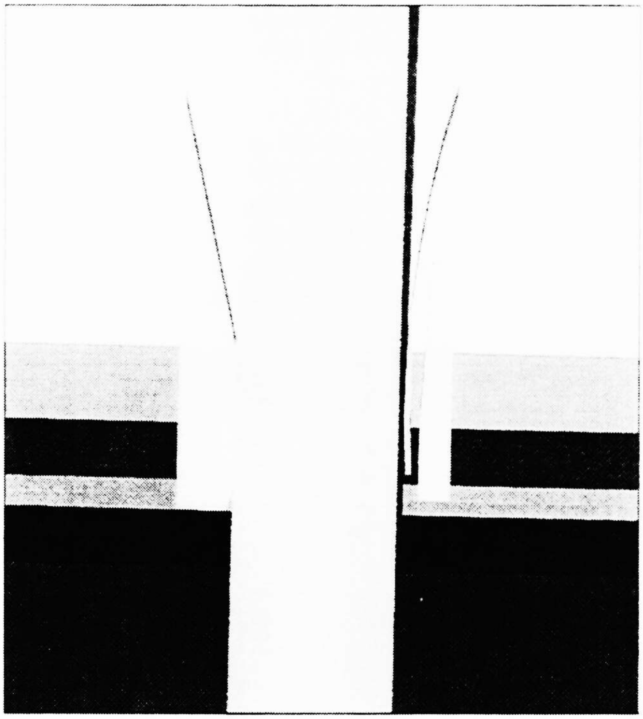

Figure 6: Schematic of alignment approach for segmented mirrors. The mirrors are held by a set of bars, front and back. Etched Si structures are used to accurately locate reflector surfaces. For each reflector, a group of bars fixed in an alignment structure locate the reflecting surface (left side of reflector) with an accuracy of less than a micron. The reflector is brought into contact with the reference surfaces by a set of bars with springs (right side of reflector). Once the reflector is positioned, it is epoxied to a less precisely machined mounting bar, and the alignment bars are removed.

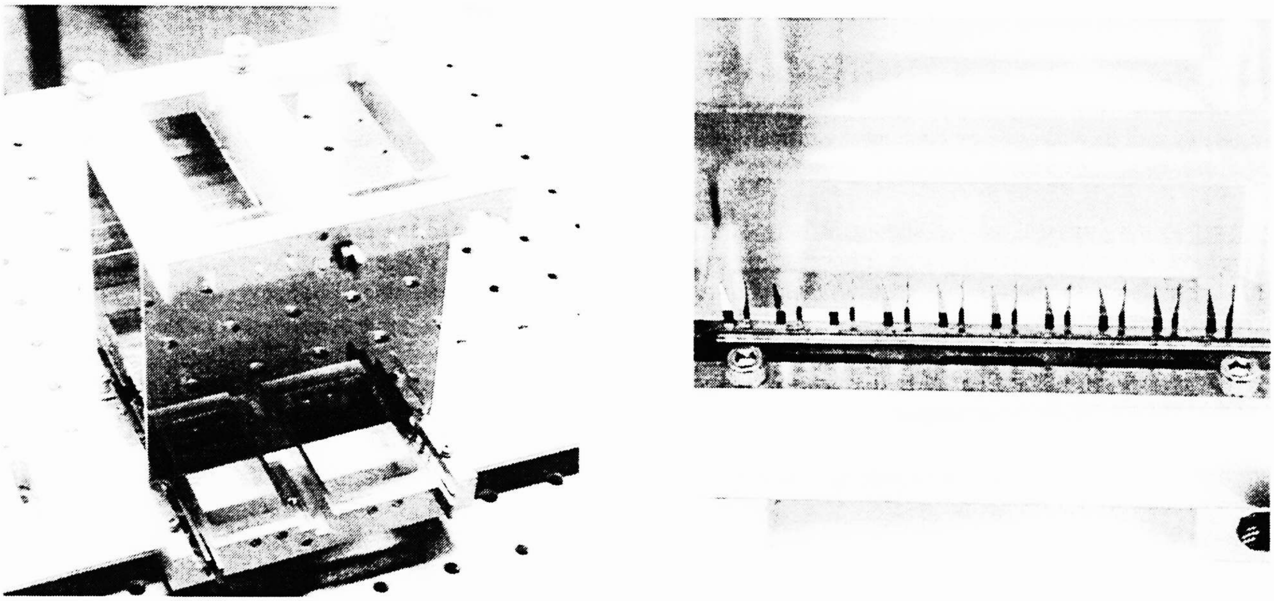

Figure 7: Fixture for testing accuracy of alignment approach using Si microstructures, using flat mirrors. Left: Assembled fixture, with flat mirror installed. Right: reference combs and spring combs in mount. Location of reference comb structure is fixed against a reference plate; spring combs slide as a unit to force reflector against reference surfaces.

6. CURRENT STATUS AND FUTURE PLANS

We are still developing the individual components and processes that will be incorporated into a segmented mirror for Constellation X: the substrates, the mandrels, the housings and the alignment mechanism. The significant progress being made indicates that the Constellation X requirement can be met. In Table 2 we summarize our status in the perspective of the best mirror system we have built thus far (ASTRO-E) and the Constellation X requirements. Significant improvement has been made on all fronts. Three things should be noted in particular. First, the error estimates for our current status are conservative, especially as regards alignment. Second, the overall error for the current status is based on component testing only, and thus is not a fair comparison to the system level value for ASTRO-E. Third, the current status still includes a substantial error contribution from the conical approximation. This term will disappear within the next few months as we perform our first replication experiments using Wolter mandrels.

Over the next few months we intend to address a number of key issues, some of which have already been mentioned. These include: using accurate mandrels, demonstrating that it is possible to make conical reflectors that approach the intrinsic limit of the conical approximation; demonstrating that it is possible to replicate accurate Wolter I reflectors using glass and/or Be substrates; demonstrating that large replicated segments can be produced; determining the ultimate accuracy of the alignment approach in more realistic circumstances; and further characterization of the glass forming and replication processes. Our major short term goal is to construct a small prototype segment, populate it with a few glass reflectors, replicated off high quality mandrels, and perform X-ray measurements by the end of 2001.

Table 2
Component level error budget for Constellation-X segmented mirror
(units in arc seconds)

Component	ASTRO-E (system)	Current (components)	Constellation-X Requirement	Improvement
Mandrel	30	5	5	Improved figure
Substrate	30	7	5	Stiffer material, more precise forming
Alignment	60	15	5	More precise alignment mechanism
Intrinsic	12	12	0	Curved mandrels eliminates cone approx.
Overall[1]	**90**	**23**	**11.2**	

[1]Errors are root-sum-squared together. First two terms are included twice in RSS, once for each reflection stage

ACKNOWLEDGEMENTS

The Constellation-X segmented mirror program is a collaboration involving several institutions. The GSFC X-ray group is responsible for overall coordination, leading the substrate and replication process development, and overseeing mandrel procurement. Metrology and performance analysis are carried out jointly by the GSFC X-ray group and the GSFC Optics Branch.[8] The housing and alignment procedure are being developed by the MIT Center for Space Research and the High Energy Astrophysics Division of SAO. Mechanical analysis is carried out by SAO and RJH Scientific, Inc. We acknowledge the assistance of our colleagues at Marshall Space Flight Center The Constellation-X Mission Formulation Project is managed by Ms. J. Grady of GSFC; Dr. N. White is the Constellation-X Study Scientist.

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