Progress towards Meeting the Constellation-X Performance Goals using Segmented X-ray Mirrors

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ABSTRACT

We present an overview of our recent progress toward the development of segmented X-ray mirrors for the Constellation-X mission. Our reference design incorporates thin glass reflector substrates, with axially curved X-ray reflecting surfaces applied via epoxy replication. Alignment is accomplished via a precision structure incorporating ultraprecise etched Si alignment microstructures (as described in associated papers). Recent efforts have been devoted to demonstrating that the figure of prototype small segments and the alignment process will allow us to meet the 15" half-power diameter angular resolution requirement. We discuss the status of this, of our efforts to fabricate meter-class segments, and of the developments of supporting metrological techniques. We summarize our plans for a laboratory demonstration of a prototype mirror meeting the Constellation-X angular resolution and weight requirements.

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

1. INTRODUCTION

Probably the most substantial technical challenge for the Constellation-X mission is the development of the Spectroscopy X-Ray Telescope (SXT). Meeting the required combination of low weight, large aperture (1.6 m diameter), high throughput (>7,500 cm^2 at 1 keV), and high angular resolution (<15 arc seconds half power diameter (HPD) for the system; <10 arc seconds HPD for the mirror) is formidable. While a number of promising avenues exist that might lead to meeting these requirements, substantial development is required.

Two approaches are being investigated, full shell mirrors[1,2] and segmented mirrors.[3,4] In this paper we concentrate on the segmented approach, describing the progress we have been making toward meeting the specifications.

2. OVERVIEW

Previous papers describe the heritage of the segmented design for the Constellation-X SXT,[3,4] and how our efforts have led to a significantly different approach from that used for the ASCA[5] and ASTRO-E[6] mirrors constructed by GSFC while preserving the advantages of the segmented approach and the epoxy replication that leads to microscopically smooth reflecting surfaces. The SXT as currently conceived incorporates the following elements. The optical design will be a true Wolter I paraboloid/hyperboloid, not a conical approximation. The reflector substrates will be either thermally formed glass or beryllium, with a 30 cm axial length for each reflection stage and subtending an azimuthal angle of 30 degrees. Replication will be performed off precisely figured and polished metal or glass mandrels. It is anticipated that for diameters larger than ~0.7 m these mandrels will not be complete surfaces of revolution, but arcs subtending an angle slightly larger than the segments figured onto a rectangular slab of glass or aluminum. The reflectors will be bonded into a stiff but not accurate housing. Prior to attachment, the reflectors will be accurately located using removable frames incorporating etched Si alignment structures.

Other papers in these proceedings describe the development of the Si alignment structures[7] and the overall mounting and alignment approach for segmented mirrors.[8] In this paper we concentrate on our recent progress in substrate development.

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3. SUBSTRATES

Two materials are being seriously investigated for suitability as SXT substrate: Be and glass. Below we describe the progress we have made investigating each:

3.1 Glass Substrate

The mechanical properties of glass make it an appealing material for this application. 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[9,10]. We use instead the Desag D263, which has a lower softening temperature than AF45. Additionally, instead of forming the glass using a concave mandrel, which preserves the microscopic smoothness of the glass but does not produce an optimum figure, we form the glass over a convex mandrel to approach more closely the mandrel figure at the expense of the microscopic surface. We then recover a good X-ray reflecting surface by epoxy replication.

Figure 1 shows a forming mandrel in our laboratory oven; Figure 2 shows a finished glass segment.

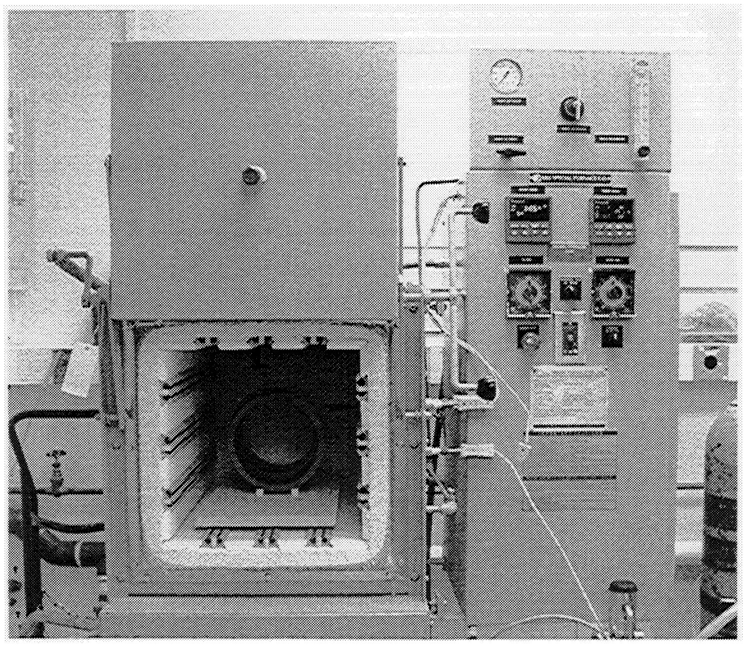

Figure 1: Glass forming mandrel in laboratory oven. Substrate is formed over the outside of the mandrel, which has been precisely figured to a conical shape, approximating the final Wolter element.

We have formed and replicated a very large number of glass substrates and performed surface metrology on many of these. We typically find that the overall figure error associated with the forming is 10 arc seconds or less. As we have generally used low quality mandrels (the ones used for ASTRO-E) for surface replication the actual optical performance is slightly worse than this. In Fig. 3, we show surface power density spectra of a mandrel and two glass replicas. Note the general correspondence of the features between two replica spectra at all frequencies, and the correspondence at high spatial frequencies between the mandrel and the replicas. Note that the mandrel whose power density spectrum is plotted is not the mandrel used to produce these replicas; for the traces shown this explains much of the difference at low spatial frequency where global figure errors dominate.

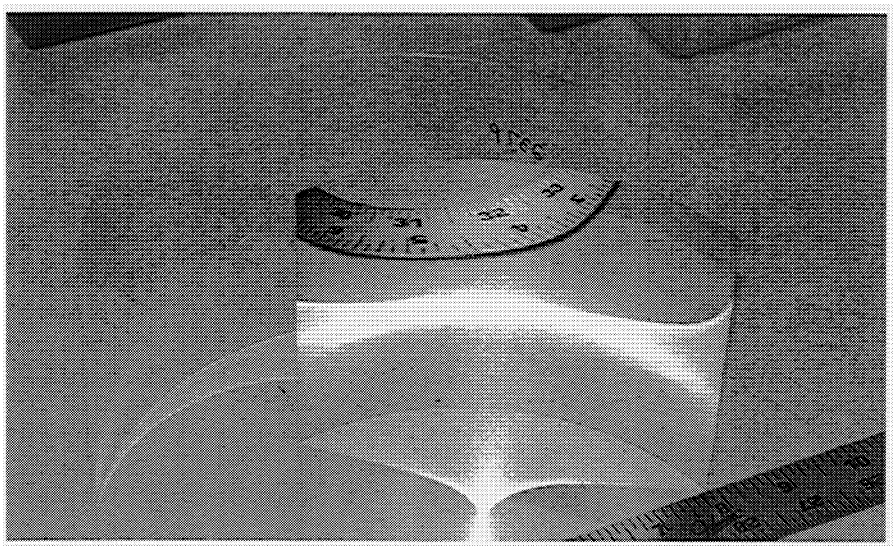

Figure 2: Thermally formed glass substrates. Examples of uncoated substrate and replicated reflector (substrate with gold surface epoxy replicated) are shown.

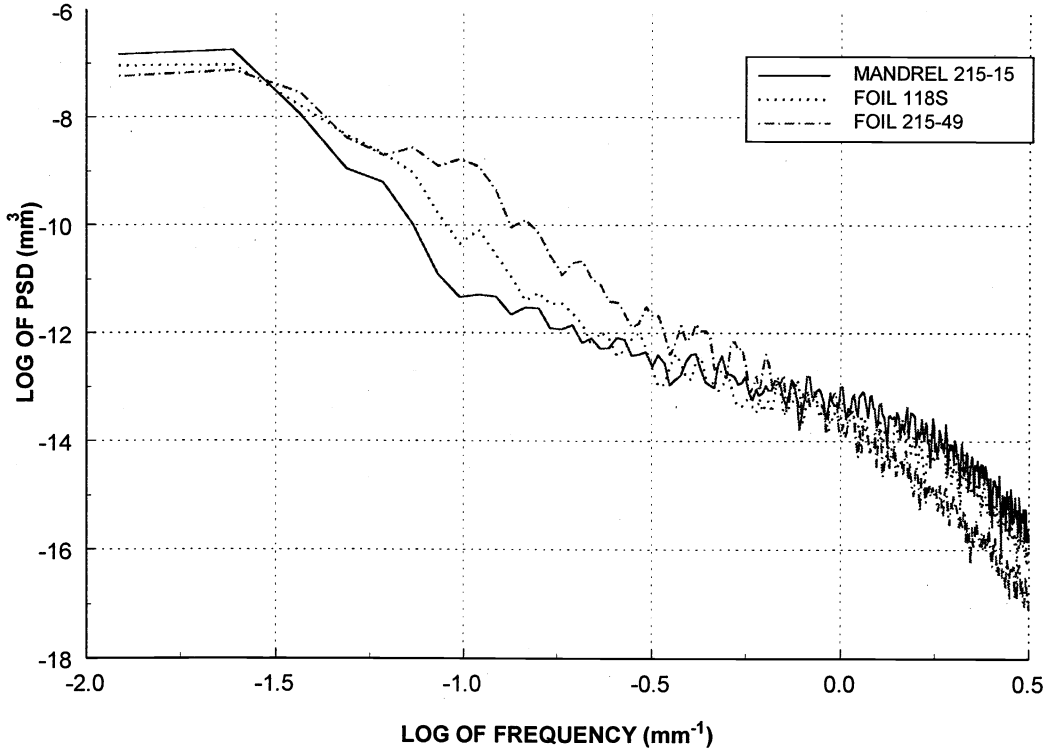

Figure 3: Power spectral density plot of cylindrical mandrel and two glass replicas. Note similarity between replica traces. Mandrel is different from that used for replication. This accounts for the differences between mandrel and replicas.

Over the past few weeks we have also been conducting extensive X-ray measurements of pairs of reflectors. A pair of reflectors is mounted on a simple four-point support mechanism, and aligned in an optical beam by adjusting the mechanical stages. The support mechanism with reflectors mounted is shown in Fig. 4. It is then transferred to our 150-foot X-ray beam line for image quality measurements. In the X-ray beam, the full surface of the primary reflector is illuminated. Thus the measured HPD represents that of the entire surface of both reflectors, not a small sector of them. Figure 5 shows the outcome of a typical measurement. The measured HPD is around 30 arc seconds. Since these are conical reflectors, the intrinsic HPD is about 12 arc seconds. Note that a substantial fraction of the figure error comes from the fact that the replication of these reflectors was performed using low quality (ASTRO-E) mandrels; misalignment and sagging of the reflectors also contributes. A ray-tracing analysis indicates that if this same measurement were performed using perfectly aligned reflectors replicated using a better mandrel, we would have measured an HPD of about 25 arc seconds. Thus the result shown is consistent with the substrates having an overall figure error of 10 arc seconds or less.

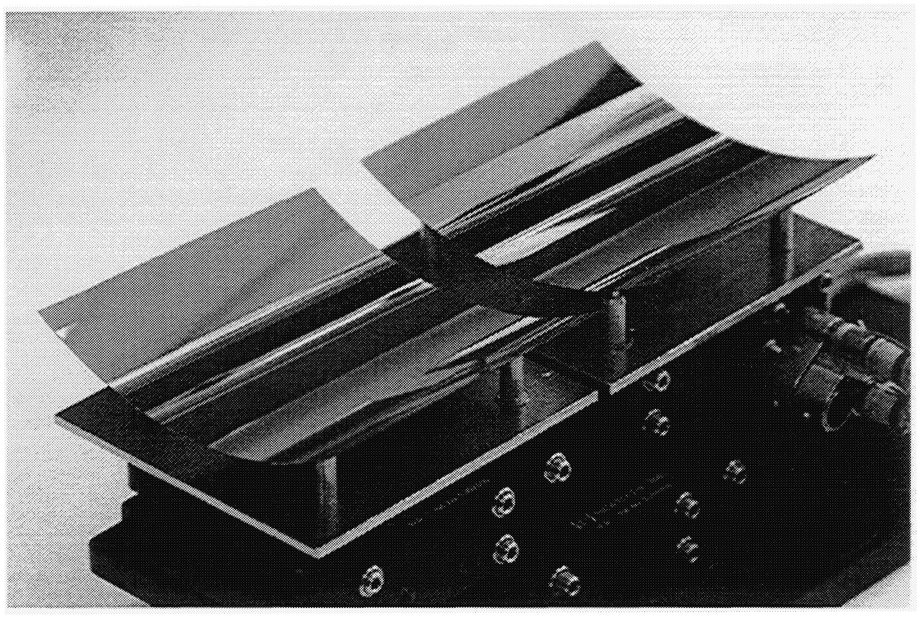

Figure 4: Glass reflectors on mounting and alignment structure for visible light and X-ray testing. Each reflector is supported at four points. The precision stages allow for multidimensional translation and rotation.

Further development of the glass process entails overcoming two formidable technical challenges. First we must scale our segment production to sizes appropriate for Constellation-X, with azimuthal sizes as large as 30 cm on a side and 30-50 cm axial lengths. This requires a substantial infrastructure investment. We must obtain access to an oven capable of maintaining uniform temperatures over a volume at least 0.5 m on a side. Such an oven has been ordered, and should be operational by the end of this year. We also need a means of attaching the large epoxy coated substrate and mandrel for replication. To avoid the expense and complication of a vacuum chamber large and versatile enough to hold any size mandrel and substrate, we have developed a portable attachment mechanism. This device attaches to the mandrel, and draws vacuum only around the surface area to which the substrate will attach. These devices are inexpensive to construct, and we would anticipate using several to accommodate the various mandrel radii of curvature. The prototype of this device is shown in Fig. 6.

The second challenge we must overcome is the introduction of axial curvature into the final reflector surface. To do this we can either produce axially curved substrates and replicate using a uniform epoxy layer, or introduce curvature in the epoxy layer over an axially straight substrate. 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 described below using Be suggest that at least the latter approach is feasible.

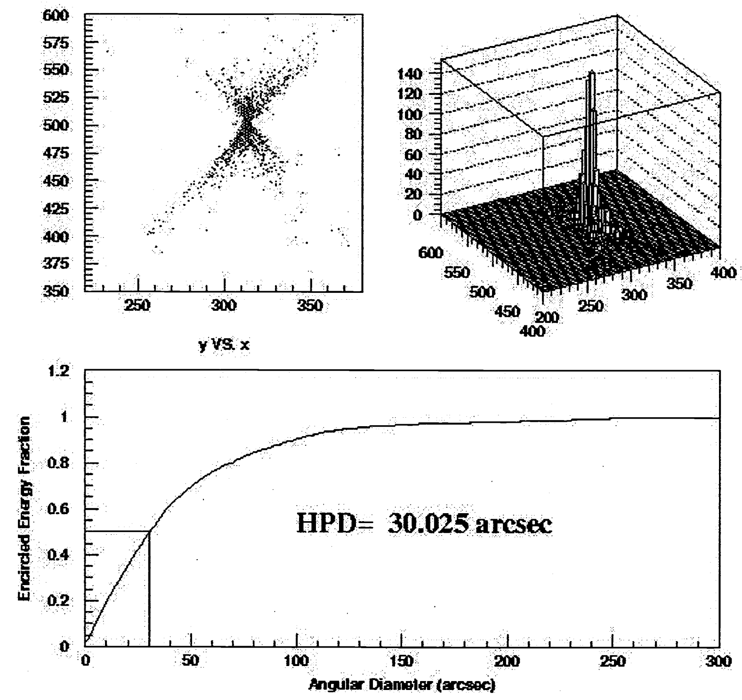

Figure 5: Result from a typical X-ray measurement of the performance of a pair of glass segments. Primary segmented is fully illuminated by the X-ray beam, and real image has been formed via two reflections. Top left: Image on CCD focal plane. Top right: Three-dimensional histogram of image, highlighting strong central peak. Bottom: Inferred encircled energy function, showing a half power diameter of 30 arc seconds.

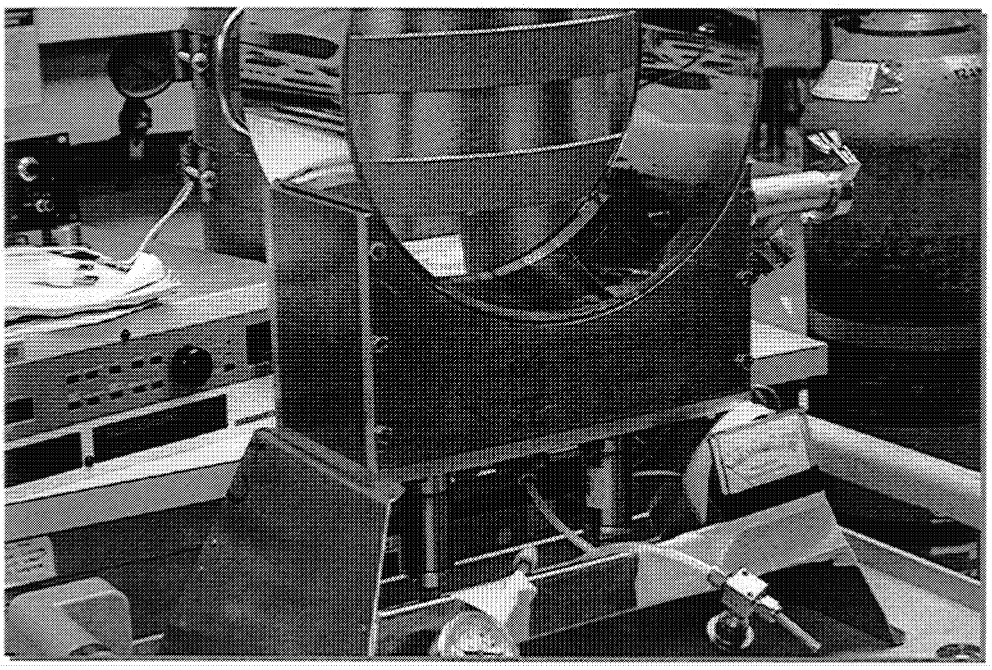

Figure 6: Portable mechanism for attaching glass substrate onto mandrel. Vacuum is drawn locally around area to which mandrel attaches. Substrate is then placed in contact with mandrel from below, using a motorized drive. Device is shown here with a 36 cm cylindrical mandrel.

3.2 Beryllium Substrates

In parallel with our investigations using glass, we are experimenting with the use of thin beryllium sheets as substrates. The beryllium is also thermally formed. In this case forming is performed by placing a flat Be sheet between a convex and a concave mandrel, and pressing it at elevated temperature. This process yields substrates that conform to the shape of the mandrel within about 25 μm. The inherently stiffer Be facilitates in principle the use of a thicker epoxy coating to better cover surface imperfections.

We have obtained and replicated two pairs of Be segments. These segments have a conical shape approximating the Wolter I surface to be replicated. They are 0.04 mm thick, 30 cm long, and are formed to subtend a 30 degree arc of a 50 cm diameter mirror. They were used to replicate the surface of a Wolter I mandrel. This mandrel was procured from Zeiss, and has been figured to have a HPD of less than 5 arc seconds.

Epoxy replication has been performed using a different approach from that used for the thin glass. The mandrel is held vertically. The paraboloid and hyperboloid segments are replicated simultaneously. Substrates are offset by a constant distance from the mandrel surface using shims. For the replications carried out thus far, the spacing was 0.005 inches. The gap between the mandrel and the substrate is sealed along three sides using epoxy. The substrates are fixed relative to each other using a rigid mounting fixture. This in principle facilitates optical and X-ray measurements of a reflector pair without the need for alignment. Epoxy is then poured into the pocket between the substrates and the mandrel, and allowed to cure. The assembly (fixture and two reflectors) is gently pried loose from the mandrel.

The first replication produced a good paraboloid, but the hyperboloid was not completely replicated, a consequence of underestimating the necessary amount of epoxy. The figure quality was not high, probably a consequence of handling. The second replication was far more successful, as shown in Figure 7. Nearly the entire surface of both reflectors was replicated.

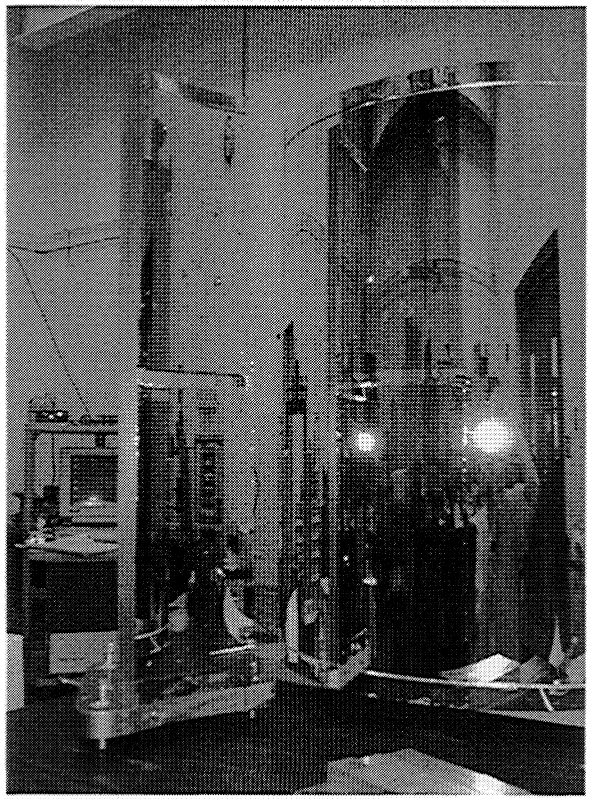

Figure 7: Outcome of replication onto Be substrates. On the left is a pair of replicated substrates, held rigidly by a mounting fixture. On the right is a 50 cm Wolter I mandrel, fabricated by Zeiss.

Many of the flaws were deliberately introduced, regions where the mandrel did not appear to have gold. Only one appreciably sized region did not lift successfully off the mandrel.

Metrology was performed on the two segments using the Vertical Long Trace Profilometer at Marshall Space Flight Center. In Figure 8 we show a typical scan profiles with and without the sag due to gravity removed. A ray-tracing analysis of the scans indicates that the optical performance of the paraboloid/hyperboloid pair has a HPD of 20.5 arc seconds. Preliminary measurements of the micro-roughness are 3.5Å for the parabola and 5.6 Å for the hyperbola.

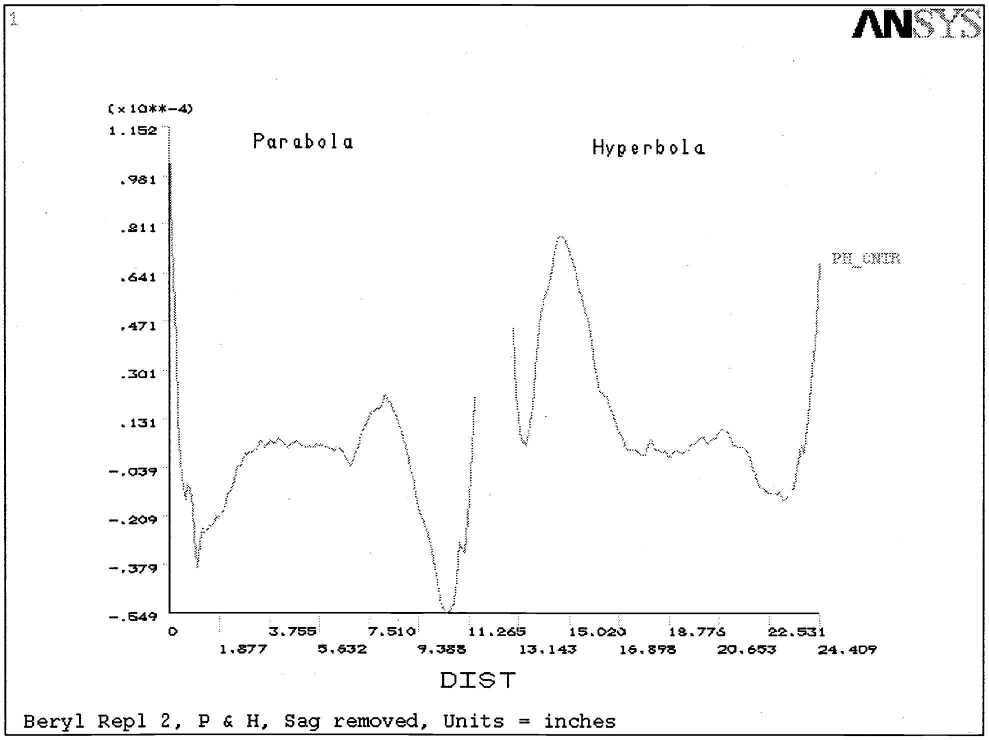

Figure 8: Long-trace profilometer scans across replicated Be segments. Vertical scale is in units of 10^{-4} inches. Predicted system HPD from these measurements is 20.5 arc seconds.

6. CURRENT STATUS AND FUTURE PLANS

Our research with substrates suggests that either glass or beryllium is suitable for a Constellation-X segmented mirror. The glass is being formed consistently with an overall free standing figure of better than 10 arc seconds; even our crude X-ray tests show that they produce better images over a large arc than was previously achieved. The replication experiments with Be show that we can replicate a Wolter I surface onto a conical substrate.

In Table 1 below, we indicate where we stand with regard to our overall angular resolution goal, based on the performance of the various components described here and elsewhere. The three key components leading to high angular resolution segmented mirrors are the mandrels (which control the final surface quality), the substrates (which dictate the figure) and the alignment mechanism. Full shell mandrels of the quality we require have been up to diameters of 0.7 m; the fabrication of larger mandrels as segments has been shown to be feasible.[11] Our progress on substrates, described here, and the Si alignment structures has brought the expected system performance considerably closer to the goal.

Over the next year we plan to develop a prototype mirror, with which we can test assembly and alignment approaches, and get a system-level measurement of the optical performance. The prototype will be a single segment, incorporating all of our mirror fabrication innovations. The housing and alignment approach will incorporate elements of the work described in the papers by Monnelly et al.[7] and Bergner et al.[8] We plan to keep the first prototype modest in size, comparable in dimensions to the ASTRO-E mirrors. We will not fully populate the segment, but fabricate a representative number of reflectors over a range of radii. Initially we will build a single reflection stage; that should allow us to refine the use of the Si bars as alignment tools. By the end of next year, we hope to be ready to demonstrate via direct X-ray test that the prototype meets the Constellation-X performance requirement.

Table 1
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	10	5	Glass or Be substrate, precise forming
Alignment	60	10	5	Si alignment structures
Intrinsic	12	0	0	Wolter I, not conical approximation
Overall[1]	**90**	**19**	**11.2**	

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

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