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Fabrication and Performance of Constellation-X Hard X-ray Telescope Prototype Optics Using Segmented Glass

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ABSTRACT

We report on the fabrication and performance of prototype optics for the Constellation-X hard X-ray telescope (HXT). The prototypes utilize segmented-glass optics. Multiple glass segments are combined to produce telescope shells. The shells are separated by and epoxied to graphite rods, and each layer of rods is precisely machined to match the required optical geometry of the corresponding glass shell. This error-compensating, monolithic assembly and alignment (EMAAL) procedure is novel. Two prototypes are described. The first used 10cm long thermally-slumped glass pieces produced by slumping into a concave mandrel with no subsequent replication. This prototype obtained 45" (2-bounce HPD). The second prototype was the first attempt to mount epoxy-replicated, thermally-slumped glass optics using EMAAL. The latter prototype demonstrated our ability to produce and mount glass shells whose figure and performance are faithful representations of the original replication mandrel. The average performance was 45", with the best replicated segment providing 33" (2-bounce HPD) performance, consistent with the ~30" measured with laser reflectometry and interferometry prior to mounting. Both these prototypes substantially exceeded the HXT requirement of 60".

KEYWORDS: Hard X-ray telescope, Constellation-X, X-ray optics, segmented glass, thermally-slumped

1 INTRODUCTION

The Constellation-X mission will carry 12 hard X-ray telescopes (HXT), three on each of four coaligned satellites. These telescopes are designed to complement the soft X-ray telescopes (SXT). The HXTs will provide spectroscopic capability from the cutoff of the SXT at ~ 8 keV out to ~ 40 keV. Because their primary goal is spectroscopic rather than high resolution imaging, the HXTs have a modest performance requirement of 60" (HPD) and goal of 30" in contrast to the SXT requirement of 15" and goal of ~5". Nevertheless, as a secondary instrument the HXTs are constrained tightly in weight (< 250 kg excluding structure) and overall cost. In addition, these requirements must be met while providing enormous geometric area (> 1500 cm^2) due to the shallow graze angles required at high energy. The relevant design parameters are in table 1.

Focal length	10 m
Minimum shell radius	3 cm
Maximum shell radius	20 cm
Shell length	25 cm
Shell thickness	300 μm
Number of shells per telescope	149
Telescope mass	190 kg

Table 1. Design parameters for the Constellation-X Hard X-ray Telescopes.

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Two approaches are being pursued for the HXT optics: Nickel replicas[1], in which the shells are monolithic, and segmented glass optics. The glass optics utilize the conical approximation to the Wolter type I geometry. Due to the long focal length of the HXT the aberrations introduced by this approximation are negligible. The integral conic shells in the glass approach are built up out of smaller glass segments which are placed close enough together so that throughput losses are negligible. We have been working with glass segments 200-300 μm thick. This is substantially thinner than the thickness of glass necessary to meet the HXT weight requirement (600 μm) but reducing the mass beyond this level is very important. The exact number of glass segments per shell in the HXTs is still under investigation. Most of our work has concentrated on 10 cm axial glass segments. For the current HXT optical design 4 such axial segments (2 each for the hyperbola and parabola sections) would be required. But we have studied axial segments between 5 and 20 cm. Designs and prototypes have been investigated with 4-8 azimuthal segments (by contrast the SXT is baselined with 12 azimuthal segments). The most likely number of segments per shell is probably ~24-32, corresponding to 6-8 azimuthal segments. The exact number will depend on replication studies, which are underway and which will determine the largest undistorted axial and azimuthal segments which can be produced. The mounting approach favors segments ~10 cm, since this has previously been shown to produce near optimal results.

The primary goal of the current research was to mount epoxy-replica glass (hereafter eGlass) using the error compensating monolithic assembly and alignment (EMAAL) approach. We wanted an end-to-end confirmation that we could produce telescopes whose performance was consistent with that expected based on the quality of the replication mandrel. Although the replication process used in this study was not capable of producing eGlass whose overall figure was comparable to the mounting accuracy of the EMAAL machine, the results were extremely encouraging. A secondary goal was to demonstrate that with modest cherry-picking of 10 cm thermally-slumped glass segments without replication (hereafter tGlass), that we could achieve performance exceeding the Constellation-X HXT angular resolution requirement (We had already done this with 5 cm segments of 200 and 300 μm thickness[2]). This was done with ease. This is significant from the project management standpoint. Some 50,000 replications must be done in short order for the HXT, and a significant fraction of the HXT telescope cost and schedule is devoted to replication. The eGlass is essential to reach the HXT performance goal of 30". However for the middle and outer radii shells tGlass has demonstrated 45", better than the 60" HXT requirement. Thus, if necessary, tGlass optics can provide important cost and schedule contingency for HXT at only moderate reduction in performance. It is only for the inner shell radii that eGlass is crucial, since tGlass has not met the HXT requirement for these smaller radii. This ability to trade performance against cost and schedule using eGlass and tGlass, but with the same mounting technique, provides important project management flexibility. This investigation is a prelude to the production of a complete Constellation-X HXT prototype using eGlass to be built later this year and which is described in the last section.

2 MIRROR FABRICATION

2.1 Thermally-formed glass optics

The mirrors used in these prototypes were produced with thermally-slumped glass. For the first prototype the glass was slumped into a concave mandrel, which allows preservation of the atomically smooth surface of the microsheet glass[3]. The glass used was Schott AF-45. While Schott D-263 is also acceptable, we find it more difficult to obtain consistently high quality segments with this glass. This tGlass approach has the advantage of being simpler because it skips the replication process. However it is not capable of obtaining as good an ultimate figure as replication since less control over figure errors is obtained in the slumping process. Consequently the glass was cherry-picked to obtain good quality pieces by scanning the free-standing slumped pieces with a laser reflectometer. The goal was to obtain ~45" (HPD, 2-bounce) in this prototype, and this required ~50% yield (i.e., one out of every two slumped pieces were considered acceptable for mounting). By contrast, in the HEFT telescopes, which also use thermally-slumped glass, a resolution of ~ 60" is obtained with > 95% yield[4]. The slumped glass was then coated with a W/Si multilayer. A typical piece of the glass that was used in prototype 1 (called Con-X0) is shown on the left of fig. 1. This is a surface map obtained with the laser reflectometer. This glass typically contains some axial distortions and out-of-phase roundness errors. We have developed a software tool which takes the laser reflectometer scanned glass samples and performs a "virtual" mounting. This assists us in predicting which tGlass samples can be expected to yield best results when mounted. An example of the mounting simulation is shown in the middle of fig. 1. We concentrate on the 10 cm glass used in Con-X0, which included both 200 and 300 μm thick segments The predicted performance, based on laser reflectometry, was ~45" for the thicker glass and slightly worse than 60" for the thinner glass. A 50% yield selection was used in both cases. However, because most of our current work has concentrated on 300 μm thick glass, we have spent very little time optimizing the slumping parameters for 10 cm length, 200 µm glass. It is anticipated that as we investigate optimal slumping and soaking times, the quality of our 200 µm samples will substantially improve.

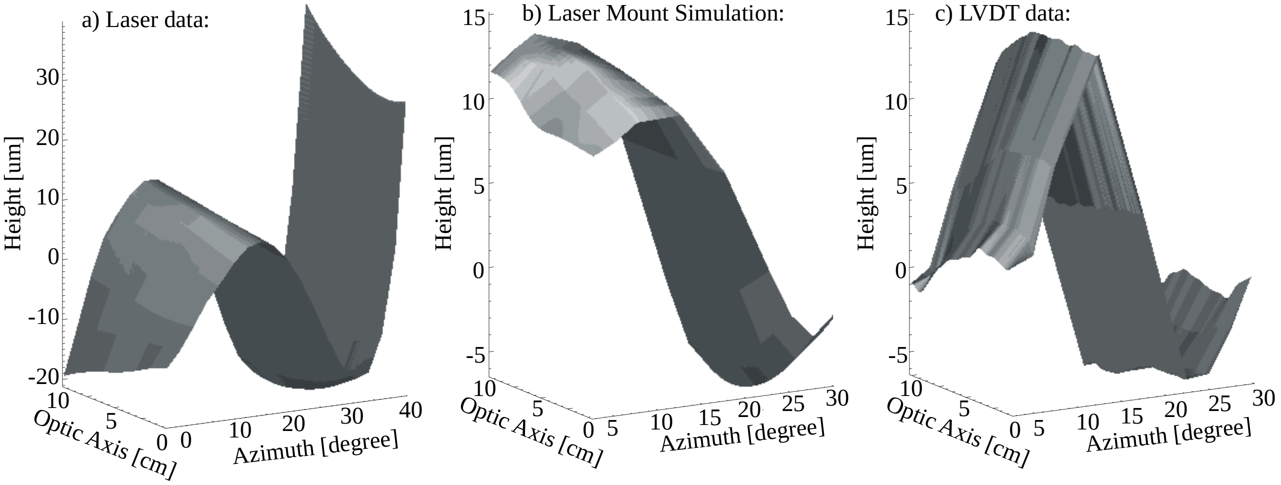

Figure 1: Laser reflectometry surface map of a Con-X0 tGlass segment (left); mounting simulation (middle); metrology of mounted segment (right)

2.2 Epoxy-replicated, thermally-formed glass optics

In the eGlass prototype, which used Schott D-263 glass, the glass is slumped very slowly onto the convex forming mandrel so that thermal equilibrium can be maintained through the process[5]. The glass conforms very well to the slumping mandrel (<~ 1 µm everywhere), however, it has mid-frequency ripple which is removed in the replication. This ripple is induced in the slumping process, since the inner and outer surfaces of the glass are subject to stresses as a result of assuming a cylindrical shape and some residual rippling present in the glass (at the ~10" level). The forming mandrel is coated with a release agent to effect removal of the glass, but this causes a degradation in the microroughness. The atomic smoothness is restored during the replication. The replication mandrel is highly polished and its figure and microroughness will determine the ultimate figure and microroughnessof the replicated piece. The replication mandrel was coated with gold. The glass is sprayed with a thin layer of epoxy (~ 10 µm) and placed on the mandrel at slightly elevated temperature to cure the epoxy. The replica is then removed. This is the same procedure employed for the SXT, except that for the HXT a multilayer will be used on the mandrel rather than gold.

The replication process is, in general, capable of producing eGlass which very accurately represents the surface of the replication mandrel. This is shown by direct comparison of a replication mandrel with eGlass segments in fig. 2. However, the eGlass segments produced for this work were made earlier in the Con-X development cycle and utilized a much thicker epoxy layer (~50 µm) than is currently recognized as optimal (~10 µm). This results in a figure error when the eGlass is removed from the replication mandrel. This problem was present in all the eGlass samples used in the second prototype. Shown in fig. 3 is a typical segment used in prototype 2 (called Con-X1). The data was obtained with a laser reflectometer at Columbia University and through interferometry at GSFC. The center section of these pieces are of exceptionally high quality (well exceeding the HXT goal). The outer sections are of poorer quality (not meeting the HXT requirement) and illustrate the bowing near the edges associated with imperfect separation from the mandrel. In all cases though, the area averaged performance of these eGlass samples substantially exceeded the HXT requirement. The average of the interferometry and laser reflectometry was ~45" (HPD, 2-bounce) for all the shells, except for one segment whose average performance was ~30".

One thing to note in comparing figs. 1 and 3 is the good axial uniformity of the eGlass samples in comparison to the tGlass samples. This is exceptionally useful, because while the EMAAL process can remove some out-of-phase roundness errors during the mounting process, it results in no suppression of axial figure errors. In this sense the replica glass approach nicely complements the capabilities of the EMAAL process.

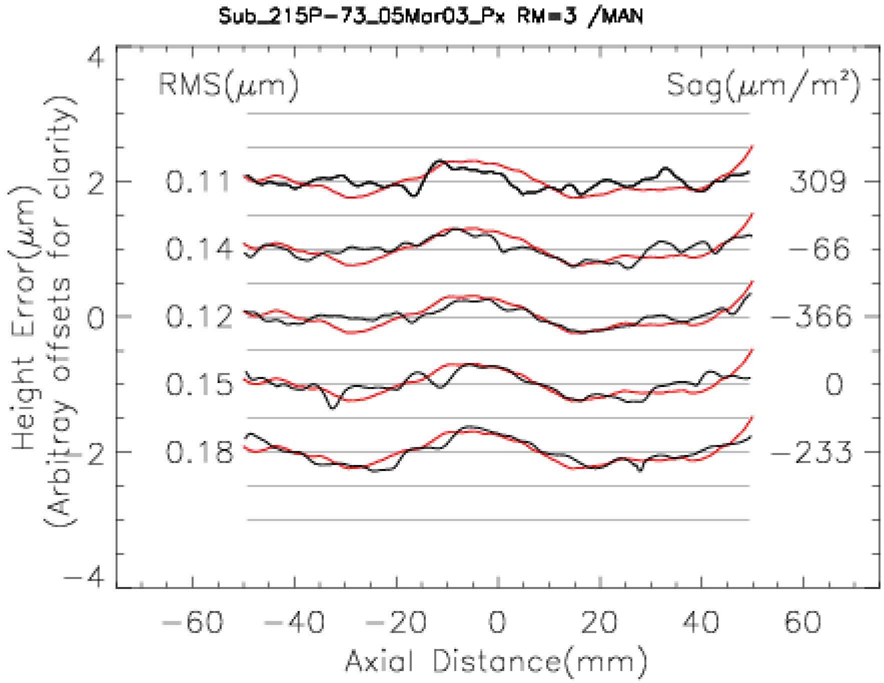

Figure 2: Scans of eGlass samples produced from polished silica mandrel – samples (black) and mandrel (red).

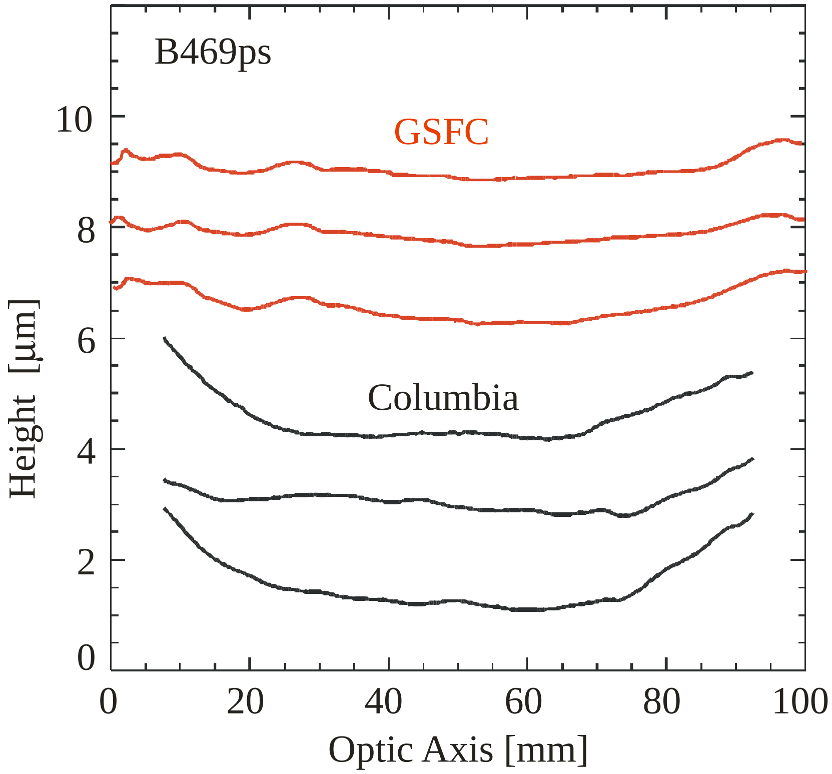

Figure 3: Laser reflectometry and interferometry generated azimuthal scans of a Con-X1 eGlass segment.

3 ERROR-CORRECTING MONOLITHIC ASSEMBLY AND ALIGNMENT (EMAAL)

The EMAAL process was developed in collaboration with Colorado Precision Products, Inc. (CPPI) in Boulder, Colorado. CPPI machined the SiC grating substrates used for the Reflection Grating Spectrometer on the XMM-Newton Observatory. The assembly machine we are utilizing was developed for the High Energy Focusing Telescope (HEFT) project[6]. We are continually upgrading that machine to accommodate the more demanding requirements of Constellation-X, as well as the potential needs of other future space missions. This work has been described in detail elsewhere[7]. We concentrate on the key aspects of the EMAAL process and describe the salient aspects of performance, as previously verified.

The mounting process is shown in fig. 4. A lightweight Titanium mandrel serves as the base upon which the optic is constructed. The mandrel is mounted on a spindle with arcsecond accuracy. The mandrel can be removed and replaced with a repeatability of better than 5". Graphite rods are epoxied along the optic axis at multiple azimuthal positions on the cylinder. Mirror segments are then epoxied to the graphite rods, and another layer of graphite rods are epoxied to the glass. The process is repeated for each layer. The crucial point is that each layer of graphite rods is machined with respect to the optic axis so that their surface geometry exactly matches that required for the shell to be mounted at that position. Therefore the front surface of the glass exactly conforms to the desired position – there is no stackup of errors in this approach.

There are a number of other very significant advantages that this approach affords in the fabrication of segmented glass optics. Because the optical axis is defined by the spindle, and the machining of the graphite rods with respect to it, there is no need to worry about a detailed alignment between the telescope mandrel and the spindle axis. Because the glass is an integral part of the mounting structure, the resultant telescope is extremely rugged. We have successfully environmentally tested a 24 shell prototype[8]. In addition, while cut glass is potentially vulnerable to edge fractures, the use of graphite rods provides a barrier to the propagation of cracks. Moreover, the thickness variations of the glass are irrelevant, since it is the front surface of the glass that is mounted against the precision-machined rods. In effect, the EMAAL process integrates the assembly and alignment procedure into a single step which is verified by precision metrology performed during the graphite rod machining. This saves a great deal of time by eliminating the need for an independent, potentially iterative, alignment procedure. Detailed metrology of the graphite spacer machining has indicated that current accuracy is better than 8", including the effects of epoxy thickness errors. Indeed, we have so far been unable to fully test the limits of the EMAAL process – current results are totally limited by the quality of the glass substrates. Our expectation is that the next generation of Constellation-X eGlass, to be produced in the next few months, will enable us to mount substrates whose figure contribution to the total telescope error budget is comparable to that of the EMAAL process (see section 5). A picture of an eGlass segment mounted on the Con-X1 mandrel is shown in fig. 5. The 5 spacers onto which it is mounted are visible.

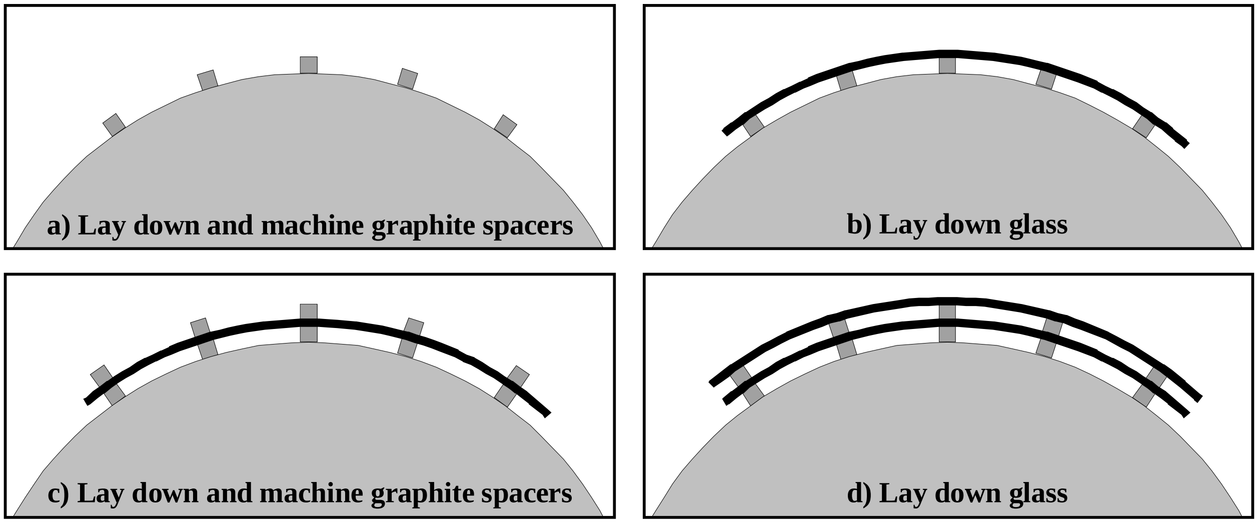

Figure 4: Telescope Assembly. A glass-graphite rod-epoxy matrix is built up from a telescope mandrel. The rods for each shell are machined so that the front surface of the glass is at the proper position, leading to zero stackup errors.

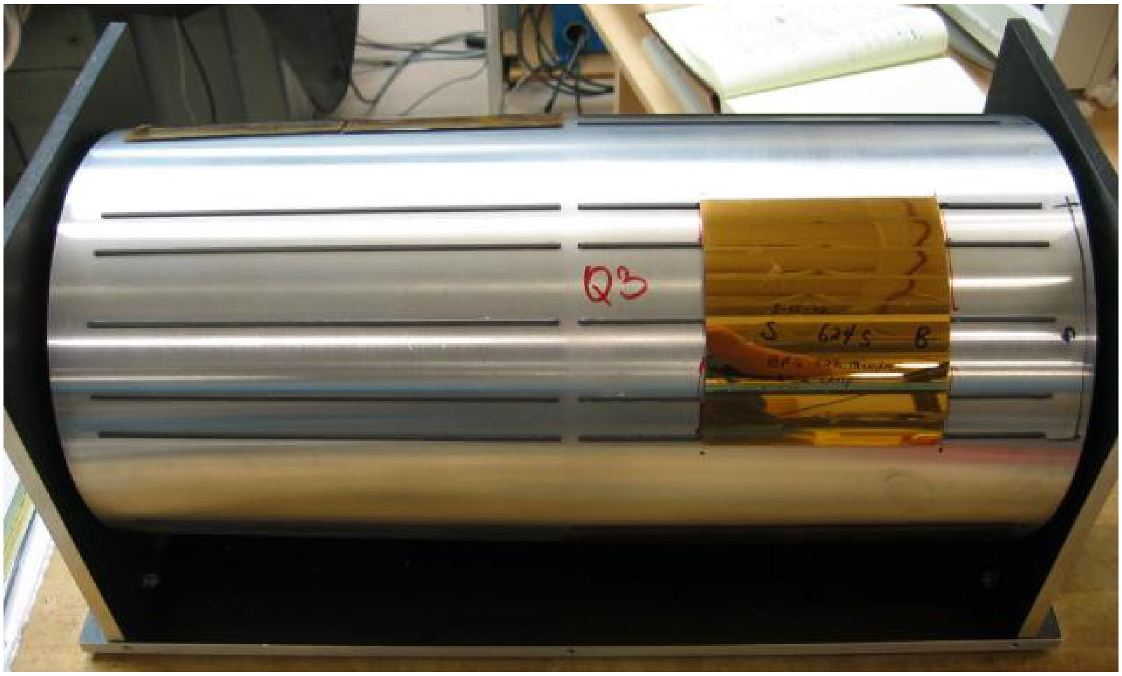

Figure 5: Con-X1 eGlass segment epoxied to 5 graphite spacers on the titanium mandrel.

4 TELESCOPE METROLOGY

Both in-situ metrology during the mounting process and X-ray measurements were used to characterize the performance of the prototypes. These are described in this section.

4.1 Linear Voltage Digital Transformer (LVDT) metrology

For the tGlass employed in Con-X0, it is possible to obtain real time analysis of the assembly process. The LVDT is a low force (<~ 0.1 gm) mechanical probe which exerts a constant force during surface measurement through use of an air bearing with constant air pressure. The high probe stiffness in the radial direction combined with the minimal surface distortion makes it essentially a zero force metrology tool. From a practical standpoint it is very fast as well. This enables us to mount an entire shell of glass and obtain detailed surface scans using the LVDT in less than a day. During construction of the HEFT telescopes we perform only limited checks on the glass shells, but during this Constellation-X R&D phase we are employing more extensive metrological testing. The lower right section of fig. 1 shows a surface map image produced from LVDT data on a 0.3 mm x 10 cm glass segment in the Con-X0 prototype.

While the LDVT image does not match the mount simulation image in detail, the predicted performance, when averaged over many glass segments, is good. Sixteen pieces of glass were utilized, comprising ½ of a full shell. The surface height data is processed to remove spikes in the data caused by dust particulates and passed through a 5th-order Butterworth filter to suppress high frequency noise. It is then converted to surface slopes, which are passed to a ray trace program to simulate the image performance. LVDT data for additional quadrants/shells can be combined to form a composite image. The LVDT synthetic images are generally in excellent agreement with those obtained through X-ray analysis. The LVDT data predicted an image of 46" (HPD, 2-bounce), compared with the 45" measured in X-rays and reported below.

For the Con-X1 optic we attempted LVDT metrology but did not obtain useful results. Since the LVDT probes the back surface of the glass, it can only obtain useful results when the back surface is a faithful representation of the front surface of the glass, which is mounted against the graphite spacers. We have verified with independent measurements that the tGlass has very good thickness uniformity between front and back surface leading to surface parallelism of ~ few arcseconds. Thus, back surface metrology in tGlass is a useful diagnostic. In the case of eGlass, the thickness variation of the epoxy renders the back surface metrology unusable. Because of our strong desire to have such real time metrology during assembly, we will address this issue in our next Con-X prototype. We will use a Keyence interferometer to produce interferograms of both the back and the front surface of the glass in-situ. A Keyence interferometer at LLNL is currently being cross-calibrated on glass samples taken with the laser reflectometer at Columbia in preparation for its use at CPPI.

4.2 X-ray Measurements

X-ray measurements were performed at 8.0 keV at the Danish Space Research Institute (DSRI). The X-ray tests provided data on both image quality and throughput. A triple-axis diffractometer utilizing high resolution, channel cut monochromator and analyzer crystals was used. Pinholes in front and behind of the optic define the optical axis. The optic is adjusted in two axes so that it is aligned to the pinholes. Lack of wobble when the optic is rotated confirms the alignment of the optic to the optical axis. Measurements are done at various azimuthal positions on the optic with full illumination along the length of the optic. At each azimuthal position the optic is rotated horizontally in order to scan for the incidence angle with highest X-ray intensity. The primary effect of any residual misalignment is an off-centering from the nominal graze angle, and thus an apparent decrease in throughput. However this effect will not be significant unless there is a severe misalignment – much more than our 15" estimated alignment accuracy. Our throughput measurements are therefore estimated to be low by no more than a few percent. More details on the calibration system can be found elsewhere[9] .

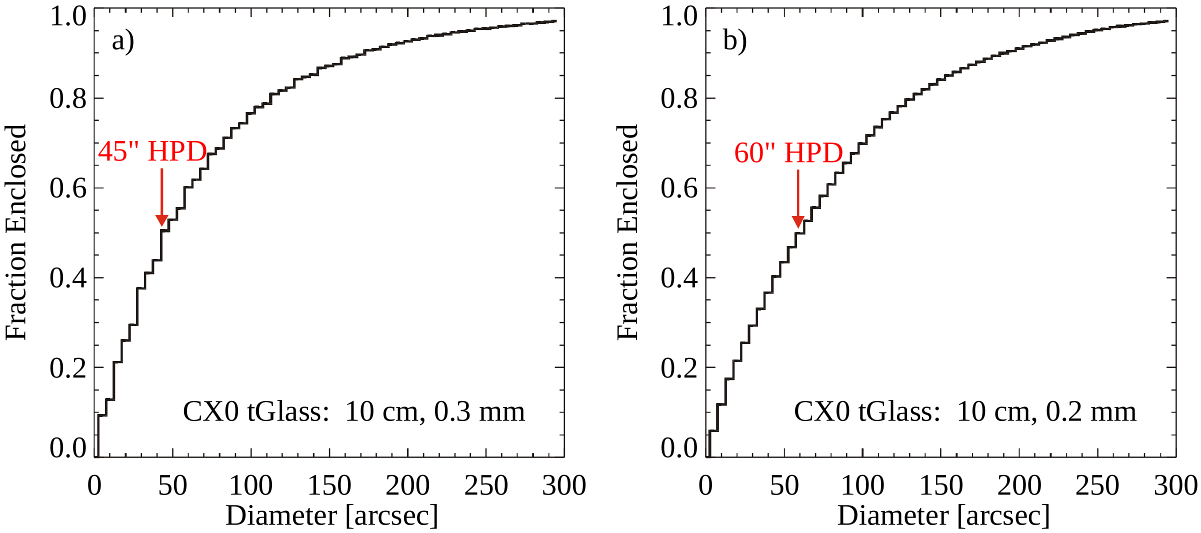

Figure 6: Encircled energy as a function of diameter for 0.3mm (left) and 0.2mm (right) tGlass in Con-X0.

4.2.1 Imaging

The plots in fig. 6 show the integral enclosed power as a function of diamter for the 0.3 and 0.2 mm glass segments in Con-X0. The 45" (HPD, 2-bounce) for Con-X0 exceeds the HXT requirement of 60". The 60" resolution for the 0.2mm glass meets the HXT requirements. We have previously reported similar performance in another prototype using the 0.2mm glass (table 2). While the eGlass prototype did not yield better results than the tGlass prototype, it holds great promise for the future for several reasons. Firstly, the ultimate performance of the eGlass will be much better than in the thick epoxy eGlass used on Con-X1. It should be much more comparable to the <~ 8" capability of the EMAAL process. Secondly, the performance of the individual eGlass segments mounted in Con-X1 closely matched their free-standing performance as measured with the laser reflectometer. In particular the 30" (HPD, 2-bounce) measured for the best eGlass segment from the average of the interferometer and laser reflectometer measurements is very near the 33" measured for the same segment in X-rays. An X-ray encircled energy plot of the *entire* surface of this segment is shown in fig. 7. This confirms what we have seen in previous prototypes in which we have used extreme downselect of tGlass segments to obtain high quality – that we can mount glass substrates whose free-standing figure is ~25-30" with negligible contribution from the

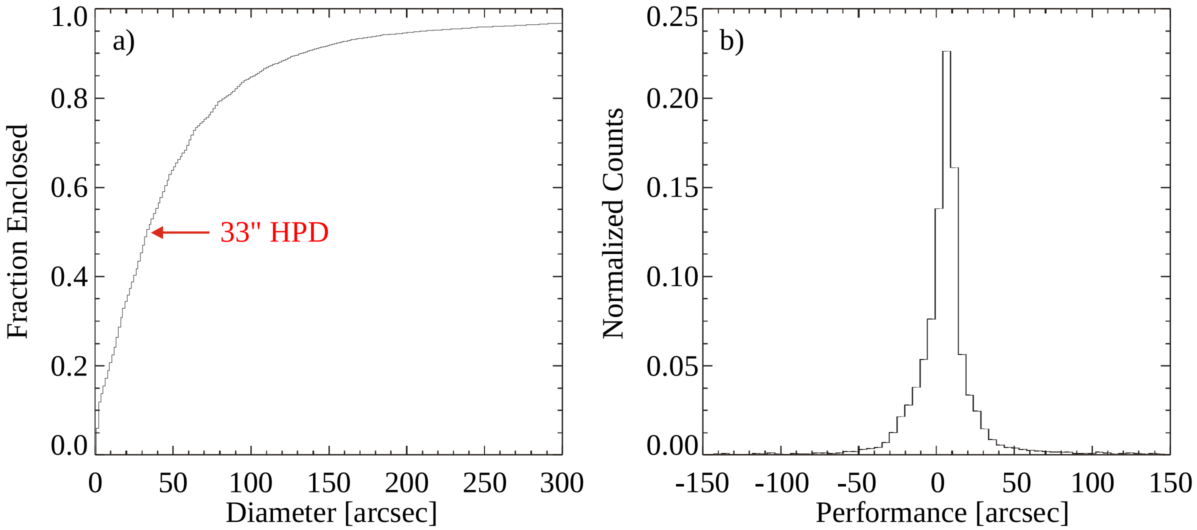

Figure 7: Encircled energy for a full surface pencil beam scan of the best Con-X1 eGlass segment (left) and a scan through the center section of the same glass segment yielding 20" (HPD, 2-bounce) (right).

EMAAL process. This is certainly to be expected given our understanding of the accuracy of the EMAAL process. It suggests that when the anticipated high quality eGlass substrates become available in a few months (see section 5), that we will be able to exceed the Constellation-X HXT performance goal of 30". The good agreement between the LVDT prediction of angular resolution and the X-ray measurements has been consistently observed by us in other prototypes with tGlass. This agreement is expected to hold as long as the glass is flat on length scales less than ~1 cm. We always consider it prudent to periodically evaluate the tGlass stock with X-rays to ensure that short lengthscale features in the glass are not a problem. We have, on occasion, noticed such problems arising with some production runs of the Schott glass. The right part of fig. 7 shows a scan through the center part of this eGlass segment and is typical of the behavior over the ~80% of the segment not seriously affected by the figure distortion associated with the replication. The 20" resolution measured in X-rays substantially exceeds the HXT goal and suggests the type of performance that can be expected in the full prototype utilizing eGlass with thinner epoxy replicas as described below.

In table 2 we summarize our work to date on X-ray imaging using the EMAAL process to mount segmented glass. This is a compilation of work done for HEFT as well as R&D for Constellation-X and other future space missions.

4.2.2 Throughput measurements

The 8 keV X-ray throughput was also measured for Con-X0 using data obtained from pencil beam scans taken at 2.5˚intervals. The net throughput for the 10 cm, 0.2 and 0.3mm shells was 88-90%. This may be a lower limit on throughput since some difficulty was encountered in precisely positioning the telescope at the proper incidence angle. However the overall throughput matches very closely the ~90% measured in a detailed analysis of shells from the first HEFT flight telescope[4].

length/thickness/section	X-ray HPD (arcsec)	Type of glass	reference
5cm/0.3mm/octant	45	tGlass	2
10cm/0.2mm/octant	58	tGlass	2
10cm/0.3mm/quintent	~60	tGlass	4
10cm/0.2mm/octant	60	tGlass	This work
10cm/0.3mm/octant	45	tGlass	This work
10cm/0.3mm/octant	45	eGlass	This work

Table 2: Summary of segmented glass optic prototypes built with the EMAAL process.

5 FUTURE WORK

The main goal over the next 5 months is the construction of a 3 shell prototype of the HXT using eGlass. The baseline calls for utilizing 10 cm/300 µm glass which will be replicated off of a gold-coated mandrel. The gold-coated eGlass will then be coated with a multilayer. Shells will be placed at 100, 200 and 400 mm diameters to cover most of the HXT telescope range of diameters. Some of the forming and replication mandrels have been received and others are on order. The replicated glass will be characterized with interferometry, laser reflectometry and X-rays, and then mounted at CPPI. Interferometry will provide a real time capability to monitor the assembly. The prototype will be X-ray tested at DSRI. Given the success of the EMAAL process in mounting glass substrates with figure close to that in their free-standing state, our goal is to obtain results substantially exceeding the HXT goal of 30". One key issue that needs to be addressed is the level of figure distortion induced by pulling the eGlass replica off of a multilayer coated mandrel. If large scale figure error is introduced along the axial direction, it will manifest itself in the mounted piece, although some out-of-phase roundness errors will be suppressed. Given that our very first attempt with the eGlass has produced 45" optics, we are confident that use of thinner epoxy can only result in substantially improved performance. The exact magnitude of that improvement can only be determined when the prototype is constructed.

For the tGlass our effort will concentrate on improving our ability to cherry-pick the best glass for mounting in optics. We have been doing this by evaluating the surface topology of the glass segments using laser reflectometry. However, the complex structure shown in the tGlass makes it difficult to do this selection, even though we use a code which performs a virtual constraint of the glass in the mounting geometry using the free-standing surface topology of the glass segment as input. We need to better avoid the mounting of statistical outlier glass segments, which degrade the angular resolution in our prototypes. To that end we have been investigating surrogate mounts. The surrogate mounts allow us to mount glass in the laser reflectometer with similar mounting rod and pressure constraints as those applied in the EMAAL process. The idea is that by evaluation of the surrogate mounted performance of a given tGlass segment, instead of free-standing performance, we can better select the highest quality glass for use in telescopes, and suppress outliers which are currently being mounted. An example of a piece of glass mounted in the surrogate mount is shown in fig. 8. Early results on this approach to improving tGlass telescope performance are encouraging and will be reported elsewhere.

Figure 8: tGlass mounted in a surrogate mount on the laser reflectometer.

6 SUMMARY

We have constructed two prototypes of the Constellation-X HXT. Their 45" resolution falls between the HXT requirement of 60" and goal of 30". Throughput of ~90% has also been measured. We have, for the first time, mounted epoxy replica segmented optics with the error-correcting monolithic assembly and alignment procedure. End to end testing confirmed that the figure of the replication mandrel was preserved in the replica glass substrates and after the mounting process. The best eGlass segment had 33" performance, close to the HXT goal. The figure of the eGlass replicas dominated the error budget of the optic, and should be vastly improved when the replication tests are repeated with new forming and replication mandrels and thinner epoxy. Our expectation is that the next prototype will exceed the Constellation-X HXT goal.

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