Constellation-X Mirror Technology Development

W. W. Zhang

for
the Constellation-X Spectroscopic Telescopes Mirror Technology Development Team

J. Bolognese, K.W. Chan[1], D.A. Content, T.J. Hadjimichael[2], Charles He[2], M. Hong[3], J.P. Lehan[1], J.M. Mazzarella[3], D.T. Nguyen, L. Olsen[3], S.M. Owens, R. Petre, T.T. Saha, M. Sharpe[3], J. Sturm, and T. Wallace
NASA Goddard Space Flight Center
[1] also University of Maryland, Baltimore County
[2] Ball Aerospace and Technologies Corp.
[3] Stinger Ghaffarian Technologies, Inc.

M.V. Gubarev[4], W.D. Jones, and S.L. O'Dell
NASA Marshall Space Flight Center
[4] also Universities Space Research Association

W. Davis, M. Freeman, W. Podgorski, and P.B. Reid
Smithsonian Astrophysical Observatory

ABSTRACT

As NASA's next major x-ray astronomical mission following the James Webb Space Telescope, Constellation-X requires technology advances in several areas, including x-ray optics, x-ray detectors, and x-ray gratings. In the area of x-ray optics, the technology challenge is in meeting a combination of angular resolution, effective area, mass, and production cost requirements. A vigorous x-ray optics development program has been underway to meet this challenge. Significant progress has been made in mirror fabrication, mirror mount and metrology, and mirror alignment and integration. In this paper we give a brief overview of our development strategy, technical approaches, current status, and expectations for the near future and refer interested readers to papers with an in-depth coverage of similar areas.

Keywords: X-ray optics, lightweight optics, Constellation-X, space optics

1. INTRODUCTION

The construction of a space astronomical observatory is always a complex and significant undertaking. It requires the effort of many hundreds of people over many years and an investment of many millions of dollars. By design it requires the expansion of technology frontiers and poses engineering challenges. As NASA's next major x-ray observatory, Constellation-X is no exception. It requires advances in x-ray micro-calorimeters, x-ray gratings, x-ray CCD, and x-ray optics.

With its emphasis on x-ray spectroscopy, the Constellation-X mission requires x-ray optics that has a moderate angular resolution, 15" half-power diameter (HPD), and a very large effective area, ~30,000 cm^2 at 1 keV. Given volume and mass capabilities of existing launch vehicles and an ever tighter budget

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environment, these two requirements cannot be met with existing x-ray optics technologies, represented by the three currently operating x-ray observatories: Chandra, XMM/Newton, and Suzaku.

Table 1 shows comparisons of key parameters of the Constellation-X observatory with those of the three currently operating x-ray observatories. In terms of angular resolution, Constellation-X has to implement the same 15" HPD with a factor of ~6 less mass than XMM/Newton. With similar mirror mass areal density, Constellation-X has to achieve a factor of 8 improvements in angular resolution in comparison with Suzaku. The comparison with Chandra is somewhat involved. Although its angular resolution is a factor of 30 less stringent than Chandra, Constellation-X has to do it with a factor 50 lower mass areal density. It also has to manufacture ~40 times more physical mirror area.

The conclusion of these comparisons and further investigation of the various mirror fabrication technologies (Chandra's traditional grinding and polishing, XMM/Newton's electroforming of nickel, and Suzaku's epoxy-replication of aluminum foils) is that a new approach needs to be developed to meet the Constellation-X challenge.

Table 1. Comparison of the Con-X SXT with the mirrors of three currently operating missions, representing the state of the art of X-ray optics fabrication and integration.

	Con-X/SXT	**Chandra**	**XMM/Newton**	**Suzaku**
No. of mirror assemblies	4	1	3	5
No. of shells per assembly	163	4	58	168
Total mirror physical area (m^2)	~800	~19	~158	~125
Angular resolution at 1 keV (″ HPD)	15	0.5	15	120
Mirror Technology	Thermally formed float glass segments	Ground and polished Zerodur shells	Electroformed nickel shells	Epoxy replicated aluminum segments
Typical mirror areal density (g/m^2)	1	~50	8	0.5
Mirror manufacturing Cost per unit area	Low	Extremely high	Moderate	Moderate to Low
Year of Launch	2018 (?)	1999	1999	2005

2. Technical Approach

Many technical, practical, and management considerations have led to the unambiguous conclusion that the Constellation-X mission must adopt a modular approach to the observatory construction [Petre et al. 2007]. Figure 1 illustrates this approach. The entire observatory has four identical mirror assemblies, each of which has an outer diameter of 1.3 m and a focal length of 10 m. Each mirror assembly in turn has a number of mirror modules: 5 inner ones and 10 outer ones [Reid et al. 2007].

Each mirror module, either inner or outer, comprises an appropriate number of both primary (parabolic) and secondary (hyperbolic) mirror segments. While we are committed to this modular approach, we do expect that the number of modules, both inner and outer, to evolve and change over time as we understand and optimize more aspects of the observatory design and implementation.

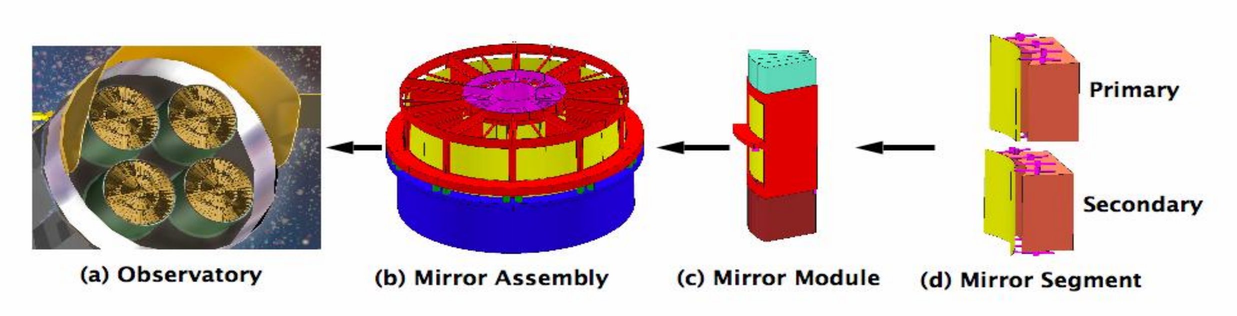

Figure 1. An illustration of the modular approach of the Constellation-X mission: (a) the observatory comprising four identical mirror assembles; (b) a mirror assembly comprising identical inner modules (purple) and identical outer modules (red); (c) a mirror module comprising primary and secondary mirror segments; and (d) a pair of mirror segments on their rigid mounts for the purpose of metrology, transportation, and alignment and integration into a module.

Figure 1 is a graphical illustration of the modular approach. It depicts the hierarchy of going from individual mirror segment pairs to the final observatory that has four identical mirror assemblies. The singular purpose of Figure 1 is to give guidance to our technology development program definition. While one would always desire to mature and perfect every aspect of the entire process in Figure 1, one must also take into account the fact that a technology development program, by its nature, is to deal with new and unique aspects of a mission that go above and beyond requirements and demands of previous missions. Examination and analysis of Figure 1 and comparisons with previous missions clearly show that technology, experience, and expertise exist in both industry and government institutions (1) to integrate mirror assemblies onto the spacecraft and (2) to integrate mirror modules into mirror assemblies. What is unique to the Constellation-X mission that no previous mission has demonstrated is: (1) the fabrication of the lightweight and therefore flexible mirror segments shown in Figure 1d and (2) how to align and integrate many of them into a mirror module.

Another important consideration as part of our technology development strategy relates to requirements to be imposed on individual mirror segments. There are two schools of thought on this point. The first one thinks that each individual mirror segment should meet a set of well-defined requirements in and of themselves. In other words, each mirror segment must be able to form images of the required quality without any external help. The second school of thought is that one should take advantage of the flexibility of the mirror segments to use mechanical or other actuators to repair or otherwise ameliorate any figure errors that the mirror segment may have. In other words, in this school of thought, the requirements on each mirror segment itself can be somewhat relaxed.

The pros and cons of each of these two schools of thought can be argued and debated, but the final deciding factor is a combination of many systems level considerations. For the sake of efficiency and clarity, we have adopted the first school of thought with a clear understanding that, if there is insurmountable difficulty in making each mirror segment meet optical requirements without external help, one is all but forced into adopting the second school of thought. Conversely, if one can relatively easily and straightforwardly make and metrologically demonstrate that each mirror segment meet all optical requirements, the second school of thought becomes irrelevant.

Figure 2 depicts all the elements of our technology development process. The rest of this paper presents descriptions, purposes, and the status of each of these elements.

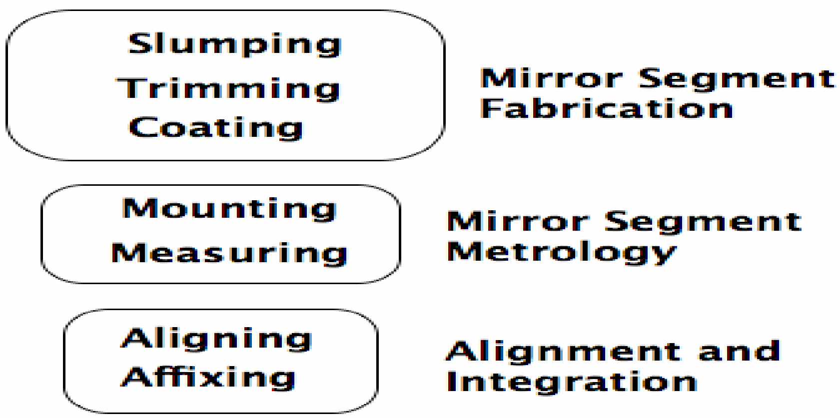

Figure 2. A list of the elements of technology development whose purpose is to make each of these elements a well-understood procedure that can be reliably repeated many times.

3. Mirror Segment Fabrication

The mirror fabrication process starts with a flat glass sheet, Schott D263 or AF45 [Zhang et al. 2007, 2006, 2005, 2004, and 2003]. Its thickness, 0.4mm, is dictated by an overall mass budget imposed by the Constellation-X mission design. This flat glass is thermally formed on a precisely figured and polished fused quartz mandrel, as shown in Figure 3. The objective of this forming process is to copy, as precisely as possible, the figure of the mandrel onto the glass sheet.

Figure 3. An illustration of the thermal glass forming process. From left to right, the temperature gradually rises until and glass sheet (gold-colored for clarity) slumps under its own weight and wraps itself around the mandrel (blue).

After the forming process is completed and the glass sheet is properly annealed and cools to room temperature, each formed piece is cut to required dimension using a hot-wire technique, as shown in Figure 4 (left panel). A properly shaped Ni-chrome wire heated with electric current passes on the glass surface breaks the glass with heat stress, leaving an extremely smooth edge free of micro-fracture, as shown in Figure 4 (right panel).

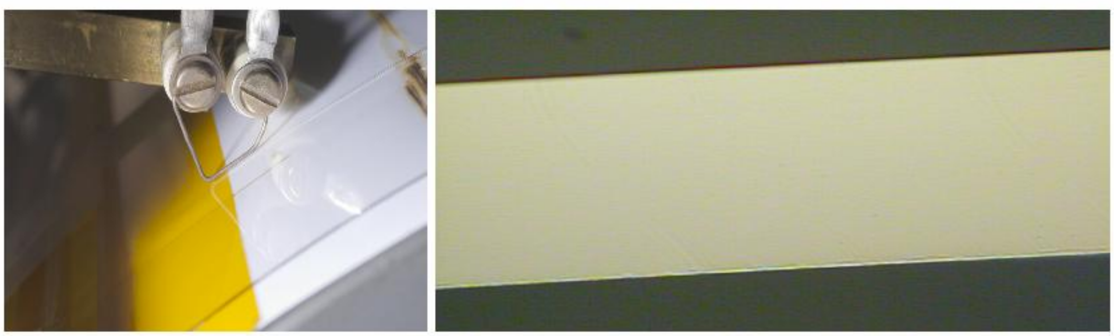

Figure 4. The photograph on the left shows the hot-wire glass cutter. It uses heat stress generated by the ni-chrome wire to crack the glass. The micrograph on the right shows the smooth edge resulting from the hot-wire cutter, smooth and free from of micro-fracture.

After a mirror segment is formed and trimmed to dimension, it is cleaned and then magnetron-sputtered with ~15 nm of Ir to maximize its x-ray reflectivity in the vicinity of the Fe K line, the study of which is one of the most important scientific purposes of the Constellation-X mission. Figure 5 shows the coating equipment and a finished mirror segment.

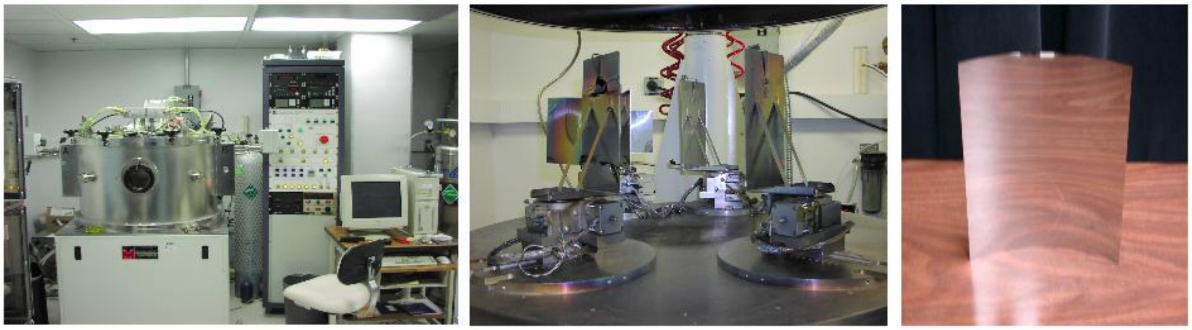

Figure 5. Coating of the mirror segment with Ir to enhance the mirror's x-ray reflectivity. The photo on the left shows the outside of a sputter chamber. The middle photo shows the inside of the same chamber with mirror holding fixtures. The photo on the right shows a finished mirror segment, reflecting the wood veneer of the table surface.

4. Mirror Segment Metrology

Adequately supporting a mirror segment so that it is free from distortion caused by either gravity or other forces is a significant challenge because of its very large aspect ratio of 750 (~300mm in the largest dimension over its 0.4mm thickness). Figure 6 shows the four methods of mirror support that are being pursued concurrently [Lehan et al. 2007a, and 2007b].

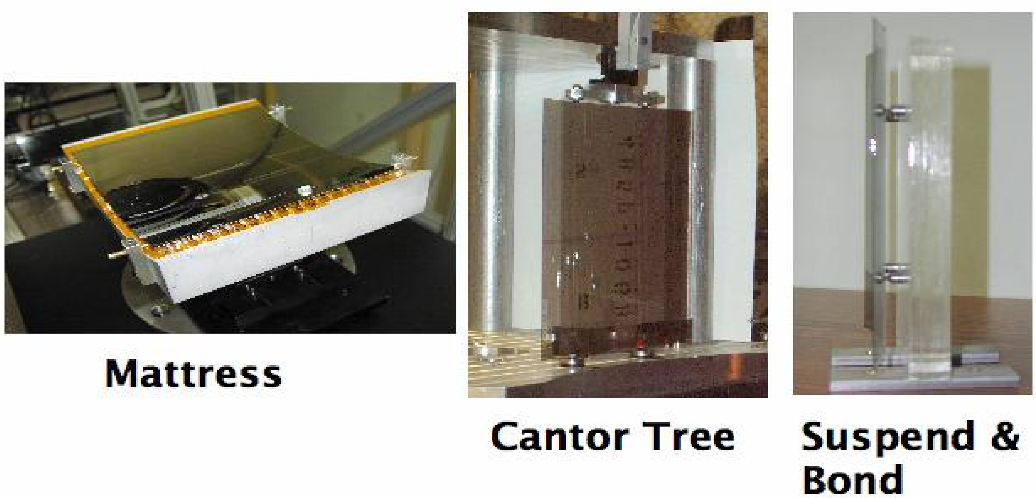

Figure 6. The three mirror segment mounts that are being investigated. Left: mirror mattress that uses a larger number (~200) of soft springs to balance the gravity; Center: The Cantor tree mount that holds the mirror segments at four points, two on the forward edge and two on the

aft edge; Right: the "suspension mount" which uses epoxy to bond the mirror at four points on the convex side.

4.1 MIRROR CRADLE AND MATTRESS [Hadjimichael et al., 2007]: The mirror segment lies on its back (convex side) supported by many, typically 200, very soft springs, which, in turn, are supported by a cradle made of the same type of glass and in approximately the same shape as the mirror segment. The operating principle of this cradle and mattress system is that, given an amount of pressure or force that the mirror segment and the springs exert on each other due to gravity or other reasons, the soft springs compress or deform orders of magnitude more than the mirror segment. In our specific implementation, the weight of the mirror segment, ~50g, compresses the 200 or so springs by ~5mm each.

Results achieved with the cradle and mattress system are mixed. It appears that the cradle and mattress system can adequately support the central 60% of the mirror segment to achieve reliable and good axial figure repeatability. The 40% of the mirror segment near the azimuthal sides do not always have repeatable figure, indicating that the edge effects are quite large. Finite element modeling of the cradle and mattress system is under way [Chan et al., 2007] to understand the complex interaction between the springs and the mirror segment. Further experimentation and optimization are also underway to empirically study the effects of placement of individual columns of springs.

4.2 CANTOR TREE [Lehan et al., 2007]: In this mount, the mirror segment' optical axis is parallel or very close to being parallel to the local gravity vector. It is supported at two positions at the forward (or bottom) edge and prevented from shifting at two positions at the aft (or top) edge. At each of the four contact points is a bearing to ensure minimal forces are exerted to the mirror segment.

Initial measurement of two mirror segments has resulted in excellent repeatability from three consecutive mount and dismount operations. Further tests and more trials with more mirror segments are necessary to assess the property of this method.

4.3 "SUSPEND AND BOND: [Chan et al. 2007] The mirror segment is first suspended with two wires from the ceiling. The two wires are as parallel as practically possible. The lower end of the wires are tack-bonded to the top edge of the mirror segment at two positions such that the center of gravity of the segment is in the same plane as the two wires. Then a glass plate with four standoffs is maneuvered with precision stages to come in contact with the mirror segment on the convex side. The four mounting points (tips of the standoffs) are each dabbed with a small bead of epoxy for the purpose of tacking to the back surface of the mirror segment. After the epoxy cures, the suspension wires are cut and the mirror segment, being tack-bonded to a rigid plate via four mounting points, has effectively turned into a rigid body. It can be easily transported and maneuvered for metrology and other purposes.

Initial trials with this method have resulted in a mirror segment successfully bonded and measured with excellent repeatability. We are in the process of assessing whether the repeatability can be extended to many trials of "bond-debond-bond" cycles.

4.4 METROLOGY: The next step is to measure the mirror segment in all of its aspects so that its x-ray image can be definitively determined. Four types of instruments are used to measure the optical figure quality of each mirror segment: phase-measuring interferometers, a cylindrical null lens system, surface profilers, and a Hartmann setup to measure focal length and focus quality.

Table 2 is a summary of how all the quantities of each mirror segment is measured. Once a mirror is properly supported and/or mounted, it can be treated as if it were a rigid body. Its average radius is measured with a custom-designed and –built cylindrical coordinate measuring machine. Then it is placed on a six degrees of freedom stage in a parallel beam of visible light so that its focal length can be determined with a precision of 0.5mm. The full illumination parallel light can be apertured down such that a small fraction of the mirror segment in azimuth can be illuminated at a time to determine its focus position in the focal plane. As is typically the case, the visible light image is diffraction-limited, but its centroid is a good indicator of the overall slope of the mirror sector.

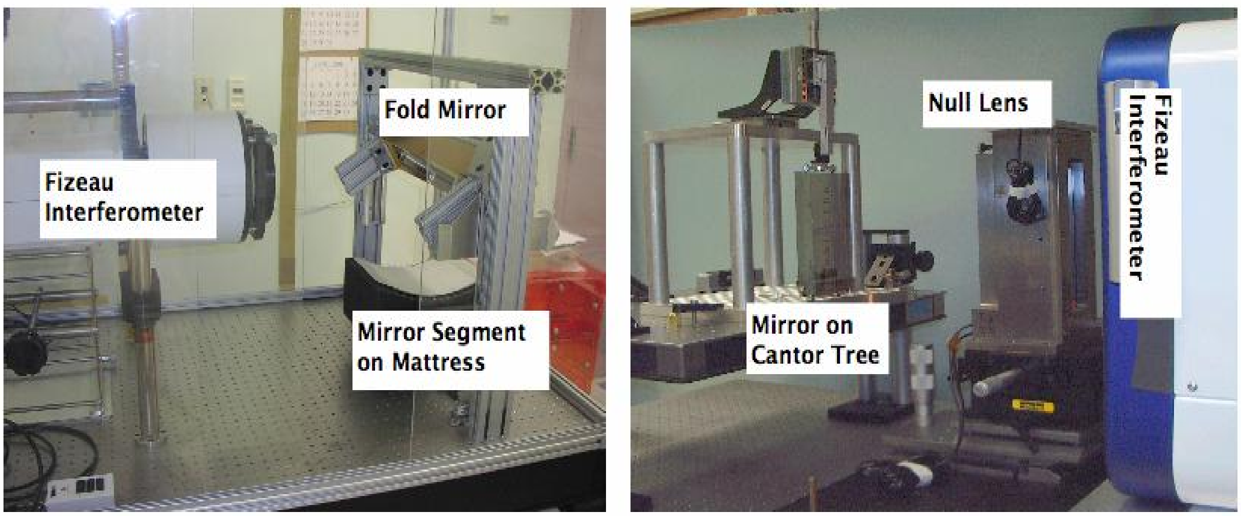

Figure 7. Two metrology setups. The photo on the left shows a mirror segment lying on a mattress being measured with an interferometer in the line scan mode. The photo on the rights shows s mirror mounted on the Cantor tree being measured with a cylindrical null lens and an interferometer.

Table 2. A tabulation of the complete metrology information of a single mirror segment that enables definitive predictions of its x-ray imaging performance**.**

<table>
<tr><th colspan="2">Quantity</th><th colspan="2">Measurement Method</th><th>Comment</th></tr>
<tr><td colspan="2">Average radius</td><td colspan="2">Custom-designed and -built Cylindrical Coordinate Measuring machine</td><td>~10 micron repeatability achievable, final result dominated by systematics</td></tr>
<tr><td colspan="2">Focal length
(average cone angle and radius)</td><td colspan="2">Grazing incidence beam (Harmann test)</td><td>~0.5 mm repeatability and accuracy easily achievable</td></tr>
<tr><td colspan="2">Focus Quality
(cone angle and radius variations)</td><td>Hartmann test</td><td rowspan="4">Phase-measuring interferometer and null lens</td><td>Sub-arcsecond repeatability and accuracy achievable</td></tr>
<tr><td colspan="2">Sag
(P-V magnitude of 2nd order)</td><td rowspan="3">Axial Scans using an interferometer</td><td>Accuracy determined by mirror mount repeatability/accuracy; Measuring instrument can easily do ~50 nm</td></tr>
<tr><td rowspan="3">Axial Figure</td><td>Low Frequency Figure
(200mm-20mm)</td><td>Required repeatability and accuray easily achievable</td></tr>
<tr><td>Mid-Frequecy Figure
(20mm-0.2mm)</td><td>Overlap regime between two instruments; Detailed and quantitaive comparison always needed</td></tr>
<tr><td>High-Frequency Figure
(0.2mm-0.001mm)</td><td colspan="2">Zygo Newview 5000 surface profiler</td><td>0.3nm RMS measurement accuracy easily achievable</td></tr>
</table>

5. Alignment and Integration into a Module

After a mirror segment is measured and qualified in all its relevant aspects, it is aligned and transferred to a permanent housing, as shown in Figure 8. The alignment and integration step is meant to accomplish two purposes. The first one is to align each mirror segment, either primary (parabolic) or secondary (hyperbolic), to the common focus. The alignment step is simple and straightforward after each mirror segment has been bonded to its metrology mount, effectively converting it into a rigid body. Each mirror segment is facilitated with a 6 degrees-of-freedom stage that maneuvers it into the required position and orientation as defined in Figure 8. The next step is critical, which is to transfer the mirror segment, both position and orientation, from the metrology mount into the module housing. At present, we envision the attachment of the mirror segment to the module housing is accomplished with appropriately selected epoxy or other adhesive. We are investigating two methods of attachment: (1) hard bond, and (2) encapsulation. In the "hard bond" case, the epoxy (or any other adhesive) is used in the traditional way. It wets the mirror surface. During and after curing, it can exert both tensile and compressive pressures on the mirror segment. In the case of encapsulation, the mirror surface is treated such that the epoxy cannot wet it. The epoxy only acts as a filler. It can only exert compressive pressure, but not tensile pressure. Figure 9 illustrates the two methods.

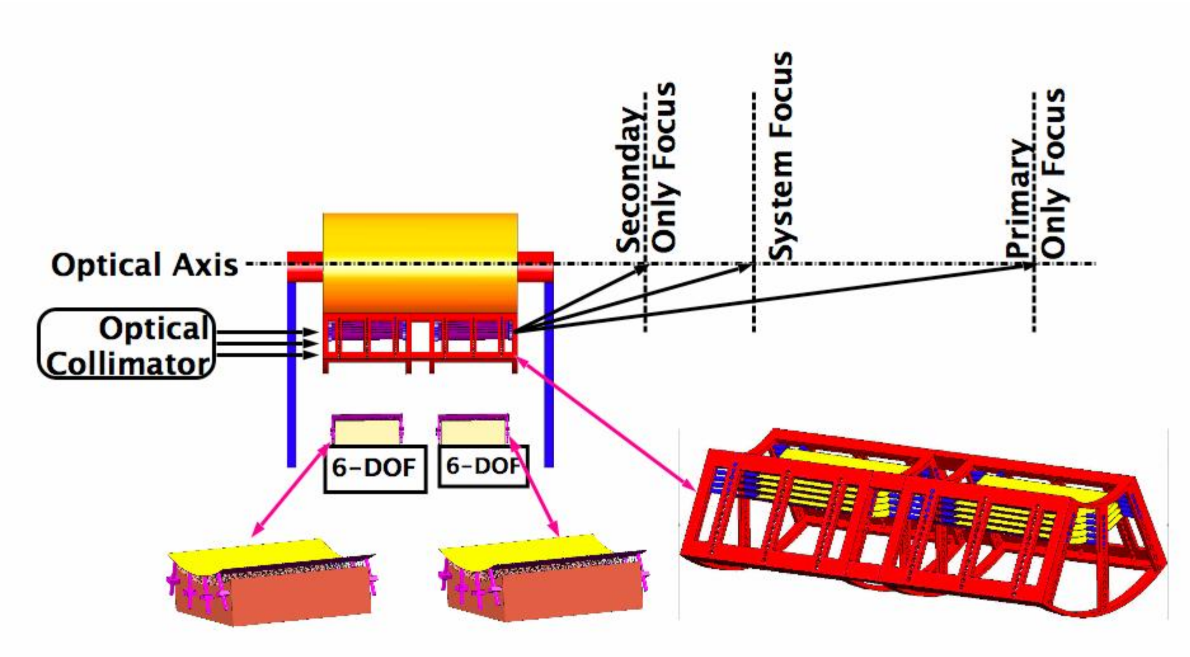

Figure 8. An illustration of the process transferring and attaching or affixing a mirror segment to a permanent housing. Each mirror segment is individually aligned and attached to achieve optical performance.

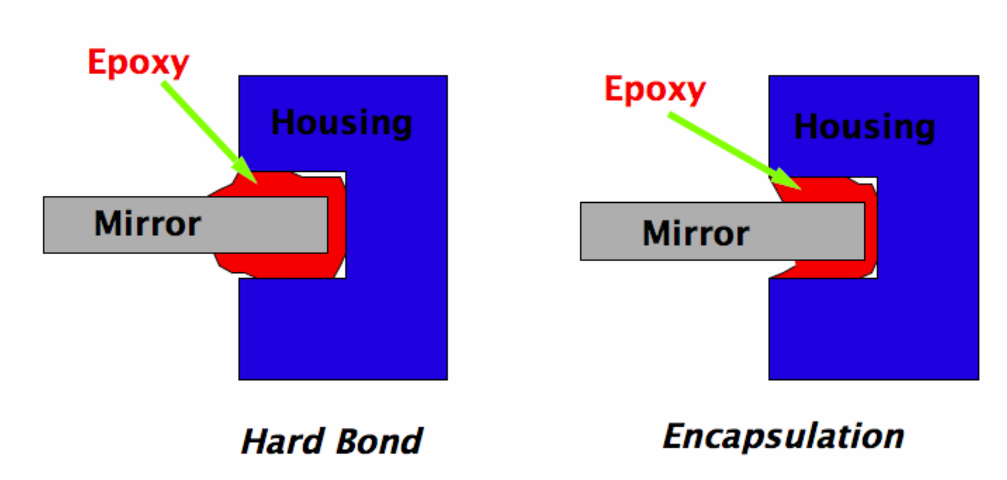

Figure 9. An illustration of the two attachment methods being investigated. Left: "hard bond" where epoxy wets all the surfaces that it comes in contact with; Right: encapsulation, where epoxy does not wet, therefore does not bond with the mirror segment.

6. X-Ray Test and Performance Verification

After a mirror pair is aligned and attached to a permanent or even a temporary housing, it is placed in an x-ray beam line to verify its performance: both angular resolution and effective areas at a number of energies. This x-ray test and verification process serves important purposes. It is a comprehensive and definitive method of verifying the normal incidence metrology data and our methodology of arriving at performance predictions. It is the only true “whole” surface metrology that really matters. When measuring microroughness with a surface profiler, we can only sample a very small fraction of the mirror surface. Despite various statistical tests, the only truly definitive way to know whether we have adequately sampled the mirror surface is though full surface illumination x-ray tests.

There are at least two x-ray beam facilities easily available for our technology development program: one at the Goddard Space Flight Center and the other at the Marshall Space Flight Center. Each facility has its own advantages and disadvantages. The GSFC one is more easily available and can be utilized without much planning and does not require extensive funding. But its beam diameter (9 inches) is relatively small. The MSFC one is of much higher quality both in terms of beam size and other associated parameters, but it is less available and is relatively expensive to use.

Our plan is to perform preliminary tests at GSFC. After kinks have been worked out of the mirror alignment and attachment process, we will conduct definitive tests and characterization at the MSFC facility.

7. Summary of Status and Outlook

Significant progress has been made toward enabling the Constellation-X mission. In the mirror fabrication area, we have demonstrated that direct slumping alone, without epoxy replication as we originally envisioned, can meet mission angular resolution requirements, resulting in significant savings for the mission. In this area we are currently working on two issues: (1) understanding factors that affect the sag of mirror segments, and (2) improving and optimizing the slumping process to increase reproducibility and reduce the duration of each slumping cycle to the minimum possible. Factors that affect mirror sag include the annealing part of the slumping cycle, Ir coating, and the mount and measurement process.

In the mirror segment metrology area, we have built up a complete set of metrology equipment that allows definitive and complete characterization of each mirror segment, leading to definitive x-ray performance predictions. We will continue the work on mirror mounts to arrive at the best way of mounting and temporarily bonding a mirror segment. We expect to reach definitive conclusions on the three methods of mirror mounting in the next year and will pursue other new methods as necessary.

In the area of mirror attachment to permanent housing, we will complete the characterization of both the “hard-bond” method and the encapsulation method. Should they proven to be inadequate either for temporary transfer stability or long-term stability, we will investigate other methods which may or may not use epoxies or other adhesives.

Figure 10. Photos of a 600-m x-ray beam facility at the Goddard Space Flight Center. It will be used to perform x-ray tests of single pair mirrors.

8. ACKNOWLEDGEMENTS

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