Arc-Second Alignment of International X-Ray Observatory Mirror Segments in a Fixed Structure

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Abstract—The optics for the International X-Ray Observatory (IXO) require alignment and integration of about fourteen thousand thin mirror segments to achieve the mission goal of 3.0 square meters of effective area at 1.25 keV with an angular resolution of five arc-seconds. These mirror segments are 0.4 mm thick, and 200 to 400 mm in size, which makes it hard not to impart distortion at the sub-arc-second level. This paper outlines the precise alignment, verification testing, and permanent bonding techniques developed at NASA's Goddard Space Flight Center (GSFC). These techniques are used to overcome the challenge of transferring thin mirror segments from a temporary mount to a fixed structure with arc-second alignment and minimal figure distortion. Recent advances in technology development in addition to the automation of several processes have produced significant results. This paper will highlight the recent advances in alignment, testing, and permanent bonding techniques as well as the results they have produced. [1][2]

Table of Contents

1. Introduction

Aligning thin glass segments used for the optics of the International X-Ray Observatory (IXO) poses an interesting challenge. IXO is a project designed at building upon the success of previous x-ray missions such as Chandra and XMM Newton. (For IXO mission background see [1]). It will have a much larger effective area than any previous x-ray mission with 3.0 square meters at 1.25 keV with an angular resolution of five arc-seconds. The designed double reflection focal length of the system is 20 meters. (It was previously 8.4 meters). A Wolter-I type telescope design was selected to enable the mirror segments to be nested in order to achieve the targeted effective area. In the Wolter-I type design, the incoming x-ray photons graze off of a primary mirror and a secondary mirror at a very small angle to get to the detector. The nested mirror segments were selected to be 0.4 mm thin to conserve mass and maximize collecting area. Meeting the angular resolution requirement of five arc-seconds with such thin glass segments presents a challenge.

To accommodate all of the mirrors for the telescope, a modular design was conceived. The Flight Mirror Assembly (FMA) will support 60 modules arranged in three rings, 12 inner, 24 middle, and 24 outer [2]. There will be 200 to 280 mirror segments per module for a total of about fourteen thousand mirror segments. The primary and secondary mirrors must be aligned to each other to meet the strict angular resolution requirement. In addition, all of the mirror pairs must focus to the same point within the required resolution.

There are currently three approaches being developed to solve the challenge of aligning and mounting the mirror segments into a permanent structure. In the first approach, the mirror is adjusted with small high resolution linear actuators to correct for axial and figure errors. This method is being pursued by a team at the Smithsonian Astrophysical Observatory (SAO) [3]. The second method involves forcing the mirror segment into a prescribed geometry. This approach is being investigated at the European Space Agency (ESA) and associated industries [4]. The third method is to preserve the fabricated state of the mirror and not introduce any distortion or figure error throughout the alignment and mounting processes. This third method, known as the suspension mount, is being developed at NASA's Goddard Space Flight Center (GSFC) and will be discussed in this paper.

For the suspension mount method, there are five major processes. First, an individual mirror segment is suspended to minimize distortion on the mirror and replicate its free state and optimal figure. Next, the mirror is temporarily bonded to a strongback, essentially a flat plate with pins

[2] IEEEAC paper #1581, Version 3, Updated October 30, 2009.

protruding from it. The strongback freezes the mirror segment in this optimal distortion-free state, and allows for the mirror to be transported and tested. The mirror segment is then aligned to achieve optimal focus. Next, the mirror is permanently bonded into a mirror housing structure that supports multiple mirror segments. Finally, the temporary bonds are released, leaving the mirror fully supported by the permanent structure.

2. Mirror Segments

Mirror Segment Background

The individual mirror segments are slumped from D263 glass onto polished mandrels [5]. The mirror segments are 200 mm long in the axial direction and have a circumferential span of up to 360 mm. This makes each mirror about the size of a standard sheet of paper.

The mirrors are grouped into three rings of modules with 12 to 24 modules in each ring, with an average of 240 mirror segments in each module. The combined group of mirror segments, modules, and support structure forms the FMA. The total mass of the FMA is about 1300 kg [6].

The prime goal of this mission is to be fit 3 m^2 of effective area at the soft x-ray band within this mass envelope. Previous high angular resolution x-ray imaging missions such as Chandra and XMM-Newton had much larger mass to area ratios. Per aperture area, Chandra and XMM-Newton require nearly 20,000 kg and 2,000 kg per each square meter of aperture, while IXO will be 1 to 2 orders of magnitude better at about 300 kg/m^2. To accomplish this mass-to-area ratio, IXO uses thin segmented optics instead of full thick shells. This comes at a trade off, as the thin nature of the segments equals a low stiffness. With a low stiffness, the forming, mounting and alignment are all a challenge as the thin segments can be easily distorted. Because of the thickness and large mass to area ratio of the Chandra for instance, 0.5 arc-seconds of angular resolution was achieved. Nevertheless, IXO aims to achieve a factor of nearly 3 better angular resolution than that of XMM-Newton, and at the same time maintaining a magnitude better mass-to-area ratio.

Preliminary Budget of Error Contributions

With the best current knowledge of how these mirror segments may be made and form the FMA, an error budget is developed to reach the resolution of about 4 arc-seconds at the FMA level. Overall mission level requirement is defined at 5 arc-seconds. In Table 1, the allocation of high level error components is listed. The measurements are traditionally reported in Half-Power-Diameter (HPD), where the resolution is defined as the angular size within which half the photons were enclosed. The running sum column in Table 1 is simply the root-sum-square difference of the consecutive individual process contributions. Despite the fact that HPD cannot strictly be root-sum-squared, the values of individual components serve as an excellent guide in process development.

As shown in **Error! Not a valid bookmark self-reference.**Table 1, a total of 1.26 arc-seconds of error is budgeted to be introduced to the mirror during the temporary mount and permanent bond procedures. This can be further broken down into 0.89 arc-seconds for the temporary mount and 0.89 arc-seconds for the permanent bond. This feeds into the plan to have a final error of 4.14 arc-seconds at the FMA level of assembly which will meet the final 5 arc-second requirement of the mission.

Table 1. Error budget from fabrication to flight

		Running Sum (arcsec)	Individual Process Contribution (arcsec)
One Reflection	Forming Mandrel	1.47	1.47
	Mirror Fabrication	2.41	1.91
	Temporary Mount and Permanent Bond	2.72	1.26
Two Reflection	Module	3.86	0.34
	FMA	4.14	1.50

The value of 0.89 arc-seconds for the permanent bond procedure is further broken down into individual components. These values are measured using interferomic metrology, Hartmann tests, and some are not yet able to be measured. The Hartmann test mainly measures cone angle variation, which is the largest contributor at this time.

3. Temporary Mount

The temporary mount method being used at NASA's Goddard Space Flight Center (GSFC) is the suspension mount [7]. The idea behind the suspension mount is to preserve the optical figure of the mirror during alignment and bonding into a permanent structure. First, the mirror is hung using four strings to minimize the gravity distortion on the mirror as shown in Figure 1.

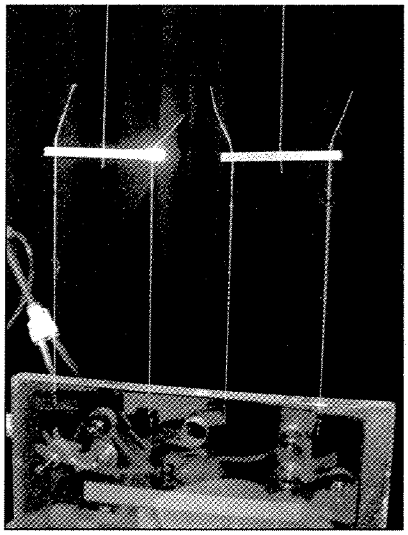

Figure 1 – Four string suspension mount

Once the mirror is hanging vertically, it is captured by a strongback. The strongback is essentially a plate with a set of pins protruding from its front surface. These pins are set in near-frictionless air bearings so that they apply minimal force when making contact with the mirror. The pins are bonded to the back of the mirror as shown in Figure 2, but are still able to float freely to compensate for the mirror swaying or moving. When the mirror settles into its relaxed state, the back of the pins are bonded to strongback, to freeze them in place. This essentially freezes the mirror in its hanging state where the distortion is minimized.

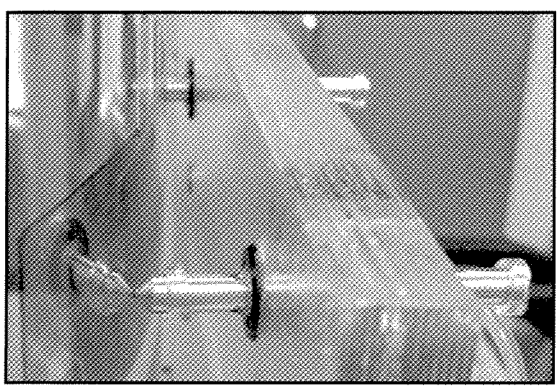

Figure 2 – Pins in air bearings bonded to mirror

The strongback enables the mirror on it to be transported, tested, aligned, and transferred onto the mirror housing.

4. Mirror Alignment

Once the mirror is temporarily bonded, it can be tested for surface quality, and then put into proper alignment. Finite element modeling and practice demonstrate that small adjustments in re-orientation in the gravity field do not distort the mirror figure significantly. The alignment is done with respect to a parallel beam light source.

A six degree of freedom hexapod is used to align the strongback with the temporarily bonded mirror. The hexapod has a repeatability of ±0.5 μm in the linear X, Y, and Z directions (see Figure 3). The controller outputs the absolute position of the hexapod in X, Y, Z coordinates to 0.1 μm. The rotational position of the hexapod in U, V, and W coordinates (see Figure 3) is reported to 10^{-4} degrees. Knowing the absolute position of the mirror to this level of accuracy enables calculations to be performed to determine the necessary adjustments for optimizing the image.

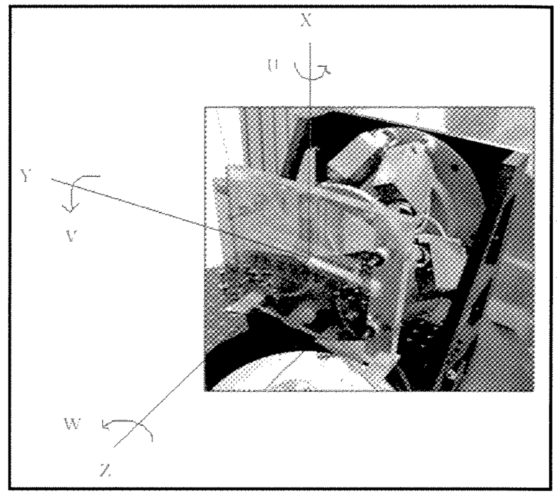

Figure 3 – Hexapod coordinate system

The alignment is mainly adjusted by tilting the mirror in the V direction, and by tilting the mirror in the W direction. The final way to obtain a better image is to adjust the focal distance by moving the CCD camera at the end of the beam.

There are three main focal distances that are used for the specific mirror segment being tested. The current mandrels for slumping glass segments were designed for the earlier mission specification of an 8.4 meter focal length even though the current specification is 20 meters.

Table 2. Focal distances of various segments

Type of Segment	Focal Distance (m)
Primary	17.056
Secondary	5.654
Primary and Secondary	8.400

To achieve this long focal distance when the mirror is in a vertical position, a light source is positioned above the mirrors, shone downwards, and then bent 90 degrees using a 45 degree fold mirror so that it is parallel with the optical bench surface. It is then bounced back and forth using flat fold mirrors to achieve the necessary focal length. The light source is a red beam assumed to have a wavelength of 633 nm, which is in the visible light spectrum. Using visible light is a safer way to do testing than shorter wavelengths such as ultraviolet or x-ray. Also, using visible light allows for the path of the light to be traced in order to find the image when large adjustments are made.

The mirror reflection starts as an arc shape (similar to the shadow of the curved mirror) which becomes smaller and smaller until it focuses to a small hourglass shape as shown in Figure 4 (also known as rotated bow-tie). Past the focus, the arc becomes inverted, and grows in size. The focus location determines one component of the alignment. The location of the center of the hourglass itself determines the rest of the alignment. The location of the center of the hourglass is characterized by performing a Hartmann test.

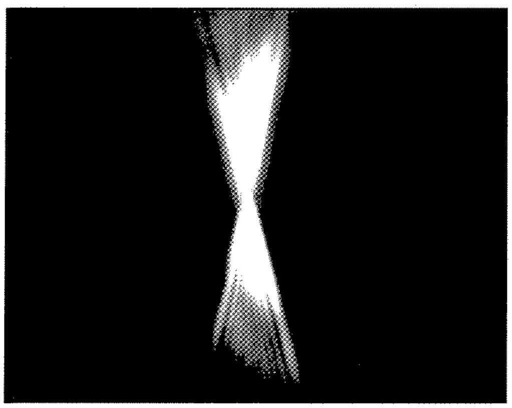

Figure 4 – Image of mirror reflection at focus

Due to the light source generating a beam of light with a wavelength of about 633 nm, there is a noticeable diffraction effect in the image. Because of the small cone angle of the primary mirror segment, this diffraction effect is large when measuring primary segments.

In order to achieve a good result, the mirror must be tilted at a very specific angle in which the light distribution at the focus is symmetrically distributed across the hourglass shape. A rough estimate of this symmetrical distribution of light can be done by simply looking at the image and correcting. Fine tune adjustments are calculated using the analyzed data. Once a Hartmann test is complete, the general shape of the data set in addition to the magnitude of the errors can be used in conjunction with a set of equations to calculate the necessary adjustments needed for the optimal result. Because the relative position of the mirror between tests is known from the hexapod coordinates, it is possible to quantitatively calculate adjustments. Once a mirror is set-up, the automation of the Hartmann test and data analysis on-site makes it possible to run a test and have results in five minutes. This allows for multiple adjustments to be made and to run iterations to perfect the alignment of the mirror segment. Previous to the use of the hexapod and automated Hartmann analysis, several days were required to align a single mirror segment.

5. Verification Testing

Test Fundamentals

A modified Hartmann test is used to test the alignment of the mirror. The test is basically to measure focusing of the mirror by measuring the light ray from sub-apertures of the mirror being tested. In the case of segmented cylinder-like mirror shells such as those of IXO, the simplest sub-aperture is an azimuthal slit. This simplifies the test significantly as the test is then a one-dimensional test.

To perform the test, a mask is used to cover the reflection light coming off of the mirror (see Figure 5). Only a specific slit of light is allowed to pass through the mask. The mask is then rotated to allow light from different strips of the mirror to be analyzed independently.

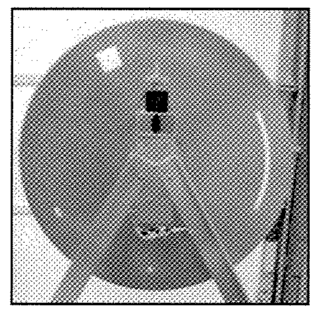

Figure 5 – Hartmann mask

In regards to the hourglass shaped focused image, when only a thin segment of the reflection arc is allowed to pass through the Hartmann mask, a line is displayed. When the lines formed by each stripe of the mirror are put together, they form the hourglass shape as shown in Figure 6.

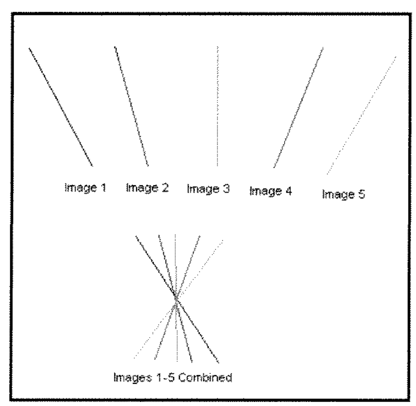

Figure 6 – Combined image explanation (only five images shown to simplify diagram)

A CCD camera is used to capture an image of each line recording the brightness value of each pixel. The theoretical centroid of the brightness values should be in the center of the hourglass. Therefore the alignment error can be determined from the deviation between the centroids of each of the separate images.

The final outcome of the test is a plot showing the deviation of each centroid location from the average location as shown in Figure 7. Motorized linear stages and a rotational motor have been utilized to automate this entire test.

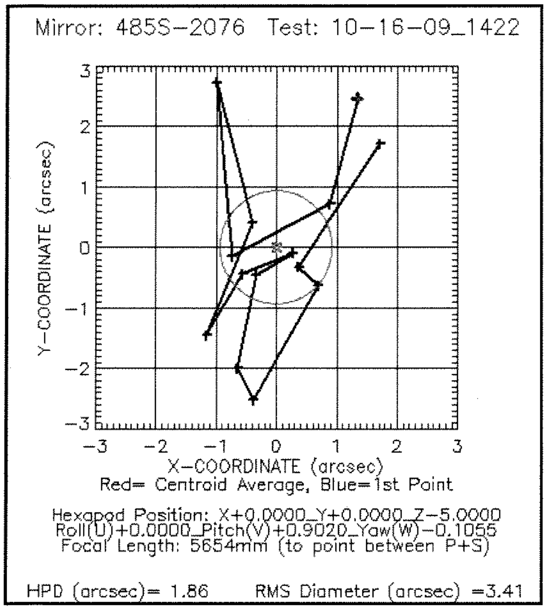

Figure 7 – Sample plot of centroids

The mirror segment alignment parameters are labeled on the graph to track settings used to achieve the image. This helps to understand what changed between trials to improve or degrade the image. The parameters are listed in five major categories. The mirror number is reported to show which mirror is being used. The test number reports the date and time (24 hour format) that the test was performed. The hexapod position shows the coordinates that the hexapod was programmed to in order to translate and tilt the mirror to the alignment used during the test. The focal length reports the distance between a fixed point P+S and the CCD camera. The point PS is a point located 24 mm above the top of the secondary mirror or 26 mm below the bottom of the primary mirror in the permanently mounted configuration. The HPD and RMS ratings give a value of the spread of the centroids which is used to rate the mirror. The HPD rating of the mirror stands for "half power diameter". It is the diameter of the circle around the average centroid that would contain half of the points. It is signified by the magenta circle in Figure 7. The blue cross signifies the first data point taken, which helps illustrate the shape of the mirror by tracking the individual points with the order they were taken in. The red x indicates the average of all the centroids.

Data Analysis

The data that is output after the Hartmann test is a set of images of single lines that when combine would form the "hourglass shape" shown in Figure 6. Each image is analyzed independently to find the angle of a line that passes through the sliver of light. This line is represented by a dashed line in Figure 8.

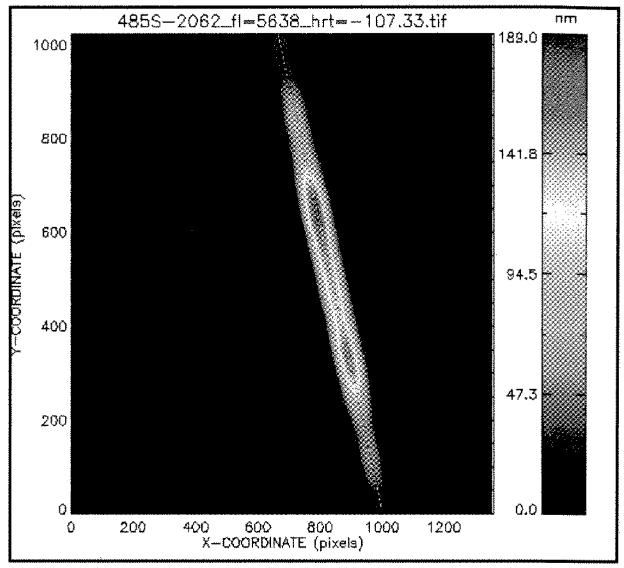

Figure 8 - Analyzed single image from Hartmann test

Once this line has been found, the points along the line are analyzed to compare the brightness of each pixel. The light intensity as a function of focal plane coordinate is shown in Figure 9. The centroid of the area under this curve is calculated to determine image's centroid. This centroid represents where the center of the hourglass is for that specific image. By comparing the centroids of all of the images, the error rating of the mirror can be determined as shown in Figure 7. The result obtained in Figure 9 closely resembles Figure 10 showing that the diffraction effect does indeed play a large role when using visible light. For this reason, the final test of the mirror alignment is done using x-rays in a vacuum chamber. X-rays have a much shorter wavelength, and the diffraction effect is essentially negligible.

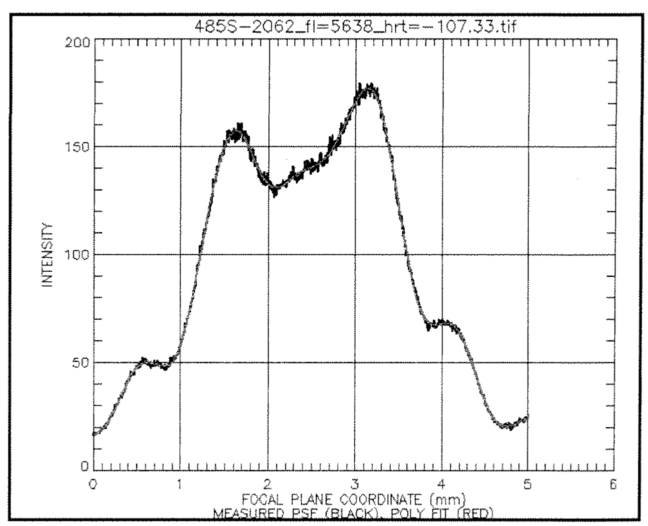

Figure 9 – Light intensity curve along sliver of light

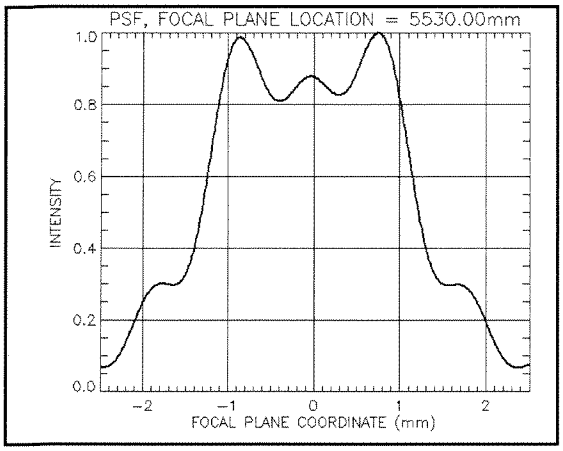

Figure 10 – Theoretical light intensity curve of a secondary mirror segment with diffraction

A repeatability test was performed to check the equipment by performing 10 consecutive Hartmann tests at the same mirror alignment position and focal distance within a span of 30 minutes to minimize environmental changes. It was found that each individual centroid was repeatable to ± 0.6 arc-seconds, and ±0.17 arc-seconds for the overall RMS mirror rating value.

6. PERMANENT BONDING

Procedure

Once a mirror segment has been properly aligned, it is permanently bonded into a mock-up of the flight mirror module. For testing purposes, a Mirror Housing Simulator (MHS) is being used to provide bond locations similar to where they would be in the final module design. The MHS is capable of supporting three mirror pairs of different radii. The MHS is constructed of a Ti-15Mo alloy which closely matches the coefficient of thermal expansion (CTE) of D263 glass mirror segments.

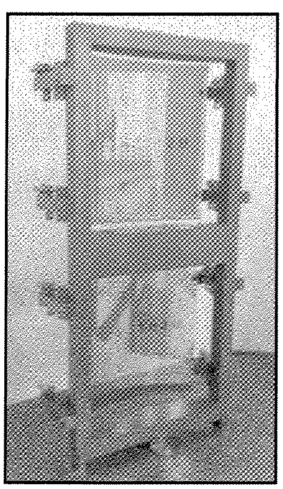

Figure 11 – Mirror Housing Simulator (MHS)

There are twelve rails, six on each side to hold the primary and secondary mirrors. For current testing purposes only the rails at the four corners of each mirror are being used as shown in Figure 11. Small flat tabs slide along the rails into position behind the mirror segment as shown in Figure 12. Once in position, the tabs are secured to the rail using a UV cure epoxy.

The epoxy injection process has been automated by using a robotic arm to rapidly position the syringe of epoxy behind each tab. The UV cure epoxy is injected to bond the mirror to the tab. Once the mirror has been bonded to all four tabs, the temporary bonds are broken by twisting the pins, and the strongback is removed. It has been demonstrated that breaking the temporary bonds does not damage the mirror.

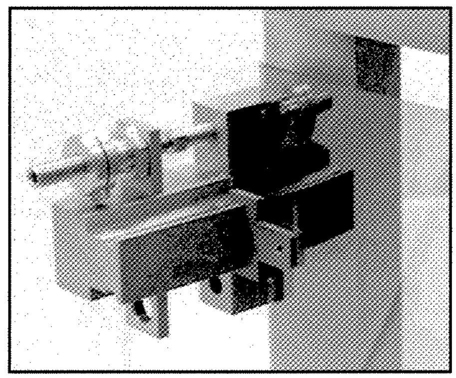

Figure 12 – MHS rail with tab and mirror

A detailed study is underway to determine a method to bond the mirror to the tab while imposing less than 0.3 microns of displacement. This is the perceived allotment of shift in mirror position that would be allowed under the current error budget scenario for preserving the shape of the mirror for acceptable optical quality. Bonding causes optical distortion due to the shrinkage of epoxy as it cures, so UV cure epoxy and Hysol 9313 have been investigated.

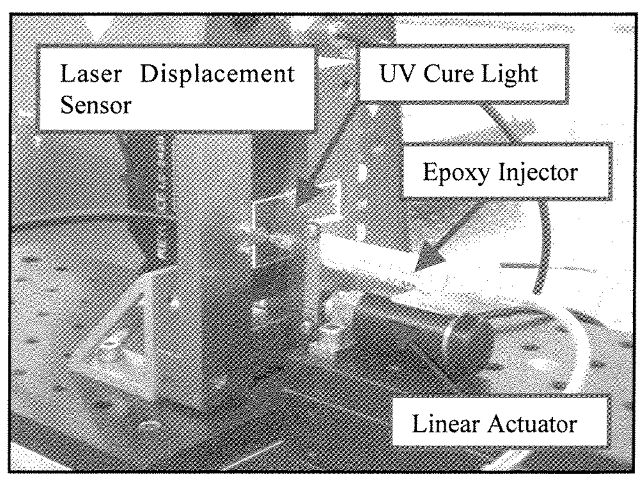

Figure 13 – Epoxy injector mounted to linear actuator

To achieve the submicron mirror displacement due to applying epoxy a zero-displacement bond method is being developed. A small high resolution linear actuator with a resolution of 30 nm is used to move the syringe. The actuator is wired into a closed loop system utilizing a laser displacement sensor with a resolution of 10 nm. The actuator oscillates the syringe tip in and out of the tab to move the mirror using the viscous forces from the liquid epoxy. The syringe is oscillated until the mirror has reached the desired offset position. This offset is determined by how much epoxy shrinkage will occur during the cure using the UV light. The epoxy is then cured, bringing the final displacement to zero. The setup for this process is depicted in Figure 13.

Data Analysis

To measure the distortion introduced during permanent bonding, a Hartmann test is performed before and after bonding, and the RMS values are compared.

$$error = \sqrt{| post\_bond^2 - pre\_bond^2 |} \quad (1)$$

The error contribution from permanent bonding is calculated using Equation 1 where error is the error introduced by permanent bonding. The post_bond term is the RMS value of the Hartmann test performed after bonding, and pre_bond is the RMS value of the Hartmann test performed before bonding.

8. CONCLUSIONS

The mission requirements for IXO of large effective area and high angular resolution do not leave much room for error in the alignment and mounting of thin mirror segments. However, this has driven the design of new hardware and procedures to accommodate these challenges. The automation of the Hartmann test and on-site data-analysis has made it possible to develop an iterative process to optimize the alignment of the mirror. In addition, the automation of the bonding process has led to advances in deformation control to the sub-micron level. Given the strict error budget allowed in the alignment and bonding of a mirror segment to its permanent housing, these advances are significant. Because of the modular design of the FMA this work should apply directly to the other segments to help make this mission a reality.

Future work includes bonding a secondary mirror with less than one arc-second change in Hartmann test results before and after bonding. The same procedure will be repeated for a primary mirror, and then for a primary/secondary mirror pair. Once this is achieved, the co-alignment of nested mirror pairs will be tested.

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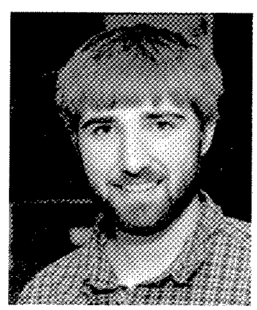
BIOGRAPHY



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