A Mounting and Alignment Approach for Constellation-X Mirror Segments

William A. Podgorski[a], David R. Caldwell[a], Mark D. Freeman[a], William N. Davis[a], Paul B. Reid[a]
Scott Rohrbach[b], William Zhang[b]
[a]Smithsonian Astrophysical Observatory, 60 Garden St., Cambridge, MA, USA 02138;
[b]Goddard Space Flight Center, Greenbelt, MD USA

ABSTRACT

The four Constellation-X Spectroscopy X-ray Telescopes require four sets of 2,600 thin mirror segments be supported with minimum deformation and aligned with arc-second level accuracy. We have developed a support and alignment system that minimizes segment deformation and allows the mirror segments to be made confocal. This system relies upon a set of five mirror support points at each of the forward and aft ends of each segment. The support points are radially adjustable so as to be able to modify the segment cone angles, thereby correcting any focal length errors. Additional adjustments enable correction of segment centration and tilts to correct co-alignment errors and minimize comatic aberration.

The support and alignment system is described and results are presented. Included are data demonstrating minimal levels of figure distortion. Results are compared with error budget allocations.

Keywords: x-ray optics, mirror support systems

1. INTRODUCTION

The Constellation-X mission is described in references 1 and 2. In its most recent conception, Constellation-X contains four Spectroscopy X-ray Telescopes (SXTs'). In order to obtain the mirror effective area required to do Constellation-X science, thin (0.4 mm), closely nested glass elements are used. These glass elements are thermally formed from thin, flat sheets of glass. These glass sheets (substrates) are limited in size, as are the mandrels which are used in the thermal forming process. Therefore, the SXT mirrors are produced as segments, which are then assembled into segmented modules. The current 1.32 meter diameter SXT design uses five 72° azimuthal segments in an inner ring, surrounded by an outer ring of ten 36° segments. The primary and secondary optics, incorporated into separate modules, must be aligned together to maintain the required optical performance.

Several mounting and alignment approaches for Constellation-X optics have been suggested. In this paper we describe one of the approaches, the "Optical Assembly Pathfinder (OAP)", and results from prototype hardware.

1.1 OAP Concepts and History

The OAP assembly and alignment concept, originally developed several years ago (references 3 and 4), utilizes separate primary and secondary housings. Individual primary and secondary optical segments are loaded into separate housings and each is supported (axially) on its front and back ends. The optics are radially adjusted using mechanical adjusters, then epoxy bonded into slots in attachment rails. Adjustment of the optics is done in the vertical orientation so as to minimize the effects of gravity on the optics.

OAP assembly and alignment concepts were initially developed and tested at Goddard Space Flight Center in the 2001-2006 timeframe. A series of optical prototypes, designated as OAP1 and OAP2, were used to develop and test the assembly and alignment concepts. In late 2003, an X-ray test was conducted on OAP2 to evaluate its performance (reference 5).

Space Telescopes and Instrumentation 2008: Ultraviolet to Gamma Ray, edited by Martin J. L. Turner,
Kathryn A. Flanagan, Proc. of SPIE Vol. 7011, 701112, (2008) · 0277-786X/08/$18 · doi: 10.1117/12.789891

1.2 OAP3 Requirements and "Lessons Learned"

The Constellation-X OAP3 is an evolutionary follow-on to earlier work on the OAP1 and OAP2 and incorporates "lessons learned" from this work. The objectives of the OAP3 work are:

1. Using GSFC produced, slumped, segmented optics, align a pair (primary and secondary) with its focus at the design location, 8.4 meters from the mid-plane.
2. Minimize optical surface distortions induced by the alignment process
3. The aligned optics within the housing should be fixed and amenable to X-ray testing
4. During the alignment process, the use of end actuators to adjust the cone angles, and thus focus position, should be evaluated.

A list of the more significant OAP2 problems and lessons learned, derived from a Scott Owens presentation (Reference 6), is given below:

1. Alignment system (both manual and piezo actuators) was subject to creep and/or drift
2. Adjuster attachment to mirrors (both piezo and mechanical) was unconstrained, leading to hysteresis
3. Alignment system, as designed, lacked an absolute system reference (optical) axis
4. Adjuster placement was not optimal – none on center
5. Initial mechanical positioning of the primary to the secondary was not adequate to achieve a reliable two-bounce alignment
6. OAP2 hardware lacked mechanical references allowing accurate initial installation of optics
7. The Centroid Detector Assembly (CDA) alignment process was not well defined
8. CDA aperture sampling was indeterminate
9. Self-weight deflection was excessive during initial installation of optics.

2. OAP3 DESIGN FEATURES AND ASSEMBLY & ALIGNMENT CONCEPT

To address the issues cited above, the OAP3 effort includes the following items; 1) redesigned optical housing and optic support system, 2) new manual optic adjusters, 3) revised alignment system including an optical axis definition, 4) revised assembly procedure using a co-ordinate measuring machine and low-force probe, and 5) revised CDA alignment process

A solid model view of the complete OAP3 is shown in Figure 1. In this view the OAP3 is in the alignment (vertical) orientation. The wide ends of each optic are up (primary on top). Both primary and secondary optics are mounted in two individual housings which are attached to a center spacer plate,. The spacer plate contains a kinematic mount which is used to mount the OAP3 in the alignment tower. Optic adjusters are shown on the top (wide end) of the primary and the bottom (narrow end) of the secondary. The bottom of the primary and top of the secondary have been bonded into their respective housings.

The attachment of the optic to the housing is shown in Figure 2. Five support rails are used at each optic end, spaced at azimuth angles of [-20,-10, 0, 10 and 20] degrees. The bonding rails are aligned with the optic radial adjusters, which are shown in Figure 3. The optic radial adjusters capture the optic at the same azimuths as the bonding rails. The optic is held between a spring-loaded ball plunger and a fixed ball. radial adjustment is done using manual differential micrometers.

In the prior OAP designs the initial optic placement was inadequate, due to a lack of precision mechanical references and metrology for accurate measurement of optic position relative to mechanical references. The OAP3 has been designed to use a Co-ordinate Measuring Machine (CMM) for initial optic placement. Figure 4 shows the setup for optics assembly into their housings. The housing sits in a fixture on the CMM surface plate. For this application an Apollo "Low-Force^{TM}" CMM probe is used. The probe applies a maximum 10 mg force on the optic during a measurement, thus allowing accurate measurement of the flexible optic surface. CMM accuracy using the low force probe is on the order of 2-5 μm.

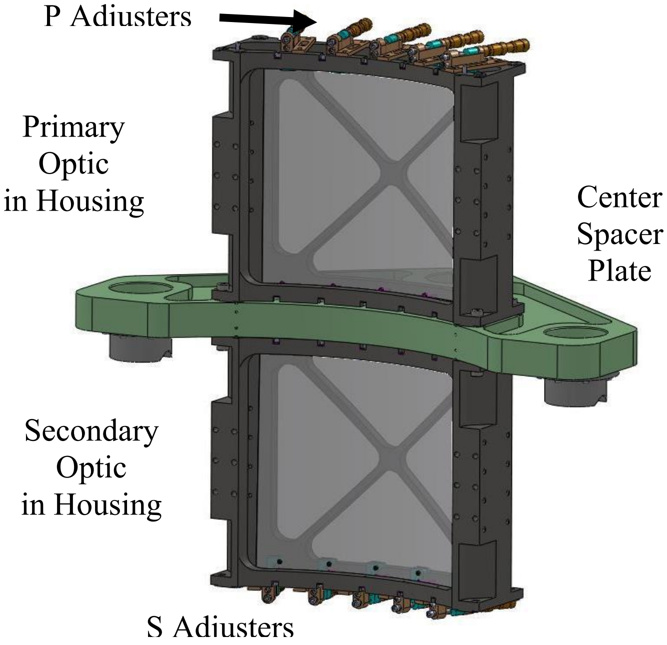

Figure 1 - OAP3 Alignment Configuration

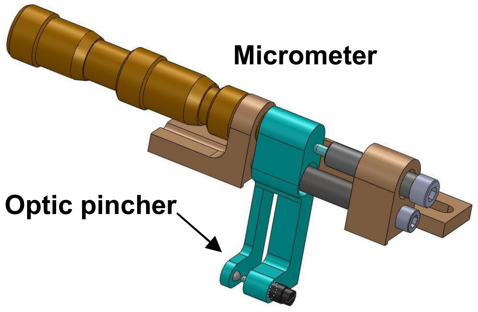

Figure 3 - Optic Adjuster

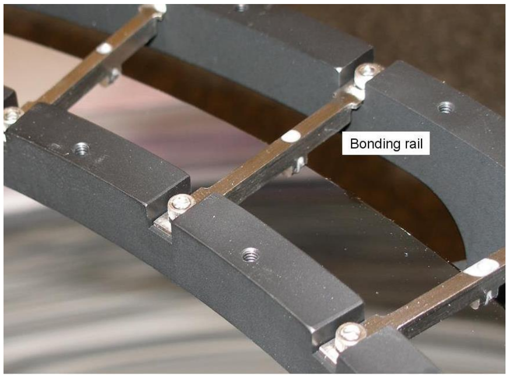

Figure 2 – Optic Support (Bonding) Rails

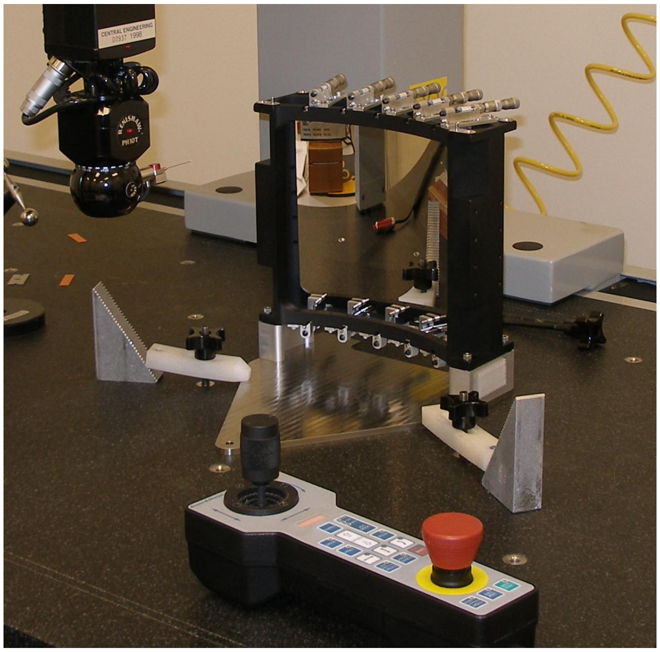

Figure 4 - Optic Installation into Housing

The overall OAP3 assembly and alignment concept is as follows:

1. Using the CMM, position the primary optic in its housing and bond the **narrow end** to the primary housing support rails. Remove the narrow end optic radial adjusters and retain the wide end adjusters.
2. Install the primary optic and housing in the alignment tower with the wide end up. Using the CDA for optical feedback, use the five wide end adjusters to adjust the primary optic to obtain the best image at the 16.8 meter primary focus.
3. Bond the primary wide end to its housing and remove the wide end adjusters.
4. Again using the CMM, position the secondary optic in its housing and bond the **wide end** to the secondary housing support rails. Remove the wide end optic radial adjusters and retain the narrow end adjusters.
5. Attach the secondary optic and housing to the center spacer plate in its nominal location.
6. Install the primary optic and housing onto the center spacer plate and, using CMM measurements of the locations of both secondary and primary optics, adjust the primary housing and optic to the required position **relative to the secondary**. This operation is performed on the CMM.
7. Install the OAP3 assembly in the alignment tower. Using the CDA for optical feedback, use the five narrow end secondary adjusters to adjust the primary/secondary pair to obtain the best image at the 8.4 meter OAP system focus.

2.1 Assembly of Primary and Secondary Optics to Housings

The narrow end of the primary optic is bonded to its support rails, which are attached to the primary housing. To do this, primary optic is initially placed into its housing in the "wide end down (WED)" orientation (allowing access to make the bonds of the optic to the support rails). The primary housing is mounted on a fixture which sits on the CMM surface plate. Five radial adjusters are installed on the bottom (wide end). Two of the adjusters (at ± 10 degrees) have vertical supports to support the optic. These two adjusters are mounted on vertical stages to allow adjustment of optic rotation about its radius. Five more adjusters are placed on the top (narrow) end. These adjusters are placed over optic support rails which are attached to the housing. The CMM co-ordinate system is aligned to the housing using precision reference surfaces (see Figure 1) on the housing. The optic radii are adjusted, using the 10 adjusters, based on CMM measurements of optic radii at the adjuster locations. The optic radii at the ten locations are adjusted to the **design** radii values within ~5 µm. A complete 2D scan of the optic is performed to verify the optic adjustment. If the adjustment is acceptable, the optic is bonded to the five upper (narrow end) rails. After the bonds have cured, the adjusters are removed and the surface figure is measured again using the CMM. It is also measured (in a series of axial slices) using a ZYGO interferometer .

The secondary optic is installed into its housing and adjusted, using a procedure similar to that for the primary. In the case of the secondary, the wide end is bonded to the housing.

2.2 Assembly of the Primary and Secondary Housings to the OAP3

Assembly of the complete OAP3 takes place after the individual primary and secondary optics have been installed into their housings (and bonded at one end) and the primary optic has been aligned to its housing using the CDA. Assembly of the OAP3 is performed on the CMM surface plate. The first step is to install the secondary optic and housing onto the OAP3 center plate. The secondary housing is bolted and pinned to the center spacer plate in its nominal location.

The center spacer plate/secondary housing sub-assembly is then moved to the CMM surface plate and supported on three spacer blocks, as shown in Figure 5. The primary optic/primary housing assembly is then installed onto the center spacer plate, using CMM measurements to obtain the optimal alignment of primary to secondary optics. Experience has shown that CMM measurements of optic position and figure are extremely sensitive to the alignment of the CMM's reference co-ordinate system. Therefore, the CMM co-ordinate system will be aligned to the secondary housing for this assembly operation. After alignment of the CMM, the optical surfaces of both primary and secondary will be measured ***in the same co-ordinate system***. The primary housing and optic will be manipulated (as a rigid body) in six degrees of freedom to obtain the optimum positioning of the primary and secondary optics relative to each other. After this is done, the primary housing will be **bonded** to the center spacer, thus preserving the alignment between the primary and secondary optics. The assembled OAP3 will then be moved to the alignment tower for final alignment of the optic pair.

2.3 Optical Alignment Using the Centroid Detector Assembly

OAP3 optical alignment is performed using the Centroid Detector Assembly (CDA), with a double-pass procedure very similar to that used for OAP2. A brief description will be given herein. A more complete description can be found in reference 3. The CDA is described in Reference 8.

The OAP3 alignment is setup is shown in Figure 6. Three 12 foot optical tables are joined to support the CDA, alignment tower and necessary fold flats. The CDA is positioned at one end of the tables. It produces a narrow laser beam which may be steered in two angular degrees of freedom. Figure 6 shows this laser beam folded to operate at the 16.8 meter primary focus. The OAP3 is mounted in a vertical orientation in an "alignment tower". A 45 degree fold flat sits beneath the tower to re-direct the CDA beam up into the OAP3 optics. After passing through the OAP3, the beam is reflected off a retro-flat and back through the system, to be imaged by a detector within the CDA. OAP3 Alignment is done by commanding the CDA to scan a series of azimuthal locations along the nominal optic aperture. If the OAP3 is positioned correctly relative CDA, and the optics are aligned, then all of the return spots will be centered in the CDA detector. Optical alignment of the OAP3 thus has three steps; 1) alignment of the setup itself without the OAP3, 2) positioning and alignment of the OAP3 with respect to the setup and 3) adjustment of the OAP3 optics to obtain the optimal set of return spot positions.

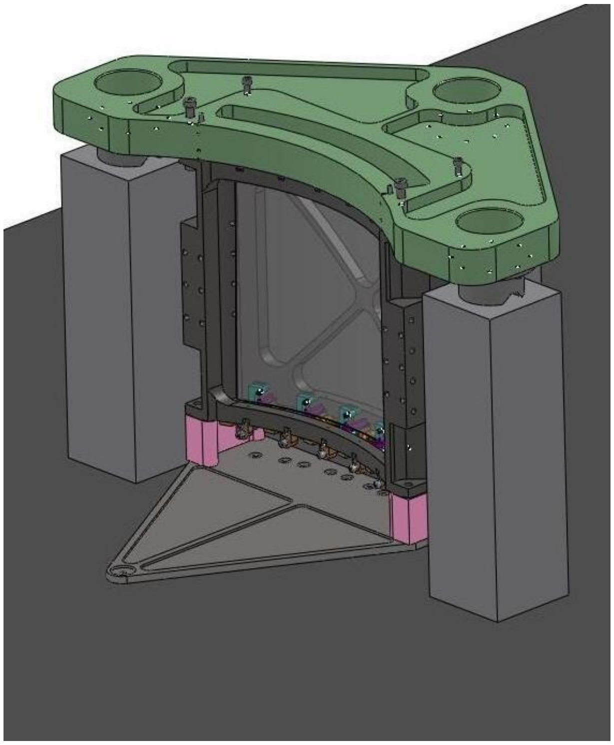

Figure 5 - OAP3 Assembly on CMM

Alignment of the Setup

The CDA was designed as a metrology tool to be used in alignment of grazing-incidence x-ray optics, and was first used in the alignment of the Chandra X-ray telescope. As such, it outputs a laser beam which has a center or "origin" position. The laser beam can be steered in two angular degrees of freedom away from its origin. Steering of the output beam is done by first entering a fixed distance, designated as the "focus distance", and commanding the beam position in 2 DOF in a plane located at the focus distance from the CDA, the "focus plane". The objective of "setup alignment " is to adjust the positions and rotations of the all the components such that the CDA "origin", or the on-axis reference beam, is reflected back on itself, thus centering the on-axis beam in the CDA detector. This process establishes the optical axis of the system.

The tower/retro-flat and 45 degree fold flat are positioned at the end of the table. The 45 degree fold flat is adjusted to a 45 degree angle, with respect to gravity, using a theodolite. The retro-flat is leveled to gravity (in one axis) by using the already adjusted 45 degree flat and the theodolite. This process is repeated in a second axis orthogonal to the first. The final result is that the retro-flat is normal to gravity. During this process, the 45 degree flat is also positioned with respect to the tower, and rotated such that it faces the long axis of the optical table.

The CDA and (at the 16.8 meter only) auxiliary fold flats are then positioned and aligned. The requirements are; 1) adjust the path length of the CDA on-axis beam to be either 8.4 or 16.8 meters, depending on the type of alignment, 2) adjust the CDA on-axis beam such that it returns onto itself and is thus centered in the CDA detector and 3) locate the CDA so that the on-axis beam hits the front lower edge of the fold flat (this allows the CDA to be used both "on-axis" and at the OAP3 radius.

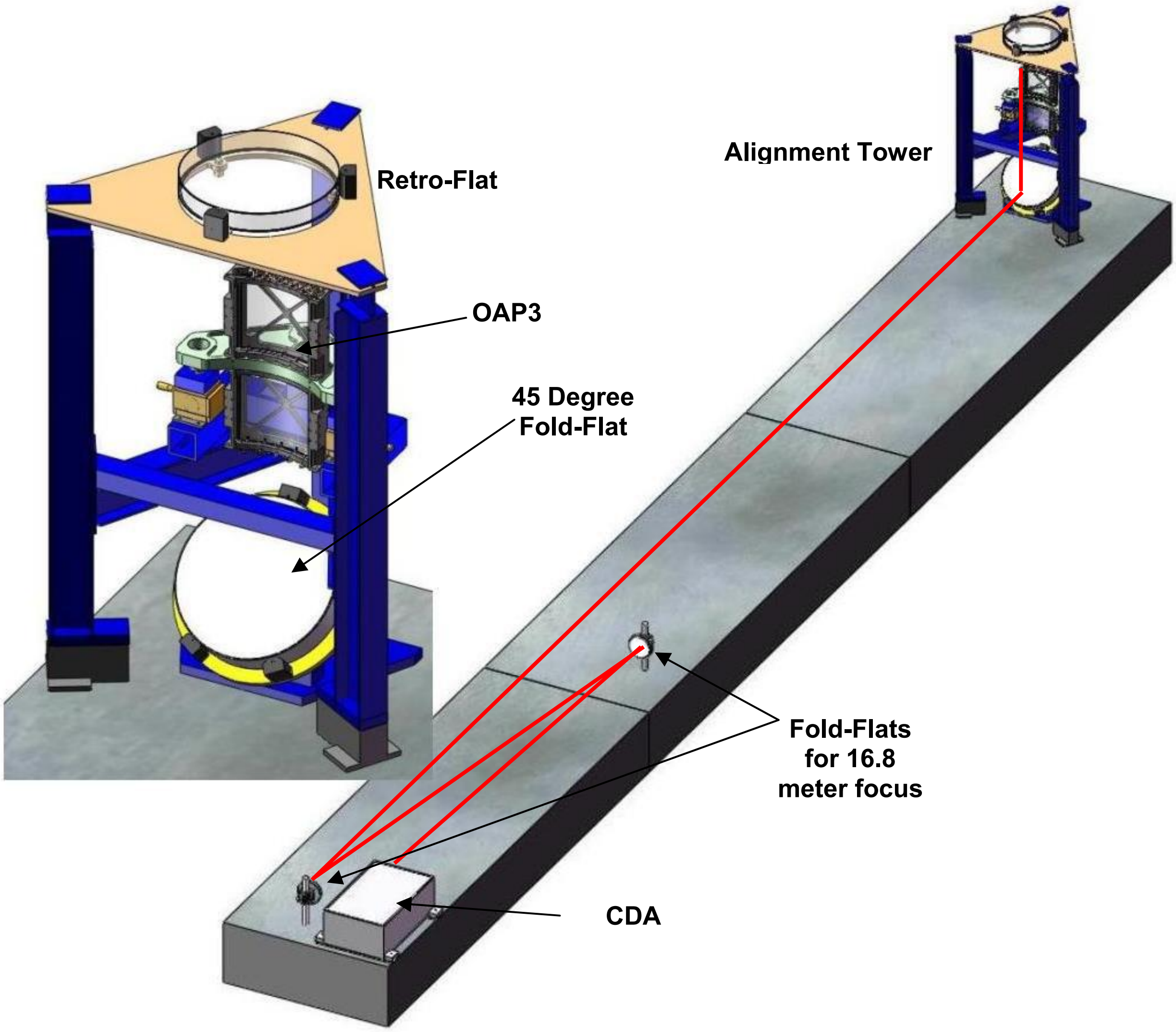

Figure 6 - Alignment Setup (16.8 meter focus)

Positioning and Alignment of the OAP3 in the Alignment Setup

After the setup is aligned, the OAP is positioned in the setup. The objective in this step is to align the OAP3 optical axis with the CDA “on-axis” beam and to rotate the OAP3 about its optical axis so that the mid-plane of the OAP3 is aligned with the (vertical) plane containing the input on-axis beam. We have provided an optical reference system on the OAP3 which consists of two small apertures, mechanically aligned to the build axis of the optic, and separated as far as possible along this axis. The on-axis apertures are incorporated into two aperture plates which also provide apertures for aligning the optics. This system is shown in Figure 7. Alignment of the OAP3 is done by translation in Y and Z and rotation about Y and Z (see Figure 7). These adjustments are iterated until the CDA on-axis beam is coincident with the line between the two on-axis apertures. This is determined by maximization of the return image power. The OAP3 is also rotated about its optical axis to align its mid-plane with the plane of the on-axis beam. The rotation needed is sensed by evaluation of the peak return power location for the various apertures.

Adjustment of the OAP3 Optics

As shown in Figure 1, the OAP3 adjuster system allows adjustment along a discrete number (5) of mirror azimuths. Between these adjustment points, we will use the Centroid Detector Assembly (CDA) to measure the average axial slope for a discrete number of apertures along the mirror's azimuthal span. The CDA is an implementation of the classic Shack-Hartmann test modified for grazing incidence optics: A laser, placed at the theoretical focus of the optic, illuminates the optic and is reflected by a flat, returning to the CDA by the same path (a double-pass system). For perfect optic, the return spots, whose positions are measured by a calibrated quad cell, would all return to the focal point. Deviations from this in the pattern of the return spots can be used to identify the nature of the deviations from the desired low-order optical performance.

We have developed software to analyze the Shack-Hartmann test data and fit it to a set of five coefficients of low-order figure: pointing (phase and magnitude), focal length, and coma (phase and magnitude). From these coefficients we develop a set of mirror adjustments which correct pointing and minimize the focus error and coma. The measurements can be repeated after each set of adjustments until the optimum mirror alignment is achieved.

3. IMAGE RESOLUTION REQUIREMENTS

3.1 Image Resolution Error Budget

The Constellation-X Image Resolution Error Budget is given in Table 1. Although this budget is for the flight system, many elements of the budget are applicable to the OAP development work. These terms are listed below, along with their allocations (HPD, in arc-seconds):

1. Gravity Release (1.50)
2. Bonding Strain (2.00)
3. P-S alignment in module using the CDA (3.38)
4. Reflector Installation in Sub-module Housing (3.54)

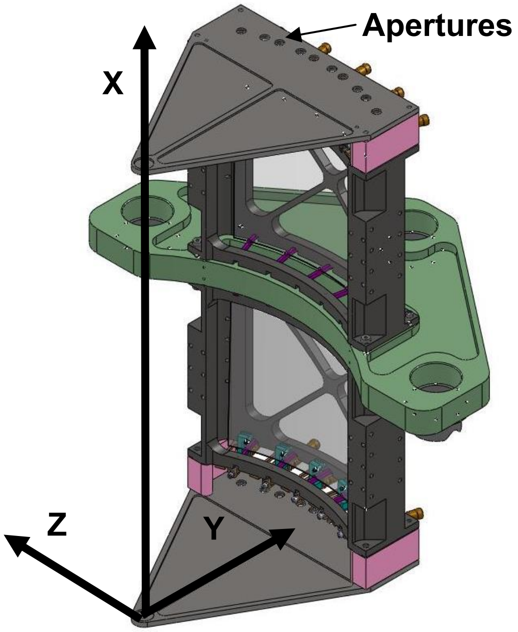

Figure 7 - OAP3 With Aperture Plates

4. RESULTS, STATUS AND FUTURE PLANS

The OAP3 hardware needed has been designed and fabricated. This includes two aluminum housings, a center spacer plate, ten adjusters, ten rails and two aperture plates. The aluminum housings are considered as prototypes, since their CTE does not match the optics CTE very well. After the concepts are proven, new housings will be machined from Titanium, which is a much better match to the optics CTE. All of the alignment support equipment has been either manufactured or purchased. The alignment system has been setup and tested.

The CMM programs needed to make the initial optic adjustments have been developed. Several primaries have been adjusted and bonded into the primary housing. Each has been measured both on the CMM and the ZYGO interferometer. We are now in the process of aligning a bonded primary in the alignment setup.

Table 1 - Constellation-X Image Resolution Error Budget

Micro-calorimeter Spatial Resolution Requirements Error Budget - Mission(4 SXTs, single Atlas V Launch)

	ITEM (HPD - arcsec)	RQMT	Margin	Pred	Allocation					RATIONALE
1	Calorimeter Resolution	15.00	6.12	13.69						4 SXTs, post-processed
2	Co-add 4 SXTs				1.00					Superposition of data using x-ray centroids
3	On-Orbit Single Telescope				13.66					RSS
4	Calorimeter pixelization error					2.78				5 arc-second pixels
5	Telescope level effects					4.80				RSS
6	Image Reconstruction errors (over obs)						4.24			RSS
7	Attitude knowledge drift							3.00		ACS Specification
8	FMA/XMS focal plane drift (thermal)							3.00		Chandra experience (no FID system)
9	FMA/XMS vibration effects						2.00			Chandra experience (jitter)
10	FMA/XMS misalignment (off-axis error)						1.00			Chandra experience
11	FMA/XMS Focus Error						0.20			Analysis - includes focal plane adjustment
12	FMA On-orbit performance					12.48				RSS
13	SXT Mirror launch shifts						2.00			Eng est based on Chandra
14	On-orbit Thermally Driven Errors						2.24			RSS
15	Bulk temperature effects							1.00		FEA Analysis for 1 deg C control
16	Gradient effects							2.00		FEA Analysis for 400µm glass, 20µm epoxy, 1 deg C
17	Material stability effects						1.00			Est based on Chandra work
18	FMA/Telescope mounting strain						1.00			Eng estimate based on Chandra experience
19	FMA, As built						12.03			RSS
20	Gravity Release							1.50		FEA Analysis using vertical assy
21	Bonding Strain							2.00		Eng Estimate, analysis in process
22	Module to Module alignment							2.00		
23	P-S alignment in module(using CDA)							3.38		RSS
24	CDA Dynamic Accuracy								0.76	Analysis of CDA (P. Glenn memo 10-23-02)
25	CDA Static Static Accuracy								1.68	Analysis of CDA (P. Glenn memo 10-23-02)
26	Thermal Drift								2.00	Est based on OAP1 Testing
27	Adjustment Accuracy								2.00	Est based on OAP1 Testing
28	Reflector Installation in Sub-module Housing							3.54		Est based on OAP1 Testing
29	Distort. & misalign. due to module packing							3.54		allocation
30	Reflector Pair (P-S)							9.90		Est based on tech dev program to date
		Rqmt		Margin		RSS Predict		Allocation		

4.1 Installation of Optics Into Housings

Several optics have been installed in housings using the procedure described above in §2.1. Experience with these optics has shown that we can adjust the optic to the desired radii, ***at ten locations near the adjusters*** , within about ±2µm. Figure 8 shows a surface map for primary optic 494P-406, plotted from CMM data, made after adjustment but before bonding. In the figure, radial deviations from the ideal optic radii are plotted vs. azimuth angle and optic height (denoted as Z in this figure). Figure 9 shows the same information, but taken after the optic has been bonded at the five upper locations and the upper adjusters removed.

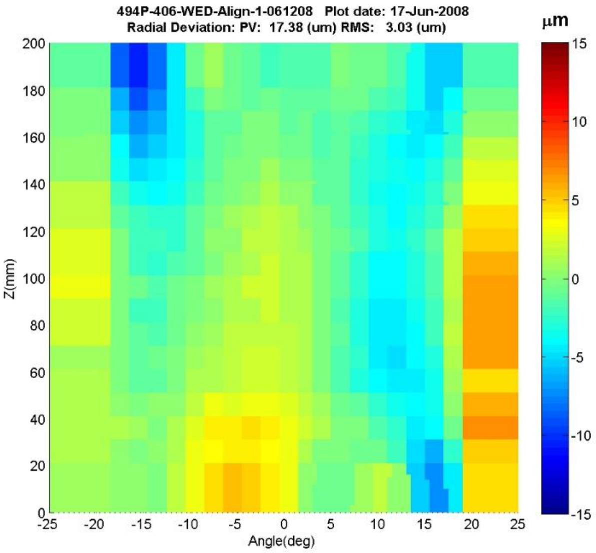

Figure 8 - 494P-406 Surface Map from CMM Data Pre-Bonding

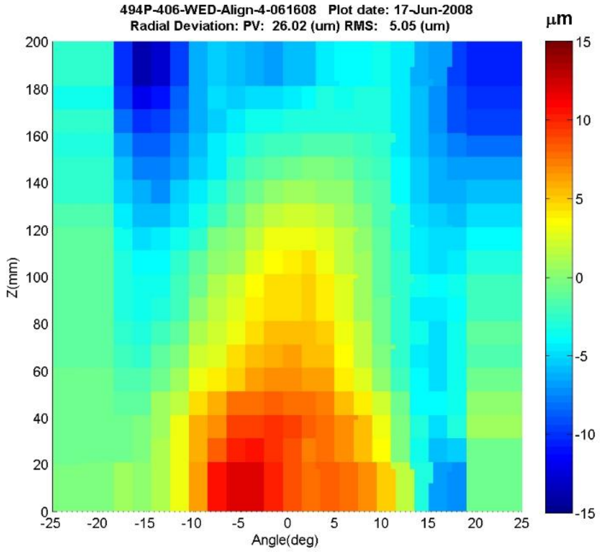

Figure 9 - 494P-406 Surface Map from CMM Data Post-Bonding

Figure 8 shows that the radial deviations at some locations on the optic are larger than the ±2µm to which it has been adjusted. We believe that this is due to small moments which are introduced into the optics by the adjusters, coupled with the optic stiffness and overall restraint conditions. Figure 9 shows the effects of bonding the optic into rails at 5 locations on the top, plus drifts (in the lower adjusters or thermally induced). The radial deviations shown in Figure 9 translate into average axial slopes of about ±15 arc-seconds, depending on the azimuth angle, and must be adjusted out during the CDA alignment process. When the slopes are adjusted out, we are left with Δ radius errors of about 15 µm, which are within the error allocations.

4.2 Interferometry on the Bonded Optic

After the optic has been bonded into its housing at one end (using the CMM adjustment process) the surface deformations are measured using a ZYGO interferometer. Figure 10 shows the surface deformations for optic 494P-406, taken after the upper end has been bonded into the housing, but prior to any further adjustments. The data in Figure 10 are taken using a plane-wave technique, which yields data as a set of axial slices of the optic figure at different azimuth angles. Piston and tilt are removed from each axial slice individually, so the resulting stitched-together map represents the optical surface after the tilts have been aligned out. The figure shows the upper 150 mm of the optic, since we are using a six inch transmission flat in the ZYGO. The roughness of the data in some locations is due to optical surface (dust) and coating imperfections.

4.3 Adjustment of the Primary Using the CDA

The primary optic in its housing is adjusted to obtain the best image possible at the 16.8 meter primary only focus. The setup for this is shown in Figures 11, 12 and 13. The optic (494P-406) in its housing, attached to the center spacer plate (Figure 13), are mounted in the alignment tower (Figure 12), which has already been aligned. We are currently performing the alignment of the primary at the 16.8 meter focus, using the procedure discussed above. In addition to alignment at the 16.8 meter focus, we will explore out ability to change the focus position by moving all the adjusters in the same direction. After these tests the primary will be readjusted to obtain the best image at the 16.8 meter focus, then bonded into the rails. ZYGO testing will be done to evaluate the optical surface quality.

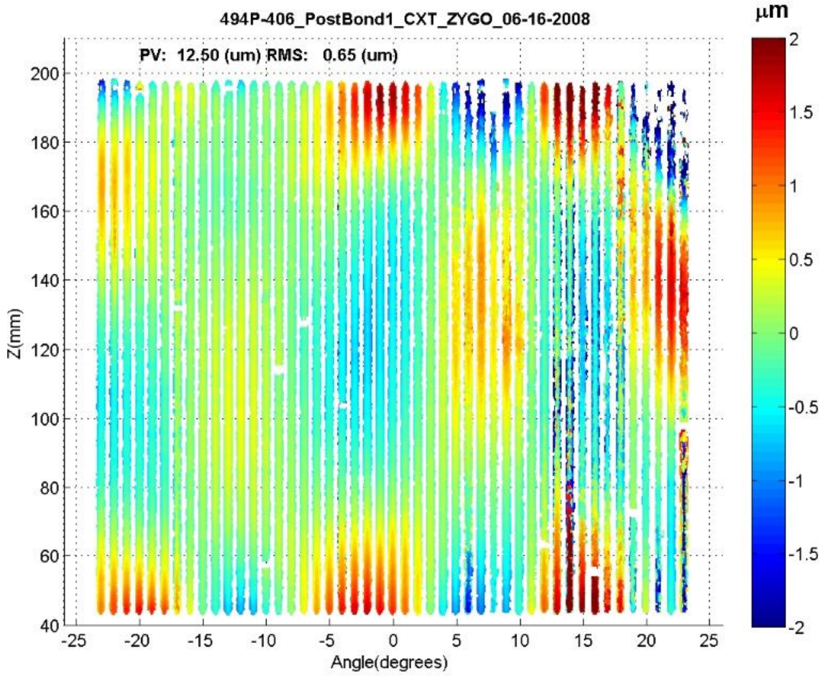

Figure 10 – Post-Bonding ZYGO Surface Map of Optic 494P-406

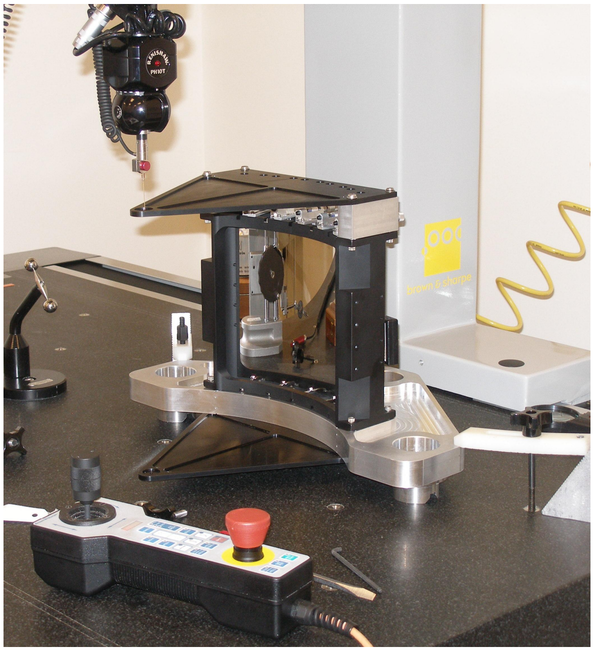

Figure 11 – OAP3 Primary and Housing with Aperture Plates

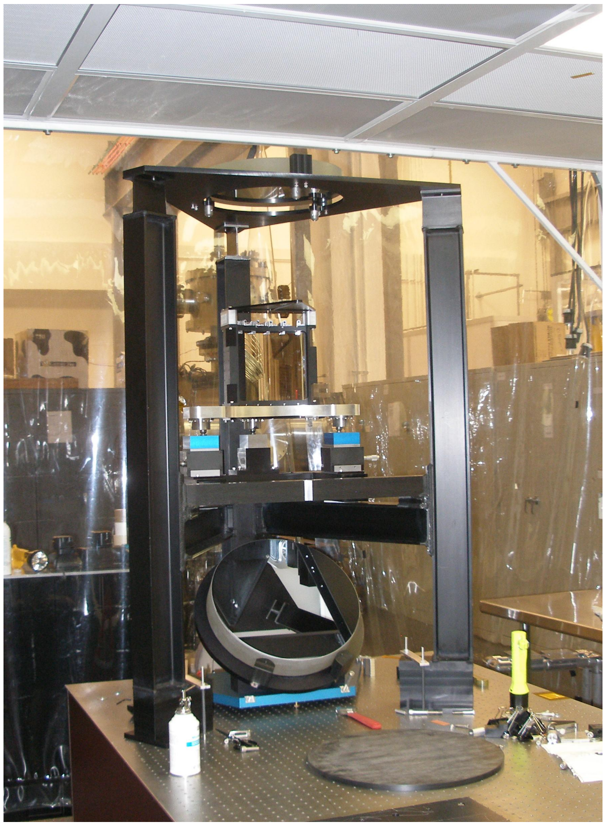

Figure 12 - Primary in Alignment Tower

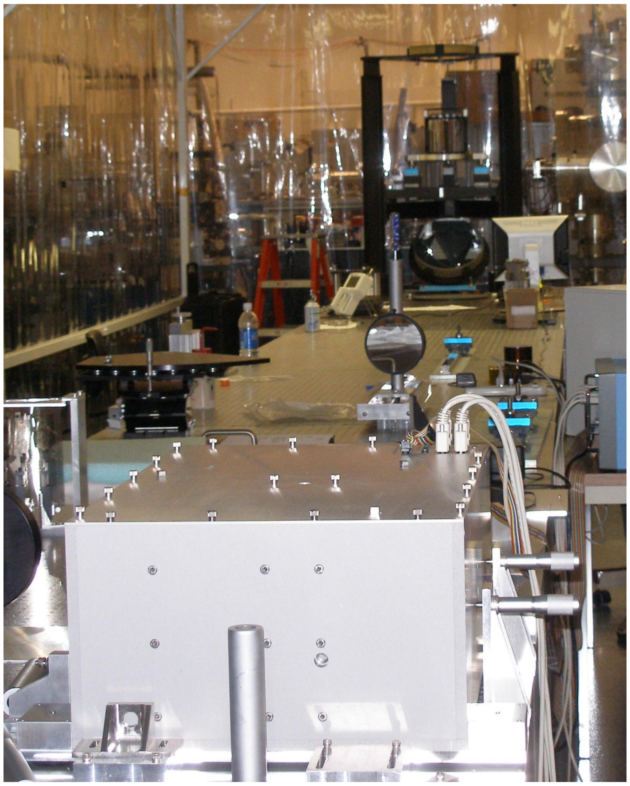

Figure 13 – OAP3 Alignment Setup

4.4 Future Plans

We are now performing the primary alignment procedure. After this is complete we will complete the OAP3 as described above, in the following sequence:

1. Install the secondary optic in its housing and bond the wide end.
2. Perform ZYGO testing on the secondary.
3. Install the secondary housing and optic onto the center spacer plate.
4. Align the OAP3 at the 8.4 meter focus.

REFERENCES

[1] N.E. White and H. Tananbaum, “Constellation-X Mission: Science Objectives and implementation Plan”, SPIE Proc., vol. **4851**, 293 (2003).

[2] R. Petre, *et al.*, “Constellation-X Spectroscopy X-ray Telescope (SXT)”, SPIE Proc., vol. **4851**, 433 (2003)

[3] S. M. Owens, *et al.*, “Constellation-X SXT optical alignment Pathfinder 2: design, implementation, and alignment”, [SPIE 5168-27] (2003)

[4] W. Podgorski, *et al.*, “Constellation-X Spectroscopy X-Ray Telescope Optical Assembly Pathfinder Image Error Budget and Performance Prediction”, [SPIE 5168-35](2003)

[5] S. L. O'Dell, *et al.*, “X-ray testing Constellation-X optics at MSFC's 100-m facility”, [SPIE 5168-34](2003)

[6] S. M. Owens, “OAP2 Problems, Potential Fixes and cost/benefit estimates”, Briefing Note, 1/25/2007

[7] P. E. Glenn, “Centroid detector assembly for the AXAF-I alignment test system”, SPIE 2515, pp352-360 (1995)