Recent Progress on the Constellation-X Spectroscopy X-Ray Telescope (SXT)

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ABSTRACT

The Constellation X-ray Observatory consists of four identical spacecraft, each carrying a complement of high sensitivity X-ray instrumentation. At the heart of each is the grazing incidence mirror of the Spectroscopy X-ray Telescope (SXT). This mirror has a diameter of 1.6 m, a focal length of 10 m, mass not exceeding ~650 kg. The required angular resolution is 15 arc seconds and the effective area at 1 keV must exceed 7,500 cm^2. Achieving these performance requirements in a cost effective way within the allocated mass is accomplished via a modular design, incorporating lightweight, multiply-nested, segmented Wolter Type I X-ray mirrors. The reflecting elements are composed of thin, thermally formed glass sheets, with epoxy-replicated X-ray reflecting surfaces. Co-alignment of groups of reflectors to the required sub-micron accuracy is assisted by precision silicon microstructures. Optical alignment incorporates the Centroid Detector Assembly (CDA) originally developed for aligning the Chandra mirror. In this talk we present an overview of recent progress in the SXT technology development program. Recent efforts have concentrated on producing an engineering unit that demonstrates all the key fabrication and alignment processes, and meets the angular resolution performance goal. Additionally, we describe the initial steps toward flight mirror production, anticipating a Constellation-X launch early in the next decade.

Keywords: X-ray mirrors, Constellation-X

1. INTRODUCTION

Constellation X is NASA's next flagship X-ray astronomy observatory. It is a cornerstone component of the *Beyond Einstein* program, an initiative by the Structure and Evolution of the Universe theme expected to receive congressional approval and initial funding starting in October 2003. The primary science goals of Constellation-X are to use X-ray spectroscopy to study the strong gravity environment & evolution of black holes, dark matter throughout the universe, and production and recycling of the elements. Fulfilling these goals requires sensitivity 100 times that of *Chandra* with higher spectral resolution. This large increase in sensitivity is accomplished by the use of four spacecraft equipped with identical instrumentation, which will be launched in pairs to the sun-earth L2 point in 2013 and 2014. The workhorse instrument is the Spectroscopy X-ray Telescope (SXT), consisting of a large, high throughput mirror, a reflection grating that intercepts half the converging mirror beam and diverts it to CCD, and a calorimeter that collects the undiverted radiation. The overall spectral resolution of the system is higher than 350 across the entire 0.3-10 keV band, and is >1500 at the important Fe band around 6 keV. The SXT angular resolution requirement is a half power diameter (HPD) of15 arc seconds; the program goal is to achieve 5 arc second HPD angular resolution.

The heart of the SXT is the SXT mirror. The performance requirements of this mirror based on the scientific objectives are listed in Table 1. The properties of the baseline design are compiled in Table 2.

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As with its predecessors on *Chandra* and *XMM-Newton*, the SXT mirror is the enabling technology of the observatory. A substantial effort has been underway over the past several years to develop the processes necessary to construct the

SXT mirror and to understand how to scale the fabrication and alignment processes so that four SXT mirrors can be constructed, calibrated and delivered in rapid succession.

Table 1
SXT mirror requirements

Performance requirements		
Bandpass	0.25-10.0 keV	
Effective area (per mirror)		
@0.25 keV	8,825 cm^2	33,000 cm^2 @ 1.25 keV and 6,900 cm^2 @t 6.0 keV for mission.
@1.25 keV	8,420 cm^2	Allows for losses due to grating and detector inefficiency.
@6.0 keV	1,720 cm^2	
Angular resolution	12.5 arc seconds HPD	Consistent w/ system level HPD of 15 arc seconds.
Field of view	2.5 arc minutes	Defined by detector field of view.
Derived requirements		
Diameter	1.6 m	To meet mission area requirements with four mirrors.
Focal length	10 m	Consistent with grazing angle requirements for 1.6 m mirror.
Reflector axial length	>20 cm	To fit within envelope and meet fabrication considerations.
Operating temperature	20±1 C	Keeps thermal distortions from driving HPD beyond 12.5 arc sec.
Mass	650 kg	Current engineering estimate.

This paper is intended to provide an overview of the Constellation-X SXT mirror technology development activities. As documented by the contributions to this conference by SXT mirror team members, progress is occurring in numerous areas.[1-8] The technical details of that progress are left to those papers; a summary is presented here. To place the technology development effort into context, an overview of the SXT mirror technology development program is presented here.

Table 2
SXT mirror baseline design parameters

Design	Segmented Wolter I
Reflector substrate material	Thermally formed glass
Reflecting surface fabrication	Epoxy replication
X-ray reflecting surface	Gold
Number of nested reflectors	140 (inner module); 90 (outer module)
Total number of reflectors	3,840
Reflector axial length	20 cm
Number of modules	6 (inner); 12 (outer)
Module housing composition	Ti alloy, CTE-matched to substrate
Largest reflector surface area	0.16 m^2
Substrate density	2.4 g cm^{-3}
Reflector thickness	0.4 mm
Reflector microroughness	0.4 nm RMS

2. BASELINE DESIGN

A schematic of the SXT mirror is shown in Figure 1. The key SXT mirror properties are listed in Table 2. The SXT mirror is a highly nested, segmented Wolter I mirror. It has an outer diameter of 1.6 m and a focal length of 10 m. The length of each reflecting segment (primary and secondary) is 20 cm. A total of 230 nested rings of reflector pairs are incorporated in the design. The inner 140 reflector pairs are segmented azimuthally into six modules, the remaining outer reflectors into twelve. Thus, 3,840 reflectors are needed for each of the four SXT mirrors. The reflector substrates consist of 400 μm glass (Desag D260) sheets, thermally formed to the correct figure. The optical surface is gold, imparted onto the substrate via replication, using a thin (~10 μm) layer of epoxy. The effective area of the mirror is at least 8,400 cm^2 at 1.25 keV and at least 1,700 cm^2 at 6 keV. In order for the SXT to meet the15 arc second HPD angular resolution requirement across its 0.3-12.0 keV bandpass, the SXT mirror HPD must be smaller than 12.5 arc seconds. The mass of the SXT mirror is required to be less than about 650 kg.

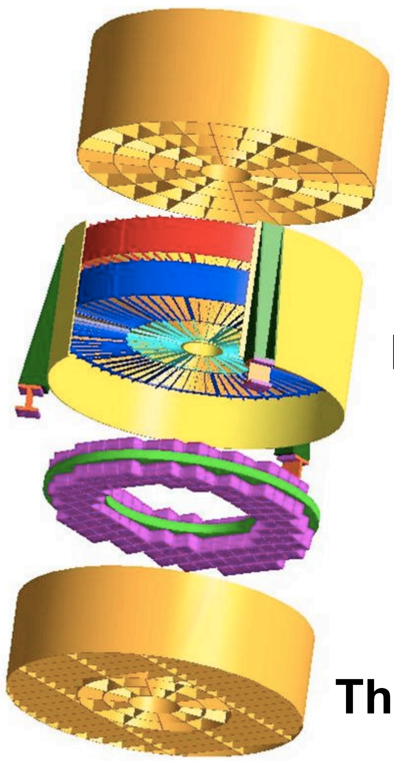


Figure 1: A schematic of the Constellation-X Spectroscopy X-ray Telescope (SXT) Flight Mirror Assembly (FMA).

The SXT mirror is embedded within the Flight Mirror Assembly (FMA), shown schematically in Figure 2. In addition to the SXT mirror, the FMA includes the reflection grating array and thermal pre- and post-collimators.

3. TECHNOLOGY DEVELOPMENT APPROACH

As with any large, complicated system, technology development for the SXT mirror follows a phased approach. The initial units are relatively simple, and increasing complexity and realism are introduced progressively in later units until a true prototype system emerges. The key steps in the technology development program are summarized below. Figure 3 shows schematics of the units in the technology development program and figure 4 summarizes the key components and goals of each.

3.1 Optical Alignment Pathfinder 1 (OAP1)

The OAP1 represented our first attempt to develop a housing that would allow manipulation of the reflectors at the micron level. It was designed to work with the 50 cm diameter, 8.4 m focal length segments, subtending a 60-degree arc. It consists of a housing with five radial struts equally spaced azimuthally at the entrance and exit aperture (front and

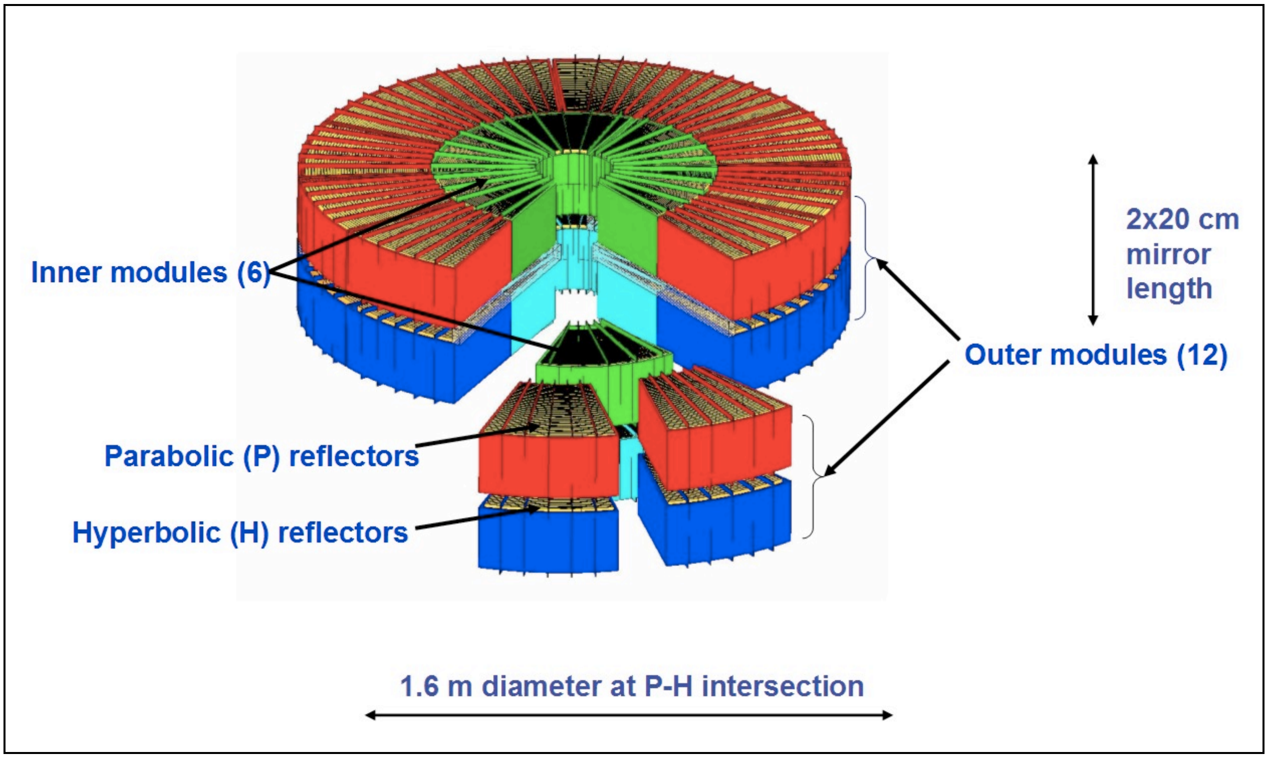


Figure 2: Schematic of the Constellation-X SXT mirror.

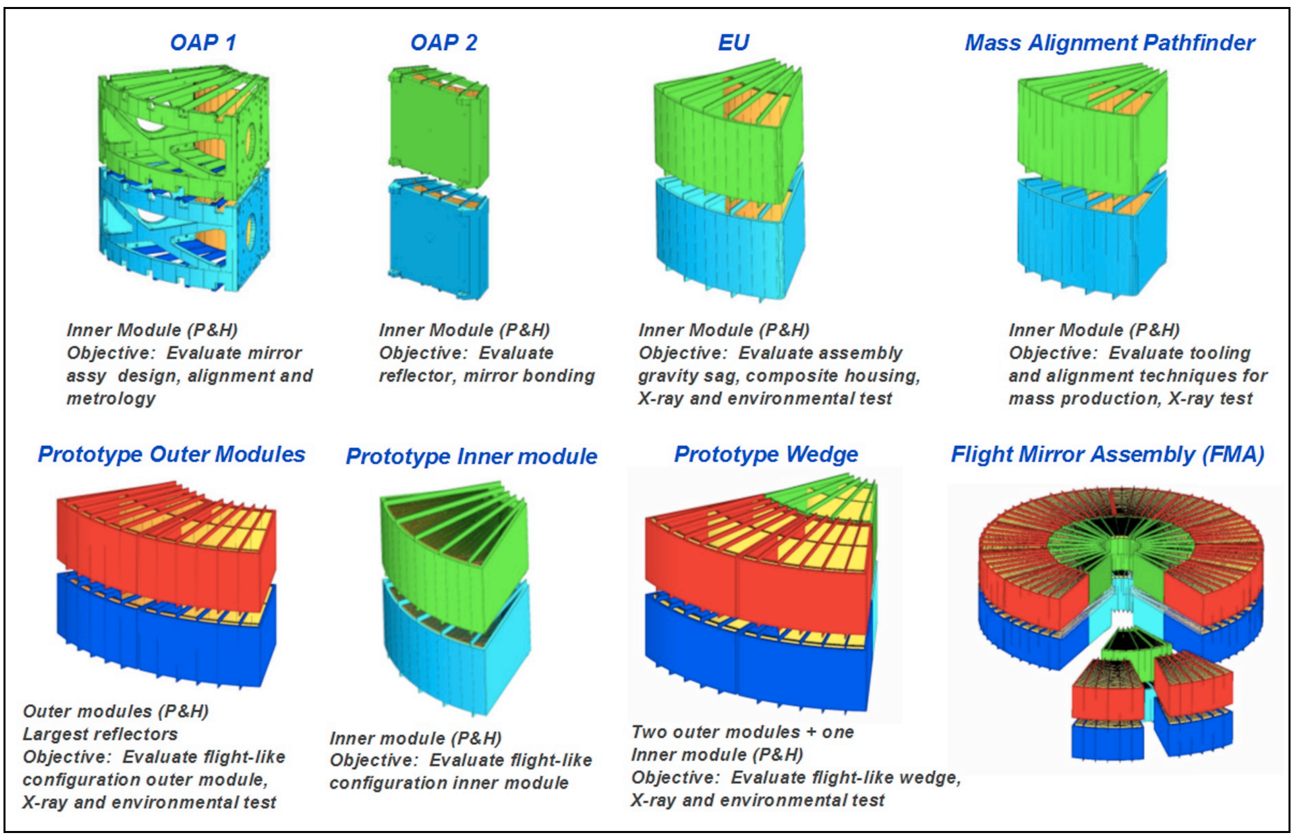


Figure 3: Phased buildup of SXT mirror modules.

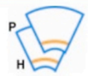
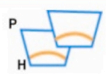
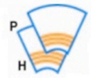
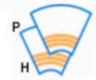
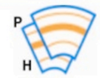
	Optical Pathfinder Assembly		Engineering Unit	Mass Alignment Pathfinder	Prototype	
	OAP #1	OAP #2				
Configuration						
Module Type	Inner	Inner	Inner	Inner	Outer	Wedge (2 Outer & 1 Inner)
Housing Material	Aluminum	Titanium	Titanium/composite	Titanium/composite	Titanium/composite	Titanium/composite
Focal Length	8.4 m	8.4 m	8.4 m	8.4 m	10.0 m	10.0 m
Reflector Length (P&H)	2 x 20 cm	2 x 20 cm	2 x 20 cm	2 x 20 cm	2 x 20-30 cm	2 x 20-30 cm
Nominal Reflector Diameter(s)	50 cm	50 cm	50 cm±	50 cm±	160 cm 120 cm± 100 cm	160 cm± 120 cm± 100 cm± 40 cm±
Goals	▪ Align 1 reflector pair (P&H) ▪ Evaluate mirror assembly design, alignment and metrology	▪ Align 1 reflector pair ▪ Evaluate reflector ▪ Evaluate mirror bonding	Requirements: ▪ Align one reflector pair to achieve <12.5 arcsec ▪ X-ray test Goals: ▪ Align up to 3 reflector pairs to achieve <12.5 arcsec ▪ Characterize assembly gravity sag ▪ Environmental test ▪ Evaluate housing design	▪ Align 3 reflector pairs ▪ Evaluate tooling and alignment techniques for mass production ▪ X-ray test	▪ Flight-like configuration outer module ▪ Environmental and X-ray test ▪ Largest reflectors	▪ Demonstrate largest and smallest diameter reflectors ▪ Demonstrate module to module alignment ▪ Environmental and X-ray test
TRL	TRL 3		TRL 4		TRL 5	TRL 6
Timeframe	Q2 of FY03	Q3 of FY03	Q4 of FY04	Q2 of FY05	Q2 of FY06	Q4 of FY06
Technology Gate			◆		◆	

Figure 4: SXT mirror technology development plan.

back). Each strut is attached to an actuator with ~micron level control for radial positioning. Two bottom struts have vertical actuators along the axial direction to remove reflector tip relative to the housing axis. In order to facilitate more rapid fabrication, and because it was never intended as a high precision tool, we chose to construct it from aluminum, and cope with the severe CTE mismatch between housing and reflectors by maintaining temperature control over the unit at least over timescales during which experiments were being performed. It served primarily as a learning tool – how to install (and remove) reflectors, how to perform in situ metrology of both axial figure and focus, how to adjust the shape of the reflectors to improve the angular resolution. Despite the fact that reflectors with acceptable figure were unavailable, the OAP1 was extremely useful as a development tool. Much of what was learned has been folded into the design of future housings to improve performance and ease of adjustment. Experiments performed using OAP1 are documented in the paper by Scott Owens et al.[6], and the results summarized briefly in §4.3.

3.2 Optical Alignment Pathfinder 2 (OAP2)

The OAP2 grew out of a desire to perform a "quick" X-ray performance test once a suitable reflector pair was produced. The OAP2 incorporates a simple, thick-walled, monolithic titanium housing, EDM cut from a single parent block. The intent of this construction is to minimize the stresses on the reflectors introduced by the housing when the unit is rotated to horizontal for X-ray testing. Titanium was chosen because it has less of a CTE mismatch with the reflectors than aluminum.

The OAP2 was designed to work in tandem with the OAP1 unit, and contains no internal adjustment mechanisms. It nests inside the OAP1 structure, and uses the precision alignment arms of the OAP1. Aligning reflectors is performed by installing the OAP2 housing with the OAP1 housing and using its actuators. Once alignment with OAP1 arms is complete, and the reflectors have been bonded to their radial support struts, the OAP2 units are removed from the OAP1, and stacked and bonded together. The OAP2 is being used to develop an approach for bonding the reflectors to the housing. It will be used to demonstrate that the glass substrates survive vibration. The alignment experiments to date using the OAP2 are also summarized in the Owens et al. paper[6].

3.3 Engineering Unit (EU)

The goal of the EU effort is to build as flight-like a structure as possible, based on the lessons learned from the OAP work and our best understanding of the modifications needed for flight. The housing will resemble as closely as possible an inner module of the flight mirror, subtending a 60-degree arc. It will be built to hold several reflectors of diameter around 50 cm. It will be constructed out of a titanium alloy whose CTE is close to that of the glass, and made sufficiently rugged that it can undergo vibration testing. Actuators with sub micron accuracy will be introduced in order to facilitate finer adjustments of the reflectors, which by the time the EU housing is available should be meeting or exceeding the Constellation-X requirement. The EU will be the first unit to incorporate multiple reflector pairs. It will allow us to test whether a single mandrel can be used to replicate substrates with a diameter different from the exact match to the mandrel (a potential cost and time saving approach to mandrel procurement). This unit will be subjected to a full suite of X-ray and environmental tests, and will be expected to meet the Constellation-X performance requirements.

3.4 Mass Alignment Pathfinder

Aside from the fabrication of reflectors meeting the angular resolution requirement, the most substantial challenge for the SXT is the accurate and rapid co-alignment of the reflectors. The Mass Alignment Pathfinder provides a platform for experimenting with approaches for doing this. Structurally, the Mass Alignment Pathfinder is identical to the EU, except that it is outfitted with
accurate robotic arms adjacent to each of the mounting struts. As the arms adjust a location along the edge of a reflector, the effect on the image will be monitored at the nominal focus (using the Centroid Detection Assembly, or CDA, and the technique described in §4.3). Using the Mass Alignment Pathfinder we will attempt to establish connections between an adjustment and a response in the focal plane that will facilitate automation. Additionally, simultaneous co-alignment of a group of adjacent reflector pairs will be investigated. This approach might incorporate the accurate etched Si microstructures developed at MIT and currently being baselined for the Constellation-X grating assembly[9].

3.5 Prototypes

The prototypes represent the first full-sized, CTE matched structure with flight like diameter and focal length. The outer prototype will utilize reflectors replicated from the precision 1.0, 1.2 and 1.6 m curvature diameter mandrels fabricated by Zeiss[3]. Two prototypes are planned. An outer module will be produced within the technology development team. Its purpose is to allow us to address issues regarding production, handling and alignment of the largest reflectors. Subsequent prototype work, the production of a full 60-degree sector (sparsely populated by reflectors), will be carried out in partnership with the FMA contractor and will serve as a vehicle for technology transfer.

4. RECENT TECHNOLOGY DEVELOPMENT PROGRESS

The SXT mirror technology development program is concentrating its efforts on 50 cm diameter reflectors, developing appropriate forming and replication facilities and designing appropriately scaled housings and alignment approaches. 50 cm is a good size to work with as it represents a typical diameter reflector from an inner module of the flight design. The 50 cm testbed size was selected because of the availability of precision mandrels with this diameter and an 8.4 m focal length. These mandrels, complete surfaces of revolution composed of Ni-coated aluminum, were procured early in the Constellation-X technology development program for electroforming of Ni shells. They have turned out to be suitable for epoxy replication experiments.

Over the past year, reflector fabrication has emerged as the critical path to meeting the angular resolution requirement. Substantial progress has been made toward fabricating 50 cm reflectors that meet the requirement, and as we document below, the steps that will allow us to accomplish this are fairly clear. In parallel, we have been developing approaches for reflector mounting and alignment, and designing the next housings along our technology roadmap. Preparations have been made for X-ray testing, and we anticipate the first X-ray measurement with a reflector pair meeting the requirement within the next several months. The highlights of our recent work are summarized below.

4.1 Reflectors

The thin glass reflectors represent the key enabling technology for the SXT mirror. As the SXT mirror is the key component of Constellation-X, the viability of the mission depends on producing reflectors that meet the angular resolution requirement. Not surprisingly, the reflectors are the highest priority of the SXT mirror team.

The first 50 cm diameter by 20 cm axial length reflectors were produced several months ago. To date no reflector of this size that meets the Constellation-X requirement has been produced. Substantial progress toward that end has been made, however, and along the way means have been established for potentially exceeding the angular resolution requirement and approaching the goal. The work on the 50 cm reflectors has led to several advances in our understanding.

The initial 50 cm scale replications yielded reflectors whose overall figure was worse than the underlying substrates, an effect not observed with the smaller, 20 cm diameter by 10 cm long reflectors. It was fairly clear that stress imparted by the thin (20 μm thick) layer of epoxy was deforming these larger surface area reflectors. One obvious means of solving this is reducing the epoxy thickness. The epoxy thickness is related to the height of the structure on the substrates it is used to mask. As long as these surface features are on the order of 1 μm, then reducing the epoxy thickness to less than 10 μm will induce "print through." The main contribution of the epoxy is to cover the mid-frequency range ripple, 0.1-10 mm in size. If these ripples can be controlled by other means, such as during the glass forming process, then the epoxy thickness can be reduced. An alternative is to use thicker glass. This has the highly undesirable consequence of driving the SXT mirror mass much higher than its requirement. The third approach, and the one that we have adopted, is to reduce the surface area covered by the epoxy. The usable area of each reflector consists effectively of six distinct zones, separated in the mirror by the shadows of the radial mounting struts. We take advantage of this, and segment the epoxy coating on the surface using the same pattern. Thus each contiguous epoxy coated surface is considerably smaller than the reflector area, thereby reducing the overall stress on the substrate.

A second issue is dust. The overall environment of the facility developed for production of 50 cm and larger reflectors is not well controlled. Despite the fact that all the major reflector production steps were carried out in clean tents, there was clear evidence of dust on the reflectors in the form of millimeter scale ripples on both the substrates and the finished reflectors. After an intensive investigation and the subsequent improvement of handling techniques and airflow in clean tents, the dust contamination has been eliminated from the replication process. It has not been eliminated during the forming, however. The primary remaining dust source is the oven. Despite a wall treatment and the introduction of a metal shield between the walls and the mandrel/substrate, dust effects are still observed, though they now have been reduced to a level where replication removes most of the remaining. We continue to introduce dust reduction approaches, and will eventually move the forming into a clean oven, possibly a vacuum oven.

The real key to producing high quality reflectors is improvement of the overall figure of the substrate. Recent experiments have demonstrated that on scales larger than a few mm, the substrate assumes the forming mandrel shape to a fraction of a micron[8]. Thus making substrates with accurate figure depends on the figure of the forming mandrel.

The recognition of the necessity for accurately figured forming mandrels represents a major shift in the overall approach to reflector development. Previously it was thought that moderately well figured forming mandrels would be sufficient and that the epoxy would remove residual figure error. Use of well figured forming mandrels solves two problems. First, it guarantees the accuracy of the overall substrate figure. Second, it reduces the role of the epoxy to removal of the mid-frequency error. In fact, accurate forming mandrels should reduce the amplitude of the mid-frequency error, allowing the reduction of the epoxy thickness. The thickness reduction, in turn, reduces the stress imparted to the reflector. Over the next few months we will obtain 50 cm forming mandrels figured to 2-4 arc second HPD, far better than required to produce a 12.5 arc second HPD mirror. Forming substrates with these mandrels will allow a determination of any limitation to surface accuracy intrinsic to the forming process or the substrate material.

4.2 Mandrels

The Constellation-X program has taken delivery from Zeiss of two precision (≤4 arc second HPD) Zerodur replication mandrels. The mandrels are monolithic P-H pairs, with a focal length of 10.0 m. Each subtends a 30-degree arc. The diameters of the full shells are 1.6 m and 1.2 m. The 1.6 m mandrel is shown in Figure.5. Delivery of a matching1.0 m diameter mandrel is imminent. Schott is producing a precision Zerodur K20 forming mandrel for the 1.6 m secondary surface. These mandrels are discussed in the presentations by W. Egle et al.[3] and T. Döhring et al.[2]

The purchase of precise replication and forming mandrels has allowed us to demonstrate the feasibility of making mandrels that meet the SXT mirror requirements. It has also allowed the manufacturers to make their fabrication more efficient and gain insight into aspects of the production line that will be necessary to supply the hundreds of mandrels for

Figure 5: A superpolished Zerodur mandrel for replicating 1.6 m diameter, 10 m focal length, 30-degree arc segmented reflectors. The mandrel has both the primary and the secondary reflecting surfaces, and accommodates replication of reflectors with axial length up to 50 cm.

the flight mirror.

4.3 Mounting and Alignment

OAP1: The OAP1 housing incorporates twelve independent actuators for adjusting a reflector. At the front and rear end of the housing are five radial actuators spaced azimuthally. These remove local slope errors in a reflector. At the rear of the housing are two vertical positioners to remove any reflector tip relative to the optical axis. The OAP1 housing is shown in Figure 6 (left) and the stacked OAP1 with reflectors installed is shown in Figure 6 (right).

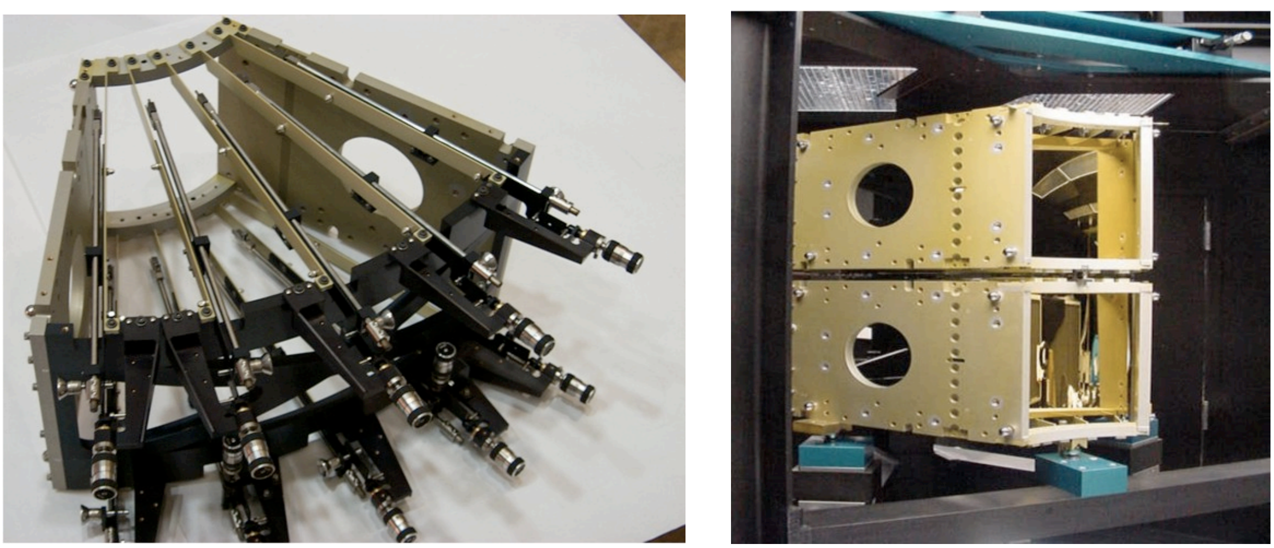


Figure 6: Left – One of two identical OAP1 housings. Top and bottom actuators at five azimuthal locations control local radial position and axial tilt of a reflector. Two vertical actuators control rotation of the reflector optical axis. **Right** – The complete OAP1 unit with reflectors installed.

Two optical devices are used to track changes in a reflector during alignment. An interferometer viewing the reflector at normal incidence through a window in the hub of the housing provides feedback on figure distortions. The Centroid Detector Assembly (CDA) originally designed and used for aligning the Chandra mirrors is used to determine focal point and reflector slope variation along its arc. The alignment configuration is shown schematically in Figure 7.

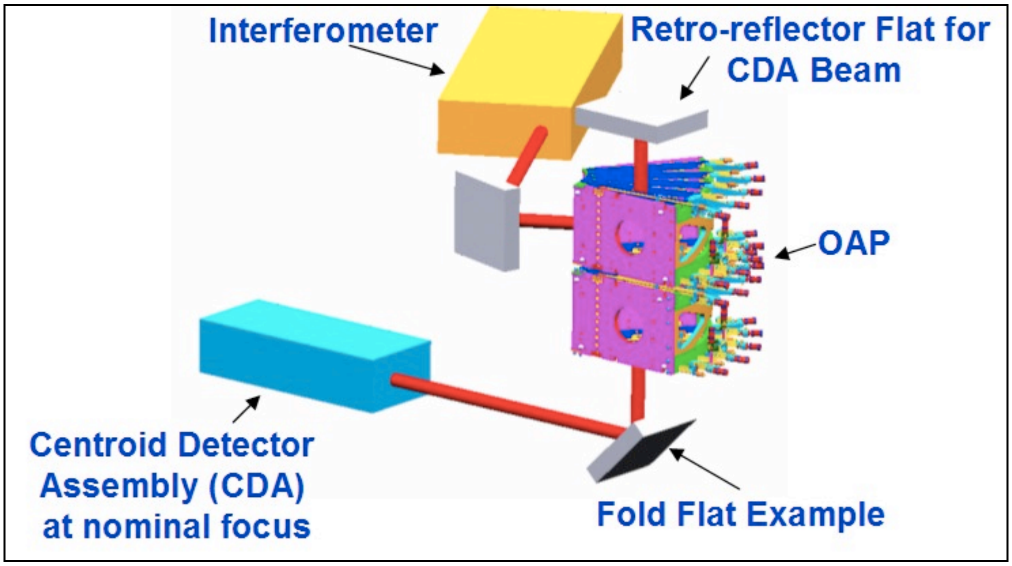


Figure 7: Schematic of the OAP alignment configuration. The CDA is used to bring rays reflecting off all portions of a reflector pair to a common focus. The interferometer is used to measure the axial curvature of the reflectors as they are manipulated within the OAP.

Use of the OAP1 system has allowed us to demonstrate that satisfactory alignment quality can be achieved with this combination of CDA and in-situ axial interferometry. Among the results we have demonstrated are: (i.) small differential adjustments of actuator pairs changes local average slope, but not local axial figure; (ii.) common mode adjustments (simultaneous adjustment of front and rear actuators at one axial location) change 2nd order axial figure, but not the local slope; (iii.) a common mode adjustment at one position will affect the 2nd order axial figure at least as far as the neighboring sets of actuators; and (iv.) simultaneous common mode adjustments of all radial actuators yields little change in a reflector's axial figure. All of these effects are what might be expected from small perturbations of a stiff sheet. These results are presented in more detail in the paper by Owens, et al.[6]

OAP2: To align a reflector in the OAP2, the unit is inserted inside OAP1, and the entire OAP1/OAP2 unit is mounted in CDA alignment facility. Initial alignment attempts with a relatively poor quality reflector pair yield encouraging results. Here the alignment concentrated on bringing to a common focus the return beams from the CDA off a group of points sampling various azimuths along the reflector pair. No attention was paid to the quality of the point spread function. The initial attempt yielded an RSS spread of 5.89 arc seconds for the sampled points. Comparing this with the 3.38 arc second requirement from the SXT mirror error budget indicates that even with poor reflectors it is nearly possible to bring an entire reflector pair into an acceptable focus.[6] The assembled OAP2 unit is shown in Figure 8.

4.4 X-ray testing

In anticipation of X-ray performance testing of reflector pairs, the MSFC 100-m Stray Light Facility has been undergoing modification. The details of the test facility can be found in the paper by O'Dell et al. in these proceedings[5]. A special, massive six degree of freedom mounting fixture has been constructed and installed in the facility to hold and precisely move a reflector housing. This mounting has been designed to accommodate the full range of SXT mirror test units from the simple, compact OAP2 unit to a full prototype (a 60-degree sector of an SXT mirror). A "dry run" of an X-ray performance test will commence within a month. It will utilize low quality reflectors mounted in the OAP2 housing, and will allow an opportunity to verify the X-ray test setup before an actual test occurs. The first genuine performance test is of course contingent upon production of reflectors that meet the Constellation-X figure requirement,

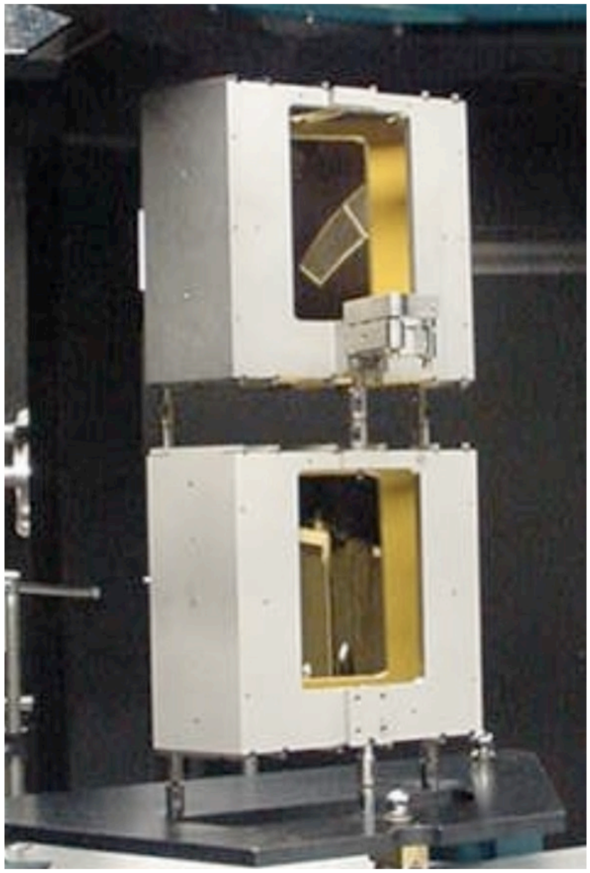


Figure 8: Assembled OAP2 unit, with reflectors installed.

and therefore must wait several months.

5. PLANS AND PROGNOSIS

This paper represents a snapshot of the SXT mirror program. Work continues, plans evolve based on tests and measurements, and the program moves ever closer to meeting its goals. Our short term plans include:

Continued improvement of the figure of the 50 cm reflector substrates. Ongoing finite element modeling of the thermal and mechanical aspects of the forming process has led to insights about controllable temperature gradients in the forming mandrel and oven. We will refine the forming environment and process in an effort to obtain an even closer match between forming mandrel and substrate shape. Our recent experiments show that that the forming mandrel figure limits substrate quality. To understand how much the forming mandrel figure influences the final substrate shape, we will obtain forming mandrels with 2-4 arc second figure, far in excess of the quality needed to meet the Constellation-X resolution requirement. Such good quality reflectors will allow us to determine the intrinsic limit of the forming process using this particular glass. We anticipate that within the next several months we will produce 50 cm reflectors that meet the Constellation-X requirement.

X-ray test of a reflector pair. Once suitable reflectors have been produced, we will demonstrate the performance of a P-H pair in X-rays using the MSFC Stray Light Facility. The reflector pair will be mounted in the rigid, simple OAP2 housing, and aligned using the methodology developed during the OAP1 and OAP2 experiments.

Construct Engineering Unit. The EU housing is currently being designed. Once constructed it will be used with the high quality reflectors to refine alignment procedures, to determine the limits of the baseline alignment approach, to demonstrate that multiple reflector pairs can be co-aligned, and to initiate study of automated alignment schemes.

Establish facility for producing 1.6 m reflectors. Like *Chandra*, the crucial SXT mirror technology demonstration is successful fabrication and test of the largest diameter reflectors. The replication mandrel for these reflectors is in hand (Fig. XX); the forming mandrels are being fabricated. What is lacking is the vacuum chambers for coating the mandrel with gold and performing the epoxy replication. These chambers have been ordered and should be delivered and brought to operational status over the next several months.

Initiate industry studies of Flight Mirror Assembly. Despite the fact that all of the SXT mirror technology development is being performed "in house" within the Constellation-X project, we anticipate that a corporate partner, to whom the technology will be transferred, will produce the flight mirrors. The prelude to selecting the FMA contractor is a six-month FMA design study. Two potential mirror contractors will carry on this study in parallel. We anticipate releasing the call for proposals in early 2004, initiation of the study in spring 2004, and selection of the FMA contractor in late 2005.

While the SXT mirror program has made substantial progress over the past year, an even more substantial effort stands between the current status and a mirror meeting the mission requirements. The success of the past year indicates that the approach we have taken and the path of progressive development along which the program is proceeding, are both technically sound and will ultimately lead to success.

ACKNOWLEDGEMENTS

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