Constellation-X Spectroscopy X-ray Telescope (SXT)

Robert Petre[a*], William W. Zhang[a], David A. Content[a], Timo T. Saha[a], Jeffrey Stewart[a], Jason H. Hair[a], Diep Nguyen[a], William A. Podgorski[b], William R. Davis, Jr. [b], Mark D. Freeman[b], Lester M. Cohen[b], Mark L. Schattenburg[c], Ralf K. Heilmann[c], Yanxia Sun[c], Craig Forest[c]

[a]NASA / Goddard Space Flight Center; [b]Smithsonian Astrophysical Observatory; [c]MIT Center for Space Research

ABSTRACT

We provide an overview of the Constellation-X SXT development program. We describe the performance requirements and goals, and the status of the technology development program. The SXT has a 1.6-meter diameter, a 10-meter focal length, and is to have an angular resolution exceeding 15 arc seconds. It has a modular design, incorporating lightweight, multiply nested, segmented Wolter Type I X-ray mirrors. All aspects of the design lend themselves to mass-production. The reflecting surfaces are produced by epoxy replication off precision mandrels onto glass substrates that have been accurately formed by thermal slumping. Coalignment of groups of reflectors to the required sub-micron accuracy is assisted by precision silicon microstructures. Optical alignment is performed using the Centroid Detector Assembly (CDA) originally developed for aligning the Chandra mirror. Recent efforts have concentrated on the production of an Engineering Unit, incorporating the components for the first time into a flight-like configuration. We summarize the status of the development of the processes for the key components and the initial metrology results of the Engineering Unit.

Keywords: X-Ray Optics, X-Ray Telescopes, Constellation-X

1. INTRODUCTION

The Constellation-X mission is designed to make possible high-resolution, broad bandpass, high sensitivity X-ray spectroscopy on a wide variety of cosmic sources. Its science goals are summarized in the paper presented elsewhere in this meeting by White & Tananbaum.[1] The mission consists of four identical spacecraft located at the earth-sun L2 point, observing the same object simultaneously. At the heart of each spacecraft is the Spectroscopy X-ray Telescope (SXT). Each SXT will have a 10-meter focal length and an aperture diameter of 1.6 m. The gross collecting area of the four mirrors is to exceed 3 m^2. The telescope (X-ray mirror plus optical support structure plus detectors) is to have an overall angular resolution of 15 arc seconds, half power diameter (HPD), with a goal of 5 arc seconds. The very large collecting SXT area, and the need for four such systems, is dictated by the mission science goals. The requirement to place the observatory at L2 places severe mass constraints on each satellite, and thus on the SXT mirror. The top-level mirror specifications are summarized in Table 1.

Table 1
SXT Mirror Parameters

Number of mirror systems	4
Optical Design	Wolter I
Mirror Diameter	1.6 m
Mirror Focal Length	10 m
Mirror (system) Angular Resolution	15" (5" goal)
Mirror Mass	<450 kg
Mirror Length	20-30 cm
Number of Nested Reflectors	230-170

* rob@hatrack.gsfc.nasa.gov; phone 301-286-3844; fax 301-286-0677; Code 662, NASA / GSFC, Greenbelt, MD 20771 USA

In this paper, we describe the SXT development program. This program has been underway for a number of years.[2-3] During that interval some important design decisions have already been reached, and significant technical progress made. We provide here an overview of the SXT program status and plans, the design choices we have made, and some of the lessons we have learned. Other papers in these proceedings present detailed descriptions of some of the elements of the technology development program: the error budget, the mechanical design of the Engineering Unit, the reflector alignment concept, and the reflector production.[4-6]

2. OVERALL APPROACH

The overriding design philosophy behind the SXT mirror is to provide the maximum possible collecting area per unit mass and achieve the required angular resolution (or better) at the lowest possible cost. The need to make four complete, identical mirrors provides a driver for seeking a means of efficient mass production. This in turn suggests we adopt an approach similar to two taken in the past, forming of full shells from cylindrically symmetrical mandrels (used for the JET-X and XMM mirrors) and replication of segmented, thin foil mirrors (used for BBXRT, ASCA, SODART and Astro-E). Initially we pursued both approaches, full shell and segmented mirrors, in parallel.

Full shell mirrors offer the advantages of mechanical robustness and fewer elements to integrate. For several years we investigated this option. For this approach to meet the Constellation X mass requirement, the shells had to be considerably thinner than the XMM reflectors. We made substantial progress in developing and testing new, stiffer Ni alloys for electroforming. The fundamental issue we encountered was electroforming pieces with sufficiently low internal stress. We also investigated the production of stiff, lightweight carriers onto which a final surface could be replicated. Among the substances we investigated were CVD Silicon Carbide and PVD Vanasil (a vanadium, aluminum, silicon mixture). While both materials showed promise, neither was entirely satisfactory. The primary reason we abandoned full shells had nothing to do with the candidate substrate materials. It became apparent that it would be impossible to obtain full shell mandrels with the required physical dimensions (1.6 m diameter by 1 meter long).

The segmented approach allows for the manufacture and handling of smaller pieces, and the use of more modestly sized mandrels. It also is well suited for mass production, as many more identical reflector modules must be produced. The experience at GSFC in producing mirrors for ASCA and Astro-E demonstrated that a production line could be successfully implemented.[7] Also, a demonstration that the kind of mandrel needed for a segmented mirror could be manufactured was provided by the XEUS program, which contracted Zeiss to manufacture a high quality mandrel segment. Disadvantages that needed to be overcome include the dimensional stability of the reflectors and the need to demonstrate that sufficiently high quality surfaces could be formed. Mounting is a more significant challenge. Nevertheless, once the shell approach needed to be abandoned due to the difficulty of obtaining mandrels, the segmented approach became the baseline.

While the segmented design draws its heritage from previous smaller mirrors produced at GSFC, the high angular resolution forced us to take new approaches to substrate formation, mandrel manufacture, mounting and alignment. Also, the conical approximation adequate for the 1' mirrors we have previously made was abandoned in favor of the conventional Wolter I design. [This has implications for the forming and/or replication] The only elements left from previous concepts is the overall segmented approach, the use of thin substrates and the epoxy replication.

3. PROTOTYPE MODULE DEVELOPMENT

The modular nature of the mirrors makes a phased development approach easy. There is little difference in size or difficulty of fabrication between largest and smallest segment. If a few segments can be properly coaligned, in principle all of them can. Module housings are all the same, and are modest in size. Our approach consists of six stages, leading to two key milestones, an Engineering Unit (EU) and a flight prototype. Our approach is summarized in Figures 1 and 2.

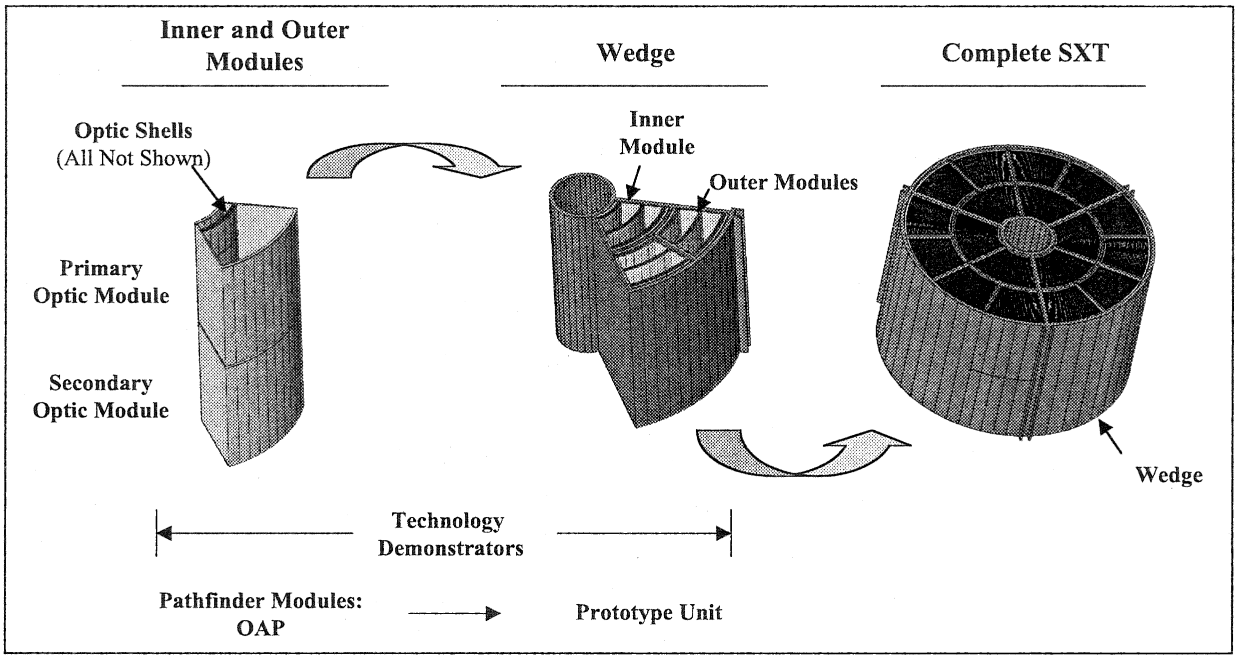


Figure 1: SXT progressive development scheme.

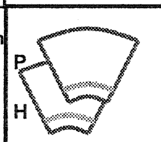
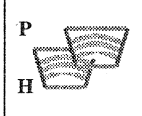
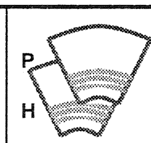
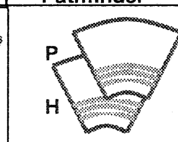
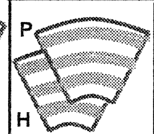
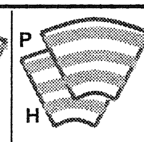
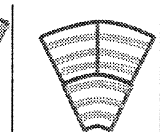
	Engineering Unit			Prototype Pathfinder	Prototype		
Configuration							
Module Type	Inner	Inner	Inner	Inner	Outer	Inner	Outer & Inner
Housing Material	Aluminum	Titanium	Titanium	Composite	Composite	Composite	Composite
Focal Length	8.5m	8.5m	8.5m	8.5m	10.0m	10.0m	10.0m
Optic Length (P&H)	2 x 20 cm	2 x 20 cm	2 x 20 cm	2 x 20 cm	2 x 50 cm (TBR)	2 x 50 cm (TBR)	2 x 50 cm (TBR)
Nominal Optic Diameter(s)	50 cm	50 cm±	50 cm±	50 cm±	160 cm± 120 cm± 100 cm±	90 cm± (TBR) 70 cm± (TBR) 50 cm± (TBR)	160 cm±40 cm± 120 cm±70 cm± 100 cm±50 cm±
Goals	•Align 1 optical surface pair (P&H) •Evaluate optic alignment techniques, optics assembly design & process, & optics metrology	•Align up to 3 optical surface pairs (3P,3H) •Gravity Sag •Evaluate bonding •Environmental and X-ray test	•Align up to 3 optical surface pairs to achieve<10arcsec •Gravity Sag •Evaluate bonding •Environmental and X-ray test		•Flight-like configuration outer module •Largest optical surfaces •Environmental and X-ray test	•Flight-like configuration inner module •Environmental (TBR) and X-ray test	•Demonstrate module to module alignment •Environmental and X-ray test
Timeframe	Q4 of FY02	Q2 of FY03	Q1 of FY04	Q4 of FY04	Q4 of FY05	Q3 of FY06	Q4 of FY06

Figure 2: Steps and goals within SXT EU and prototype development.

As chronicled here and in the other talks, we are well along with the EU development. The goal of the EU program is to produce a flight-like module. The module will have three closely spaced, coaligned reflector pairs. The SXT mirror imaging performance goal of 10" half power diameter (15" for the entire telescope system) is to be demonstrated via optical and X-ray tests, and the module is designed to survive environmental tests. The nominal reflector diameter in the EU is 50 cm, and the focal length is 8.4 m. The focal length deviation from the flight design results from the fact that mandrels we are using for surface replication were procured several years ago before the SXT focal length was revised. The imaging performance demonstration is to occur by the end of 2003.

A second issue to be addressed during EU development is how to efficiently coalign the many reflectors in a housing. We have decoupled the performance demonstration as much as possible from this formidable engineering task.

The prototype will be a full 60-degree segment of a flight mirror. It will consist of three modules, as the current flight concept has 6 inner modules (diameter 0.3-0.8 m reflectors) and 12 outer (diameter 0.8-1.6 m). Each module will contain three sets of three closely nested reflector pairs. For the outer modules, these groups will have nominal diameters of 1.0, 1.2, and 1.6 m. The focal length will have the nominal SXT value of 10 m. As for the EU, the prototype will meet the Constellation-X performance requirement and pass environmental tests.

Over the past 2-3 years we have made substantial progress toward our performance goal. Along the way we have learned a considerable number of lessons, about both how to do things and how not. We have incorporated these lessons into the design of the Optical Alignment Pathfinder (OAP), the first step toward the full Engineering Unit. Within the past couple of months we have seen our efforts culminate in the production of the first full sized reflectors whose figure approaches the Con-X goal and the assembly of the first full sized housing for testing and refining mounting and alignment approaches. The sections below briefly discuss the key SXT components and processes.

4. SUBSTRATE FORMING

Ideally, the reflector substrate material maintains the optical figure perfectly and does not distort easily under gravity or application of other forces. At the same time, it must be thin to afford high throughput despite multiple nesting, low density to meet the mirror mass requirement, and thermally stable. Our experiments and experience with the ASCA and Astro-E mirror have taught us that if we want a reflector to hold an accurate figure, the figure must be imparted by proper forming of the substrate. The epoxy coating cannot be counted on to correct significant figure errors. Nor can we expect an adjustment mechanism to reliably correct random, large figure errors.

After experimenting with several different materials we selected thin glass as the most promising, based on its mechanical and surface properties. We thermally form Desag D263 glass by placing it onto a conical mandrel and carefully heating it to ~600 C. Figure 3 shows a forming mandrel and glass substrate in our furnace and a formed substrate. Details of the forming approach can be found elsewhere in these proceedings.[6]

A key to success of the forming process is the quality of the forming mandrel. Since the overall figure is imparted during forming, we must use a mandrel whose figure is within about 2 microns of the final surface on scales larger than a few millimeters. Larger figure deviations cannot be covered up using epoxy. The mandrels not only need to survive the thermal cycling they experience, but must have coefficient of thermal expansion similar to or smaller than the substrate so that no distortions are introduced into the formed substrate as it cools. We have thus far used fused silica mandrels.

The combination of good mandrels, good substrate and carefully controlled forming has led to success. We are forming substrates whose shape conforms very closely to that of the mandrel. The conformance is in three dimensions, and demonstrates that it is in principle possible to form a substrate with an axially curved (i.e. Wolter) surface. This, in turn, would allow a reduction of the role of the epoxy to only imparting the final, microscopically smooth surface. Whether we use axially curved or conical forming mandrels for the prototype and flight mirrors could become a cost issue.

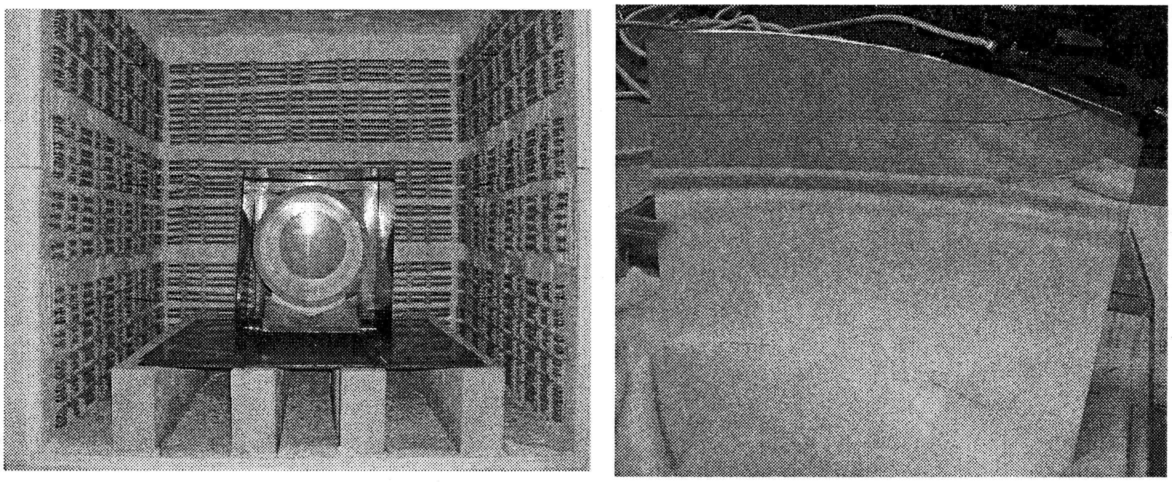


Figure 3: (Left) 50 cm diameter forming mandrel in oven. Housing around mandrel is for controlling dust. (Right) Formed 20 cm long substrate. Substrate subtends 60-degree arc of 50 cm diameter mandrel.

5. REFLECTING SURFACE REPLICATION

If replication is to be viable for producing the optical quality reflector surfaces, then not only must an approach be found that reliably transfers a high quality mandrel surface onto the substrate, it must be durable, allowing as many as 100 replications without refurbishment of the replication mandrel. These requirements have implications for the substrate surface, the transfer medium and the replicating (mandrel) surface. The substrate must be macroscopically smooth enough to not impart residual imperfections (print through) to the final surface. The transfer medium (epoxy) must accurately conform to the mandrel's surface, but flow sufficiently to fill any small irregularities between the substrate and the mandrel. It must not impart sufficient mechanical stress upon the substrate to distort it. The mandrel must be microscopically smooth, have the correct optical figure, have low adhesion to the reflecting surface material (gold or platinum), and have a surface that does not degrade after repeated replications and cleanings.

The replication approach we have adopted is based on that used for Astro-E. We use the same epoxy. We apply the epoxy to the substrate by diluting it with toluene and spraying it using a preprogrammed pattern. The epoxy-coated substrate and gold-coated mandrel are carefully brought into contact in vacuum, and then the epoxy is allowed to cure overnight at approximately 40 C. Separation requires no cooling to produce differential shrinkage, only careful mechanical separation. The fundamental difference for Constellation-X is that we apply a considerably thinner epoxy layer, 10-25 percent the thickness used for Astro-E. This reduced thickness is warranted by the need to minimize the mechanical stress imparted by epoxy curing and the CTE difference between epoxy and substrate, and facilitated by the relative conformity of the mandrel and substrate.

Most of our experiments to date have been performed using small-scale (20 cm diameter) mandrels. We have now developed processes that yield reflectors consistent with the Constellation-X requirement. We have only recently completed fabricating the equipment necessary to replicate larger reflectors. Our efforts are now focused on replicating reflectors for a 50 cm diameter, 8.4 m focal length mirror. The mandrels for this mirror were fabricated by Zeiss using the techniques developed for the XMM mandrels. We have successfully replicated reflectors; surface evaluation is underway.

We have carried out numerous replications using both glass (Pyrex, Zerodur, fused silica) and metal (nickel-coated aluminum) mandrels. Two consistent trends have emerged that have made it clear that only glass (Pyrex or fused silica) or glass ceramic (Zerodur) mandrel surfaces can be used during production of flight reflectors. First, the adhesion of the replica to a metal mandrel is significantly higher than to glass, even if the metal mandrel has been coated with a release layer. The more difficult separation leads to a lower rate of successful replications. Second, and more importantly, the microroughness of a metal mandrel increases measurably after every replication, whereas there is no degradation perceptible on a glass mandrel. Metal mandrels would need frequent reconditioning (after every 5-10 replications), while some glass mandrels have been used for over a hundred replications without microsurface degradation. This durability makes glass or glass ceramic the mandrel material of choice.

Another aspect of reflector replication we have investigated is edge effects. Invariably the outer ~1 cm around the substrate perimeter is replicated imperfectly. It is difficult to remove the imperfection without damaging the reflectors. The side edges, if they contribute significantly to the blur, can be easily masked off. The front and rear edges, however, are considerably more problematic. They can in principle contribute to the blur, but in practice this effect is minor. More significant, however, is that we had expected to use the front and rear edges as reference surfaces for alignment. This clearly is impractical. We thus are planning to use as reference points axial locations as far as 2 cm from the edges.

The requirement that the epoxy layer be thin places an important practical limitation on the optical design of the mirror. We use conical substrate forming mandrels, which means that the Wolter surface of the mandrel is imparted to the final reflector by the replication. Thus the epoxy layer has to be thick enough to hold the "sag" of the axially curved surface. The amount of axial curvature, the sagittal depth increases with both reflector radius and reflector length. For the largest diameter reflector, the sagittal depth of a 50 cm long reflector would be 15 microns, deeper than the planned epoxy thickness. Thus as long as we plan to use conical substrate forming mandrels and keep the epoxy thickness to 10 microns or less, the length of the reflectors is limited to ~30 cm or shorter. The implication of this is a larger number of nested reflectors per mirror, and thus a larger number of mandrels of both kinds.

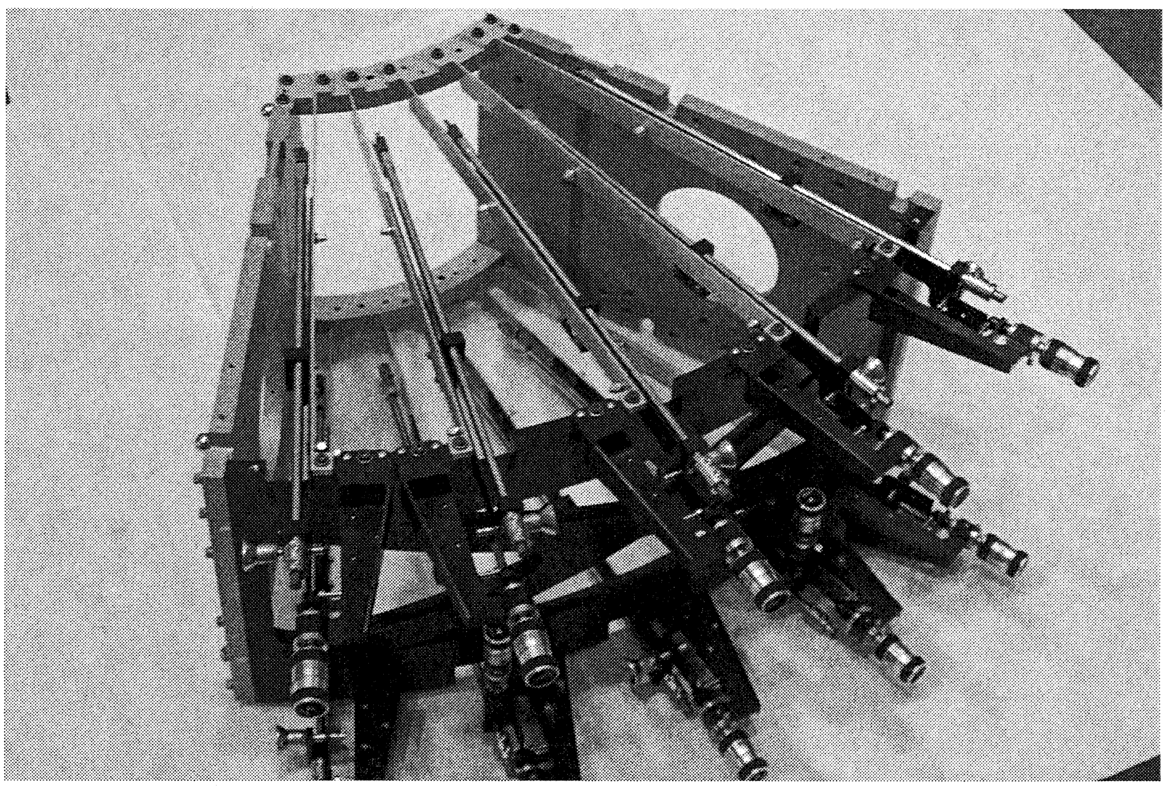


Figure 4: Test housing for aligning SXT reflectors.

6. MOUNTING AND ALIGNMENT

In an ideal situation, the SXT mirror holding fixture facilitates stress-free mounting of a set of reflectors with perfect figure. The reflectors are not perfect, however, and suffer from distortions at some level on all spatial scales. A clever implementation of the holding fixture facilitates reduction of the lowest order distortions by application of stresses to the reflectors. This approach has been used successfully for the Astro-E mirrors and their predecessors. The reflectors in these mirrors are not as stiff, and the alignment accuracy needed to meet the angular resolution requirement is a few microns.[7] (The 1-2 arc minutes attained for Astro-E translates to average radial displacement errors of 5-10 microns; a remarkable accuracy considering no precision metrology equipment is utilized.) In order to meet the SXT angular resolution requirement, submicron radial positioning accuracy must be achieved using reflectors formed to accuracy of a few microns. Thus while the absolute displacement necessary to align reflectors is considerably less than prior segmented mirrors, the accuracy required is considerably higher.

Pictured in Figure 4 is the alignment housing for the initial implementation of the EU (referred to in Figure 2 as "OAP1"). This is one of a pair of identical housings, one for each reflection stage of the Wolter mirror. This particular housing is constructed from aluminum; future housings will be constructed from materials whose thermal expansion coefficient more closely matches that of the glass reflectors (titanium or composite). The housing includes twelve precision actuators. A reflector is held by struts at five azimuthal locations along its top and bottom edges. Actuators attached to each mounting point allow accurate radial alignment, thus reducing slope errors and low order figure distortions. Actuators attached to two rear struts allow for reduction of "tip" errors, which for segmented reflectors contribute as much to blur as slope errors. The details of the housing and the alignment procedure are described elsewhere in these proceedings.[4-5]

One key aspect of the alignment procedure is the use of optical feedback. A careful analysis has demonstrated that even with the most precisely machined housings and the best actuators, the submicron alignment precision needed for the SXT cannot be achieved by purely mechanical means. Thus in-situ optical metrology is essential if the SXT is to meet its requirements. For the EU we are simultaneously using two optical measurement devices. Viewing the reflectors at normal incidence is an interferometer that can be configured to produce either axial or azimuthal profiles. This allows us to survey the reflector surfaces for distortions. Viewing the reflector from its focal point is the Centroid Detector Assembly (CDA).[8] The EU alignment configuration incorporating the interferometer and the CDA is shown schematically in Figure 5.

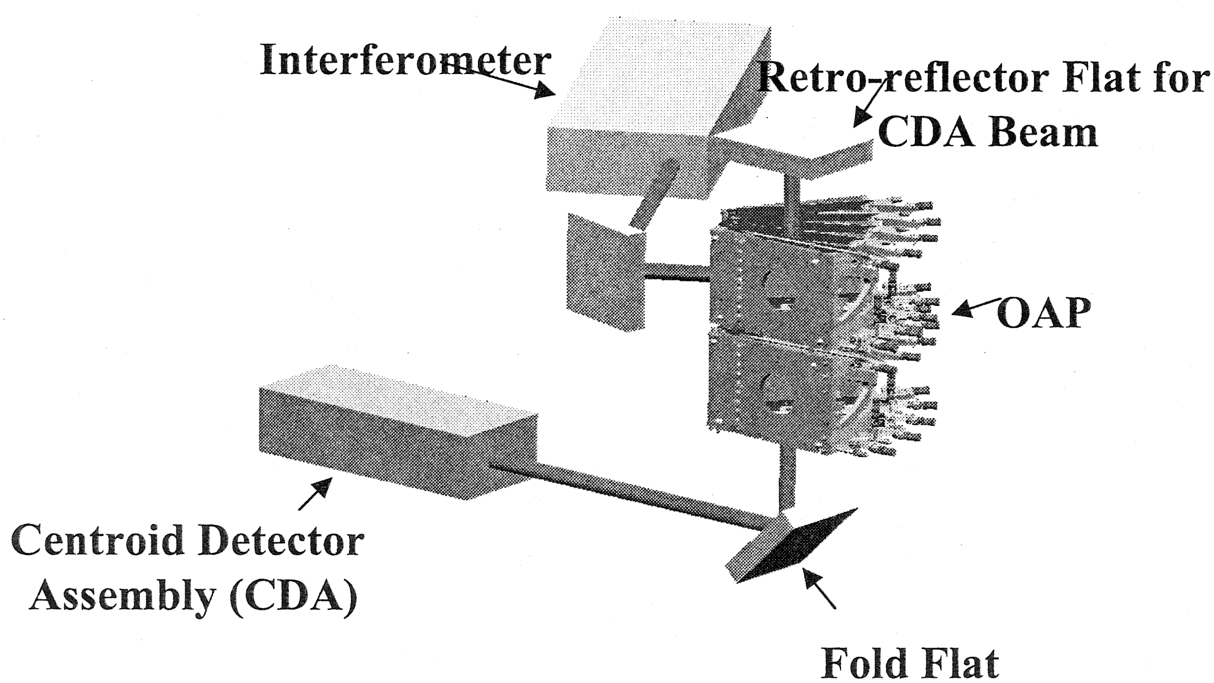


Figure 5: Schematic of optical alignment approach for EU. The interferometer is used to measure profiles of the reflector; the CDA measures focal plane distortions resulting from misalignments.

A second desirable attribute of the Astro-E alignment approach is the simultaneous alignment of many reflectors. The precision required for the SXT alignment makes this challenging. At the heart of the current mass alignment scheme are etched Si microstructures. These structures have been made to submicron accuracy. Incorporating them into an alignment housing similar to that shown in Figure 4 is an engineering challenge. In order to make the EU development proceed more rapidly toward demonstrating the angular resolution performance goal, we have temporarily decoupled considerations of mass-alignment. We will first demonstrate that the imaging performance can be accomplished using a single reflector pair, and then a small number of closely spaced pairs, before incorporating mass-alignment into the EU.

7. STATUS

As of the writing of this paper (August 2002) the SXT project is at a critical juncture, as we prepare to perform our first metrology on a flight-sized reflector in the first precision housing. The housing for the primary reflectors has been assembled; the identical secondary reflector housing is being assembled. Within the past month the equipment necessary for forming and replicating flight-like reflectors has become available. The first replications of flight-sized reflectors (50 cm diameter, 60-degree arc, 20 cm axial length) were performed earlier this month (see Figure 3). The metrology equipment (CDA and interferometer) is being configured. Over the next few weeks we will learn whether our approach will allow the SXT to meet its performance requirements.

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