High-Accuracy X-ray Foil Optic Assembly

Glen P. Monnelly[a], Olivier Mongrard[a], David Breslau[a], Nat Butler[a],
Carl G. Chen[a], Lester Cohen[b], Wendy Gu[a], Ralf K. Heilmann[a],
Paul T. Konkola[a], George R. Ricker[a], and Mark L. Schattenburg[a]

[a]MIT Center for Space Research, Cambridge, MA 02139 USA
[b]Smithsonian Astrophysical Observatory, Cambridge, MA 02138 USA

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ABSTRACT

Achieving arcsecond angular resolution in a grazing-incidence foil optic X-ray telescope, such as the segmented mirror approach being considered for the Constellation-X Spectroscopy X-Ray Telescope (SXT), requires accurate placement of individual foils. We have developed a method for mounting large numbers of nested, segmented foil optics with sub-μm accuracy using lithographically defined and etched silicon alignment micro-structures. A system of assembly tooling, incorporating the silicon micro-structures, is used to position the foils which are then bonded to a flight structure. The advantage of this procedure is that the flight structure has relaxed tolerance requirements while the high accuracy assembly tooling can be reused. A companion paper by Bergner *et al.* [1] discusses how our process could be used for the SXT. We have built an assembly truss with a simplified rectilinear geometry designed to experimentally test this alignment and mounting technique. We report results of tests with this system that demonstrate its ability to provide sub-μm alignment of rigid test optics.

Keywords: X-ray telescopes, X-ray optics, grazing incidence mirrors, Constellation-X, micro-structures, mirror alignment

1. INTRODUCTION

Segmented foil X-ray optics have been used on BBXRT, ASCA, and ASTRO-E[2–5] to achieve sizeable collecting area at a reasonable cost and weight. However, these systems are characterized by arcminute angular resolution that is considerably poorer than full shell optics, such as those used on XMM.[6] Both the segmented and full shell approach are being considered for the Constellation-X Spectroscopy X-ray Telescope (SXT). In order for the segmented approach to meet the $< 15''$ half power diameter (HPD) requirement, improvements must be made in many aspects of previous designs. For a review of these efforts, see Petre *et al.* [7,8]

One limitation of previous segmented foil systems that must be improved to meet the needed refinement in angular resolution for SXT and future missions is the alignment and mounting fixtures that support the foil optics. In previous systems, slotted alignment bars are used to support the optics from the top and bottom.[9] In the case of ASTRO-E, the alignment bars are 25 μm wider than the substrates in order to facilitate assembly, which has been estimated to contribute a 15 μm error at each mounting point.[7]

With recent improvements in substrates for foil optics, based on thermally treated, or slumped, thin glass microsheets,[10] and more advanced replication mandrels,[7] the use of this type of alignment bar would severely limit the angular resolution of the system. The current requirement for the Constellation-X SXT is a $15''$ HPD, which according to Petre *et al.* [7] will require an accuracy of better than 2 μm. Our approach promises to meet this requirement by replacing the electro-discharge machined (EDM) alignment bars with etched silicon microstructures.

Further author information: (Send correspondence to G.P.M.)
G.P.M.: E-mail: monnelly@space.mit.edu

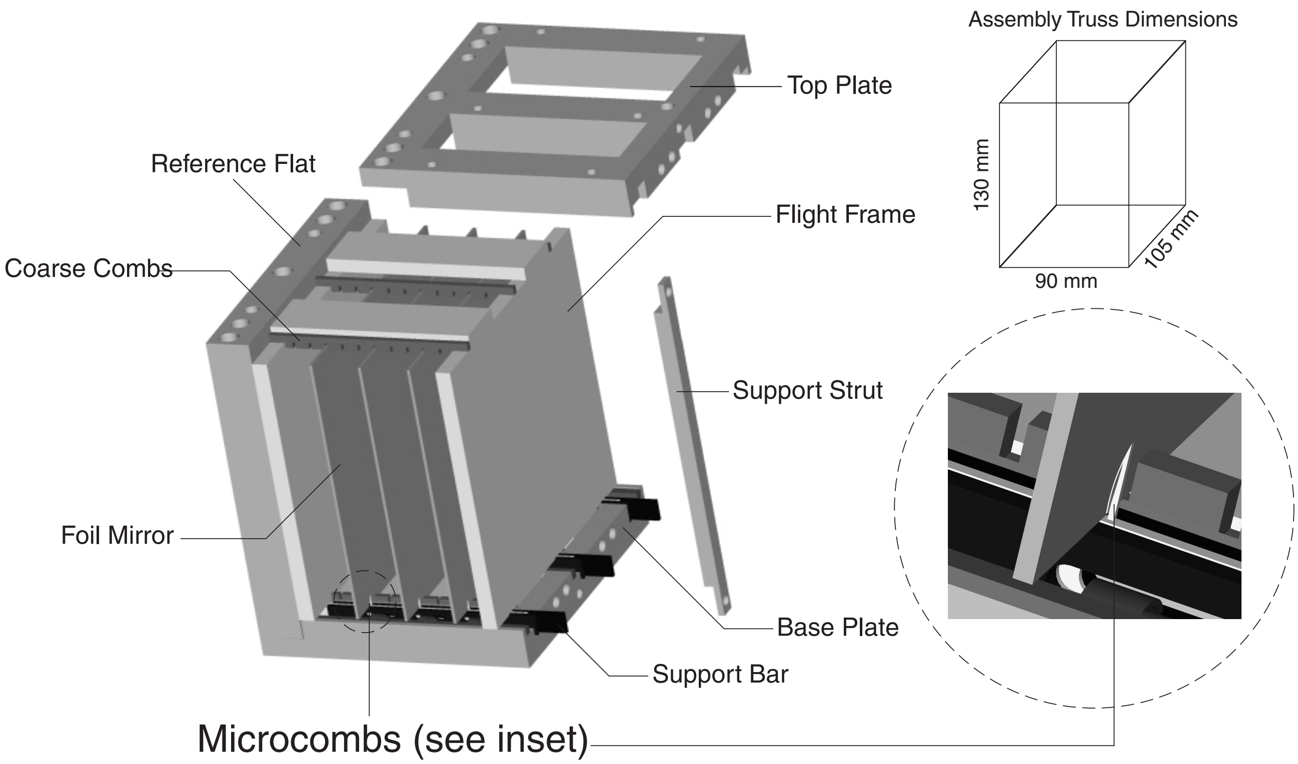

Figure 1. Assembly System and Flight Frame with simplified rectilinear geometry. The outer structure, including the base plate, reference flat, and top plate comprise the assembly truss. Foil mirrors are held loosely in the flight frame, then the assembly truss uses silicon microcombs to precisely align the foil mirror with respect to the reference flat. The foil mirrors are then bonded to the flight frame, and the assembly truss is removed. Spring and reference microcombs slide in grooves in the baseplate (see inset).

2. PRECISION ALIGNMENT CONCEPT

There are many requirements of the structures and tooling used to mount foil x-ray optics. Mounting structures must allow for simple assembly of a large number of foils. The foils must be aligned to their proper position with accuracy sufficient to reach the desired angular resolution of the optic. The foils must be held in their assembled position by a structure that can survive launch stresses, vibrations, and acoustic loading, and can maintain foil positions in a space environment.

We seek to greatly improve mounting of segmented optics by achieving these requirements with separate structures for alignment and flight. Alignment is accomplished with an assembly truss utilizing a metrology frame (Fig. 1), which uses etched silicon microstructures, referred to herein as microcombs (see Section 3) of μm or sub-μm dimensional accuracy that are mechanically mated to a precision reference surface. After alignment, foils are bonded to a separate flight frame that meets the mechanical and thermal requirements of the launch and space environments, but does not have stringent requirements for accuracy. The concept of separating the metrology and mechanical structures of a system is a common technique, particularly in cases where sub-μm accuracy is required,[11] but has not been used in previous segmented foil x-ray optic missions.

The application of this technique to the SXT is described in a companion paper by Bergner *et al.* in these proceedings.[1] The SXT employs the axially symmetric Wolter I geometry. Herein we discuss a simplified rectilinear geometry that facilitates development of the concept and is used in a breadboard test system. The goal of the breadboard test system, described below, is to prove the alignment concept by mounting rectangular optics to a high degree of parallelism. Section 4 describes a series of experiments that test specific aspects of the system's ability to provide accurate alignment of optics.

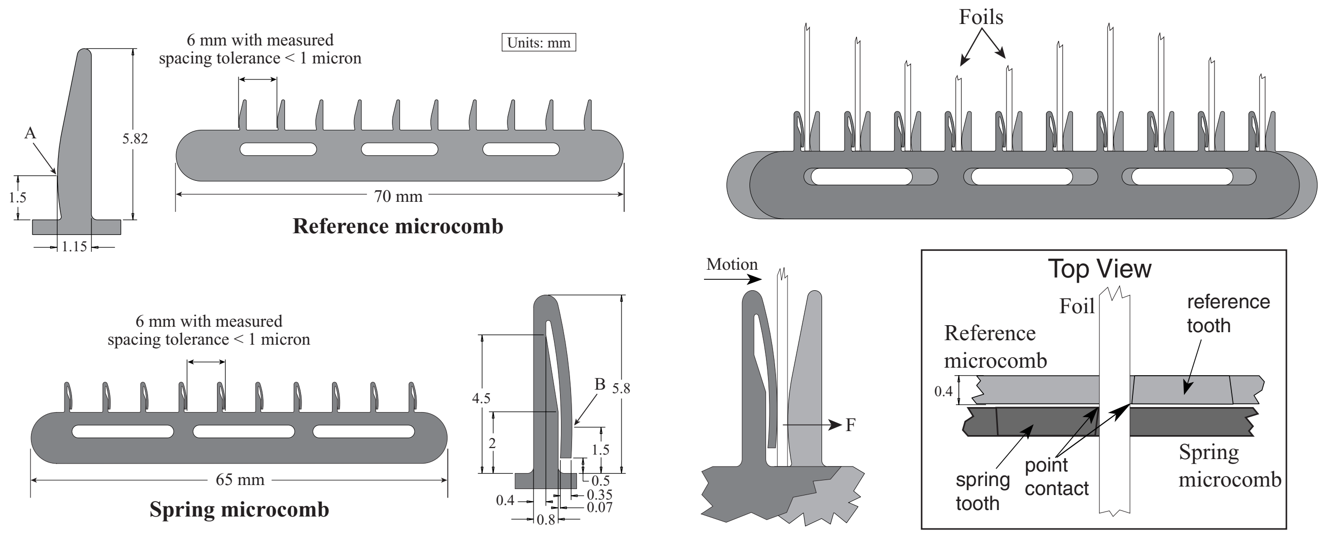

Figure 2. Spring and reference microcombs. The pattern shown is photolithographically transfered to a resist film on a silicon wafer, then the pattern is etched through the thickness of the wafer.

2.1. Assembly Truss and Metrology Frame

2.1.1. Foil Alignment

Alignment of foils is achieved with an assembly truss utilizing a metrology frame (Fig. 1). Foils are clipped by silicon microcombs with a point-like contact at their top and bottom edges which provide accurate positioning of the foils (Figs. 2 and 3). The microcombs in turn are referenced with point-like contact against an ultra-flat reference surface. These "reference microcombs" provide a precise reference between the foils and the reference flat. Another set of "spring microcombs" push the foils against the reference microcombs. Since the microcombs are part of the metrology frame they need to be durable enough for laboratory handling and repeated use in the alignment procedure.

Many of the requirements of the alignment system relate directly to the properties of the foil optics being mounted, particularly edge roughness, thickness variation, and figure errors. The baseline for the segmented foil SXT design is to use epoxy replication with a glass substrate. Because the edges of the foil are generally rough compared to interior surfaces, the mounting point should ideally be a small distance away from the edge so that contact can be made with the smooth mirror surface. The alignment bars of previous generation had no provision to mount the foils with a contact point other than the edge[9] (see Fig. 4). The reference microcombs have a rounded reference surface so the point of contact is 1.5 mm away from the edge of the foil and the rough edge is thus avoided.

Replicated foils have typical thickness variations of 25 μm, which is due mostly to the glass substrates. To accommodate them, we use micromachined leaf springs that force the foil against the reference surface of the reference microcomb. As the spring microcomb slides in its groove in the assembly truss, each foil is pushed against its corresponding tooth on the reference microcomb (Figs. 2 and 3). The replicated foil optics will generally have figure errors where the shape of the foil differs from the ideal, so that the foil will have to be distorted to make contact with the reference comb. The leaf springs are designed so that for the expected range of thickness variation, enough force is applied to the foil to move it into place, overcoming frictional forces (see Section 3) and effects of figure errors in the foils.

The microcomb etching process causes a small amount of undercutting (see Section 3), resulting in a slight taper in the surface of the comb that contacts the foil. This ensures that a point contact is made between the microcombs and foil, and that the contact point of the spring and reference microcombs are on directly opposite sides of the foil. This balance of opposing forces is necessary to prevent the combs from applying a local torque at the mounting point, causing distortion in the glass.

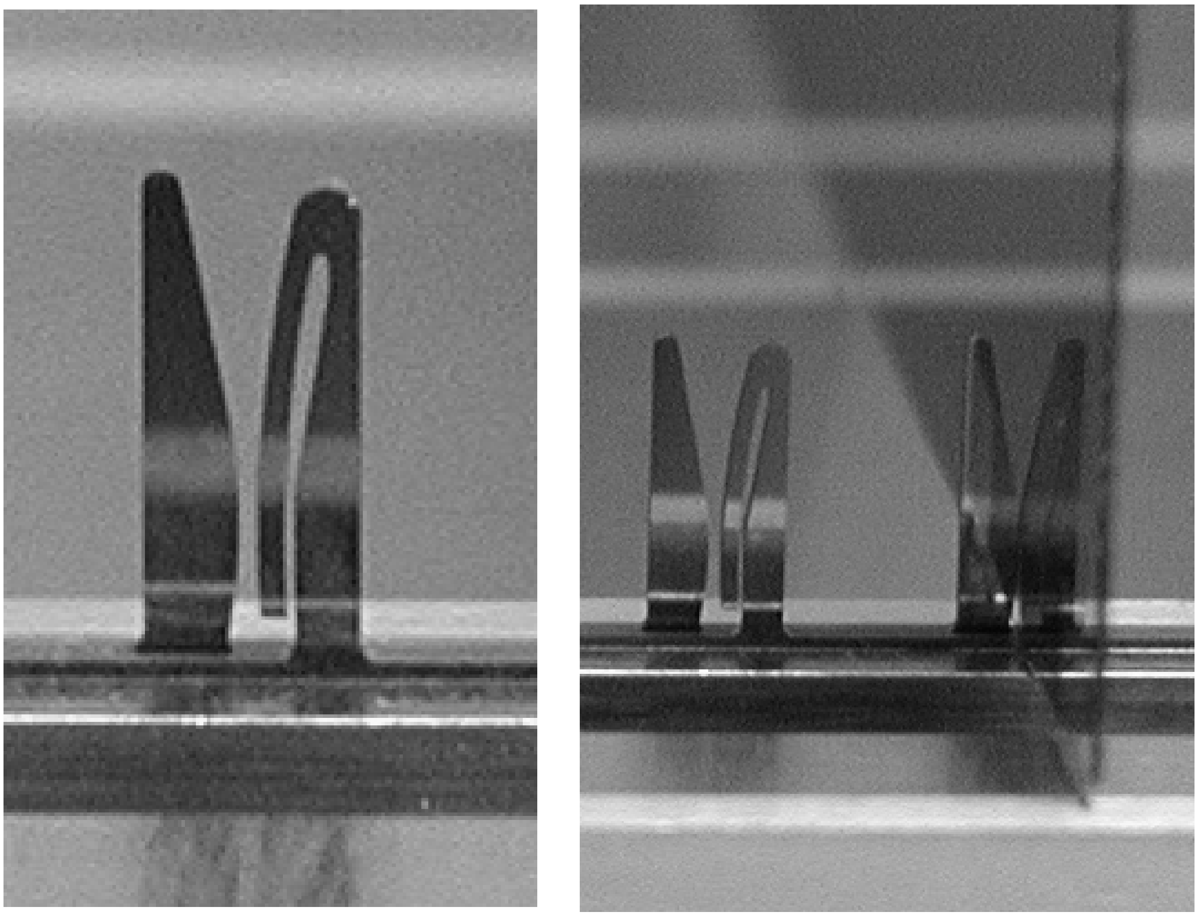

Figure 3. Side view of a spring and reference microcomb installed in the assembly truss, shown alone (*left*) and mounting a thin glass mirror (*right*).

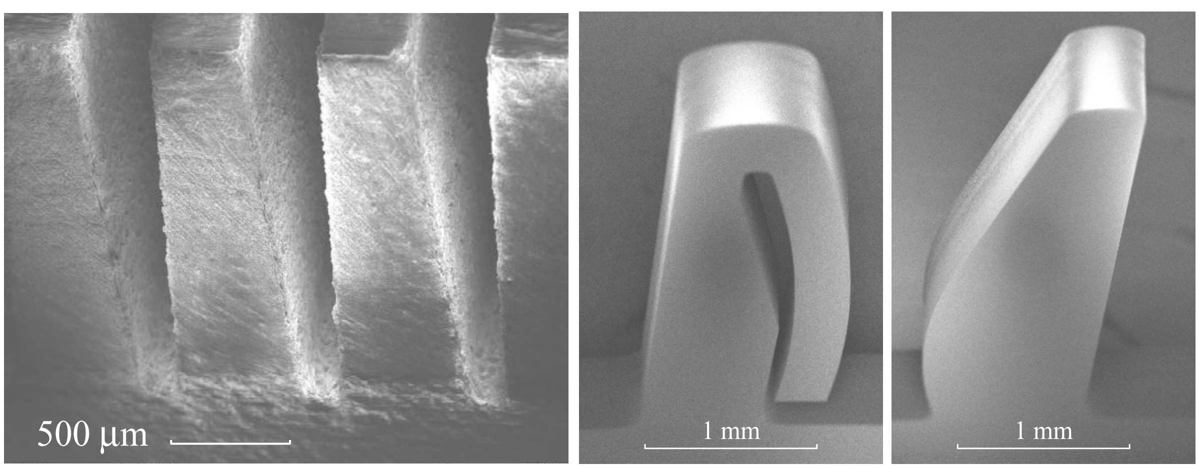

Figure 4. Scanning electron microscope (SEM) image of an ASCA alignment bar (*left*) and our silicon spring (*middle*) and reference (*right*) microcombs. The microcombs are fabricated with a higher accuracy than the EDM machined ASCA alignment bar, and have relatively intricate structures such as the leaf spring on the spring microcomb.

2.1.2. Friction and Mechanical Issues

In addition to forces associated with foil figure errors, we consider other forces from the microcombs that could distort the foils from their relaxed state. Distortions of the glass could be caused by forces in the plane of the glass, applied by the combs. For example, while the spring microcombs are being slid into place, friction from the foil edge contacting the microcomb base could produce a bending in the glass. If this becomes a problem, we will develop a simple system to lift the foils off the comb edge so that these forces are relieved and the foil can be mounted in a strain free state. These issues will be addressed in future tests.

2.1.3. Alignment Tolerance

The tolerance requirements on the alignment system are driven by the dependence of the optical performance on the various dimensions. Specifically, small displacement errors in the mounting point in the plane of the foil don't have a strong effect on the optical performance, but displacement errors perpendicular to the foils (and the optical axis) have a stronger effect on optical performance. As an ensemble, the assembly system is required to provide < 2 μm alignment of the foils, but to achieve this it is only necessary that the reference flat and the reference microcombs, which comprise the metrology frame, have μm accurate tolerances. In fact, an error in the angle of a microcomb as it sits in its groove in the assembly truss is relatively unimportant because it will not have a strong effect on the positioning of the contact point in the direction that is important: perpendicular to the foils.

As a result, the only parts of the system where μm accuracy is required are the dimensions of the microcombs and the points of reference: where the reference microcombs meet the reference flat and where the foils meet the reference microcombs. Errors such as non-perpendicularity between the microcombs and reference flat only contribute as higher order errors. In the current system, the reference flat is a diamond turned aluminum plate which also acts as a structural member supporting the base plate and top plate. However, in this design, the forces involved in bolting the system together cause distortions at the level of 0.5 μm in the reference flat. In future designs, the reference flat will be an optical flat that is kinematically mounted to the assembly truss, and will not be a structural member of the system.

2.2. Assembly and Flight Frame

The flight frame structure holds the foils during launch and in orbit. Once the foils have been aligned to their proper position by the assembly truss and metrology frame, they are bonded to alignment bars (referred to as "coarse combs" in contrast to the highly accurate microcombs) similar to those used in ASCA and ASTRO-E (Fig. 4). Because the foils are bonded into oversized grooves of the coarse combs, the tolerance requirements on the flight frame are minimal. The flight frame need only provide high stiffness and good thermal expansion match with the foils.

A description of the assembly process for our simplified breadboard system (Fig. 1) follows. Rectangular foil optics are installed in the flight frame and temporarily held in place by the oversized slots in the coarse combs. The flight frame is then installed in the assembly truss, which supports both the spring microcombs and the metrology frame (which provides accurate alignment via the reference microcombs and reference flat). Once the foils are trussed into their proper position between the reference and spring microcombs, the coarse combs are removed, precise beads of adhesive are applied, and they are reinstalled in the flight frame. Once the adhesive cures, the flight frame is removed from the assembly truss.

3. PRECISION ALIGNMENT STRUCTURES ("MICROCOMBS")

Our high accuracy alignment technique is enabled by silicon microcombs that are etched from a silicon wafer using microelectromechanical systems (MEMS) technology. They offer two distinct advantages over other techniques for mounting segmented foil optics. First, our fabrication technique provides the sub-μm accuracy which is a general characteristic of the lithographic process used in the MEMS industry, allowing for highly accurate foil placement. Second, it is possible to make intricate structures such as the leaf springs on the spring microcombs and the precisely round reference surface on the teeth and at the end of the reference microcomb.

3.1. Fabrication

The microcombs (Fig. 2) are fabricated from 100 mm diameter, 380 μm thick double-side-polished silicon wafers using contact lithography followed by time multiplexed deep reactive ion etch (TMDRIE).[12] The microcomb pattern, designed with CAD software, is written to a lithographic mask. The process allows the pattern of the combs (Fig. 2) to be transferred from the lithographic mask to a wafer with a contact masking step. The pattern is then etched through the entire thickness of the wafer with TMDRIE. The processing is done at the MIT Microsystems Technology Laboratories. For a detailed description of the procedure, see Chen *et al.*[13] and Chen.[14] One important aspect of the process is that the wafer is etched with a very small amount of undercutting, about 0.8°, resulting in a slightly angled face on all the reference surfaces (see inset in Fig. 2). This ensures that a point-like contact is made between the microcomb teeth and the foil (see Section 2).

Thorough cleaning of the microcombs after processing is required to remove photoresist and oxide, and careful handling in a cleanroom environment is necessary for repeatable sub-μm assembly. We plan to develop a process to grow a thermal oxide layer on the surface of the microcombs, which will provide a hard layer of protection against damage.

3.2. Spring Design

We have developed a simple description of the mechanical requirements of the spring microcomb's leaf spring that is used to optimize its dimensions. First, it is necessary to force the foil into position against the reference microcombs, overcoming frictional forces and bending the foil against any intrinsic figure errors. Second, since a single spring microcomb is used to force into position multiple foils, we must take into account the expected range of foil thicknesses to ensure that the thickest and thinnest foils can be accommodated. The general problem is that while a very thick, rigid leaf spring could be designed to supply sufficient force to move the mirrors, it might not have the range of motion needed to mount a particularly thick foil without fracturing the leaf spring (exceeding the 566 MPa breaking strength of silicon). Conversely, a leaf spring with a large range of motion might not be able to apply a large enough spring force to move the foils. Our analysis, based on analytic calculations and finite element modeling, allows us to search all possible leaf spring geometries (parameterized by spring length and thickness) to minimize internal stresses given the substrate mounting requirements.[13]

4. SYSTEM TESTS

Direct measurement of the dimensions of the microcombs using a microscope with a reticle eyepiece and precision translation stage have shown that the microcombs are fabricated to a higher tolerance than the 2 μm resolution of the measurement. To more accurately characterize microcombs, we have designed a series of experiments that use our breadboard test assembly system (Fig. 1) to specifically measure the alignment capabilities of the microcombs. The system has a rectilinear geometry and is designed to mount a nest of parallel foil optics. Since we are currently not able to manufacture foils with accuracy comparable to the alignment accuracy of the microcombs, we instead used rigid flat plates to demonstrate the alignment capacity. The plates are 102mm $\times$ 102mm $\times$ 2.3mm fused silica with a flatness specified to be less than 2 μm. This level of flatness is large compared to the microcomb alignment errors we are trying to measure, but we have taken care to make differential measurements where the error can be subtracted out. Utilizing rigid flat plates also removes as a source of error the flexibility of thin foils, which could potentially be deformed during the assembly process making arcsecond accurate measurements difficult. Though the issue of deformation of foils when mounted in the assembly truss is not addressed by the rigid flat plate tests, it is an important issue to be treated in future tests. The degradation of microcomb reference precision due to wear is addressed by examining relevant parts microscopically before and after measurements. Because of the large mass of the rigid flat plates, the tests don't constitute a useful test of the spring combs, which are designed to mount thin sheets.

The tests are designed to measure the parallelism of rigid flat plates mounted in different "slots" of the assembly truss, defined by the microcomb teeth (a microcomb slot is the space between one reference tooth and its corresponding spring tooth). As there are currently 10 teeth on one microcomb, there are 10 microcomb slots in a microcomb pair. They are referenced by ascending numbers from the reference flat. The goal is to achieve $\sim$1 μm alignment of the plates, measured by their degree of parallelism. The tests address whether the plate is held consistently in the same position when placed in the same microcomb slot (repeatability), whether the plate remains parallel when installed in different slots (slot-to-slot accuracy), and whether the plate is parallel to the reference surface. The

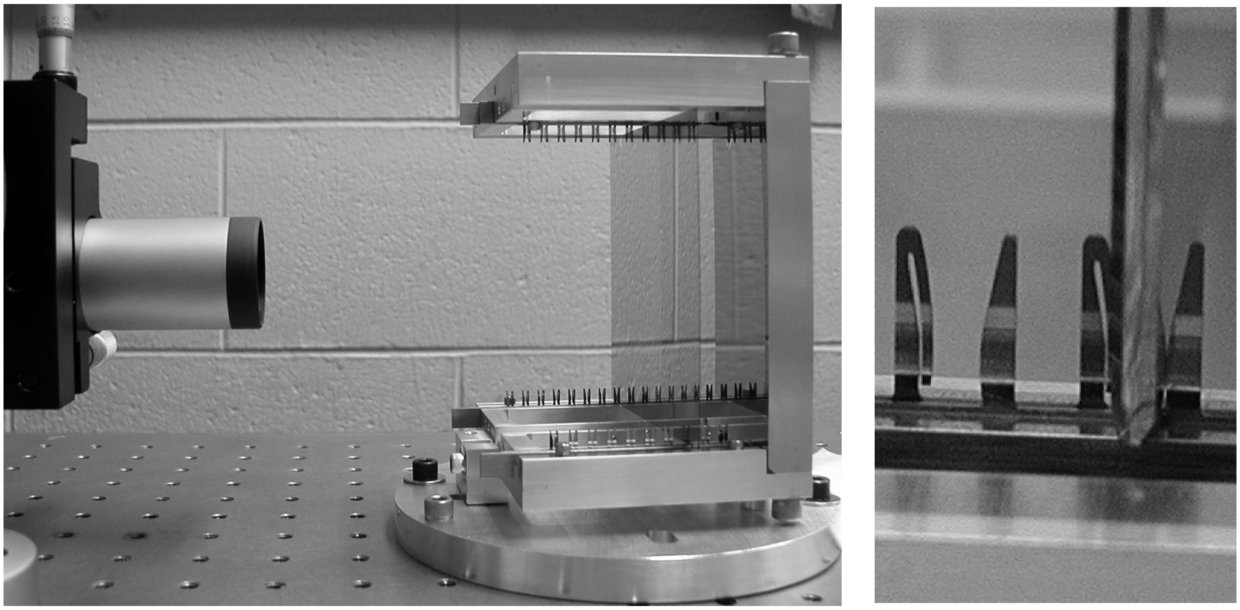

Figure 5. *Left:* Autocollimator pointing at a rigid flate plate in the assembly truss. *Right:* Closeup of microcombs mounting a rigid plate used for testing purposes

assembly system is designed to mount a thin, and therefore flexible, foil at six points (three on the top and bottom), but in these test, since a rigid plate is used, three mount points are used (two on the bottom and one on the top) to ensure a clear interpretation of the test results.

4.1. Experimental Setup

Using three spring-reference comb pairs (Fig. 5), we installed a rigid flat plate in the assembly truss in various configurations. The plate is always held in the same way, with two microcomb pairs at the bottom corners and one microcomb pair in the top middle. Angles are measured with a Newport quadrant detector autocollimator (model LAE500-C), which reads out μrad in pitch and yaw with a resolution of 0.1 μrad. Both the assembly truss and the autocollimator are fixed to a rigid optical bench (Fig. 5). The three-point mounting of the plate simplifies conversion of angles into linear displacement along the length of the microcombs. The two pairs of microcombs on the bottom are separated by 81 mm, giving a yaw conversion of 12 μrad per μm. The top pair is 100 mm above them, giving a pitch conversion of 10 μrad per μm. It is useful to note that in these tests, 0.5 μm corresponds to about $1''$.

4.2. Autocollimator drift

During early tests we noticed a significant variability in the angle of the reference flat as given by the autocollimator (more than 1 μrad per minute). This drift might be due to air turbulence, heating of the electronics inside the autocollimator or instabilities in the mounting of the assembly truss. To minimize this effect, we installed the autocollimator very close to the reference flat and waited for about one hour after turning on the autocollimator, so that it could equilibrate before beginning the tests. These precautions reduced the drift below 0.3 μrad per minute. Accuracy was further improved by interpolating between calibration measurements taken with the reference flat before and after each measurement of a mounted plate. The error associated with instabilities in the autocollimator measurements is estimated to be $\sim$0.03 μm.

4.3. Results

The repeatability of mounting of a plate in a given slot was measured by a repeated process of sliding a rigid flat plate against the reference comb teeth in a given slot, measuring its angle, then removing it. Results of repeatablilty tests (Table 1) show a typical 1 σ mounting repeatability error of $\sim$0.1 μm in both axes.

slot	displacement error (μm)					
	repeatability		slot to slot		reference flat	
	pitch	yaw	pitch	yaw	pitch	yaw
2	0.01	0.03	-0.2	0.5	-0.4	0.5
3	0.04	0.10	0.3	0.0	0.1	0.1
4	0.07	0.02	-0.1	-0.4	-0.3	-0.3
5	0.10	0.13	0.2	0.1	0.0	0.2
8	0.07	0.01	0.1	0.1	-0.2	0.2
9	0.30	0.21	-0.3	-0.3	-0.6	-0.2

Table 1. Results of measurements of the assembly system. Slot numbers are defined by successive microcomb teeth. Displacements shown are converted from angles measured with an autocollimator. "Repeatability" measures the 1σ variability in five trials of mounting a plate in the given slot. "Slot to slot" measures the deviation when the plate is mounted in different slots. "Reference flat" gives the deviation from parallelism between the reference flat and plate mounted in the given slot, after subtracting error contributions that are due only to the reference flat (see text).

To measure mounting variations between slots, the plate was installed in several different slots and for each slot, five measurements were made. In Table 1, the mounting deviation in each slot is compared to the mean deviation from all slots. Among all the measurements, variation between slots corresponds to a 1 σ slot-to-slot mounting error of < 0.5 μm in pitch and yaw.

To measure alignment between the mounted plate and the reference flat, the angle of the plate and reference flat were compared with the plate mounted in several different slots. The measurements showed a typical misalignment of about 2 μm in pitch and about 1 μm in yaw. Results of reference flat measurements, corrected to only show errors due to the microcombs (see below), are shown in Table 1.

The errors detected in the repeatability measurements ($\sim$0.1 μm) and in the slot-to-slot measurements ($\sim$0.5 μm) are typical of what we expect based on the sub-μm accuracy of the fabrication techniques used in making the microcombs. It is not necessarily surprising that the results of comparing the plate to the reference flat are slightly worse (2 μmin pitch and about 1 μm in yaw) because there are several additional sources of error. Among these, non-flatness of the reference flat and rigid plate are each estimated to contribute a $\sim$0.5 μm error to the reference flat tests. Scratches in the relatively soft surface of the reference flat (which is a diamond turned aluminum plate) could cause additional errors.

To isolate the error due to the reference flat, we repeated the measurements of Table 1 with the three pairs of microcombs permuted into different positions. This tests the hypothesis that in addition to the $\sim$0.5 μm variations seen in the slot-to-slot tests, there is an offset (due to non-flatness or scratches in the reference flat) that will be present regardless of which microcombs are used. In comparing the old and new data sets, we found that there was an offset of -2.0 μm in pitch and -1.1 μm in yaw. These offsets were subtracted from reference flat measurements to remove the error contribution from the reference flat leaving only errors in the microcomb dimensions and their ability to make a consistent reference with the reference flat. The offset-subtracted data has a mounting accuracy standard deviation of 0.3 μm in pitch and 0.4 μm in yaw. This result is encouraging for two reasons. First, it suggests that the reference between the microcombs and reference flat is as good as the reference between the microcombs and the rigid plate, both being accurate to about 0.5 μm. Second, we expect that the error due to the reference flat will be removed by replacing the aluminum reference flat with a kinematically mounted quartz reference flat (see Section 2) that will have $\lambda/4$ or better flatness and will be more resistant to scratching.

4.4. Degradation of Reference Precision

After performing the tests the microcombs were examined with a high-power microscope to search for evidence of damage from wear. Damage was noticeable on some of the reference microcomb teeth (Fig 6). The reduction in alignment accuracy caused by this damage has not yet been quantified, but it appears not to be very significant. We expect the damage will be reduced when much less massive thin microsheets are used instead of rigid plates. We are also developing a technique to harden the microcombs by growing a hard surface layer of thermal oxide. The microscope also revealed that some of the reference surfaces were contaminated by dust particles, several μm in

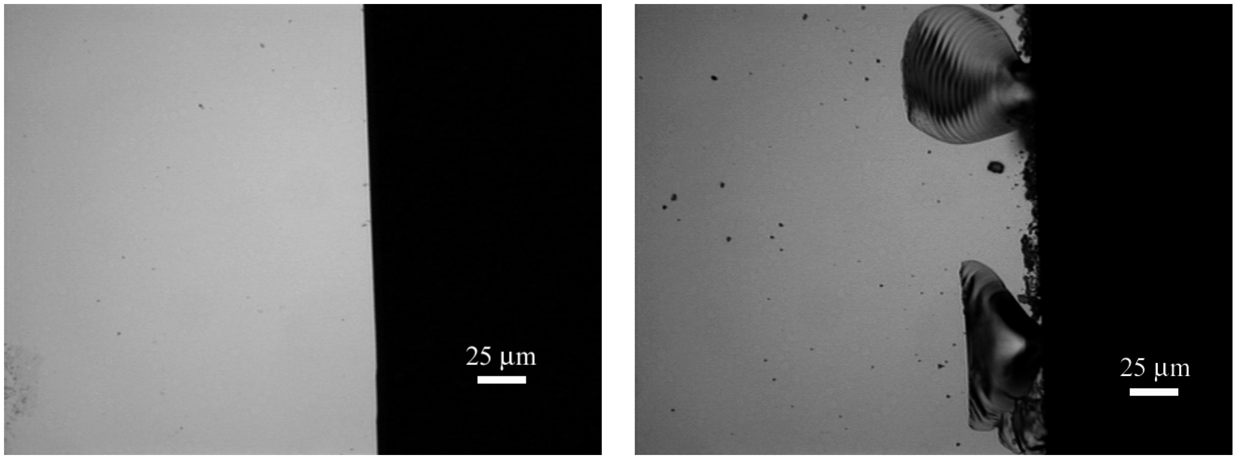

Figure 6. Close-up of microcomb tooth reference surface before (*left*) and after (*right*) repeated use.

size. We expect that this will not be a significant problem in future tests, which unlike these, will be performed in a cleanroom environment.

5. CONCLUSIONS AND FUTURE WORK

We have developed a system of alignment tooling that is designed to provide sub-μm alignment of segmented thin foil X-ray optics. Alignment is achieved with an assembly truss utilizing a metrology frame, featuring silicon micro-structures that are fabricated to sub-μm tolerance. After alignment, foils are bonded to a separate flight structure. The assembly truss is then removed, and is not part of flight hardware (and is therefore reuseable). Our approach of using a separate system for alignment and flight simplifies the alignment system by removing requirements such as mass limits and launch stress survival. It also simplifies the flight structure which doesn't have to provide high-accuracy alignment.

Tests performed thus far have demonstrated that the alignment system can mount rigid flat plates with a positioning tolerance typically better than 0.5 μm, resulting in a high degree of parallelism that for the segmented Constellation-X SXT design[1] would correspond to a $< 1''$ HPD. Future tests will characterize the system's ability to accurately position thin foil optics. In addition to the same positioning accuracy demonstrated with rigid flat plates, these tests will require that we minimize the distorting forces applied to the flexible foil.

6. ACKNOWLEDGEMENTS

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