Invited Paper

Precision Assembly Station for High Resolution Segmented Optics

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ABSTRACT

Historically, segmented optics similar to those used in BBXRT and ASTRO have achieved resolutions of a few arc minutes. Achieving substantially better performance requires significant improvement in both the optics themselves and how the optics are assembled and mounted to flight structure. While techniques for improving the optics themselves are underway at Goddard Space Flight Center (GSFC), Columbia University, and Smithsonian Astrophysical Observatory (SAO), here we address how the optics are assembled and mounted to flight structure. We have developed a concept for mounting large numbers of nested, segmented optics which require sub micron accuracy. This methodology uses lithographically defined and etched silicon alignment micro structures. A precision assembly station, incorporating the silicon micro structures is used to position the optics which are then bonded to a flight structure. The advantages of this procedure are that the flight structure has relaxed tolerance requirements and the precision assembly tooling can be reused. We show the positional requirements of the precision tooling as well as the mechanical requirements of the tooling itself.

Keywords: Constellation-X, etched silicon, precision tooling, segmented x-ray optics, SPIE Proceedings

1. INTRODUCTION

The Constellation-X (CX) mission is a key component of NASA's Structure and Evolution of the Universe theme. CX is a team of powerful x-ray telescopes that will orbit close to one another in space. These telescopes will work in unison to simultaneously observe the same distant object, combining their data and becoming 100 times more powerful than any single x-ray telescope that has come before it. CX will contain both hard x-ray telescopes (HXT) and spectroscopic x-ray telescopes (SXT). The imaging requirements for the SXT are more stringent than those for the HXT and it is the SXT which will be discussed below.

CX studies (References 1-3) have presented segmented optics for use in SXT mirror systems. The optical system of the SXT employs a Wolter type II telescope using thin shell type optics. Wolter type II optical designs that meet the program requirements may consist of 70 or more individual paraboloid (P) and hyperboloid (H) mirror surfaces as in Reference 4. This optical design consists of a P-H shell length of 1.0 meter and a working maximum diameter of 1.6 meters. Reference 1 suggested a maximum segment size of 30 degrees azimuthally: This requires a total of 12 segments to form a complete P or H shell. As a result, we require a precision assembly station capable of assembling a minimum of 1,680 individual mirror segments into the complete P-H mirror assembly for flight.

The precision required for the tooling assembly is obtained from SXT requirements of an on-orbit image quality (less detectors) of <15 arc seconds half power diameter (HPD) at 1.5 keV. SXT system tolerance requirements place ~5 arc seconds HPD on the assembly and alignment portion of the mirror module fabrication. From this, we have allocated ~2.5 arc seconds HPD for the task of precision positioning the P-H mirror segment pair (1.77 arc seconds HPD for P or H mirror segment) on the tooling. Mirror segment tilt (radial tipping of segment top or bottom with respect to its opposite end) is the largest component of tooling error and can occur at the shell top or bottom support points. For our system, a 1.0

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arc seconds of mirror segment tilt produces 4.0 arc seconds HPD. For 1.77 arc seconds HPD, the mirror segment tilt allocation is 0.44 arc seconds. Over a typical 0.5 meter shell, the radial error allocation becomes 1.1 microns.

This paper presents a concept for assembling the optical segments into a complete P-H mirror assembly that is consistent with the sub micron tolerances required for the SXT. The assembly station concept provides precision positioning to each mirror segment at eight locations along their edges. This precision positioning includes four locations in the radial and vertical directions along the bottom edge of the mirror segment and four locations in the radial direction along the top edge of the mirror segment. The concept provides sub micron precision not only to each mirror segment individually, but also sub micron precision of one mirror segment to every other (P or H) mirror segment in the optical design. Once precision positioned, the mirror segments are able to be permanently attached to the flight structure.

The precision assembly station facilitates the assembly tasks by providing removable precision surfaces in contact with the mirror segments for alignment. Two general concepts of the assembly station accomplish this. First, the assembly station provides the overall sub micron precision to key locations required for the assembly. The overall precision is supplied by three pieces of assembled metallic tooling, shown assembled in Figure 1. The second concept utilizes etched silicon micro structures that abut the precision surfaces of the metallic tooling. These etched silicon micro structures, referred to as “combs”, provide precision positioning directly to individual mirror segments as described in Reference 5. A single radial stack up of combs, also shown in Figure 1, provides precision radial positioning for all the mirror segments before bonding to the flight hardware.

The assembly of the mirror segments consists of dividing the assembly process into a series of manageable tasks, described later in detail. The mirror segments are first assembled as a flight unit in a 30 degree wedge. The 12 flight units, in turn, comprise each P or H module. Finally, the P module as attached to the H module to complete the P-H mirror assembly for flight.

The assembly process addresses many requirements to make the assembly process accurate, practical, and economical. The tooling and all precision surfaces are reusable for building multiple sets of flight hardware. The number of precision surfaces required has been minimized. The quantity of tooling required has been minimized. Access to the mirrors and other critical areas has been maximized at all stages of the assembly process. Precision assemblies can be built up and torn down with a minimum number of steps to facilitate quick replacement of a component if any damage occurs. Many portions of the assembly process can be conducted in parallel for maximum assembly flexibility and time savings.

2. OVERVIEW OF CONCEPT

References 6 and 7 provided the baseline concept for building a segmented optics assembly subject to the structural requirements imposed by the design presented in Reference 8. The major assembly steps are outlined in the following five sections:

1. Assemble the Flight Units Containing Loose Mirror Segments
2. Assemble the Precision Tooling
3. Precision Position and Bond Mirror Segments into Each Flight Unit
4. Attach Flight Units Together to Create a Module
5. Attach P Module to H Module.

The first section details the assembly of each individual 30 degree flight unit. There are twelve P flight units and twelve H flight units in the flight P-H assembly. The fundamental principle of this assembly step is to build each flight unit with the mirror segments loosely contained within the flight unit.

The second section details the assembly of the precision tooling. The precision tooling is used in every step of the assembly process for precision alignment and handling functions. The tooling provides for the installation and removal of flight units required for the assembly process. Flight unit access is achieved with a minimum number of precision

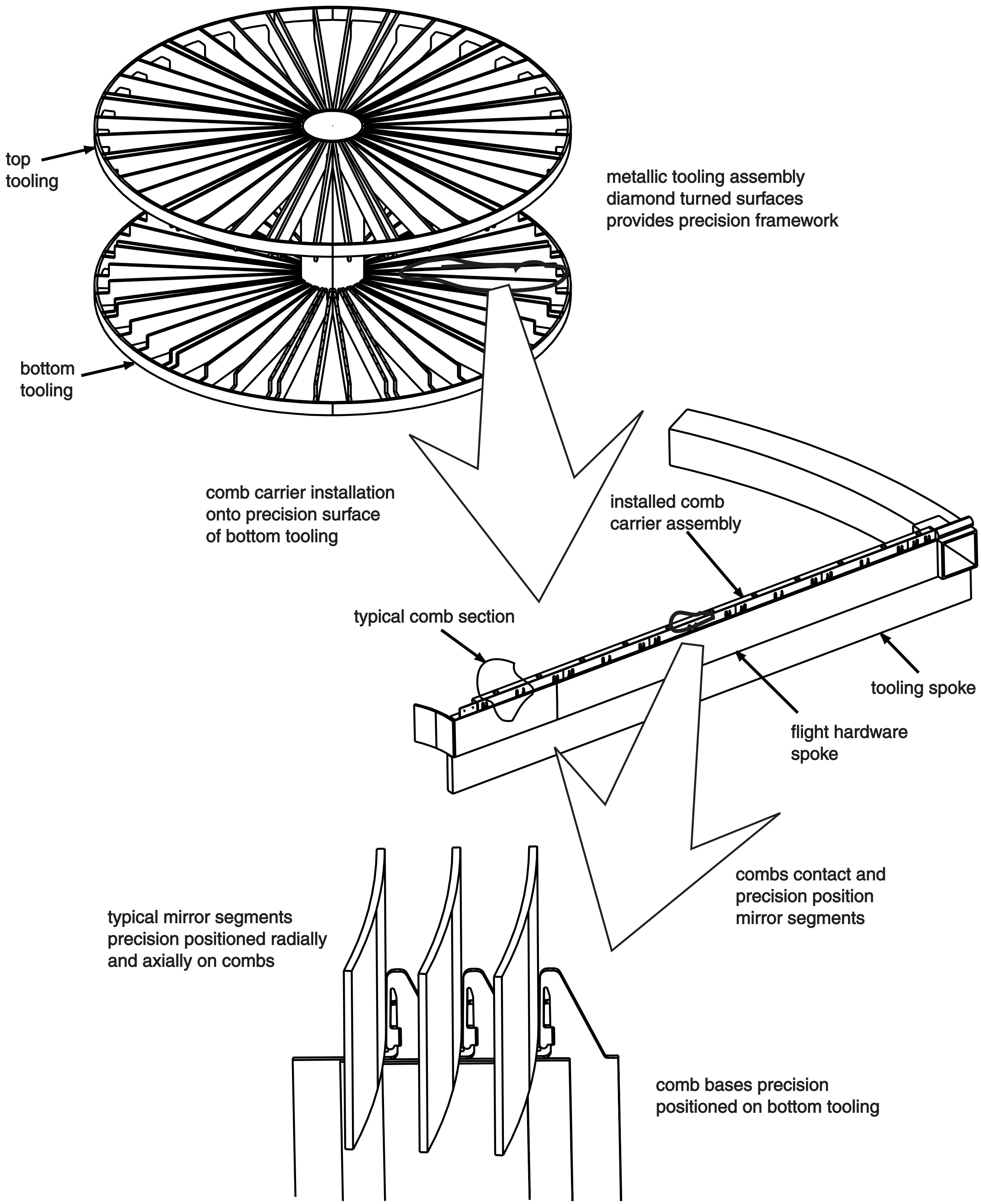

Figure 1. The Concept of Precision Postioning Segmented Mirrors

tooling assembly steps.

The third section details how the loosely contained mirror segments within the structurally complete, flight worthy units, are precisely positioned by the tooling and permanently attached to each flight unit. This section details how the flight units can be removed from the tooling such that all precision tooling may be reused on hardware for additional telescopes.

The fourth section details how the twelve individual flight units are positioned and joined together to form a module. This memo refers to a “module” as twelve P (or H) flight units that have been joined together.

The completed mirror assembly consists of a P module joined to an H module. The last section details how the P and H modules are joined to form the completed mirror assembly. This step completes the assembly process.

3. ASSEMBLE THE FLIGHT UNITS CONTAINING LOOSE MIRROR SEGMENTS

The non precision pieces of a flight unit consist of the following major parts:

- inner panel
- outer panel
- top optic support
- bottom optic support
- closeout side panel
- mirror access side panel

These parts are shown in Figure 2. There are a total of 24 flight units per telescope: 12 P and 12 H. The parts are initially assembled to form an open flight unit without optics. This step involves completely joining flight unit inner panel, outer panel, top optic support, bottom optic support, and one closeout side panel. This assembles five of the six sides of a flight unit and leaves one side open (the mirror access side panel) for the loading of the mirror segments. The parts are joined by bolting, pinning, and/or bonding. This results in flight quality joints, designed to survive flight loads, that will not be taken apart while retaining the ability to remove or replace individual mirror segments on the open side if necessary. Figure 2 shows the flight unit (with the mirror access side panel installed after mirror segment loading).

The mirror segments are loaded sequentially from the smallest to the largest radii. This allows access to the back side and the open edge of the mirror segments during “loose assembly”. At this point the mirror segments are supported by coarse comb structures. These structures are low precision slots on the bottom and top optic supports that retain the mirrorsegments loosely until they are precision positioned and bonded at a later time. Small, incremental tips of the open flight unit may be necessary to protect the mirror reflecting surfaces during the loading process. This operation is low precision. The loaded mirror segments are shown in Figure 2.

The precision of this hardware must ensure that the mirror segments do not bind on coarse combs during loading into the flight unit and after the closeout of the flight unit. Note that the flight unit precision has no effect on the final precision of the mirror segments because the mirror segments are precision positioned (as detailed later) by only the combs. The flight unit assembly precision must provide flight unit to flight unit bond joints within the nominal range for the bond line of the joint. Although this precision depends on the joint detail, we set the flight unit precision to ±25 microns.

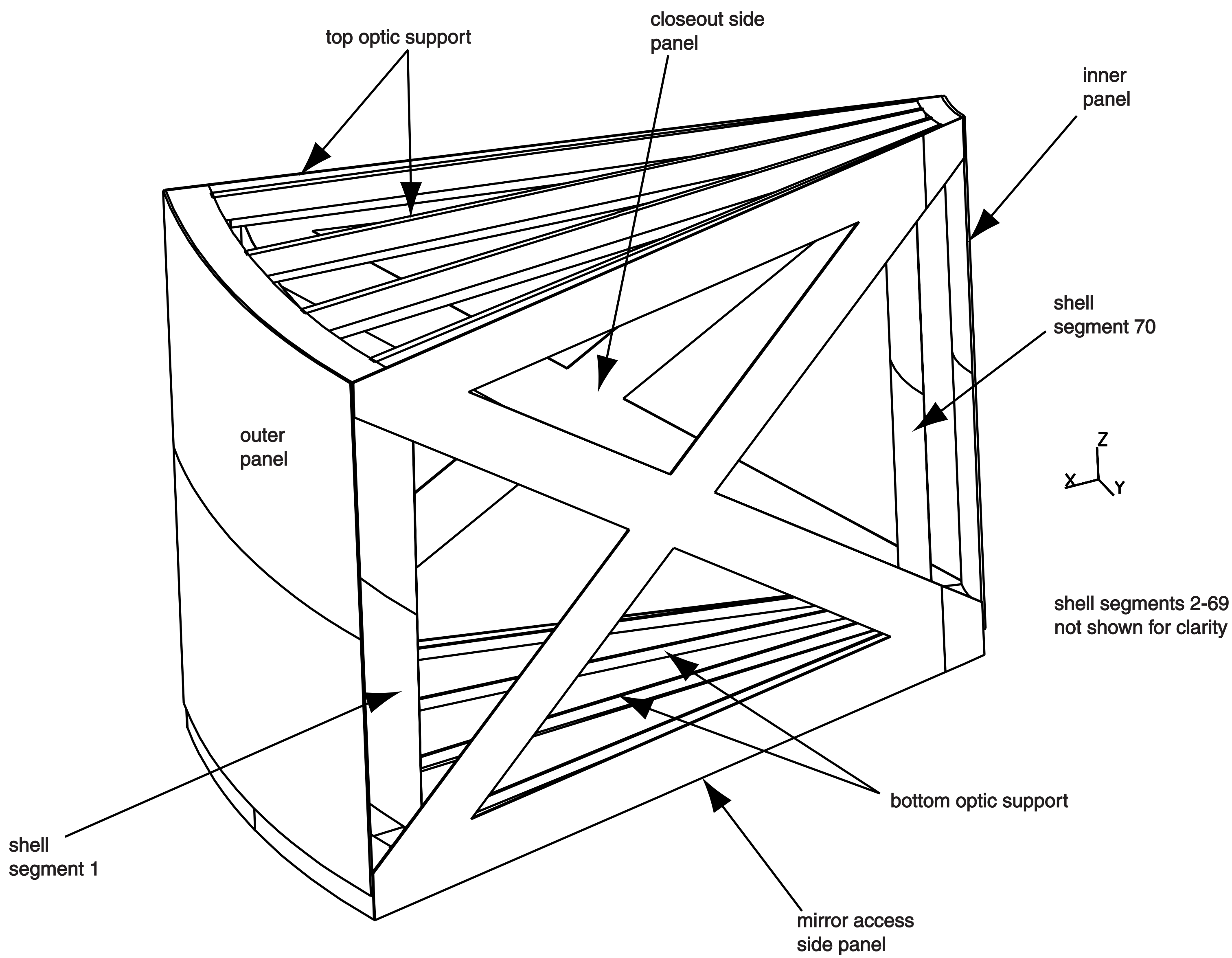

Figure 2. Flight Unit Assembled with Mirrors Loosely Trapped in Coarse Combs

4. ASSEMBLE THE PRECISION TOOLING

The precision tooling consists of the following parts:

- top tooling
- center tooling
- bottom tooling
- stop combs and installation hardware
- comb carrier assemblies including rigid and flexible combs, comb carriers, flexible comb closing hardware.

As previously discussed, the precision tooling consists of two components: The metallic tooling that provides overall tooling precision, and various pieces of etched silicon micro structures, collectively referred to as "combs", which extend the precision of the metallic tooling to the mirror segments. The metallic tooling consists of the top, center, and bottom tooling and is shown in Figures 3 and 4. To maintain sub micron precision from the center tooling precision surface 3 (shown in Figure 3) to the radial stack up of combs (detailed later), an intermediate piece, called the stop comb, must be precisely positioned and permanently bonded to the tooling spokes. All subsequent radial positioning of combs is based on abutting the stop combs. Another one time tooling assembly step (detailed later) is required to assemble the precision rigid and flexible combs into the comb carriers. The comb carriers reduce the possibility of comb damage when being handled. Because the combs are fabricated from a maximum silicon wafer size of about 150mm, the comb carriers also serve to maintain the assemblage of the stacked up combs over the inner to outer radius of mirror segments. Springs that retain the combs on the comb carriers provide the ability to open (loose fit for assembly and checkout) and close (precision align for mirror segment bonding) the combs.

The first step is to mount the comb stops onto the precision tooling. This portion of the assembly sequence consists of permanently bonding two stop combs to the precision surface of each spoke of the top and bottom tooling. The sequence involves the exclusive use of precision surfaces in the axial and radial directions. The sequence starts by assembling the top, bottom, and center tooling. The precision surfaces of the tooling are shown in Figures 3 and 4. The center tooling is hoisted onto the tooling jacks of the bottom tooling then installed into the bottom tooling as shown in Figure 5. The installation engages the precision radial, precision axial surfaces of the top and center tooling and the azimuthal alignment pin. The precision of the azimuthal alignment pin is of the order ±3 microns.

Next, the comb stops are permanently mounted to the tooling spokes. One comb stop pair is needed for each tooling spoke. Precision etched silicon is used for both the comb stops and the spacer as shown in Figure 6. The assembly to mount each stop pair consists of stop tooling, clips, spacer, and the comb stop pair. The stop tooling clips retain all parts so the assembly can be handled as a unit. Once assembled, the stop tooling is mounted to the tooling spoke with match drilled taper pins. Figure 6 shows this assembly installed on the bottom tooling. The comb stop spacer is used to precisely position the comb stop pair in the radial direction while it is bonded to the tooling spoke. There will only be one comb stop spacer used to install all comb stop pairs.

Once the comb stop pair is permanently attached to the tooling spoke, the reusable parts of the assembly are removed to be reused for the next comb stop pair. This process is repeated until the 96 comb stop pairs (4 bottom tooling, 4 top tooling over 12 segments) are permanently installed on the spokes of the top and bottom tooling. Figure 7 shows the bottom tooling with the stop combs permanently installed.

Next, we must assemble eight sets of comb carriers for repeated flight unit to flight unit use. Flight units require four top and four bottom comb carriers that will later be used to precision position each mirror segment at four top edge and four bottom edge locations. Comb carriers hold the precision etched silicon combs for ease of handling. Four carriers are shown installed on the bottom tooling spokes in Figure 7: The comb carriers fit between the tooling and the flight unit. Figure 9 shows an exploded view of a typical section of the comb carrier assembly and its relation to the flight hardware and tooling. The flexible and rigid combs are assembled into the comb carriers with retainer clips. This assembly occurs only once: The eight assemblies are reused as a unit for the precision positioning of mirror segments for each flight unit.

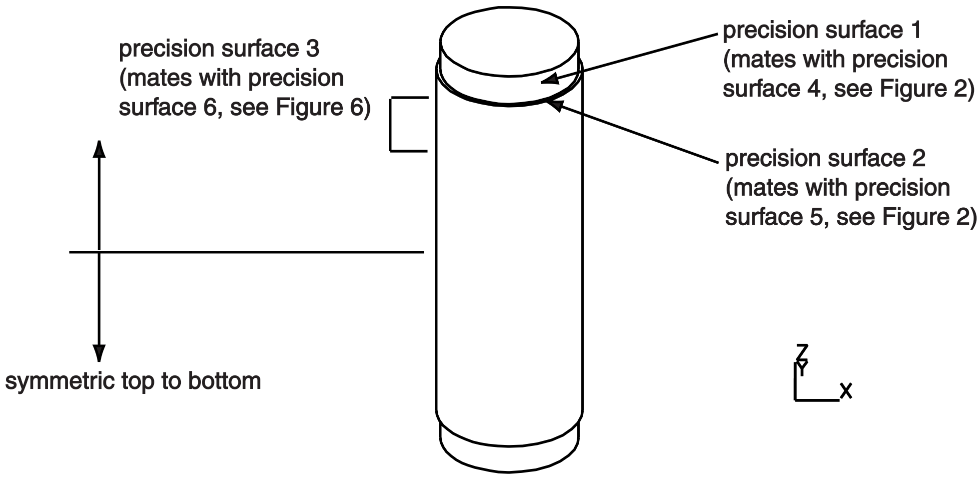

Figure 3. Center Tooling Precision Features

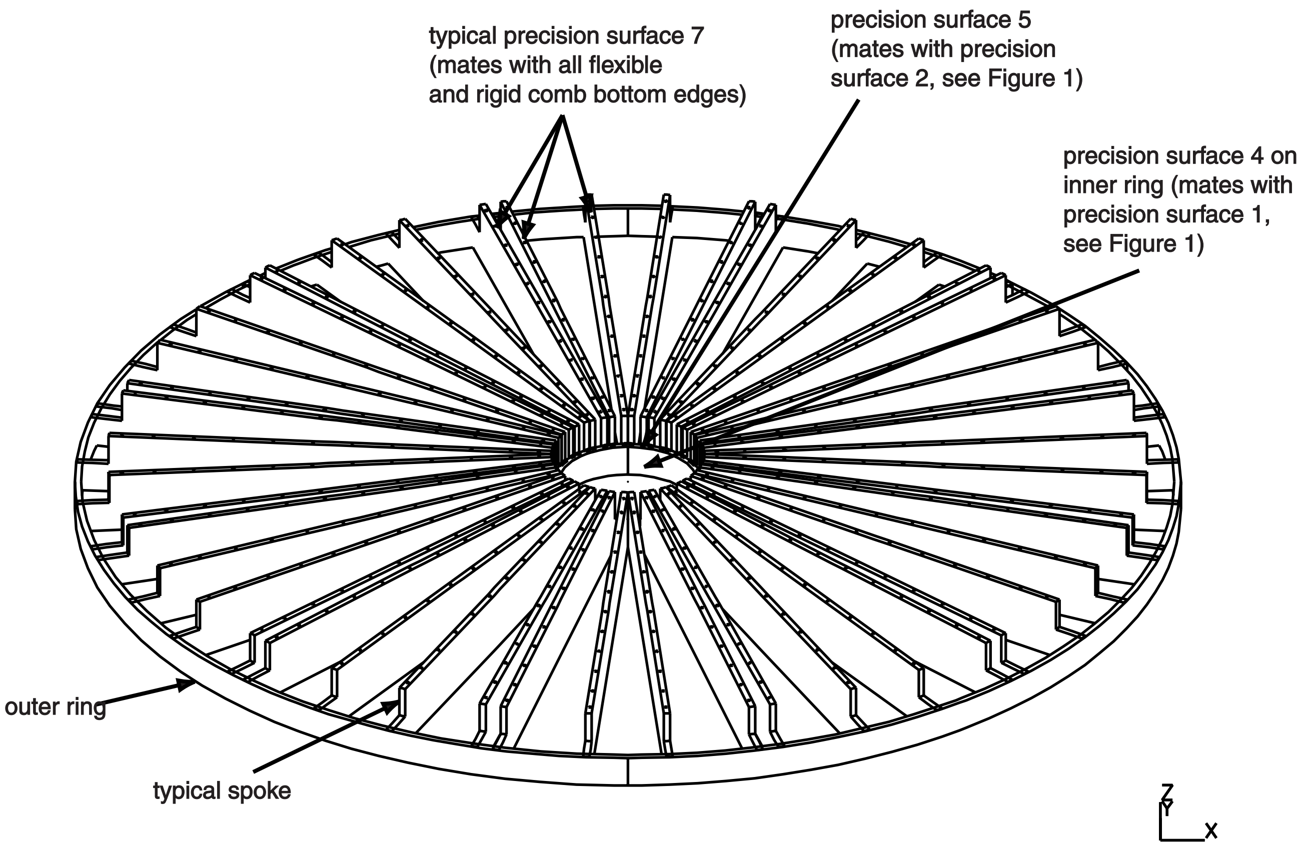

Figure 4. Bottom (or Top) Tooling Precision Features

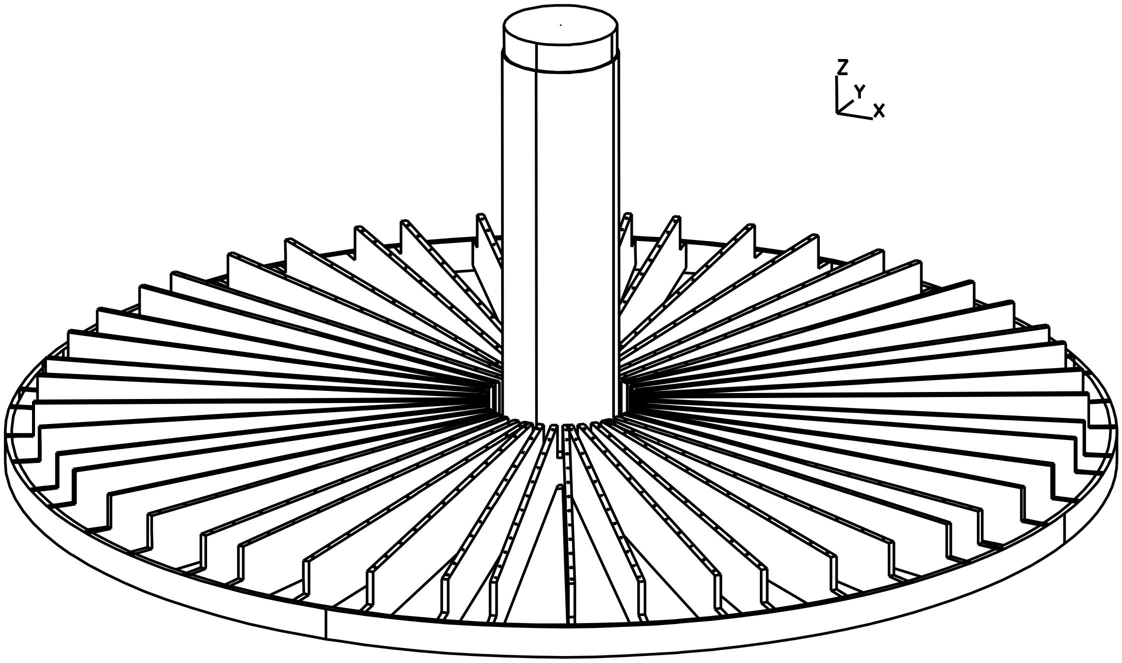

Figure 5. Jack Center Tooling into Bottom Tooling and Mate Precision Surfaces

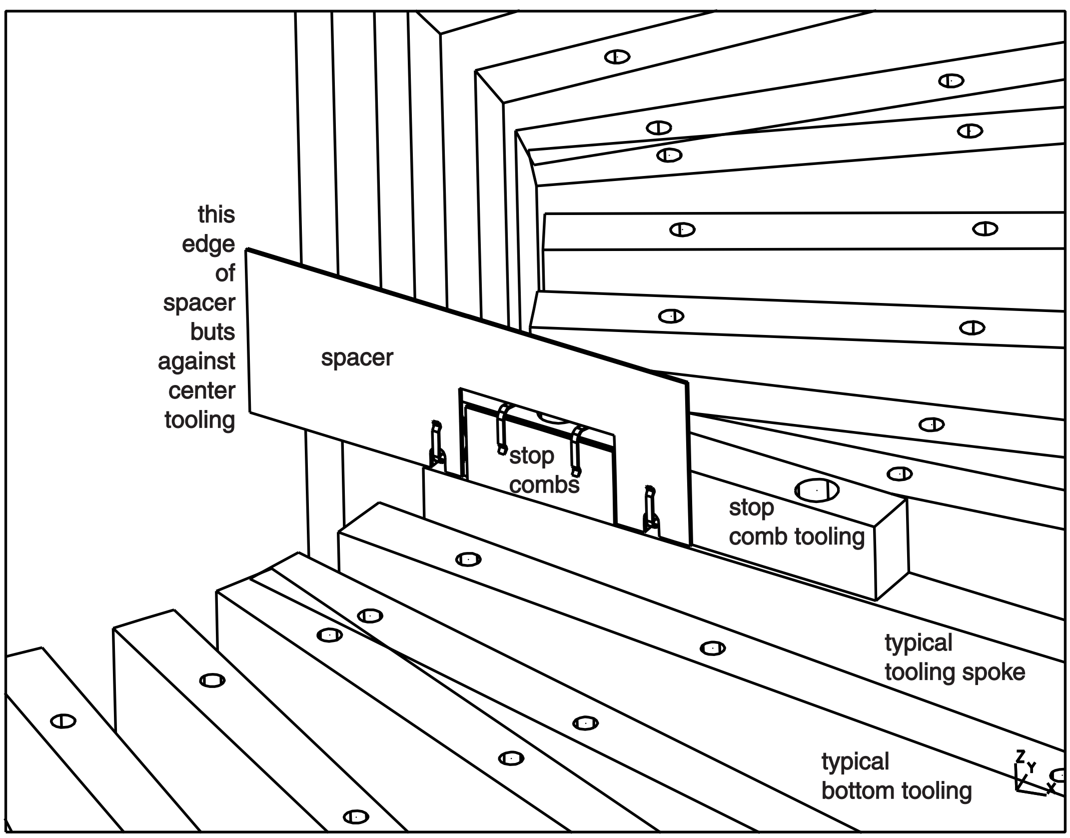

Figure 6. Install Stop Combs

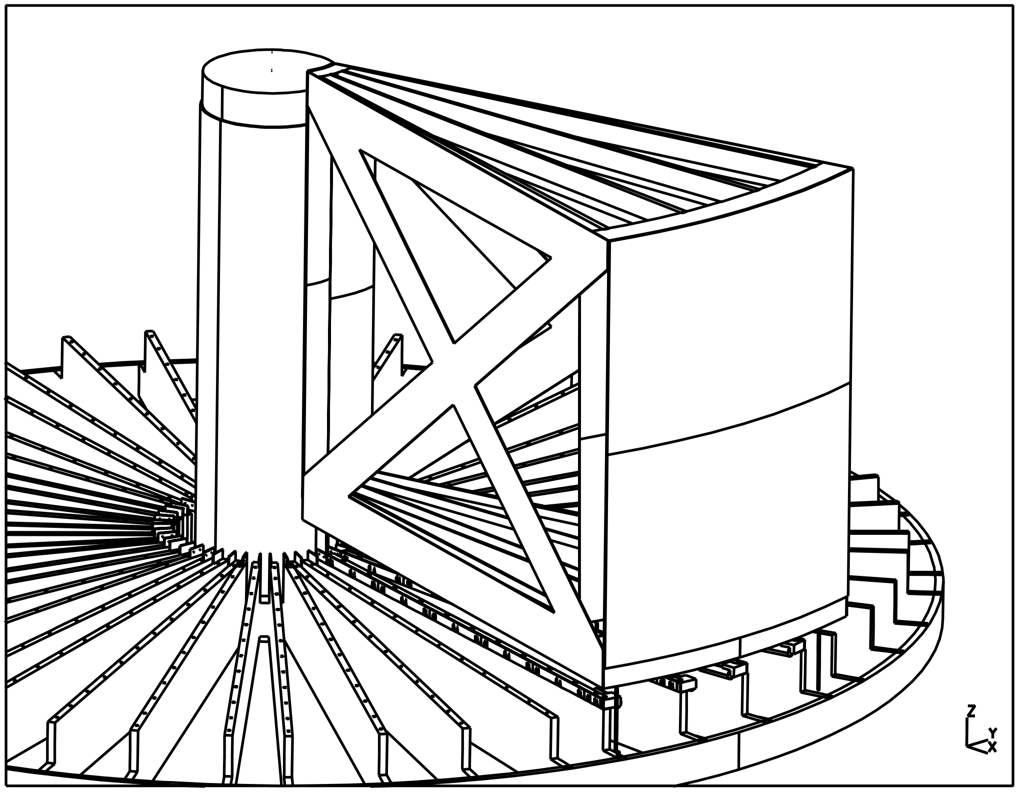

Figure 7. Hoist Flight Unit onto Jacks with Stop Combs and Comb Carriers Installed

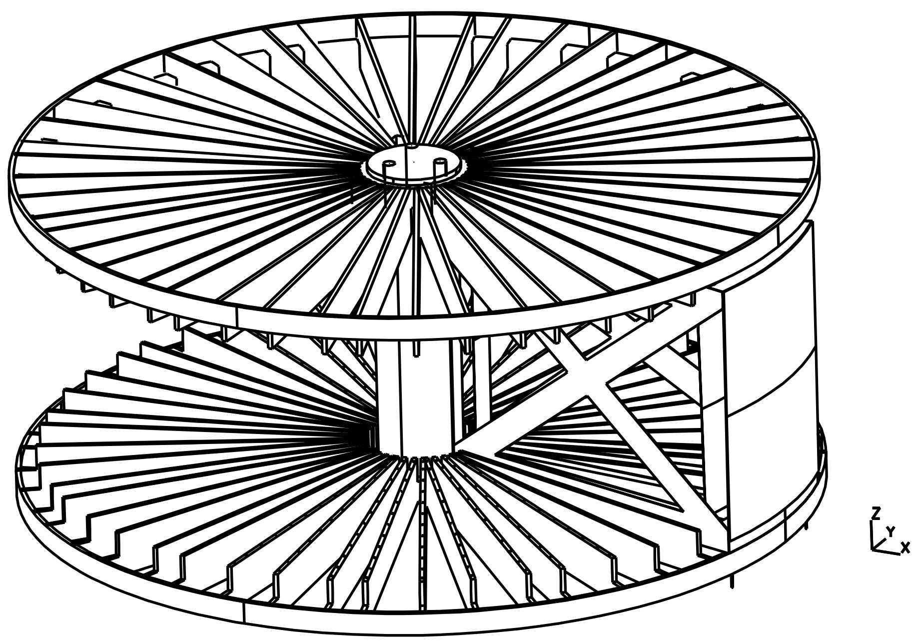

Figure 8. Jack Flight Unit into Bottom Tooling and Install Top Tooling

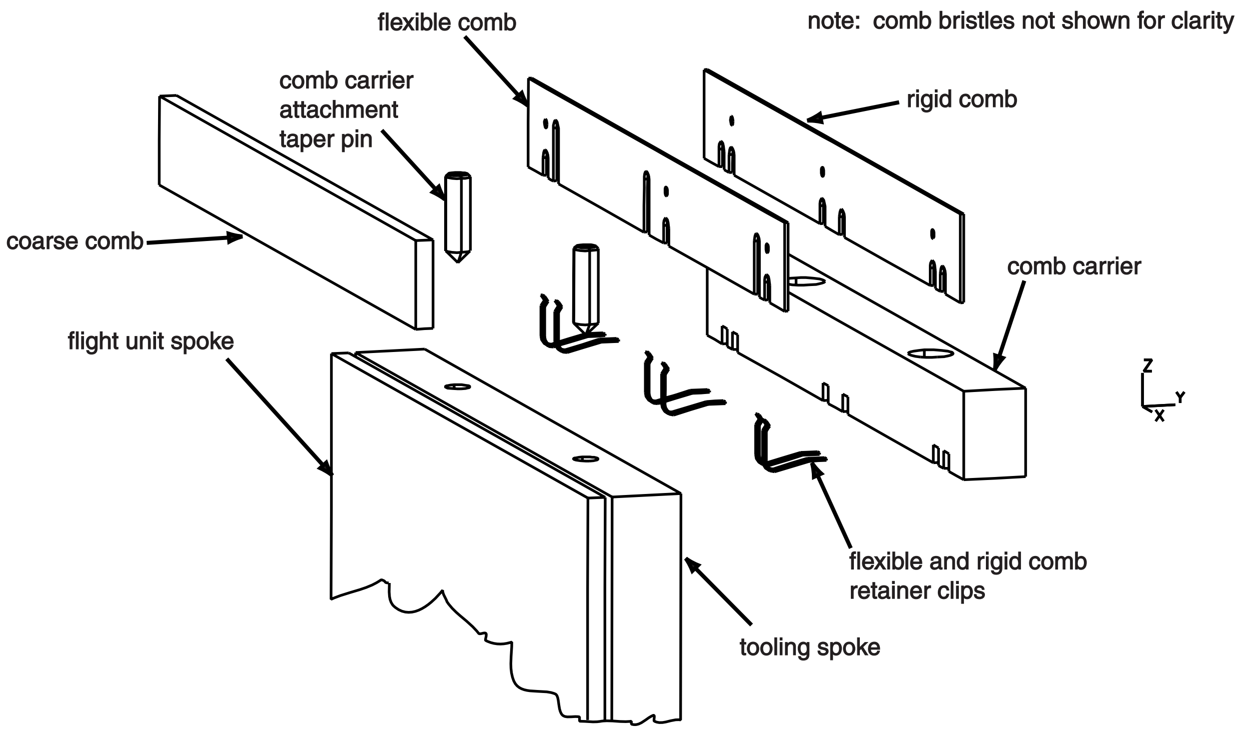

Figure 9. Exploded View of Typical Comb Section

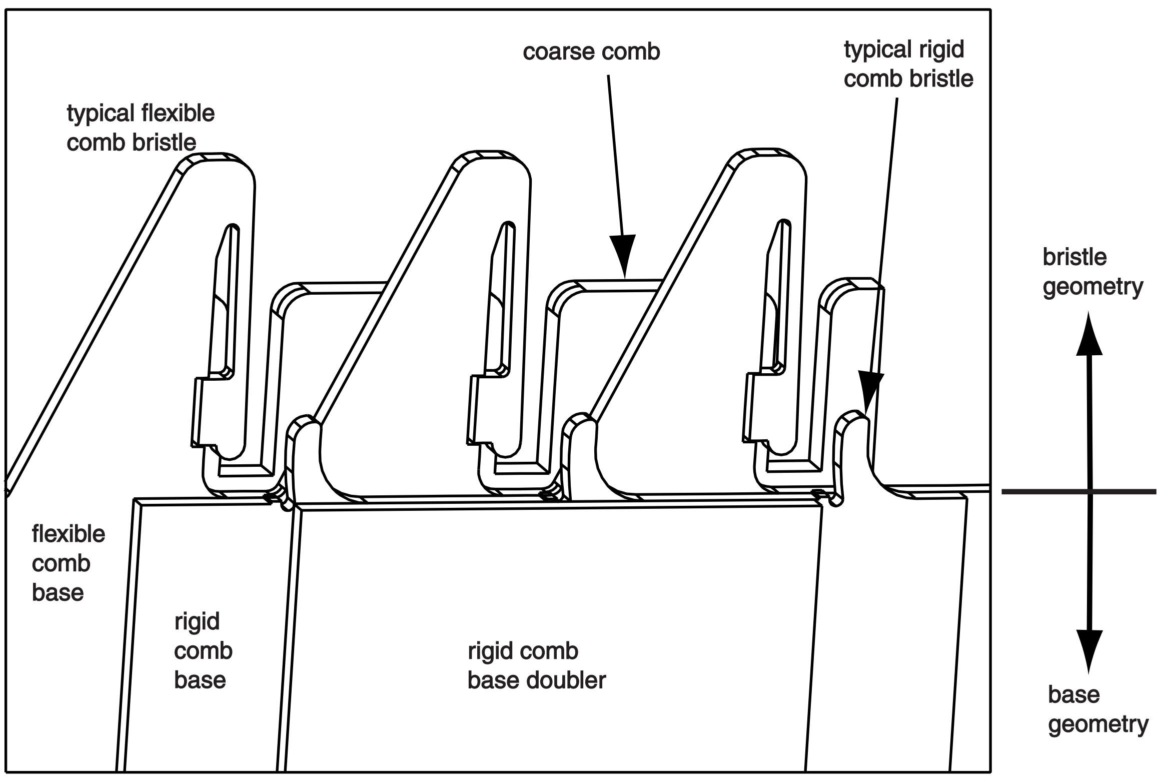

Figure 10. Comb Assembly Showing Bristle Geometry

This is a low precision assembly step. Figure 10 shows the details of the bristles of the combs. The bristles provide the precision positioning of the mirror segments by using the flexible comb bristle to seat the mirror against the rigid comb. Note that because of the complex geometry of the comb bristles, they are only shown in Figure 10 and have been omitted from all other figures.

5. PRECISION POSITION AND BOND MIRROR SEGMENTS INTO EACH FLIGHT UNIT

Precision positioning and bonding of the mirror segments is key to the concept. This is where the precision stack up of diamond turned metallic surfaces are engaged to the precision combs assembled in the comb carriers. The comb surfaces, in turn, precisely position the mirror segment for bonding. It is important to mention that when the bonding takes place the mirror segments are positioned only by the precision combs and not the lower tolerance flight unit.

The installation of the comb carriers for the first flight unit is shown in Figure 7. This step involves the precision alignment of the rigid combs to the stop comb, the rigid combs to one another, and the outboard rigid comb “lightly engaged” to the rigid comb retention block. The flexible combs should be touching each other and test cycled open/closed.

Next, the flight unit containing loose mirror segments is hoisted onto the three jack screws located in the bottom tooling. The flight unit is engaged to the three flight unit jacks at the ID and OD corners of the flight unit. The flight unit jacks are threaded into the bottom tooling and provide installation/removal of the flight unit.

The flight unit is jacked to engage the flight unit alignment pins and the flight unit alignment pads. This step is shown in Figure 8. This step requires sub micron repeatability into the flight unit alignment pins and onto flight unit alignment pads to maintain flight unit to flight unit mirror alignment. Each bottom optic support has three alignment pads that repeatedly mate with the bottom tooling (shown in Figures 7 and 8) . Together with alignment two pins (hole and slotted hole) at the ID and OD, this mating method would be repeatable, but not absolute, to micron level precision.

The top tooling is now replaced and jacked to the closed position. These steps are shown completed in Figure 8. Note at this point all rigid combs are precision aligned.

The tooling is now tipped so the inner mirror is vertical. This minimizes flexible comb load when these combs are closed to precision position the mirror. The flexible combs are closed and the inner mirror is permanently bonded into place at eight locations to the flight unit. Once the bond cures the flexible combs are opened. The above steps of tipping, comb closing, bonding, and comb opening are repeated for each mirror until all mirror segments of the flight unit are permanently bonded.

The above steps are essentially repeated for each of the remaining 11 flight units. Each flight unit may be removed from the tooling after its’ mirror segments are bonded.

6. ATTACH FLIGHT UNITS TOGETHER TO CREATE A MODULE

At this point we have 12 individual flight units with all mirror segments precision bonded for flight. The bottom tooling is used to ensure flight unit to flight unit alignment for the joining of the flight units to form a completed module. The flight units may or may not be installed in the bottom tooling at this time.

The flight unit to flight unit attachment sequence begins by opening all flexible combs of the flight units. The top tooling is removed by jacking it to the release position and completely removing it. The flight units are loaded one by one onto their respective flight unit jacks and installed onto the bottom tooling (if necessary). Repeatable flight unit to flight unit alignment is maintained by each flight unit resting on its three flats and engaged at its two alignment pins. The 12 flight units are bonded together as shown in Figure 11. This operation results in a completed P or H module.

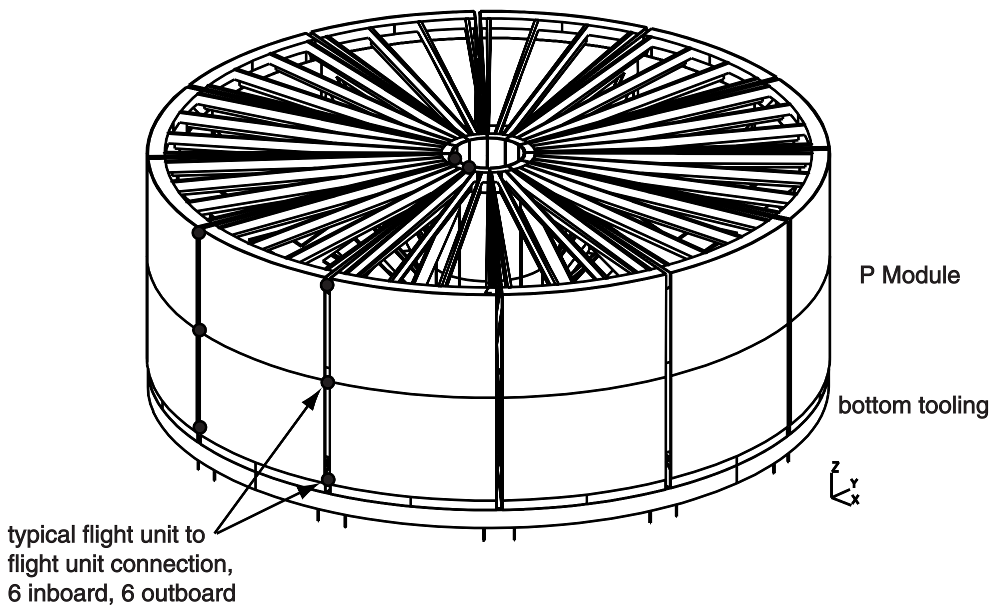

Figure 11. Bond All P Flight Units to Form P Module

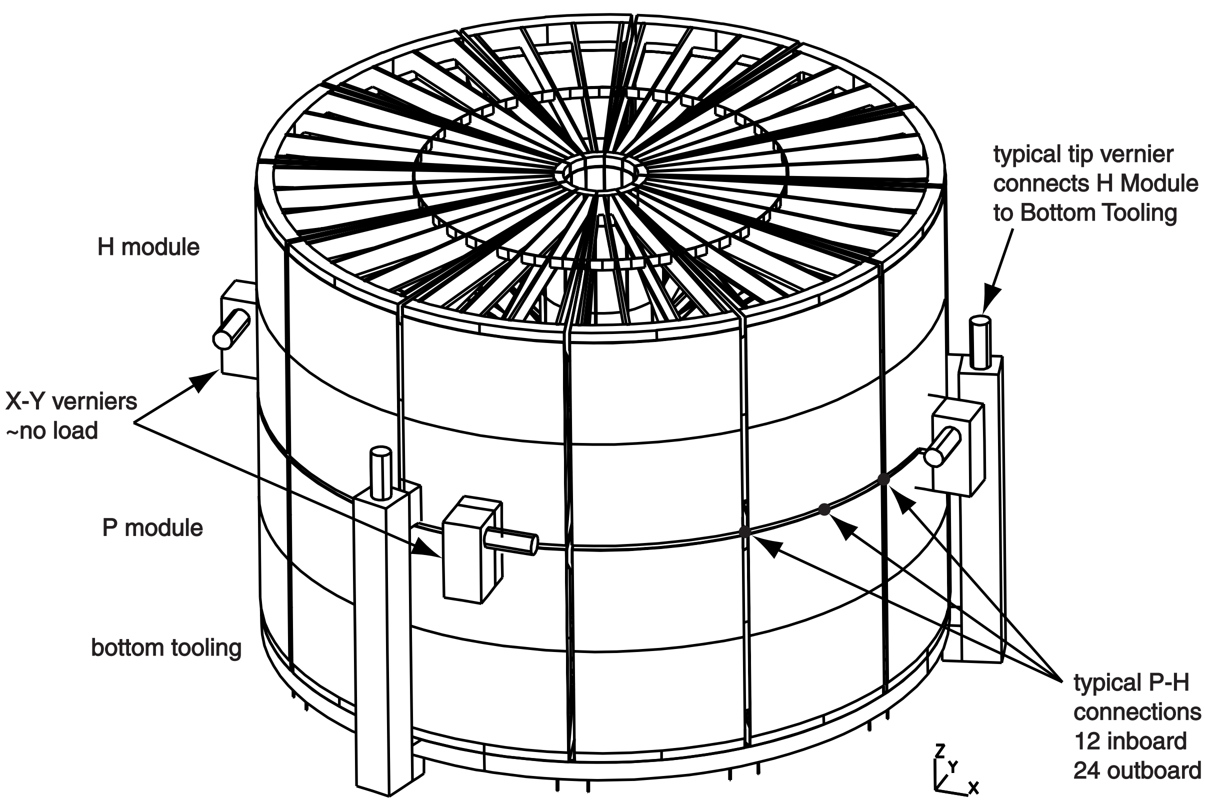

Figure 12. P to H Module Assembly

7. ATTACH P MODULE TO H MODULE

The last sequence of the assembly process is to attach the P module to the H module. First, the H module must be removed from its tooling. The P module is positioned in its bottom tooling with the H mating end up.

The positioning hardware is installed on the bottom tooling, P module, and H module. The H module is then hoisted to the positioning hardware and the positioning hardware is engaged as shown in Figure 12. The H module weight is supported by the positioning hardware at the three tip vernier locations. The tip hardware is assumed to have features that allow for “frictionless” X-Y motion so that the H module can be aligned in tilt, X, and Y with minimum external load introduced into the P or H modules.

The P module to H module alignment takes place next. This operation is performed with the vernier adjustments. The precision of this operation is of the order ±3 microns to produce a tilt error of less than 2.5 arc seconds HPD.

Once the modules are aligned, the modules are bonded together. The P to H bonds can be easily made at 24 locations on the OD of the assembly. Because the center tooling was removed from the assembly, P to H bonds are also able to be made at 12 locations on the ID of the assembly, as shown in Figure 12.

The alignment tooling is removed from completed P-H assembly. The P-H assembly is removed from the bottom tooling with the flight unit jacks at three or six locations. Once the P-H assembly is released from the alignment pins it can be hoisted from the tooling to complete the assembly process.

8. SUMMARY

A precision assembly station concept has been established to meet Constellation-X SXT requirements. The assembly station utilizes metallic tooling that has precision surfaces at key locations. The precision from the metallic tooling is extended using etched silicon alignment micro structures, or combs, that precision position the segmented mirrors withing lower tolerance flight hardware. The mirror segments are bonded to the flight hardware to sub micron precision to form a flight unit. The assembly station provides repeatable precision positioning of each flight unit relative to each other for precision alignment of mirrors from one flight unit to another. Twelve flight units attached together comprise a P or H module of the Wolter type II optical design. The P and H modules are then attached to each other to complete the process.

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