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# Critical alignment techniques for precision lens assemblies

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## ABSTRACT

Advancements in one area of technology nearly always create increased performance demands in related fields. Development of better, larger, and more dense focal plane arrays has stimulated the design of lens systems of larger aperture, longer focal lengths, and nearly diffraction limited performance over larger fields of view. As performance requirements, and the number of optical elements increase, the process of aligning lens elements during assembly rapidly becomes a critical issue. Tolerances on spacing, centration, and tilt become very challenging, as do the requirements on stability over extreme ambient excursions. This paper is intended to give a top level, general treatment of the subject, while describing certain techniques that incorporate precision alignment and measurement of critical lens parameters during assembly. These methods also allow monitoring during the accompanying bonding and curing cycles used throughout the build process. Examples will serve to illustrate some of these techniques, and results will be presented for specific cases. It will be shown that centering, as evidenced by axial runout, can be set to the ten microinches level with a few microinches accuracy and maintained to about 50 microinches through the assembly and bonding process. With the use of computer data logging and analysis techniques, this can be extended to below five microinches.

## 1.0 BACKGROUND

The process of assembling a number of discrete optical and mechanical components in a precise way, in order to produce a high performance lens assembly, is often a very complex procedure. Depending upon some particular set of an extremely broad range of options, many hard choices must be made. These choices dictate the shape of lens edges and other features, design, shape, and type of spacer rings, lens barrel, seats and retainers, and assembly algorithm. These are all influenced by environmental requirements such as survival and operational temperature, rate of temperature change, and vibration and shock loads. When describing some particular aspect of lens assembly, it is not possible to anticipate every mix of initial conditions. Many of these considerations are described elsewhere in recent texts. Instead, only some basic assumptions will be made concerning starting points for a couple of specific assembly techniques. Some measuring equipment will be described, and their use will be discussed. These will be applied to a refractive and a reflective optical system assembly process.

## 2.0 WIDE ANGLE REFRACTOR ASSEMBLY

Normally, a lens assembly must interface with the rest of the optical system in a precise way. Therefore, the optical axis is made to be concentric to the outside diameter of the lens barrel and perpendicular to some reference surface on it. Figure 2.0-1 is a representation of a multielement f/5.6, twelve inch focal length lens with a field of nearly +/- 12 degrees. The assembly consists of an inner cell containing five elements, and an outer assembly that houses three larger elements. Here, the optical axis of the inner cell is established concentric with two lands of the outside diameter and perpendicular to the back end. The lens is assembled in two stages. The five elements are assembled into the inner cell barrel, and then this subassembly is bonded into the outer housing using a slip fit between the lands and corresponding surfaces on the inside of the housing. The remaining three lenses are then aligned to the axis established by the inner lens group. A sensitivity analysis showed centration and tilt of several elements to be very critical. The following discussion will focus on alignment and assembly of one of these as an illustration .

### 2.1 Initial conditions

The basic alignment tools are an alignment telescope, an auxilliary light source called a "pip" generator

(PG), and at least two electronic indicator heads with readout. The inner lens cell is centered on a precision rotary air bearing table and secured, as shown in Figure 2.0-2. Using an electronic indicator, the table is adjusted in tilt until the indicator shows zero runout when measuring the top reference surface (back end) of the cell (or the table top if the front, or bottom end cell surface is chosen as the reference). Centration alignment is achieved when the outside diameter land indicates zero runout as well. The mechanical axis of the cell is then coincident with rotational axis of the table. The accuracy required is generally not severe, and relates to an assembly tolerance with regard to centration of the focal plane detector, etc. What is important is that the whole set up must be extremely stable, so that there is some way to verify and re-establish precise alignment from time to time during the build process. This could be several days if individual lenses need to be bonded, monitored, and allowed to cure one at a time. Generally, axial runout of small (eight to 12 inches) rotary tables is no more than about five microinches, and these adjustments can be made to about the same level. If both surfaces of the lens are accessable, electronic indicators can be used to indicate both surfaces, but this is not always feasible. There may not be room, or the cell may not be machined accurately enough with respect to the reference surfaces. For the inside elements, tolerances may be too tight to count on machining to establish proper alignment, and may require precise centering of a spacer to set the tilt of the first (bottom) surface. In this case, an indicator may be used to set the second (top) surface, but an alternate method is needed to bring the first surface into alignment. As shown in the figure, an alignment telescope is positioned and adjusted to be perpendicular to a small mirror placed on top of the end reference surface of the cell. This allows an optical line of sight to be established parallel to the cell axis. Again, the telescope mounting must be extremely stable. By using the PG attachment to the telescope, it is possible to align the telescope axis coincident with the cell axis, and to detect misalignment of the lens surfaces as the assembly proceeds.

## 2.2 Pip generator

The schematic representation of an alignment telescope shown in Figure 2.0-2 includes the pip generator (PG) used with a small autocollimating flat, for the initial setup, before insertion of the first lens element. In normal use, the internal source illuminates a reticle. When the autocollimating flat is aligned perpendicular to the telescope axis, the reflected image of the reticle is made coincident with itself when viewed through the eyepiece. The PG lens L-1 produces an image of the small arc source S-1. The rays from this image are directed toward the mirror by the small prism P-1, and reflected back into the telescope. By focussing the telescope, the "pip", or image of the point source S-1 can be brought to a sharp focus. S-1 is adjusted so that its image lies exactly on the optical axis of the telescope, and centered on the reticle crosshair. As each lens element is positioned into the barrel, the telescope may be focussed to obtain an image of S-1 after reflection from the surface being aligned. This method is very sensitive, and can be used as an aid to achieve and monitor alignment of each lens element. Generally, it is useful to mark the focus knob as elements are added to the barrel during the build, so that the pip from each surface can be uniquely identified. Before starting the assembly, a raytrace is performed to determine the pip diameter in the eyepiece from each surface, and the tilt or centration error for that surface as a fraction of the pip image diameter. For a perfectly aligned element, the pip from each of the two surfaces will be centered on the crosshair and remain there as the table is rotated.

## 2.3 Typical application

Table 2.0-1 lists the pip image radius at the telescope eyepiece, and the equivalent surface tilt for one-half of a pip diameter image shift, for each surface. Also given are the tilt tolerances and the pip image locations for each surface. The tightest requirements are on the second and third lens elements at 60 microradians. The pip image diameters are also very small for the two facing surfaces, making it more difficult to detect small displacements. The operator really must align both surfaces so no image motion is observed as the table is rotated. Fifty microradians at the edge of a two inch diameter lens corresponds to +/- 50 microinches of axial runout. The technique is very sensitive and non-contacting. Once the seating mechanism for the first surface has been adjusted to remove tilt, (i.e. its center of curvature lies on the optical and mechanical axis) and locked in place, an indicator may be used to zero out the top surface. This is accomplished by sliding the element on its seat, that is rotating it about the center of curvature of the first surface, until the center of curvature of the second surface also lies on the same axis. This may be confirmed by observing the second surface pip in the telescope. The sensitivity table previously calculated may then be confirmed by noting the indicator reading when the pip is misaligned by a convenient amount prior to final positioning. The element may be potted or otherwise fixed in position at this point, and allowed to cure. The same methods may be repeated to complete the build.

## 3.0 REFLECTOR ASSEMBLY

As long as the equipment errors are small compared to the alignment tolerances, and the mechanical and optical parts are made to comparable accuracy, the methods described above work quite well. In real life, there is always some periodic error or runout in the rotary table, or the setup exhibits some thermal instability. The lens cell is usually oval, or the lip that is intended to seat the lens surface is non-planar. If the cell is oval, usually the lens seat is as well. This means that the lens contacts the seat in only two places and can rock. The mechanical problems can be dealt with in a variety of ways, including the use of shims, or stress relieving and recutting the seat, or grinding the seat with a tool that has the same radius as the lens surface. But in order to take out systematic errors in the alignment equipment when pushing accuracies much below the 25 microinch level, it is often necessary to make use of data logging and computer reduction of data from alignment sensors like the electronic indicator gauges.

### 3.1 Application

Such extreme accuracy is required between elements of grazing incidence x-ray telescopes. In order to measure the relative tilt between the optical axes of the two cylindrical, conical aspheric elements, the arrangement shown in Figure 3.0-1 has proven to be extremely accurate. This technique was applied to an assembly with an inside diameter of about 10.5 inches, with an axial separation of 1.23 inches. The true circularity contour was determined to an uncertainty of 0.58 microinch rms, averaging four sets of collected data. The two elements were actually polished onto one monolithic piece of glass, so data that was collected was used to polish the glass in order to bring the two axes into alignment.[1] An alignment of 0.2 arc-sec was achieved, implying a 1.23 microinch tilt deviation over the length of one surface as compared to the other.

For this case, two gauges were positioned outside the clear aperture of each surface. The normal meter readouts were retained for convenience to aid initial alignment, and to guide corrective alignment adjustments of the parts. The output from each of the gauges feeds into a twelve bit A-D converter, and then to a PC. A small motor drive rotates the table. A timing pulse is generated once per revolution and triggers the computer to begin logging the signals from the indicators. Data is recorded on alternate revolutions at half degree intervals. Software is used to calculate the best fit circle to the data and to find the centers of each trace, as well as to fit higher order terms. In this way, rigid body displacements and tilts associated with less than perfect alignment of the optics to the rotary table, and coning errors of the table, can be detected and removed. The resultant misalignment between the elements can then be calculated and displayed in graphical form.

The same method was used to set the alignment of the optical axis of the telescope with respect to the telescope mounting interface. Figure 3.0-2 plots this misalignment as a function of azimuth, and displays the magnitude and clock position of the error. As shown by the dashed trace, this was accomplished to less than an arc-second. The solid trace documents the tilt of the opposite, non-functional end surface of the telescope. While illustrated here on cylindrical elements, the method is quite general, and applicable to conventional lenses as well as mechanical parts and assemblies.

## 4.0 ACKNOWLEDGMENTS

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## 5.0 REFERENCES

1. C.G. Hull-Allen, et al, "Precision Optical Fabrication and Test Methods Applied to the SXT Grazing Incidence Mirror Assembly", *SPIE Proceedings, X-Ray Optics for Astronomy and Microscopy*, Vol. 1160, (1989)/ 465.

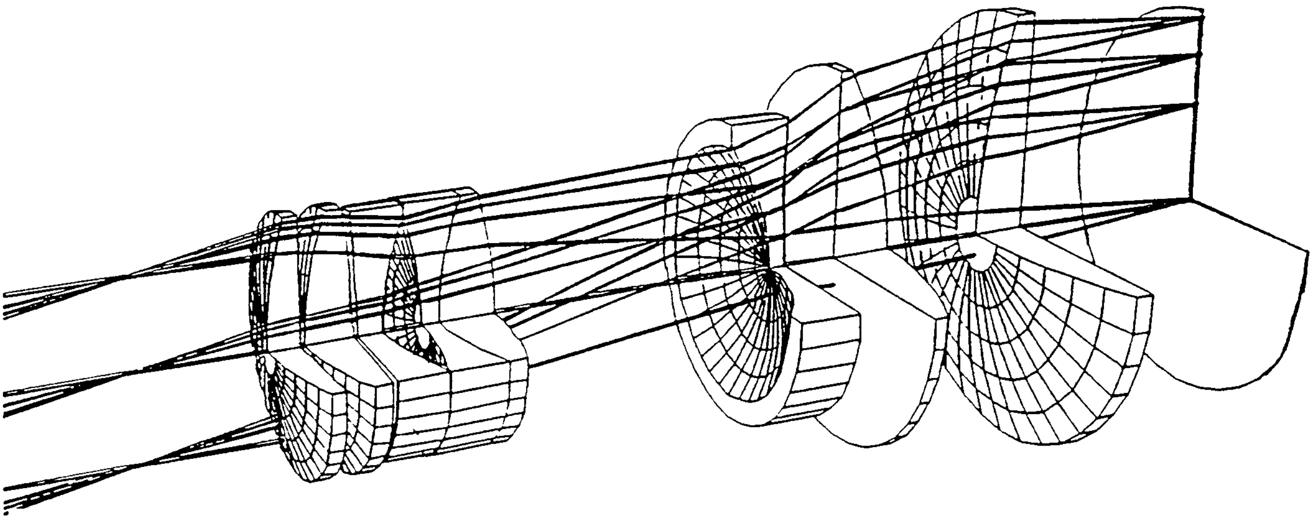

Figure 2.0-1 **F/5.6 Lens Assembly**

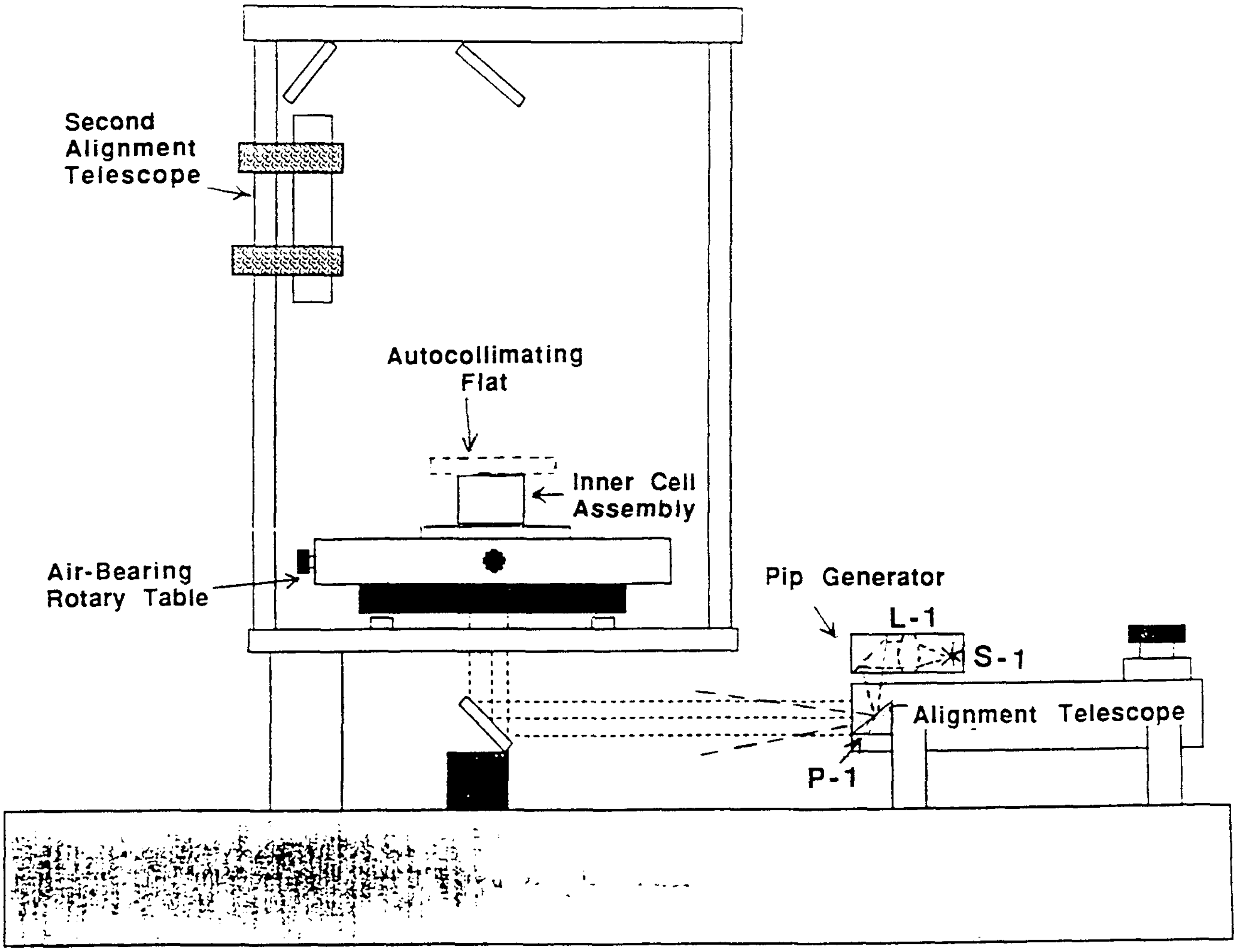


Figure 2.0-2 **ALIGNMENT STATION**

| Element Number | Surf. | Axial Pip Location | Distance From Surface | Pip Image Radius | Half-Pip Equiv. Surface Tilt (urad) | Element Tilt Tolerance (urad) |
|---|---|---|---|---|---|---|
| 1 | 1 | 24.138 in | 2.138 in | 0.009 in | 70.15 | 90 |
| 1 | 2 | 14.278 | -8.101 | 0.033 | -67.89 | 90 |
| 2 | 1 | 25.498 | 3.093 | 0.012 | 64.67 | 60 |
| 2 | 2 | 21.061 | -1.907 | 0.006 | -52.45 | 60 |
| 3 | 1 | 21.045 | -1.983 | 0.006 | -50.44 | 60 |
| 3 | 2 | 27.044 | 3.740 | 0.015 | 66.85 | 60 |
| 4 | 1 | 21.353 | -2.429 | 0.009 | -61.76 | 90 |
| 4 | 2 | 26.151 | 2.170 | 0.009 | 69.12 | 90 |
| 5 | 1 | 26.155 | 2.172 | 0.009 | 69.06 | 90 |
| 5 | 2 | 21.409 | -3.255 | 0.012 | -61.44 | 90 |
| 6 | 1 | 32.160 | 3.965 | 0.015 | 63.05 | 200 |
| 6 | 2 | 82.104 | 53.711 | 0.093 | 28.86 | 200 |
| 7 | 1 | 94.053 | 65.003 | 0.096 | 24.61 | 1000 |
| 7 | 2 | 33.398 | 3.607 | 0.03 | 138.61 | 1000 |
| 8 | 1 | 452.860 | 421.789 | 0.534 | 21.10 | 500 |
| 8 | 2 | 22.666 | -9.075 | 0.063 | -115.70 | 500 |

Table 2.0-1 Pip Image Radius, Displacement and Equivalent Tilt

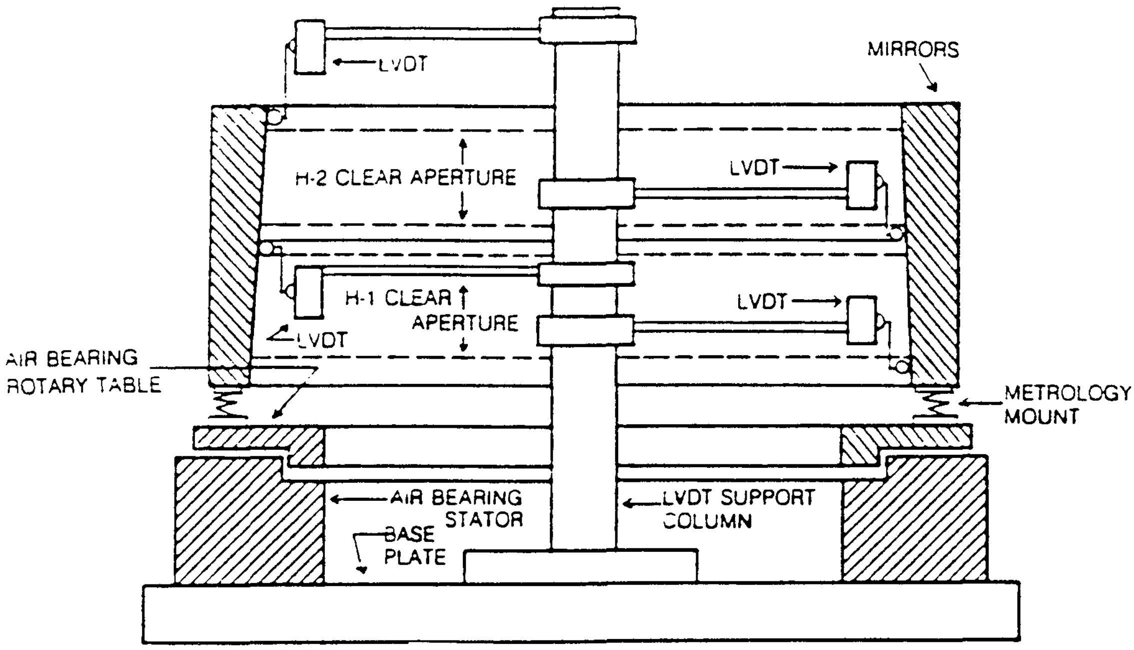


Figure 3.0-1

# Schematic of Circularity Test Stand

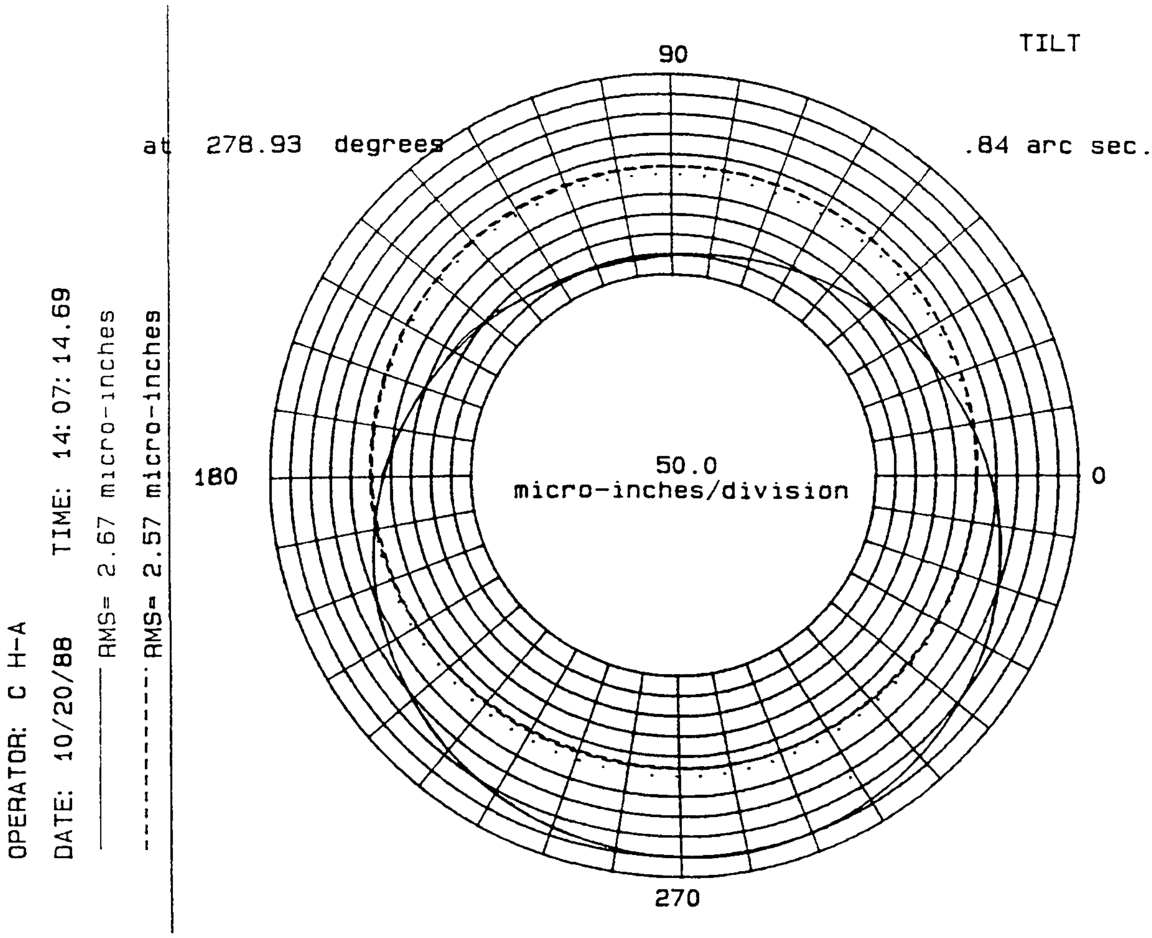


Figure 3.0-2 Relative Axis Alignment Plot