Alignment technique for optical assemblies

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Abstract

A non-contact approach for the alignment of optical elements and systems is described which allows the operator to clearly distinguish tilt and decentration errors of the individual optical elements. Advantages over alternate methods are discussed, and several examples of the use of the alignment tool are presented with experimental results.

1. Introduction

A wide variety of techniques are available for aligning precision optical assemblies. The selection of the optimum technique depends on many factors including:

-alignment accuracy required
-measurement sensitivity (resolution)
-path length of the optical system
-wavelength of operation
-ease of operation

Often, the approach used in precision optical assemblies is to force the optical fabricator to edge individual lenses to extremely tight tolerances, and then use mechanical constraints (precision bores and seats) to align the lenses. There are, however, many cases where this is not practical:

(1) Lenses which must withstand severe environmental conditions (temperature, vibration, and shock) often must be completely encapsulated in potting compound. This means that the lenses must be centered and tilted within the ID of the lens barrel without the use of hard mechanical constraints on the OD of the lens.

(2) Optical systems which have subsystems which must be aligned with respect to each other but are separated by great distances often can not rely on mechanical positioning along to meet demanding tolerances.

(3) Optical systems which include aspheric surfaces often have very demanding tolerances on decentration of the unique aspheric axis.

2. Background Discussion

Methods for controlling and evaluating centration of optical surfaces in an optical system can be divided into four broad categories –

2.1 Displacement of Principal Points

Most techniques use a collimator to project a reticle pattern which is then imaged by the lens under test. Some approaches for testing negative lenses in this manner require additional optics to recollimate the diverging beam. One example of this approach is the projected image test per MIL-O-13830. Other examples have been documented_. Angular sensitivity is a function of the focal length of the collimator lens used, but is generally accurate to 0.5 – 1.0 arcminutes_. Disadvantages include the lack of sensitivity to small surface tilts, the inherent inability to determine misalignments of individual surfaces, and the potential that a lens tilted about the second nodal point of the element will not exhibit image rotation from a collimated beam_.

2.2 Direct measurement of mechanical runout

These methods measure total indicator runout of an optical surface between the clear aperture and the physical diameter of the element. Although this is often the easiest method to implement, it becomes difficult if the tolerances are extremely tight, the elements can not be rotated, the elements to be tested are not accessible, or mechanical gauges pose too great a risk to soft optical materials or coatings.

2.3 Image or Wavefront Evaluation Techniques

These techniques include image evaluation based alignment techniques (visual and computer-aided), and Seidel coefficient-based alignment algorithms.

For example, the alignment error of an optical system can be diagnosed from the wavefront distortion in the exit pupil of the optical system[14.] The optical system is tested interferometrically and the wavefront data as a function of field is entered in the exit pupil of the system model in an optical design code. The system alignment errors can be determined using reverse optimization or forward optimization by setting user defined merit functions to optimize the ideal system to the aberrated wavefront.

This technique lends itself to particular types of alignment problems, including reflective telescope systems. However, the method is limited to available interferometric wavelengths, and can be difficult to implement in very long path lengths in hostile environments. Caution must also be exercised in wide field of view systems exhibiting significant pupil distortion, where errors can be introduced when the phase information is entered in the exit pupil in the form of Zernike coefficients.

2.4 Displacement of Centers of Curvature

The misalignment of optical surfaces can be determined by measuring the displacement of the image formed by each optical surface in the system. This can be accomplished with either a projected reticle or a point source[1], and can be used on refractive or reflective surfaces[1].

This technique offers several advantages:

(1) Lens elements and assemblies do not have to be rotated in order to distinguish alignment errors. This is particularly useful in systems with very large elements.

(2) The operator can determine the alignment of individual refractive surfaces buried deep in an optical system.

(3) The tilt and decentration of elements can be determined independently, identifying the source of the alignment error.

(4) The technique is effective over long path lengths and can be used in turbulent environments.

3. OPTICAL ALIGNMENT APPROACH

An alignment telescope is often used to define the optical axis of an optical system under test. When a point source is added in the center of the field of the telescope, the instrument can then be used to determine the misalignment of optical surfaces.

The alignment principle is illustrated in Figure 1. A diverging point source will be re-imaged by each of the spherical surfaces of the lens element. The “pip”’s from each of these surfaces can be identified and measured as the alignment telescope focus is adjusted.

FIGURE 1 - POINT SOURCE / TELESCOPE ALIGNMENT APPROACH

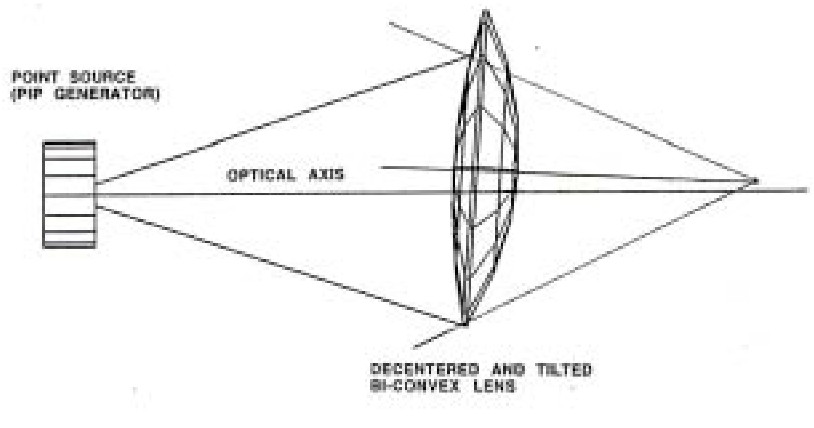
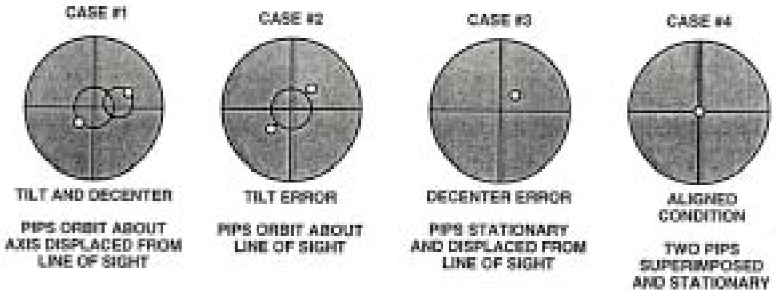


Figure 2 illustrates what the operator sees when using the technique. If the lens surfaces are both tilted and decentered with respect to the optical axis (Case 1), the pips will be displaced from the telescope reticle. If the lens under test is rotated, each pip will orbit about an axis displaced from the line of sight. Case 2 shows pure tilt of the element, where the pips orbit about the line of sight. If the lens is only decentered (Case 3), the two pips will remain stationary when the lens is rotated, but are displaced from the line of sight. When aligned (Case 4), the two pips are each stationary and centered on the alignment reticle.

FIGURE 2 - ALIGNMENT TELESCOPE "PIP" IMAGES FROM SINGLE REFRACTIVE ELEMENT



ALIGNMENT PIPS OCCUR IN TWO DIFFERENT FOCUS SETTING OF ALIGNMENT TELESCOPE

Rotation of the lens under test is not required to converge to an aligned condition, but will make it easier for the operator to distinguish small displacements of the pips.

The tilt of the optical surface can be calculated as:

$$\frac{\text{pip displacement}^{1}}{\text{image distance (vertex to image)}^{b}} \times \frac{1}{\text{magnification (telescope)}}$$

a - As measured in the alignment telescope with verniers
b – Determined by ray trace analysis

The **decentration** of the optical element is measured directly by the alignment telescope (displacement of pip/magnification of telescope).

The magnification of alignment telescopes typically vary as a function of object distance, but this magnification can be determined by imaging a known target at the object distances. A surface of any radius of curvature, from extremely short radii (such as microscope objectives) to plano surfaces can be measured with this technique if the point source is at a distance such that the images formed are within the focus range of the telescope. In the case of plano surfaces, the image distance is the distance from the point source to the surface under test.

4. INSTRUMENTATION

A schematic of the Model 10 alignment pip generator[4] is shown in Figure 3. The alignment tool uses a 2 W tungsten arc lamp as the illumination source (0.005" diameter). The **white light point source** produces alignment pips that are easy to resolve and devoid of speckle often produced from coherent sources. The white light also allows the operator to distinguish surfaces with different optical coatings by the "color" of the alignment pips. The source is powerful enough to allow detection of anti-reflection coated surfaces that have reflectivities much than less 1%[7].

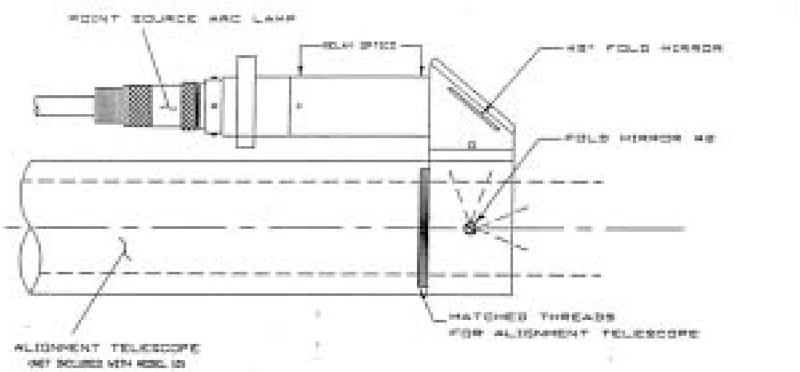


FIGURE 3 - SCHEMATIC OF THE MODEL 10 PIP GENERATOR

An achromatic 1:1 relay system relays the point source to the center of the field of view of the alignment telescope. A miniature fold mirror is used as the second fold, limiting the obscuration of the alignment telescope.

The pip generator is designed so that it will attach to the front of most alignment telescopes. Adjustments for two degrees of tilt adjustment and rotation of the second small fold mirror are built into the anodized aluminum housing. When attached to the telescope, the unit is completely portable and does not restrict the use of the alignment telescope (no "flip-in" mirrors or moving parts). The pip generator is mechanically very stable and will remain aligned once the initial alignment to the telescope is achieved.

5. EXPERIMENTAL ALIGNMENT SAMPLES

5.1 Doublet Example

The pip generator can be used for aligning cemented doublet with tight tolerances on the tilt of the optical surfaces. Figure 4 shows a doublet which must be cemented with the convex surface #3 aligned to within 30 arcseconds with respect to the flat mounting annulus.

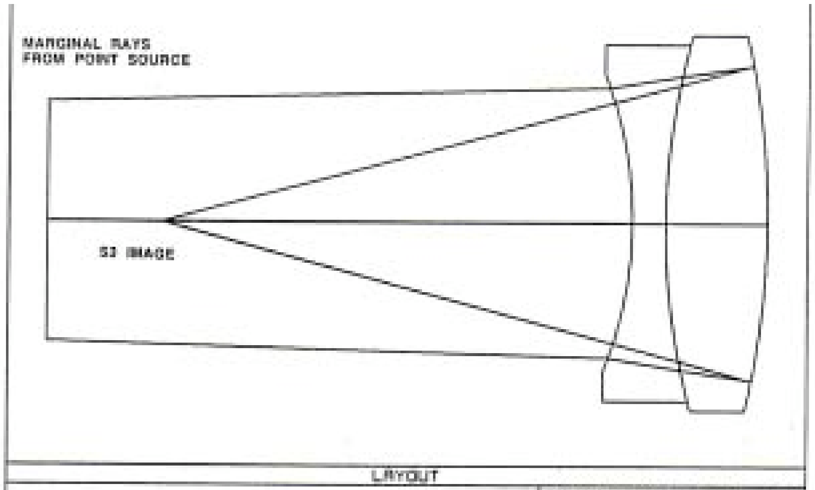


FIGURE 4 - CEMENTED DOUBLET LENS EXAMPLE

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With a 10 inch working distance from the first surface, a ray trace of the doublet shows the following:

Surface Number	Image Position[a] (inches)	Image Distance[b] (inch)	Pip Radius[c] (inch)	0.001” Alignment Sensitivity (arcseconds)
1	9.594	-0.405	0.0025”	20.3
2	10.562	+0.496	0.0018	16.6
3	9.051	-1.224	0.0039	6.7

a – From alignment telescope
b – From vertex of surface in question
c – Assuming 25x telescope magnification

The last column indicates the equivalent angular sensitivity for 0.001” lateral displacement of the alignment pip in the alignment telescope. Depending on operator skill and the size of the pip, alignments have been achieved to ±5 microns (±0.0002”) when the lens under test is rotated (effectively doubling the sensitivity).

The 30 arcsecond tolerance over the 18 millimeter diameter is equivalent to a 2.6 micron (0.0001”) total indicator runout. Although this is achievable with mechanical indicators, in practice it is often difficult to align small (< 20 mm diameter) doublets with mechanical indicators because the force of the indicator tends to “push” the lens during cementing.

This example demonstrates that although the pip generator/alignment telescope is less sensitive with short radii surfaces, even in this "worst" case it is an inexpensive, non-contact method for cementing doublets.

5.2 Lens Assembly Example

The pip generator was used to align the ATARS mid-altitude reconnaissance lens shown in Figure 5. The eight element precision assembly required melt recomputation of the nominal design to account for glass melt data variations in order to meet the nearly diffraction limited MTF performance requirements over the 22 degree field of view.

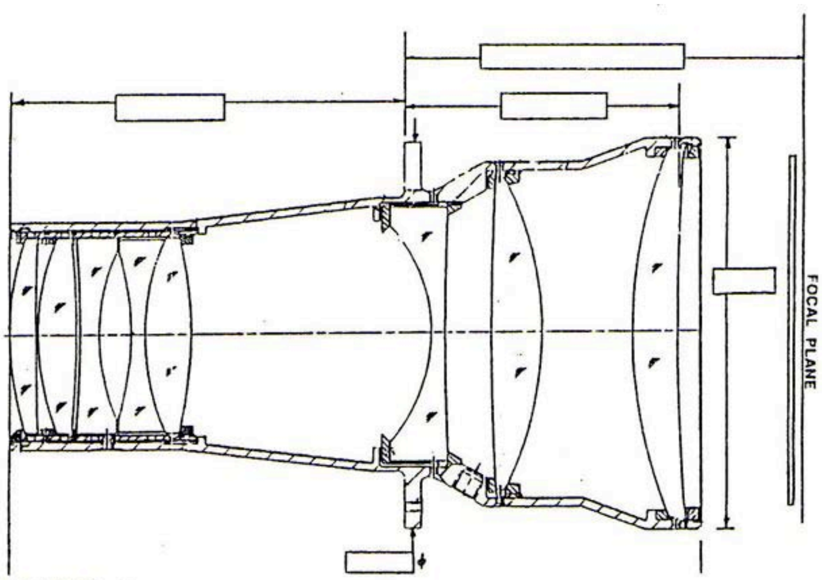


FIGURE 5 - LENS ASSEMBLY EXAMPLE
AERIAL RECONNAISSANCE LENS ASSEMBLY

The alignment tolerances were established from a surface sensitivity evaluation performed by ray trace analysis. These misalignment sensitivities vary greatly throughout the lens assembly. Figure 6 shows the square root of the variance of the wavefront error produced by a radian angular tilt of each optical surface to illustrate the wide range in alignment sensitivities. The alignment tolerance budget developed from this sensitivity analysis required that most surfaces in the first five elements must be aligned to within the 5 microns (0.0002”) total indicator runout (TIR).

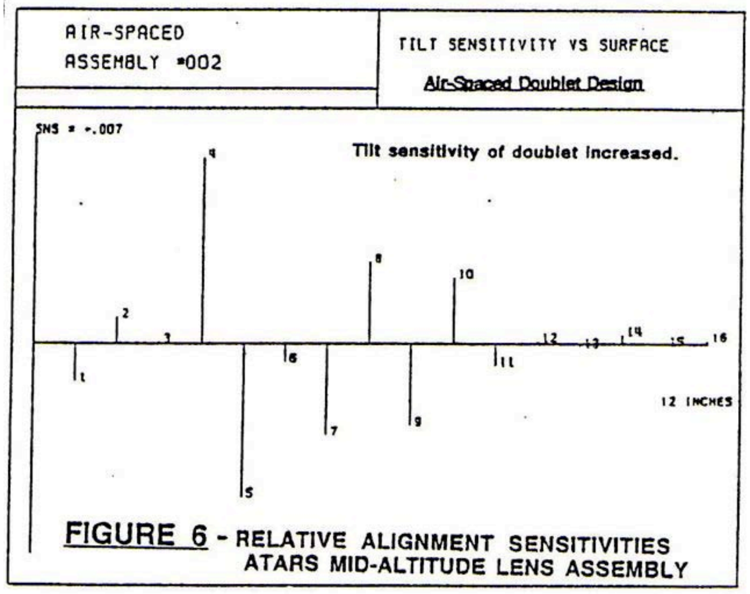
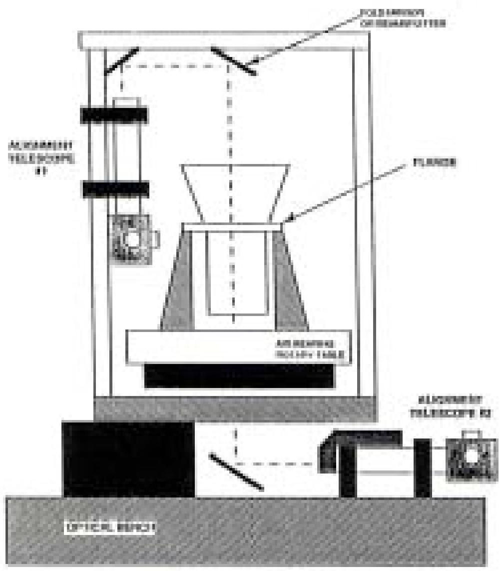


FIGURE 6 - RELATIVE ALIGNMENT SENSITIVITIES ATARS MID-ALTITUDE LENS ASSEMBLY

This alignment can be achieved using electronic indicators on the “top” surfaces of the lenses, but the thin spacers between several of the elements could not be manufactured round and flat enough to rely on this mechanical technique alone.

In order to achieve the required alignment tolerances, the assembly was built using the alignment test stand shown in Figure 7. First, the air bearing rotary table is aligned in tilt centration using electronic indicators. The lens assembly housing is then mounted on an air bearing rotary table, and the external mounting surfaces are centered using additional electronic indicators.

FIGURE 7 - ALIGNMENT TEST STAND



The optical axis of the alignment telescope/pip generator is aligned with the rotational axis of the air bearing table by autocollimating off of a tooling ball located in the center of rotation of the table. A second alignment telescope is then autocollimated with the first telescope to maintain boresight alignment during the assembly process and to serve as an independent monitor to make sure that the position of the primary telescope is maintained throughout the alignment process.

It was determined that the #4/5 cemented doublet would not survive the thermal shock environment due to the CTE mismatch between the two optical glasses (KzFS1/PSK53A). Modeling of the MTF performance of the lens determined that the MTF of the lens would not be significantly degraded if the doublet lens was "separated" into an air-spaced doublet using thin (0.002") shims between the lenses.

In practice, the "de-cementing" of this doublet proved to be a less than desirable solution. The tilt and centration sensitivity of the two "air-space" surfaces increase dramatically, and any small defect or non-uniformity in the 0.002" film used to establish the airspace produced unacceptable tilt error on the first surface element 5. Even though the surfaces were identical in radius and axially separated by 0.002", the alignment pips from the two AR coated surfaces were resolvable in the alignment telescope. Tilt errors on the convex surface of element #5 caused by variations in the spacing film of 2.5 microns (0.0001", equivalent to 10 arcseconds) were detectable with the pip alignment method.

6. SUMMARY

Precision optical assemblies are aligned using a wide variety of techniques. One technique, a bright point source alignment attachment used with an alignment telescope, has been described. The instrument is a versatile, portable, non-contact means of aligning optical elements in centration and tilt within demanding alignment tolerances. While not a solution for every alignment problem, this method is a valuable tool in the optical engineer's toolbox.

7. ACKNOWLEDGEMENTS

Some of the work described in this paper was performed while the authors were at United Technologies Optical Systems, Inc. under contract to Loral Fairchild Systems. The authors wish to express appreciation to Joe Taylor of UTOS for his cooperation in the preparation of this paper, and to Joe Sullivan, Mike Kaplan and the rest of the COSTAR team at Ball Aerospace for their support.

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