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PHOTOHELIOGRAPH ALIGNMENT SYSTEM

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FOREWORD

This report covers work on one phase of the photoheliograph development task, NASA Code 945-84-00-01-00, for the period November 1967 through June 1968. The photoheliograph has been proposed to NASA for the Apollo telescope mount (ATM) by Caltech, with Professor Harold Zirin as the principal investigator and Dr. Robert Howard of Mt. Wilson and Palomar Observatories the co-investigator (see TM 33-369, November 1967). The objective of the investigation is to obtain high resolution cinematographs in white light near ultraviolet and narrow band hydrogen alpha. Because of the ATM program uncertainties, emphasis has been placed on areas of technology that are somewhat mission-independent, but the ATM spacecraft has been used to establish design constraints.

ABSTRACT

This report describes the design and operation of an optical alignment system for use on the proposed Photoheliograph. The optical alignment system has the following characteristics:

(1) Capable of aligning the telescope while the telescope is in use and pointed at the sun.

(2) Operable by personnel that need not be optics specialists.

(3) Capable of aligning the telescope within the optical tolerances that have been defined by computer studies of an essentially diffraction-limited telescope.

(4) Conventional design utilizing established technology throughout. Adaptable to breadboard design techniques and the data obtained from an evaluation of the breadboard will apply directly to the proposed Functional Verification Unit.

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ILLUSTRATIONS

SUMMARY

The alignment system described and analyzed in this report is capable of aligning the optics of the Photoheliograph within the optical alignment tolerances defined by a computer analysis of an essentially diffraction-limited Solar Telescope. The misalignment of the optical axes of the secondary and primary mirrors can be detected within ±0.0002 inch with respect to translation shift, compared to the ±0.003 inch tolerance allowed. The misalignment of the optical axes of the secondary and primary mirrors, with respect to tilt, can be detected within 0.0001 degree, compared to the allowable ±0.0125 degree tilt tolerance.

The alignment system is utilized in two distinct operational modes. In one mode, translation of the optical axis of the secondary mirror assembly with respect to the optical axis of the primary mirror is detected using a bore-sight technique. A "Pinlite" is located near the center of the secondary mirror. A lens in the alignment sensor focuses the image of the alignment light on the alignment sensor, which detects the actual translational shift of the secondary mirror assembly.

To detect tilt misalignment errors, a variation of the autocollimating technique is used. The normal autocollimating technique is not applicable here since it would not be possible to pass a sufficiently wide beam through the small hole in the field-stop (heat stop) mirror at the prime focus. To restrict the beam size at the field-stop aperture, spherical reflectors are used, one located at the center of the primary mirror and one at the center of the secondary mirror. The radii of these spheres are chosen so that the focus of the spherical segment in the secondary mirror and the center of curvature of the spherical segment located in the primary mirror are coincident at the field-stop aperture. A light source in the alignment sensor is imaged as a small dot in the field-stop aperture by the spherical segment in the center of the secondary mirror. This being an aerial image, the light proceeds to the spherical segment at the center of the primary mirror and is returned back to the aperture in the field-stop. If a tilt misalignment exists between the primary and secondary mirrors, the returned image will be displaced from the original aerial image in the field-stop aperture. The spherical segment in the

secondary mirror refocuses the returned aerial image onto the knife-edge in the alignment sensor at a magnification of 13, providing good sensitivity for tilt misalignment detection.

The use of the alignment system imposes some design criteria on the telescope itself. In the essentially diffraction-limited telescope design under consideration, the alignment of the secondary and the primary mirrors is critical. The use of the alignment system thereby implies that these mirrors must be adjustable with respect to each other. By treating the primary mirror and the alignment sensor as a rigid body; and by then treating the secondary mirror, off-axis alignment sphere, and the two folding flat mirrors utilized to direct the image to the alignment sphere, as another rigid body that is adjustable with respect to the fixed primary mirror/sensor assembly; it is possible to align the telescope. The mechanical design of the telescope is thereby guided by this design philosophy.

The alignment system is operable while the telescope is in use and looking at the sun and can therefore monitor alignment constantly, if necessary. The system lends itself to either semi-automatic or fully-automatic control devices and is operable by flight personnel who are not optics experts.

The system can be designed to be maintainable in orbit and is fully compatible with its proposed environment. It follows established technology throughout and is capable of being built as a full-sized breadboard to facilitate testing and the accumulation of data and experience.

PHOTOHELIOGRAPH ALIGNMENT SYSTEM

INTRODUCTION

This report describes and evaluates an optical alignment system for use in the Photoheliograph. The two basic objectives of the alignment system are:

(1) That the alignment system align the optics of the telescope such that the imagry is essentially within the diffraction-limit over the entire field.

(2) That the system be capable of analyzing, and correcting, if necessary, alignment while the telescope is pointed at the sun and in use.

The fact that this alignment system is to be utilized to align what is essentially a diffraction-limited telescope imposes some severe accuracy requirements on alignment. It has been determined that the optical axes of the secondary and primary mirrors must be aligned within ±0.003 inch with respect to translation, and that the maximum permissible tilt of the optical axes of the secondary mirror assembly, with respect to the optical axis of the telescope, can be no greater than ±0.0125 degree.[1]

In the discussion that follows, the proposed alignment system is fully described as to both design philosophy and feasibility. The proposed system is evaluated with respect to the desired and the attainable accuracy, and any factors that might affect alignment accuracy are considered.

DESIGN OBJECTIVES

The optical alignment system described and evaluated in this report has been designed to fulfill th optical requirements dictated by its use in an essentially diffraction-limited optical system. These optical requirements are listed below:

(1) The translational alignment of the optical axis of the secondary mirror, with respect to the primary mirror, must be within ±0.003 inch.

[1] Tolerances defined in JPL Report by R. A. Becker, Photoheliograph Optical System.

(2) The permissible tilt of the optical axis of the secondary mirror, with respect to the primary mirror, must be within ±0.0125 degree.

In addition to these two stringent optical requirements, there are three operational constraints imposed:

(1) The alignment system must be operable while the telescope is pointed at the sun and is in use.

(2) The entire alignment system must be easily operable by an astronaut who is not necessarily an optics specialist.

(3) The system must be maintainable while in orbit.

The alignment system is designed to meet these requirements. A discussion of the theory of operation in each of its modes (tilt and translation) follows, along with a consideration of those factors that affect alignment of the telescope both in pre-launch and post-launch configurations. A theoretically obtainable accuracy is defined, as is a proposed breadboard version of the alignment system and its probable evolution into a Functional Verification Unit.

DESIGN PHILOSOPHY

The basic telescope design is that of a modified Gregorian. A schematic representation of the telescope's optical system is shown in Fig. 1. The use of a field-stop for heat rejection purposes requires the diagonal flat mirrors to transfer the image to the focal plane. The design philosophy of the alignment system is as follows:

The primary mirror and the alignment sensor (located near the focal plane of the telescope) are considered to be a rigid body. The secondary mirror and the two diagonal flats are considered to be another rigid body. The design of these two segments of the telescope is such that all components located in these rigid bodies are rigidly located with respect to each other. The body that consists of the primary mirror and the alignment sensor is considered to be the fixed, reference block; the body that contains the secondary mirror and the two diagonal flats is considered to be the adjustable block, which is adjusted to align with the reference block.

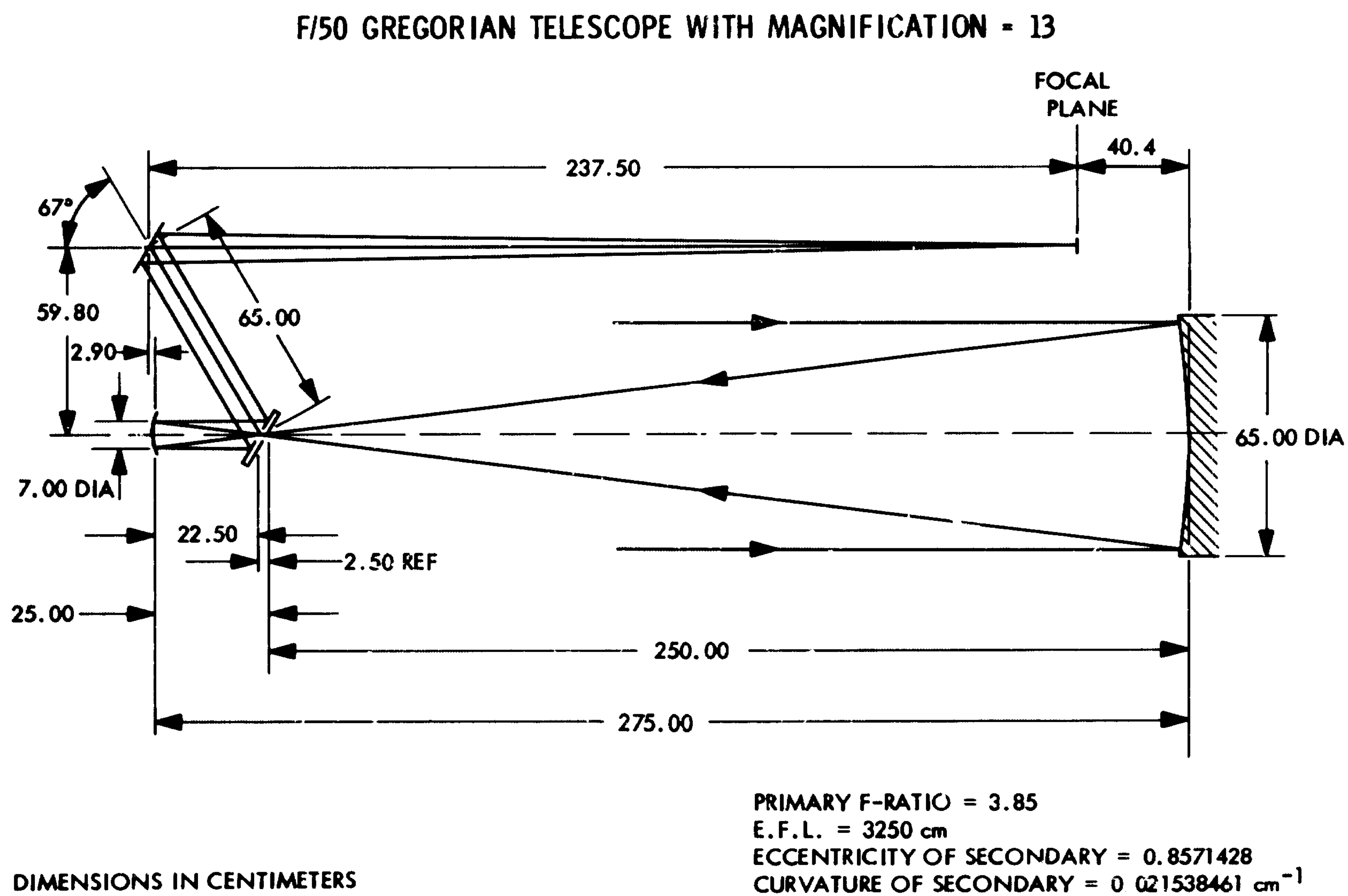


Figure 1. Telescope Optical System

The alignment system itself is also comprised of two blocks. The spherically-fig.. ed center of the primary mirror and the alignment sensor are one block; the off-axis alignment sphere near the center of the second ry mirror and the associated flats, are the second block. The optical schematics of the alignment stem in each of its two modes of operation are shown in Figs. 2 and 3.

The design philosophy is to utilize the alignment system to detect any error in positioning between the optical axes of the second rigid body (the secondary mirror assembly and flats) and the first rigid body (the primary mirror and alignment sensor). If any misalignment is detected, the alignment system will then adjust the second rigid body to bring the misalignment within allowable tolerances.

FACTORS THAT AFFECT TELESCOPE ALIGNMENT

The factors that affect telescope alignment can be divided into two basic groups: those factors that occur pre-launch, and those that occur post-launch. These two groups of factors can be further subdivided with respect to those factors that are correctable via a post-launch alignment and those that are not.

The limiting factors to alignment that are correctable during a pre-launch alignment are those that can be attributed to fabrication and assembly tolerances. During the pre-launch alignment, any eccentricity of the secondary mirror in its mounting cell, which would introduce a translational shift of its optical axis, will be compensated for. Compensation will be made for any tilt misalignment of the secondary mirror in its cell. The positioning of the second diagonal flat, with respect to the fixed, first diagonal flat, will be established. The true center of the rotating knife-edge device will be adjusted to coincide with the true optical centerline of the alignment system. The objective lens located in the sensor prism is used during translation alignment only and it will be adjusted to ensure that the alignment light image that is formed at the rotating knife-edge during translation alignment is coincident with that image formed at the rotating knife-edge during the tilt alignment. In short, the relative positions of the various elements of the telescope optics system and the alignment system will be established during a pre-launch alignment utilizing the techniques

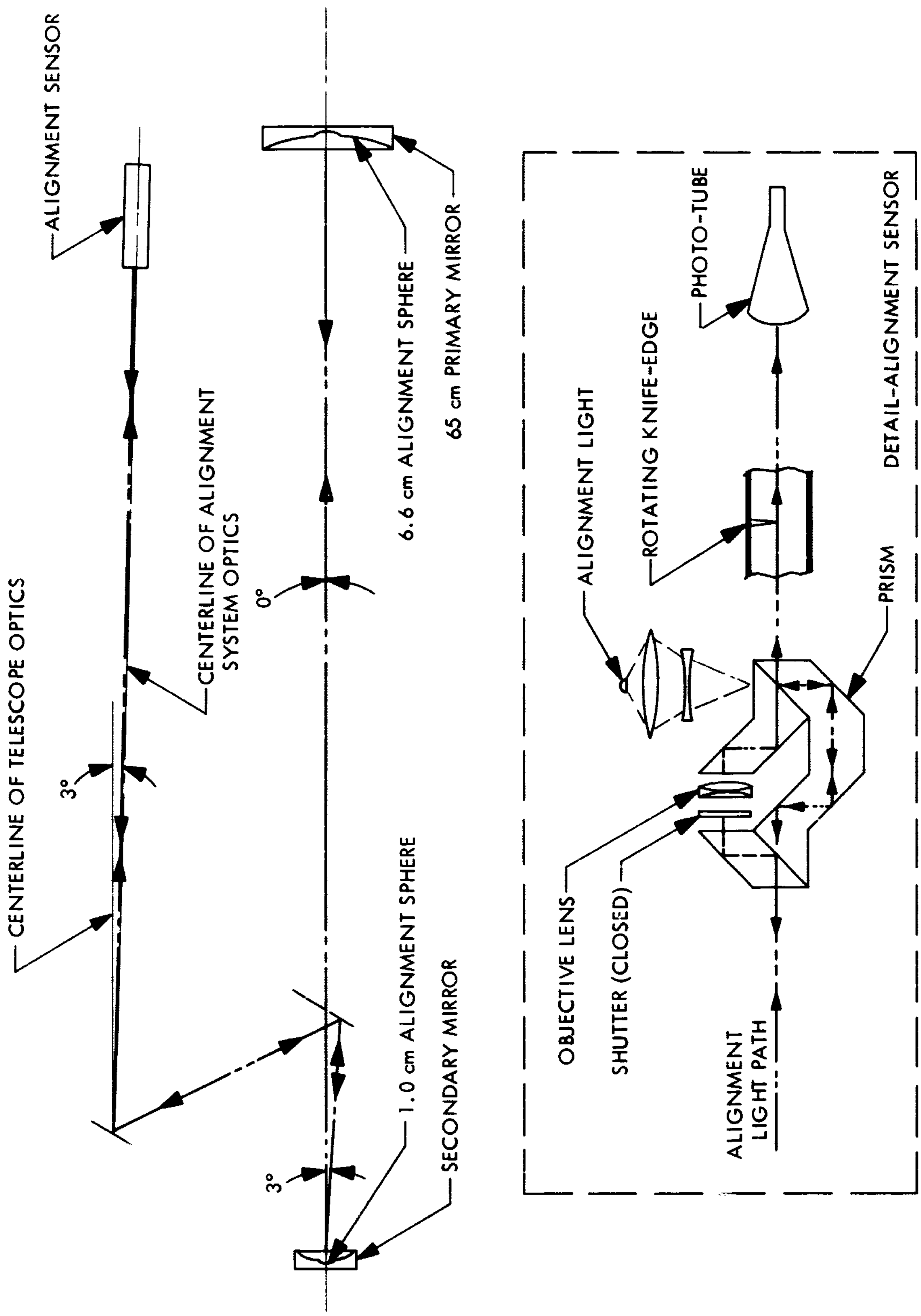


Figure 2. Alignment System – Translation Alignment Mode

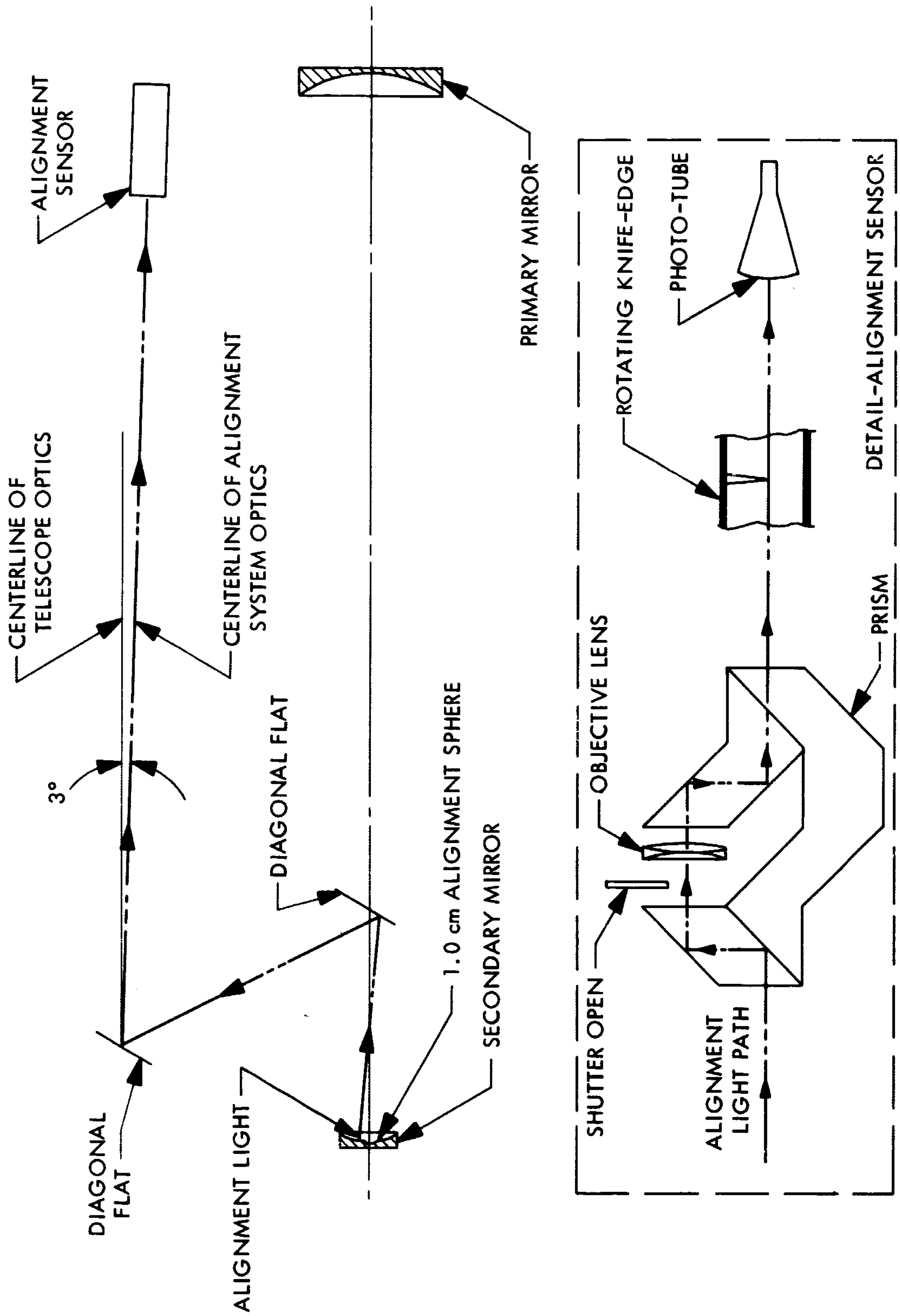


Figure 3. Alignment System – Tilt Alignment Mode

of interferometry. The only noncorrectable factor would be any eccentricity of the rotating knife-edge caused by bearing run-out. It will be shown that this runout is negligible.

Once the telescope has been aligned and the alignment system calibrated to correct for any errors caused by tolerance build-ups due to fabrication and assembly, the probability still exists that this alignment will be disturbed by the launch environment. Since the alignment system is capable of aligning the secondary mirror assembly in both the translational and tilt modes, these launch induced misalignments will be capable of correction. The only possible misalignment condition caused by the launch environment that cannot be corrected by the alignment system will occur if certain of the optical elements of either the telescope or the alignment system shift during launch. This contingency would cover such items as a shift of the primary mirror or of the diagonal flats, with respect to each other or with respect to the secondary mirror. A sound engineering approach to the construction of the telescope can eliminate this problem.

MODES OF OPERATION

The alignment system is used in two distinct modes. One mode (see Fig. 2) is used for the translational alignment. The secondary mode (see Fig. 3) is used for the tilt alignment. Both modes make use of the optical "Hole" in the main telescope caused by the secondary mirror casting its shadow on the center of the primary mirror (see Fig. 4). By using this optical "hole" and by tilting the axis of the alignment system 3 degrees off axis with respect to the secondary section of the telescope, it is possible to have an alignment system that is usable at all times, even when the telescope is in use and looking at the sun.

OPERATION IN THE TRANSLATION ALIGNMENT MODE

With the alignment system in the translational mode, a small light source is illuminated at the edge of the 1.0-cm diameter off-axis alignment sphere located at the center of the secondary mirror. This light is then reflected through the system as shown in Fig. 2, until it arrives at the alignment sensor proper. In this alignment sensor (see Fig. 5), the light passes along a predefined path through a prism that incorporates a fixed objective lens and a

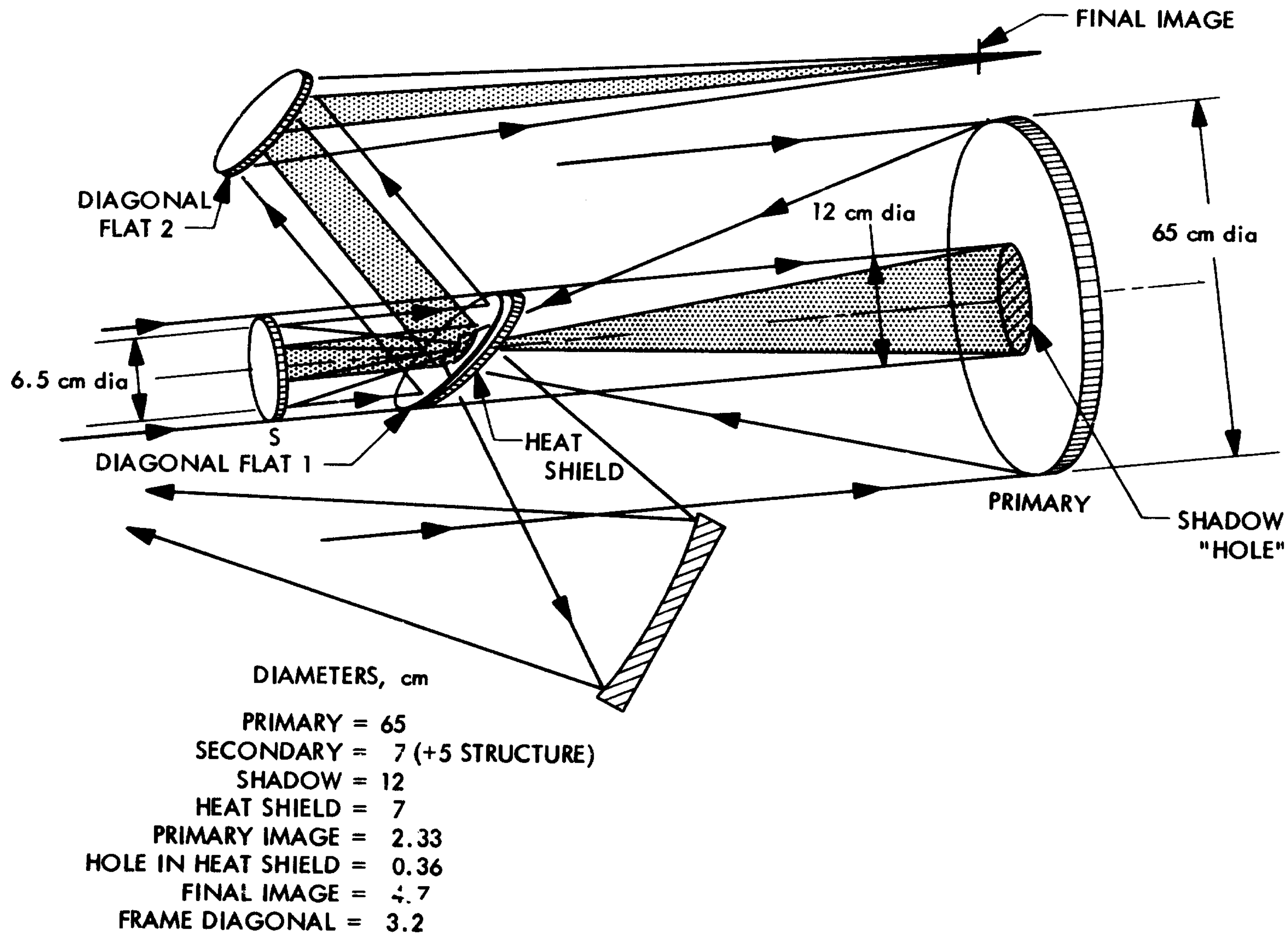
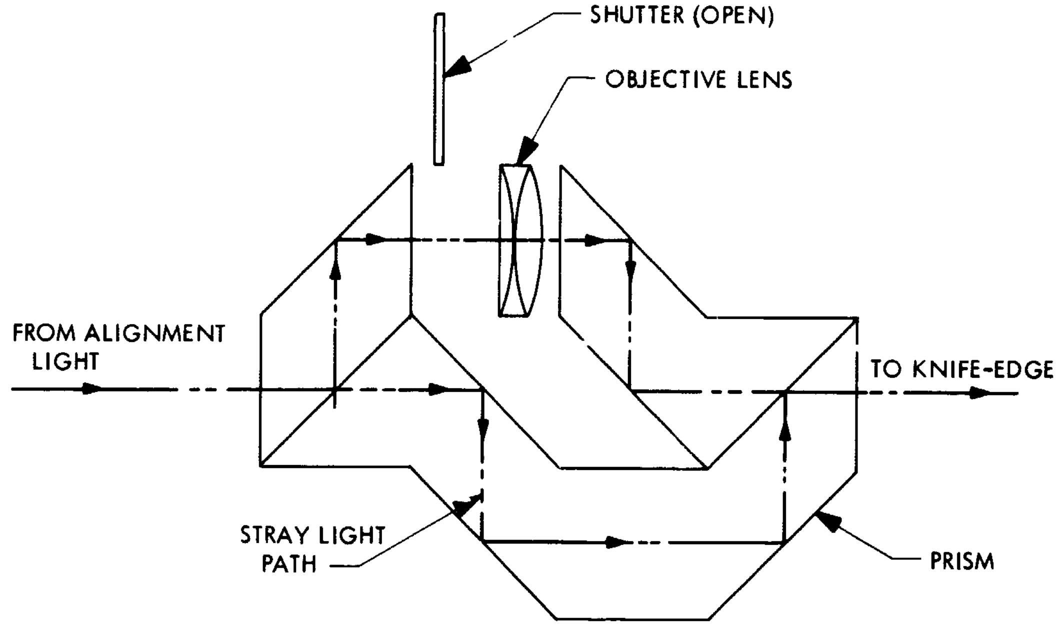
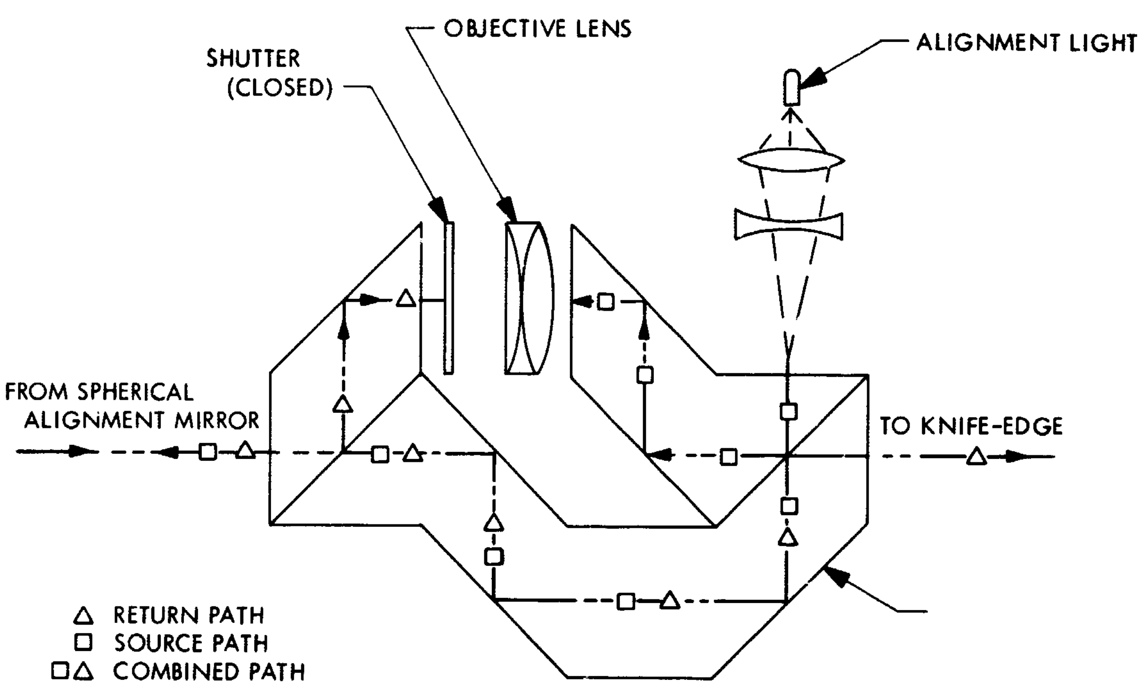


Figure 4. Shadow "Hole" in Telescope Optical System



a) PRISM - TRANSLATION ALIGNMENT MODE



b) PRISM - TILT ALIGNMENT MODE

Figure 5. Prism Alignment Modes

shutter just ahead of the lens. (Any stray light following the alternate path through the prism will be an out-of-focus blur at the knife-edge, and will not affect the alignment procedure.) The shutter is utilized to define a particular light path when the system is being used in the tilt alignment mode. With the shutter in the open position (the translation alignment mode), the light is focused by the objective lens at a knife-edge which is rotated at a constant RPM by a synchronous motor drive. The light passing by the knife-edge impinges on the face of a photo-tube. The output of this tube is then used to determine the translation shift of the secondary mirror assembly, since the drive motor is phase-locked and its position at any given time can be determined. When the optics of the system are aligned, the knife-edge will exactly split the alignment light spot in half. As the knife-edge rotates, it will continue to split the spot in half, thus yielding a constant output from the photo-tube. At any condition of misalignment that produces a spot that is not on the optical centerline of the alignment system, the rotating knife-edge will not split the spot exactly in half and the photo-tube output will not be constant. The degree of variation of this output is a function of the degree of misalignment. Figure 6 shows a pictorial representation of what the photo-tube output will look like for the aligned and the misaligned conditions.

OPERATION IN THE TILT ALIGNMENT MODE

With the alignment system in the tilt alignment mode, a variation of the autocollimating technique is used. The normal autocollimating technique is not directly applicable here since it would not be possible to pass a sufficiently wide beam through the small hole in the field-stop (heat stop) mirror at the prime focus. To restrict the beam size at the field-stop aperture, spherical reflectors are used, one located at the center of the primary mirror and one at the center of the secondary mirror. The radii of these spheres are chosen so that the focus of the spherical segment in the secondary mirror and the center of curvature of the spherical segment located in the primary mirror are coincident at the field-stop aperture. A light source in the alignment sensor is imaged as a small dot in the field-stop aperture by the spherical segment in the center of the secondary mirror. This being an aerial image, the light proceeds to the spherical segment at the center of the primary mirror and is returned back to the aperture in the field-stop. If a tilt misalignment exists

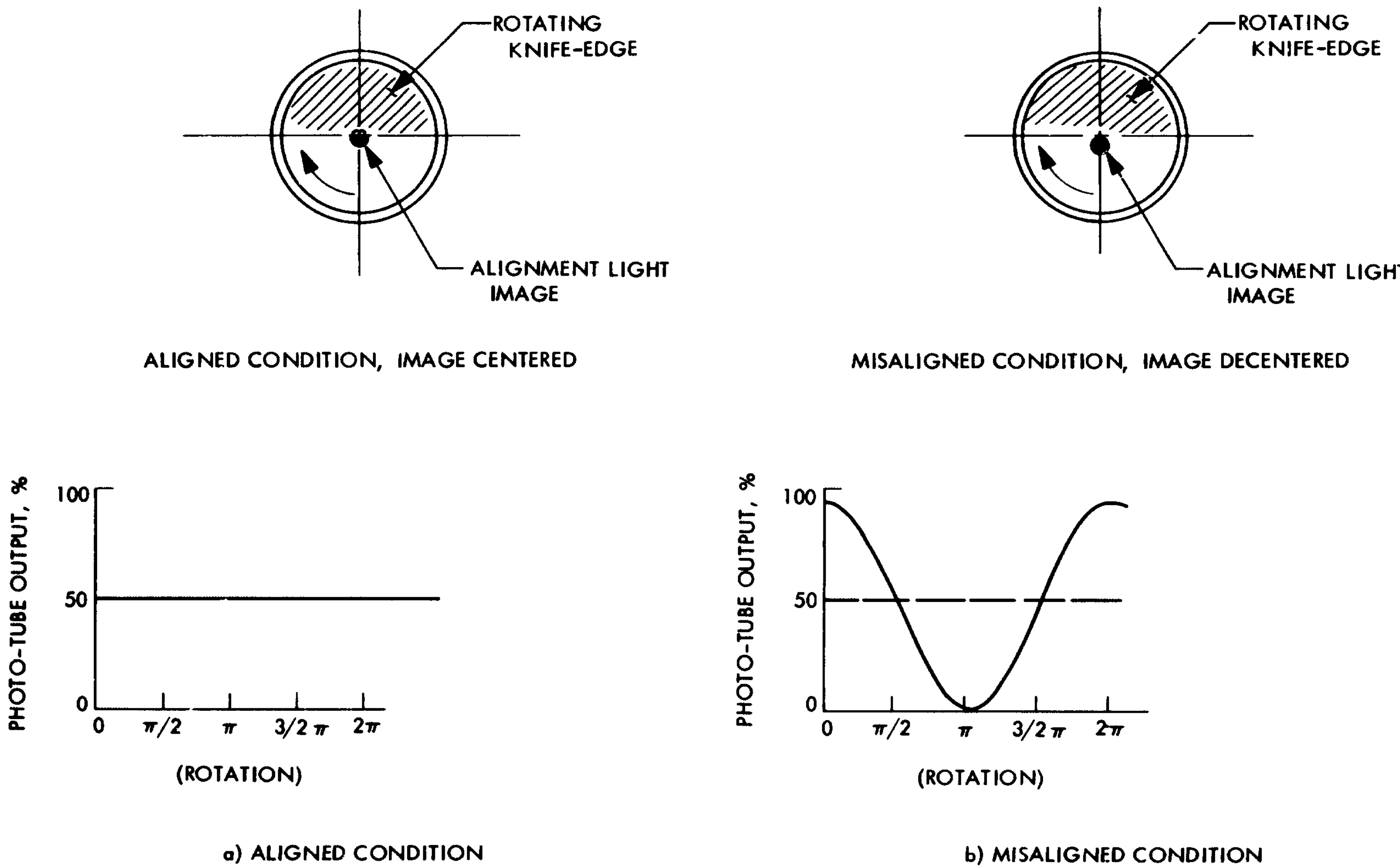


Figure 6. Photo-Tube Output Comparison

between the primary and the secondary mirrors, the returned image will be displaced from the original aerial image in the field-stop aperture. (Translation misalignment must be eliminated first by an independent method.) The spherical segment in the secondary mirror refocuses the returned aerial image onto the knife-edge in the alignment sensor at a magnification of 13, providing good sensitivity for tilt misalignment detection. See Fig. 7 for a comparison of standard autocollimating technique and the technique utilized in the alignment system.

If the system is aligned with respect to tilt, the returned image and the original image will coincide and the rotating knife-edge will once again pass a constant light input to the photo-tube. If the system is misaligned, the light input will change and the output of the photo-tube will vary, as it does for translation misalignment.

ATTAINABLE ACCURACY WITH PROPOSED ALIGNMENT SYSTEM

This alignment system is to be utilized in two distinct operational modes. Due to this fact, it seems logical at this point to examine the attainable accuracy in each of these modes separately.

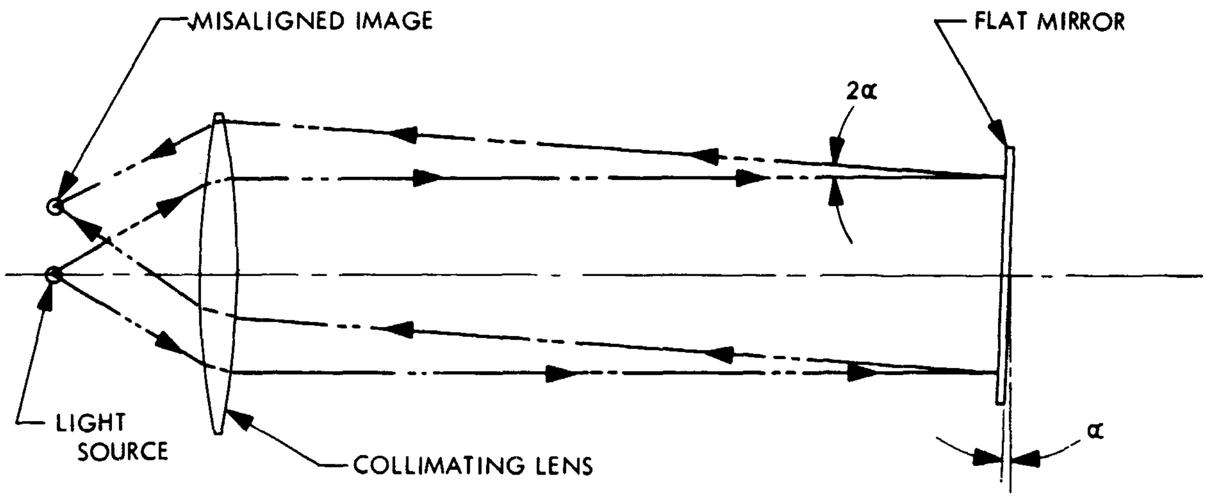
ATTAINABLE ACCURACY IN TRANSLATION ALIGNMENT MODE

As shown in Fig. 5, an objective lens is mounted in the cutout in the prism located in the alignment sensor. The purpose of this lens is to focus the image of the alignment light, located near the center of the secondary mirror, at the rotating knife-edge. The alignment light emitting area will be about 0.030 inch in diameter. The objective lens will be an f/10 lens with a focal length of 25 cm. The diameter of the lens is then 25 cm/10 = 2.5 cm.

For a wavelength of 0.5 μ, the diameter of the smallest spot that an f/10 lens can resolve is defined by:

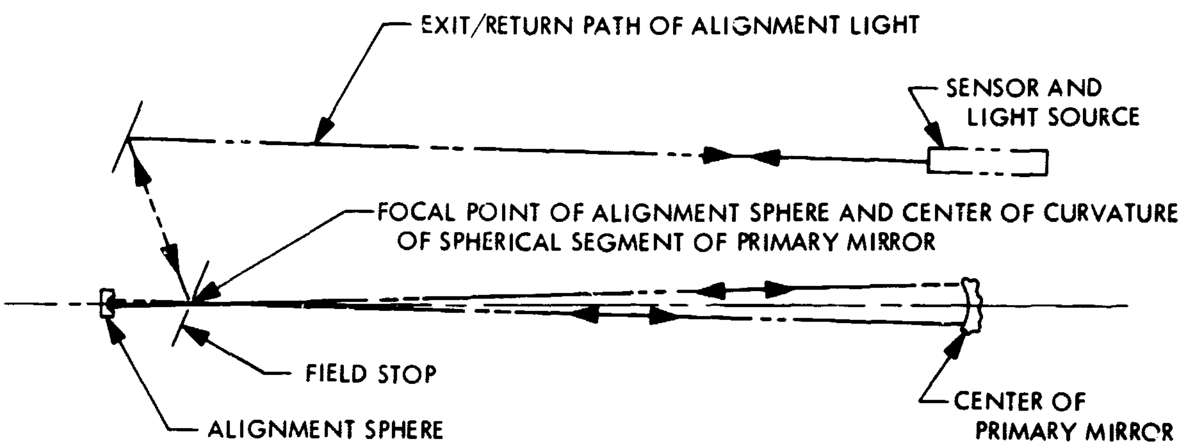
Diameter (in microns) = 1.22 x F-number = 1.22 x 10 = 12.2 μ = 0.00048 inch. The demagnification of the lens is the ratio of image distance to object distance. In this case:

$$\frac{25 \text{ cm}}{325 \text{ cm}} = \frac{1}{13}$$



α REPRESENTS MISALIGNMENT OF SURFACE FROM DESIRED POSITION

a) STANDARD AUTOCOLLIMATING TECHNIQUE



b) AUTOCOLLIMATING IS APPLIED TO SOLAR TELESCOPE ALIGNMENT SYSTEM

Figure 7. Comparison of Autocollimating Techniques

If the light source has a 0.030 inch diameter, the image will be:

$$\frac{0.030 \text{ inch}}{13} + 0.00048 = 0.0023 + 0.00048 = 0.00278 \text{ inch diameter } (0.007 \text{ cm})$$

If the light is misaligned (displaced) by 0.005 inch at its source, then the misalignment (displacement) at the rotating knife-edge will be:

$$\frac{0.005 \text{ inch}}{13} = 0.0004 \text{ inch} \quad \text{or} \quad 0.001 \text{ cm}$$

Figures 8, 9, and 10 illustrate the variations of intensity with respect to incremental displacements of the image from the perfectly-aligned condition. As can been seen by an examination of these figures, the variation of intensity volume over the range that is considered to be within the alignment region is essentially linear. The intensity of light from the image that passes by the knife-edge in the perfectly aligned condition is 50% of the total intensity contained in the image. If the system is out of alignment sufficiently for the image to be displaced an amount equal to its radius, a 100% modulated condition exists. When perfectly aligned, 0% modulation exists. This modulation percentage is defined by:

$$\% \text{ modulation} = \frac{V_{max} - V_{avg}}{V_{avg}} \times 100$$

where

V = intensity volume.

For the perfectly aligned case:

$$V_{max} = \frac{\text{total volume}}{2}$$

$$V_{avg} = \frac{\text{total volume}}{2}$$

$$M = \frac{V_{max} - V_{avg}}{V_{avg}} \times 100 = \frac{0}{V_{avg}} = 0\%$$

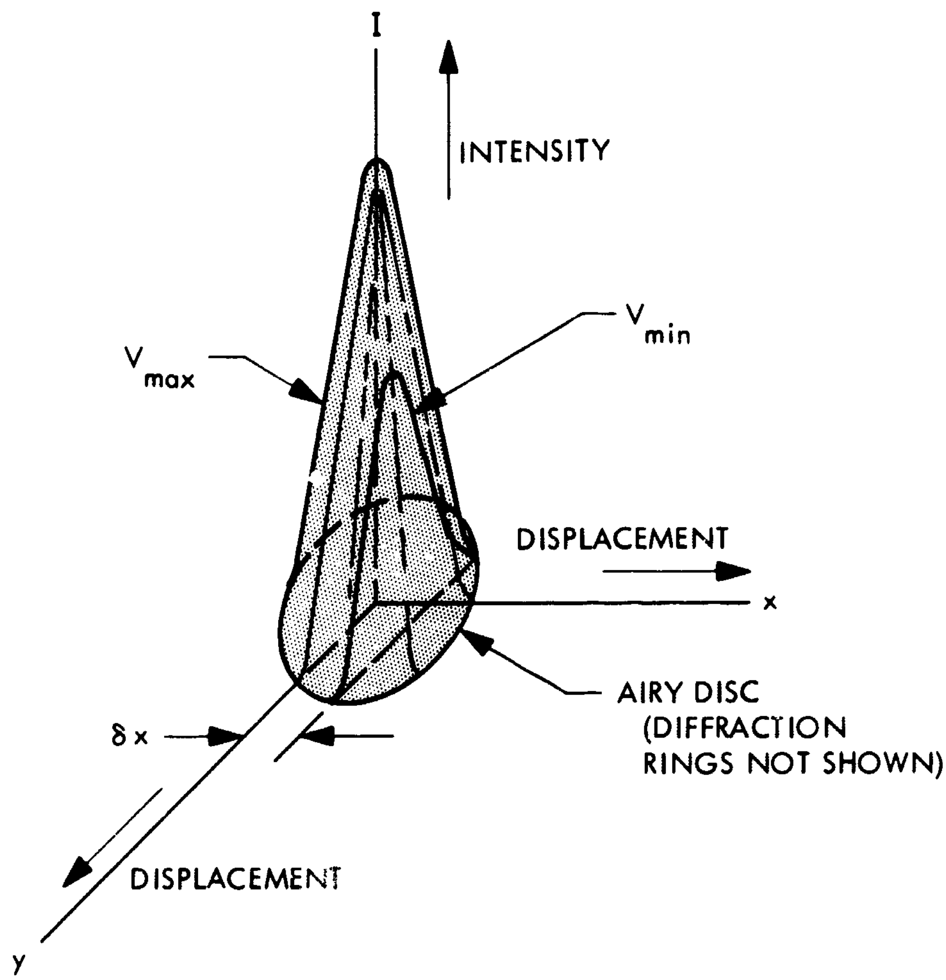


Figure 8. Three Dimensional Representation of Light Intensity Distribution (Intensity Volume)

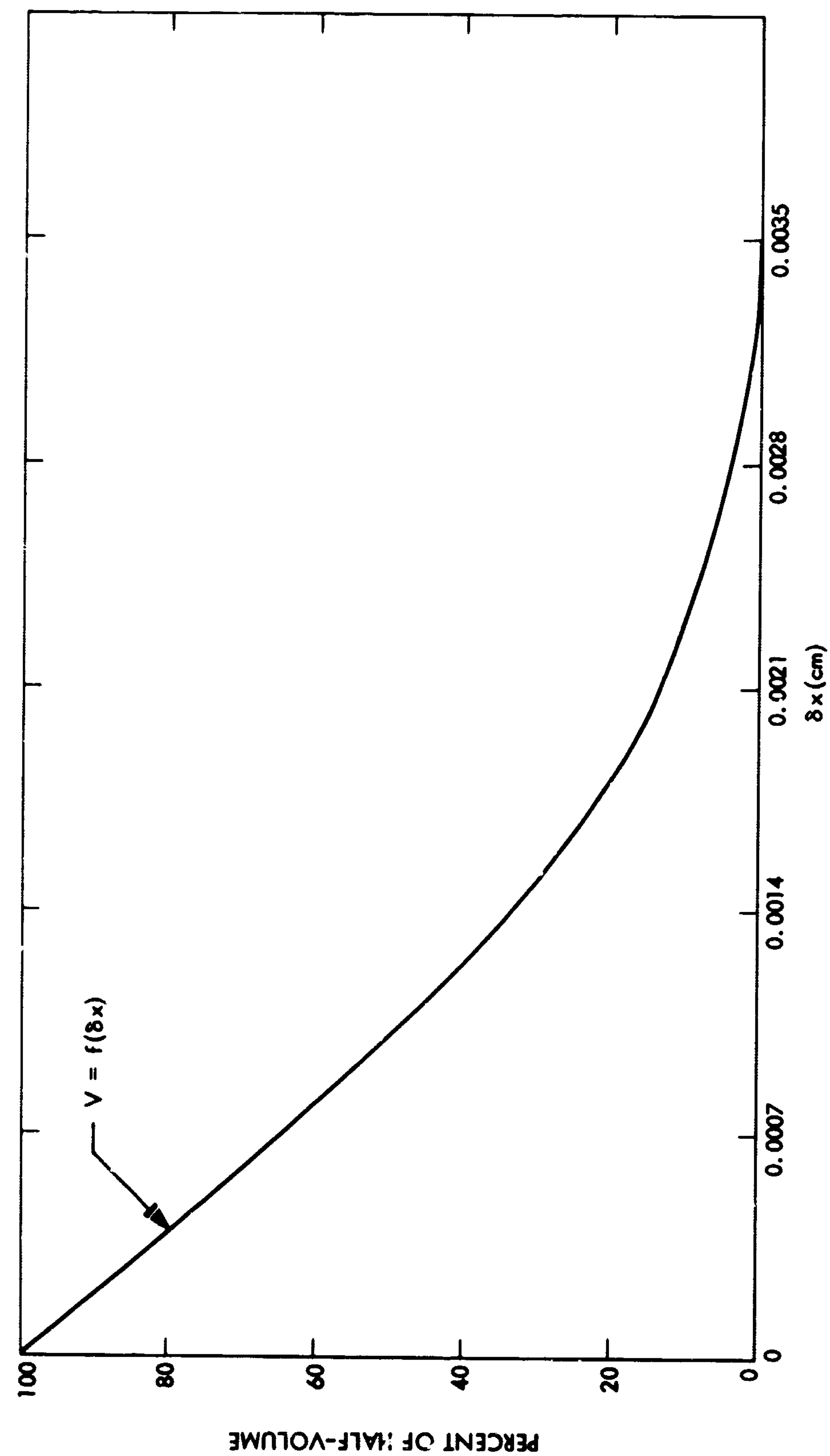


Figure 9. Percent of Intensity Volume as a Function of Displacement – Entire Airy Disc to First Dark Ring Translation Mode

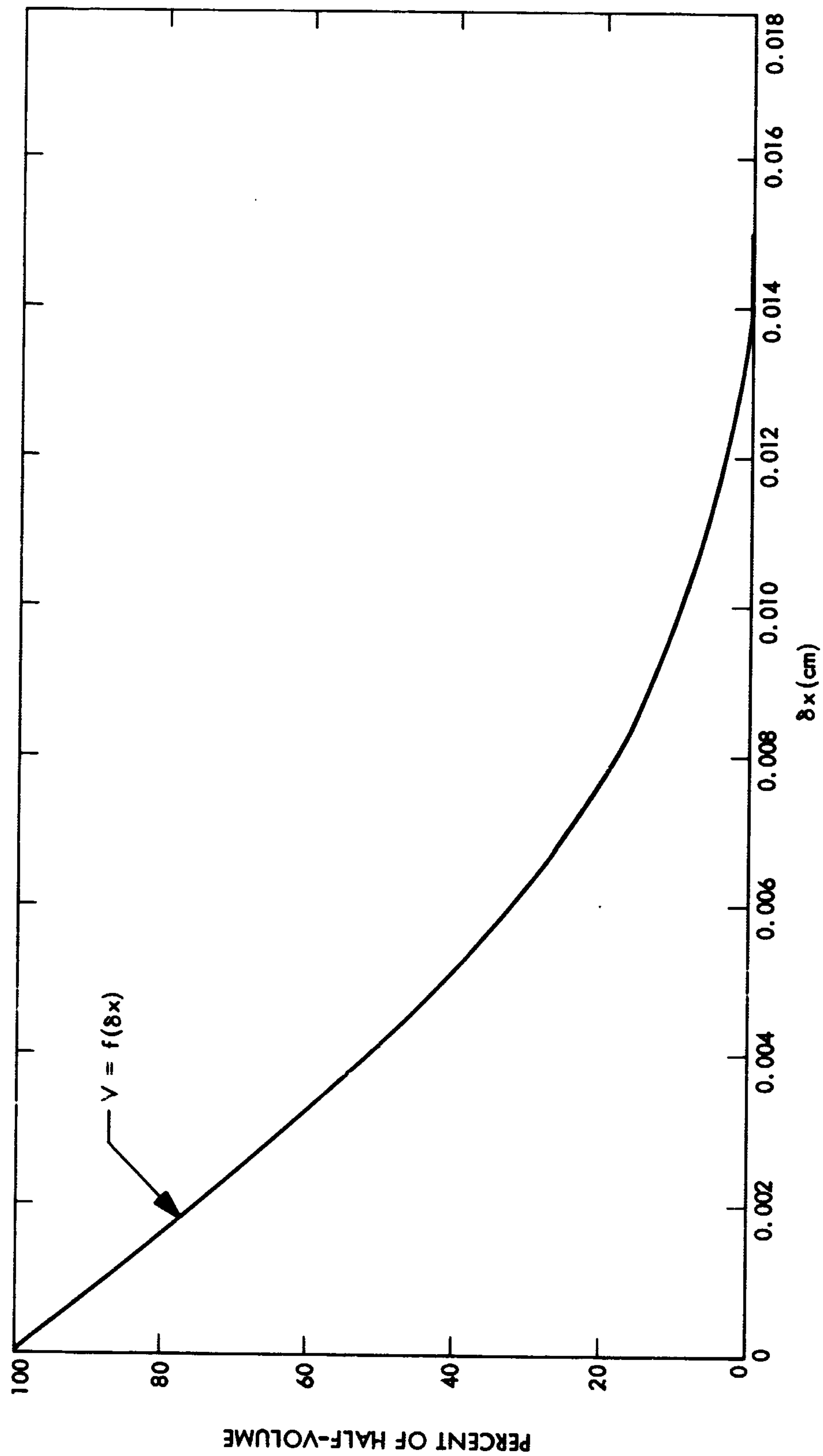


Figure 10. Percent of Intensity Volume as a Function of Displacement — Entire Airy Disc to First Dark Ring Tilt Mode

For the misaligned case where the image is displaced an amount equal to its radius:

$$V_{max} = \text{total volume} = 2V_{avg}$$

$$V_{avg} = \frac{\text{total volume}}{2}$$

$$M = \frac{2V_{avg} - V_{avg}}{V_{avg}} \times 100 = 100\%$$

For the case of maximum permissible misalignment, the secondary mirror is off axis. 0.003 inch with respect to translation. The image at the knife-edge is then shifted off-center by 0.003/13 = 0.00023 inch (0.0006 cm). At this displacement the modulation is 30% (see Fig. 9). The variation of intensity in this range is essentially linear with respect to displacement and amounts to 10.2% modulation per 0.001 inch of misalignment. This misalignment of 0.0002 inch, which produces a modulation of approximately 2%, will be detectable.

ATTAINABLE ACCURACY IN TILT ALIGNMENT MODE

As shown in Fig. 3, a different technique is utilized for the tilt alignment mode. The optics of the alignment system provide a variation of the autocollimating technique required by the location of the field-stop at the prime focus. The image, after reflecting through the alignment system optics, is formed at the rotating knife-edge.

The alignment sphere, located at the center of the secondary mirror, has conjugate foci at 25-cm and 325-cm. This provides a demagnification factor of 13. The Airy disc at the knife edge can be approximated by the summation of all of the Airy disc diameters of the light source images formed in series by the optics of the alignment system.

Airy disc diameter caused by 25-cm focus of spherical mirror:

f_{no} = 25, Diameter = 1.22(25) = 30.5μ = 0.0012 inch

Airy disc diameter caused by 325-cm focus of spherical mirror:

f_{no} = 325, Diameter = 1.22(325) = 396.5μ = 0.0156 inch

Airy disc diameter caused by spherical center of primary mirror:

$f_{no} = \frac{250}{6.6}$ = 37.878, Diameter = 1.22(37.878) = 46.211μ = 0.0016 inch

Total diameter of composite Airy disc = 0.0012 + 0.0156 + 0.0016 = 0.0184 inch.

Assuming an alignment light diameter of 0.090 inch, the alignment light image will be 0.090 + 0.0184 = 0.108 inch.

If the secondary mirror is allowed to tilt 0.0125 degree on one of its axis, the displacement of the image at the rotating knife-edge will be 0.056 inch. Utilizing the same definition for modulation that is used for the translation mode, 100% modulation would result. In fact, a tilt of 0.0012 degree will yield 100% modulation. This indicates that the sensitivity of the alignment system in the tilt mode is very high. A tilt of approximately 0.00002 degree will yield a modulation of 2%, approximately the same percentage of modulation that is produced by 0.001 inch translation shift.

BEARING RUNOUT AND ITS EFFECT ON ACCURACY

The large bore, thin cross-section, bearing used to support the rotating knife-edge is equal to or better than ABEC5P specifications. The total radial runout of the bearing does not exceed 0.0004 inch (0.001 cm). This is defined to mean that the eccentricity of the inner ring bore (the bearing I. D.) to the outer ring diameter (the bearing O. D.) cannot exceed 0.0004 inch. Any bearing manufacturing tolerance included in this total 0.0004 inch tolerance is thereby less than the total tolerance allowed. In the proposed bearing application, the outer ring is stationary and any eccentricity of the raceway of the outer ring to the O. D. of the bearing has no effect. The only tolerances that can effect the knife-edge accuracy are the eccentricity of the inner ring raceway to the bore (I. D.), and the manufacturing tolerances pertaining to the sphericity and diameter of the balls. The bearings will be lightly preloaded which will minimize the radial play of the bearing. The balls are manufactured to extremely close tolerances, 0.000050 inch or less tolerance for ABEC5P bearing balls. The eccentricity caused by the inner ring and the ball raceway not being coaxial can be compensated for by adjusting the knife-edge at assembly. The knife-edge assembly will be installed under a high-power microscope and the centering of the knife-edge will be accomplished by rotating the knife-edge and accurately adjusting its position until it is on the true centerline of the rotating part of the bearing.

ERROR DISPLAY AND DEGREE OF AUTOMATION

The design of the alignment system lends itself to automation techniques. In a semi-automated control circuit, the photo-tube will produce an output which can be utilized to drive a variety of display devices. The output can be displayed on a meter, along with a phase relationship indicator, to determine direction and magnitude of shift. The astronaut will then turn a control to null the meter which will be the aligned condition. The output can also be displayed on a Pulse Position Indicator which provides a single visual output that indicates the direction and magnitude of the misalignment error. The alignment control will actuate the servomotors that mount the secondary mirror assembly. The servomotors will drive the secondary mirror assembly into a position such that the alignment requirements will be met.

The system can also be fully automated by incorporating a telescope alignment circuit which would control both modes of alignment and which would be actuated automatically after an indication of misalignment is signaled. In the fully-automated mode, the servomotors would be part of a closed-loop servo system. Any misalignment will generate an error signal. This error signal will be detected and the information passed on to the servo. The servo will compare the error signal with a reference signal that indicates an aligned condition. The servo will then drive the mirror assembly in the proper direction(s) until the error signal is nulled. The telescope will then be aligned.

ENVIRONMENTAL CONSIDERATIONS

The alignment system, to be fabricated of the same materials and being designed under the same constraints as the main telescope itself, will be able to withstand the same environmental conditions as the rest of the system. All components of the system will be designed in such a manner that in-flight maintenance, if necessary, will be possible by the crew. Those items subject to failure after extended life (i.e., lamps and phototube), will be modularized to permit rapid and accurate replacement.

PRESENT STAGE OF DEVELOPMENT

At the present time, a breadboard unit is being designed to provide data and experience for a practical evaluation of the performance of the alignment system. The breadboard will yield valuable data for evaluating the performance of the system. When the Functional Verification Unit telescope is built, the alignment system will be included. Thus, a valid test and evaluation of the system under simulated flight conditions will be possible.