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Testing of the Kuiper Airborne Observatory 91-CM Telescope

Robert E. Parks

Optical Sciences Center

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Robert E. Parks

Optical Sciences Center
University of Arizona
Tucson, Arizona 85721

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NASA
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Ames Research Center
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1. INTRODUCTION

The resolution and ultimate utility of an airborne telescope depend upon the degree to which sources of image degradation can be reduced to a minimum. These sources of image degradation include the boundary layer of the aircraft, vibrations coupled from the airframe and turbulent air into the telescope, optical figure errors in the surfaces of the mirrors, and misalignment of the optical components. In order to measure the latter two sources of image degradation, the 91-cm telescope of the Kuiper Airborne Observatory was put through a series of tests at the Optical Sciences Center, University of Arizona.

When the present set of optical components are installed in the telescope in proper alignment, the telescope will produce an image with 80% of the energy in a circle of 1.50 arc seconds in diameter; that is, a 0.11-mm spot diameter in the focal plane.

The primary mirror, an f/2 parabola, was tested against a flat and found to be of a quality that puts 80% of the energy in a 0.51 arc second diameter spot.

Two principal sources account for the residual error: the tertiary folding flat and the chopping secondary. It appears that the method of mounting the folding flat causes some distortion and that the secondary mirror has some residual spherical aberration in its figure although it is well within its original manufacturing specification.

The weakest part of the system from an alignment point of view is the secondary chopper mechanism. More will be said about this later.

2. SCOPE

The statement of work provided by NASA-Ames requested a static system test with the secondary mirror not oscillating, then a dynamic system test with secondary chopping. Individual component tests were to be performed if there were any significant sources of error in the system test so that the component or components contributing to the error might be isolated. After a period of time to allow for a recoating of the telescope, it was to be recollimated and returned to NASA-Ames. Because of the delays in the return of the aircraft, both systems tests and component tests were performed. Also, several minor mechanical problems that had accumulated over the years were resolved.

The system was tested both with the air support for the primary mirror turned off and with this air support system turned on. Further, all separate optical components were separately tested in their own null configuration. This included the primary mirror, the tertiary folding flat, the Cervit secondary mirror, which was installed in the telescope when it was received at Optical Sciences, and the auxiliary fused silica secondary. A brief look was also given at the guide scope and CRT camera system.

Following the report of these separate tests below, we describe a scheme worked out for system alignment. There follows a section on system mechanical problems including the primary mirror decentering in its cell; problems with the air flotation system for the primary mirror, the chopping mechanism for the secondary mirror, and the large amount of clearance in the mounting of the secondary on its mounting stud; and problems with the method of mounting the tertiary mirror. The final section of this report discusses system optical design aspects of problems such as the amount of optical aberration induced by various amounts of misalignment of the secondary mirror and optical degradation due to using the telescope at the improper conjugates or with an improperly positioned focal plane.

3. RESULTS OF OPTICAL TESTS

Static System Test

The 91-cm telescope of the Kuiper Airborne Observatory was put through a series of system tests at the Optical Sciences Center, University of Arizona. Imagery obtained with this instrument was reported to have a spot size of 5 to 10 arc seconds during actual flight, although the original specifications called for 80% of the energy to be concentrated in a 1 arc second image. In order to find the source of the image degradation, checks on the optical alignment and figure errors were performed.

The method of performing the system test is illustrated in Fig. 1. The telescope was set up at 45° from zenith looking at a 40-in. diameter optical flat. An interferometer was placed in the focal plane of the telescope looking in the trunion axis at the tertiary mirror. The optical path is as shown in the figure with the light from the interferometer going from the image plane to the tertiary, the secondary, the primary, and finally hitting the flat at normal incidence. From the flat the light returns by the same path back to the interferometer making a complete double pass through the telescope. When this test was originally set up, we found that the fringe pattern had so many fringes that it was impossible to perform an interferometric test. We then replaced the interferometer with an alignment telescope and discovered that the secondary mirror was lying 3 mm off axis. This amount of decenter would have yielded 48 fringes of coma in the test setup we had. Thus the first thing we had to do was recollimate the telescope before the optical test could be performed.

After the telescope was recollimated, the interferometer was replaced at the location shown in Fig. 1 and interferometry was attempted again. However, a ground loop problem in the secondary chopper mechanism caused the secondary to vibrate at a very low amplitude at the zero offset setting. The only way we found to reduce the vibration to a level where interferometry could be performed was to put a mechanical clamp on the flex pivots of the secondary chopping mechanism. When this was done we obtained suitable interferograms.

The results of the interferometric tests, which are a measure of the wavefront quality through the telescope, were reduced on a computer program called FRINGE to yield the actual encircled energy produced by the wavefront going through the telescope. These numbers were divided by 2 to account for the fact that during the test the light traverses the telescope twice. The resulting energy concentration for the telescope is shown in Fig. 2. The two curves in the figure represent energy concentration both with the air support for the primary turned on and for the case where the air is turned off and the primary is resting solidly on the three defining points. As can be seen from the curve, although there is slight variation in energy concentration as a function of spot diameter, the ultimate performance of the telescope is roughly equivalent whether the air support system for the primary is turned on or or off. However, as is obvious from the curves in Fig. 2, the ultimate performance of the instrument does not seem to be significantly changed, independent of whether the air support system on the primary is

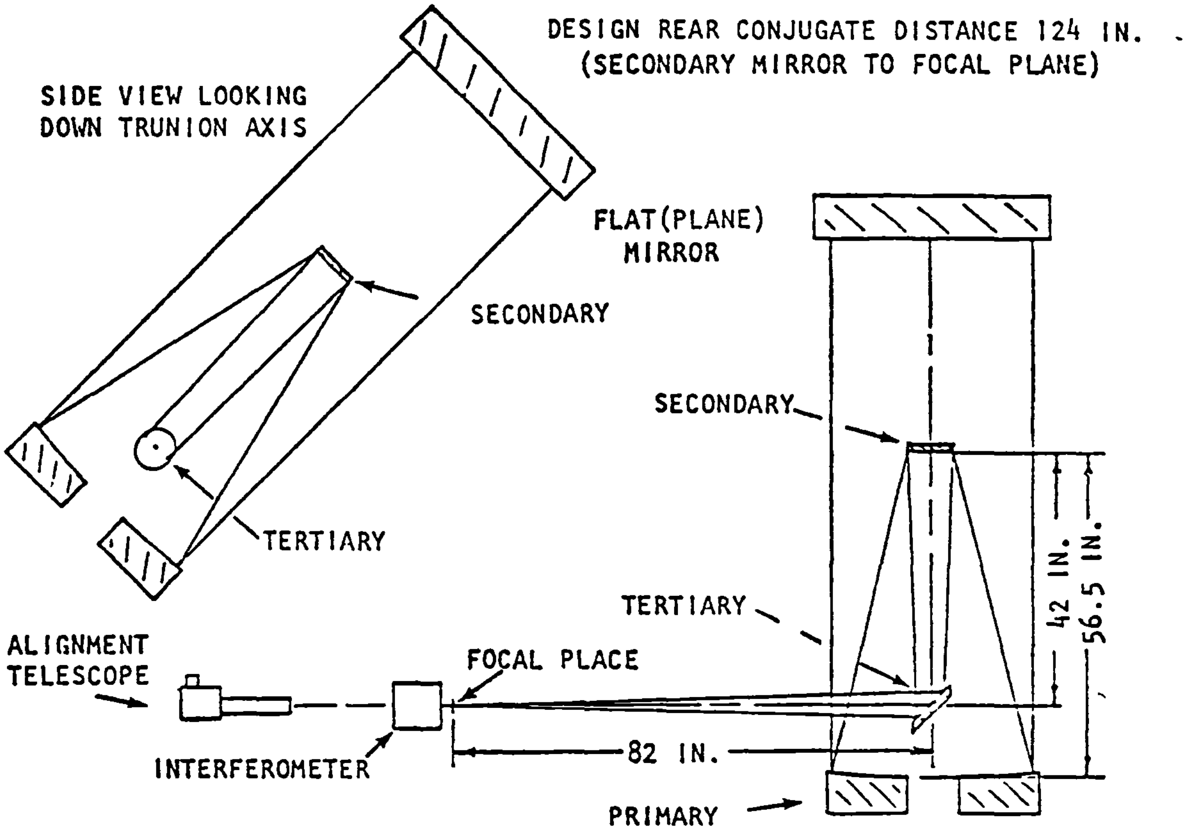


Fig. 1. System Test Against a Plane Mirror.

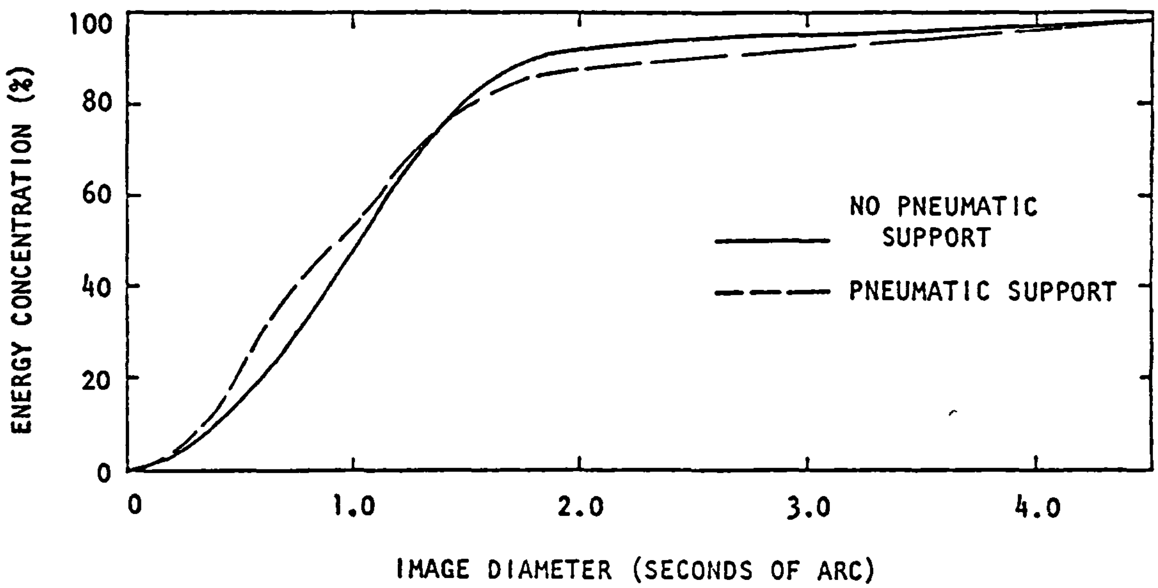


Fig. 2. Energy Concentration vs Image Diameter from Static System Interferometric Test.

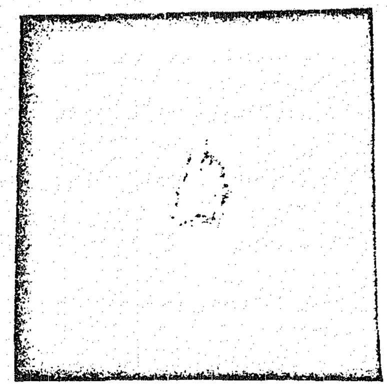
functioning or not. While this may be of some concern to the design people interested in the proper primary support, it is certainly an encouraging indication that the system is much less sensitive to primary support than might have been originally thought.

Dynamic Systems Test

Following the static system test with the secondary mirror in an unchopped or locked mode, we attempted to perform exactly the same test with the secondary mirror chopping. We found that there was enough jitter or bounce at the end of the chop cycle that we could not perform interferometry. The fringes we were attempting to photograph were completely washed out even though we attempted to synchronize the interferometer with the chopping cycle in a strobe type fashion. At this point we dropped the idea of using interferometry in the dynamic test and instead placed a point source in the focal plane of the telescope. The point source was projected using a point source microscope, and we placed a camera looking into the retical eyepiece of a microscope imaged on the return point source. This allowed us to photograph the return image after a double trip through the telescope. Keep in mind that during these tests we were using the same test setup as we were in the statics test, namely that shown in Fig. 1. The only difference was that the interferometer was replaced with a microscope that projected a point image.

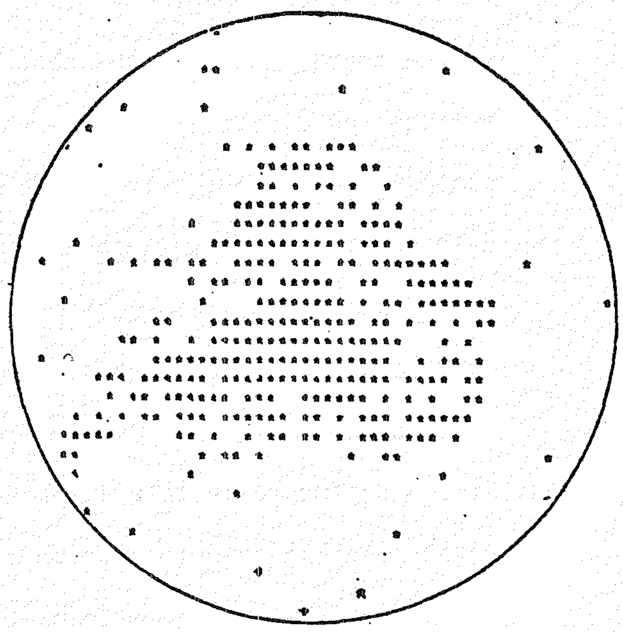
The first tests that were performed were in a static mode. In one test the secondary mirror was centered and in another the secondary mirror was set the end of the chop cycle. The two return images obtained from this test are shown in Fig. 2. The images are roughly triangular in shape because the air was turned off under the primary support. Also the two images, the one from the centered sceondary and the one from the secondary at the end of its chop cycle, although slightly different in structure, are approximately the same size and shape. This leads us to the conclusion that the chopping secondary does not significantly enlarge the diameter of the image because the telescope is used in the chopping mode. The tilt of the secondary is sufficiently small that it does not introduce a large enough amount of coma to significantly degrade the image size. Although in these two photographs it is difficult to see any scale, the scale of these photographs is the same as those seen in Fig. 4. By comparison we can conclude that the images in Fig. 3 are approximately 4 seconds in diameter. This is a satisfying result when we compare this photograph of the return image with the size calculated from the interferometric results in the static test.

Although the static tests are satisfying and indicate that the instrument is capable of producing images on the order of 1.5 seconds diameter or better, the results with the secondary in the chopping mode are far less encouraging. In Fig. 4 we show the images at the end of chop cycles for several different chopping frequencies. In these photos the scale is readable in most cases. Eleven of the smallest divisions are equal to a 1 second image. All the photographs have the same scale. It is immediately obvious that the 12 and 17 Hz chop rates lead to very large images. In fact, the 12 Hz image is approximately 8 seconds in length while the 17 Hz image is about 10 seconds in length. In both cases it is clear that the secondary mirror reaches its end stop and



RETURN IMAGE AT
ZERO CHOP OFFSET
(SECONDARY ON AXIS)

RETURN IMAGE AT
END OF CHOP CYCLE
(SECONDARY AXIS TILTED)



COMPUTER SIMULATION OF RETURN
IMAGE BASED ON STATIC SYSTEM
TEST WITH PNEUMATIC PRIMARY
SUPPORT NOT WORKING

Fig. 3. Return Images from Point Source Test of Static System Test (Air Support Off).

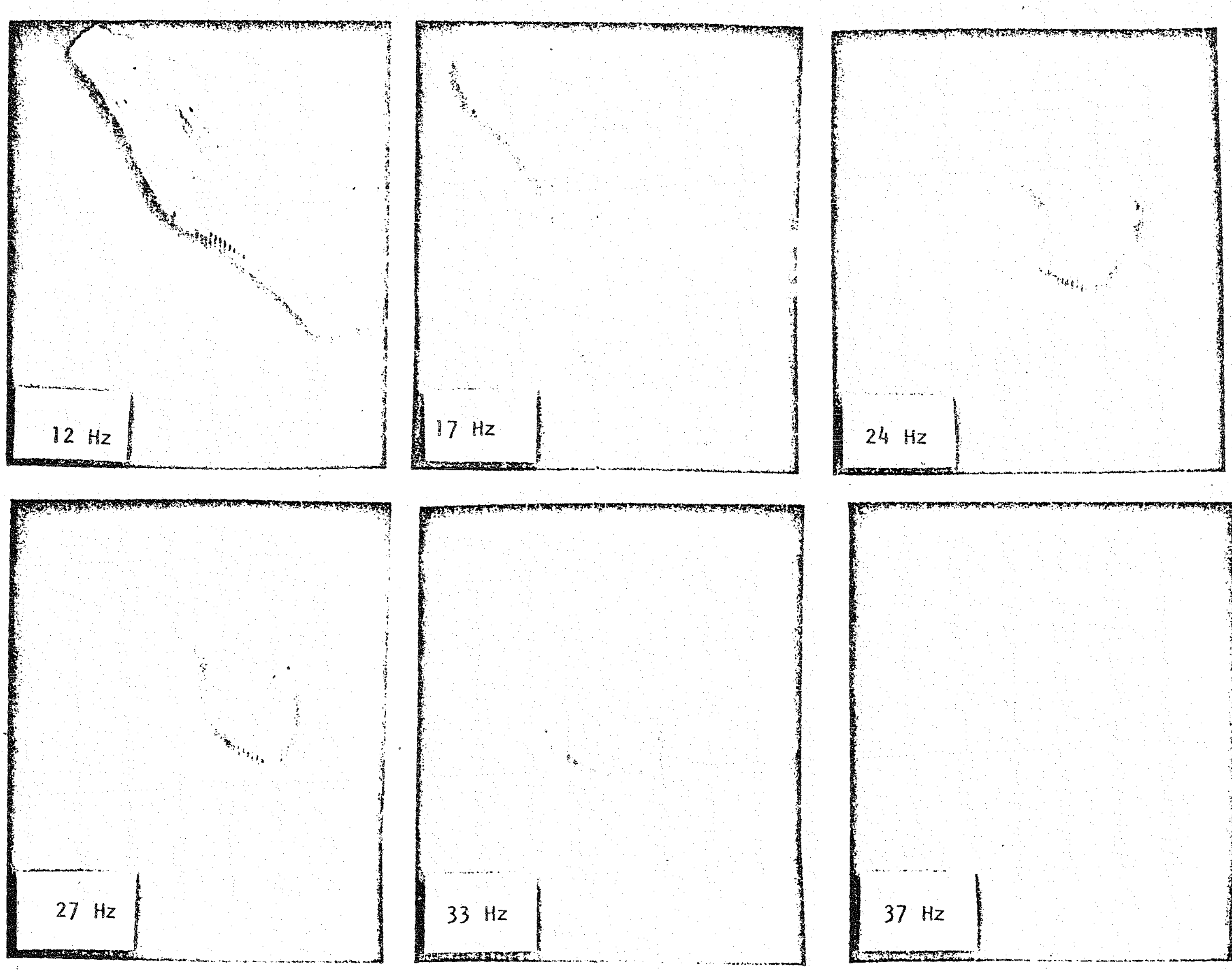


Fig. 4. Return Images from Dynamic System Test at Various Chopping Secondary Drive Frequencies.

then bounces when in fact the mirror should be stationary. The situation greatly improves for the region between 24 and 37 Hz although in all these cases except perhaps the 37 Hz case the image is two to three times larger than it is for the static case. The photographs in Fig. 4 indicate a substantial problem in the mechanism supporting the secondary mirror at certain chopping frequencies.

We conclude from these tests that the system does not perform up to the original specification of 80% of the energy in a 1 arc second circle. However, it performs statically many times better than the 8 to 10 second spot size observed during flight. At this point, the individual optical components were tested to find out where the source of error lay that kept the system from performing up to the original specifications.

<u>Secondary Mirror Test</u>

Because of some worry about the quality of the Cervit secondary supplied with the system, it seemed logical to test this component first. The classical test for both the manufacture and verification of quality of hyperbolic secondary mirrors is the Hindle test shown in Fig. 5. The secondary mirror is supported by its center mounting hole with its optical axis horizontal. An interferometer is placed at the long focus or conjugate of the secondary mirror at the same distance from the secondary as is the focal plane in the actual telescope. A Hindle sphere is placed with its center of curvature at the short focus or conjugate of the secondary mirror. This conjugate is at the same position relative to the secondary mirror as the focus of the

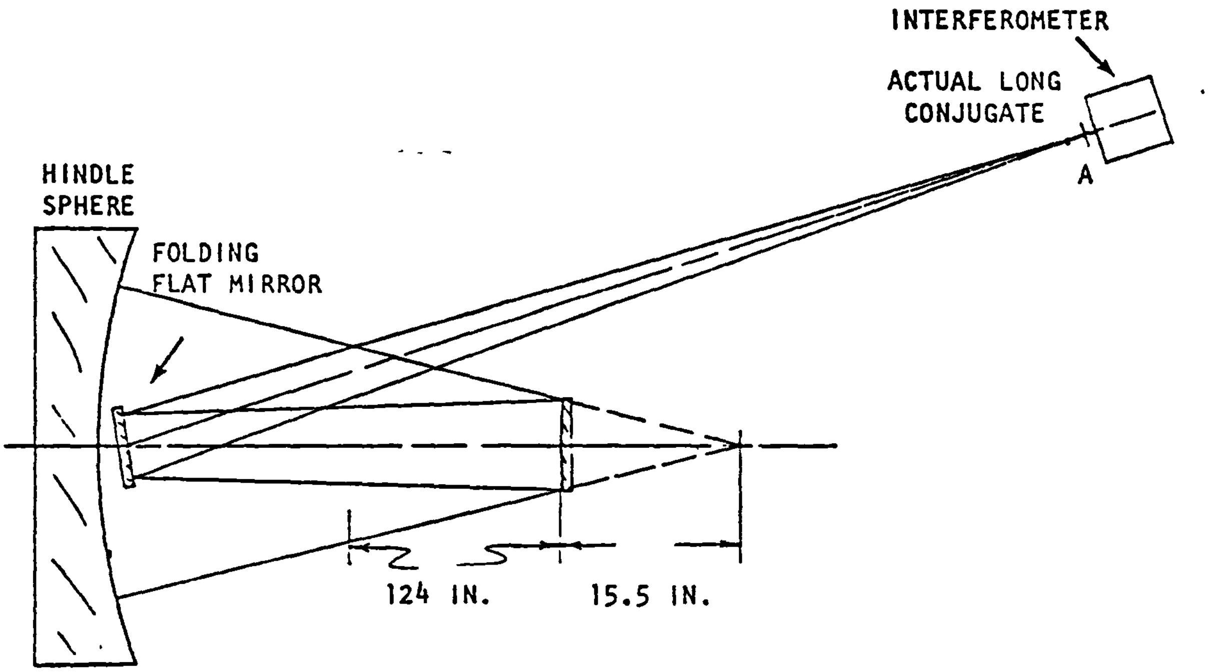
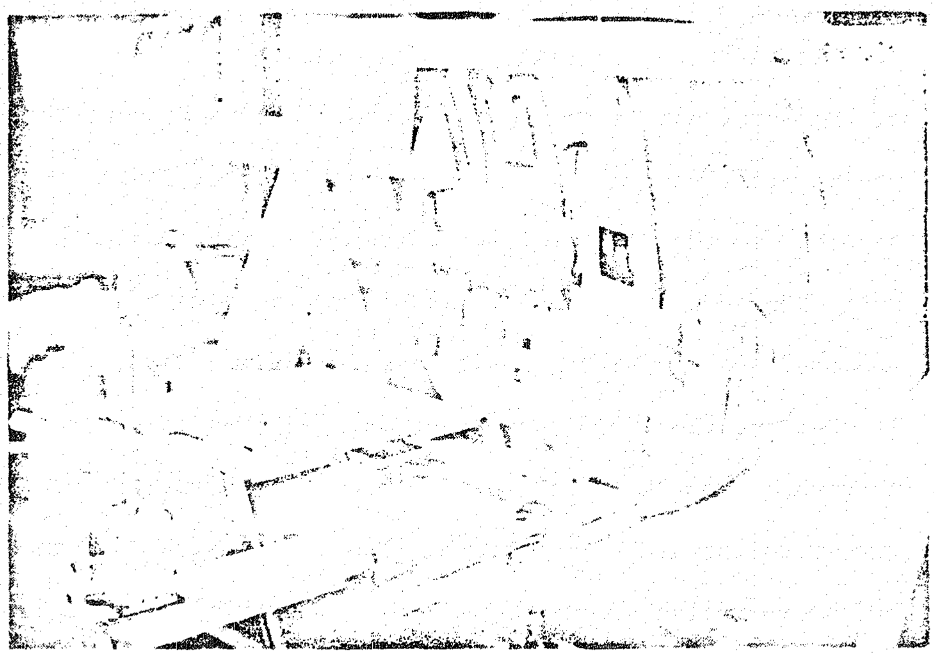


Fig. 5. Hindle Test for Hyperbolic Secondary Mirror.
A is the focal plane or long conjugate.

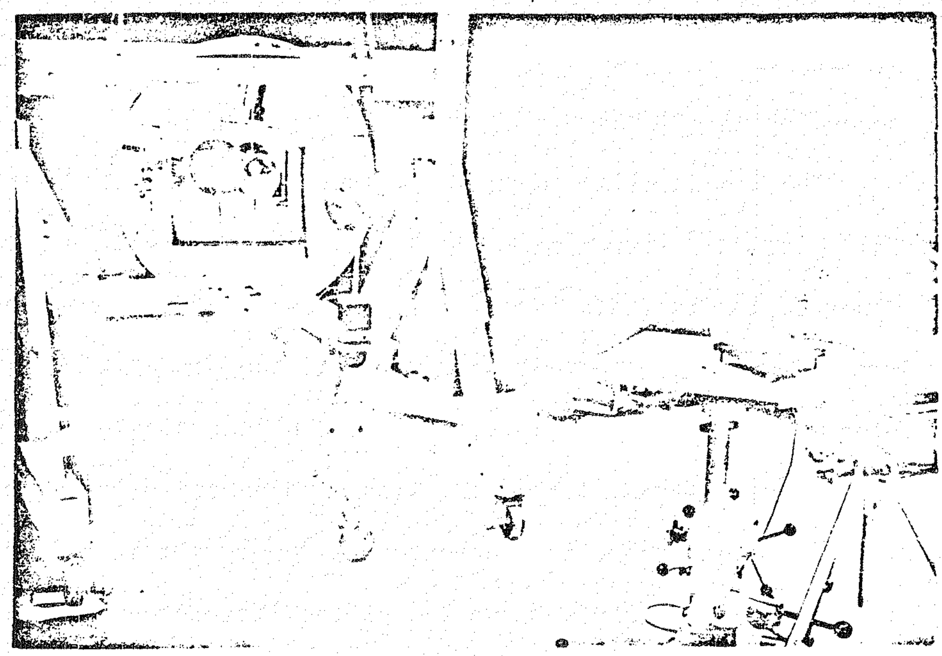
primary mirror is in the telescope. (The short conjugate is at the Newtonian focus of the primary mirror). In this configuration, light from the interferometer diverges up to the secondary. It causes a further divergence, making the light appear as though it were coming from the short conjugate or the secondary. This light diverges from the secondary in a spherical wavefront and is directed toward the Hindle sphere at normal incidence. The light then reverses direction at the Hindle sphere and returns to the interferometer. The data gathered by the interferometer show twice the wavefront error that the secondary would produce if it were in the actual telescope. Thus all the data obtained from our interferometric measurements were divided by two to account for the double sensitivity of the test of the secondary mirror.

The photographs in Fig. 6 show the actual test setup. Figure 6a is a closeup of the secondary mirror at the left mounted on a three-axis translation stage. The Hindle sphere is to the right center of the photo with a folding flat near the middle of the Hindle sphere. Fig. 6b shows the overall test setup with the interferometer and the camera at the far right of the photo. Notice that a folding mirror was used to obtain access to the long conjugate beam rather than using a Hindle sphere with a central hole.

Because it is difficult to talk about the errors of individual optical components in terms of the image spot size they produce, we will present the data from the interferometric tests on the secondary mirrors in terms of their effect on the wavefront. In the case of the Cervit secondary that was supplied with the telescope, the easiest way to look at its wavefront error is to compare the radial profile, or zonal



(a)



(b)

Fig. 6. Hindle Secondary Mirror Test.

profile, or the wavefront produced by this mirror with a radial profile of the wavefront of the total system. Figure 7 shows these two average radial profiles. As may be seen, both average radial profiles show a severe down edge at the inner edge and at the outside of the aperture both show an up edge. Over the central annulus of the aperture, the two profiles differ by less than a tenth of a wave. The great similarity between these two average radial profiles is a strong indication that the error in the system average radial profile is due almost entirely to the secondary mirror. This conclusion is further supported by the very high quality of the primary mirror as will be reported later. The Cervit secondary mirror had this zonal error as its only major figure defect. It was virtually free of astigmatism and other azimuthally varying errors. The peak-to-peak wavefront error produced by Cervit secondary mirror was 0.87 waves.

The fused silica secondary was tested in exactly the same fashion. This secondary mirror appeared free of zonal or radial irregularity. However, it did suffer from nearly 0.7 wave of astigmatism. This error was the principal optical defect of this component although it was coupled with other irregularities to give a peak single pass wavefront error of 1.4 waves. Thus, the Crevit secondary mirror, in spite of the error at its center, is the better mirror by almost a factor of two in wavefront. Figures 8 and 9 show the interferograms of these two secondary mirrors as well as computer-reduced contour plots of the wavefronts the two mirrors produce.

Because of the great difference in the figure errors between the two secondary mirrors, both tests were repeated using the same mount through

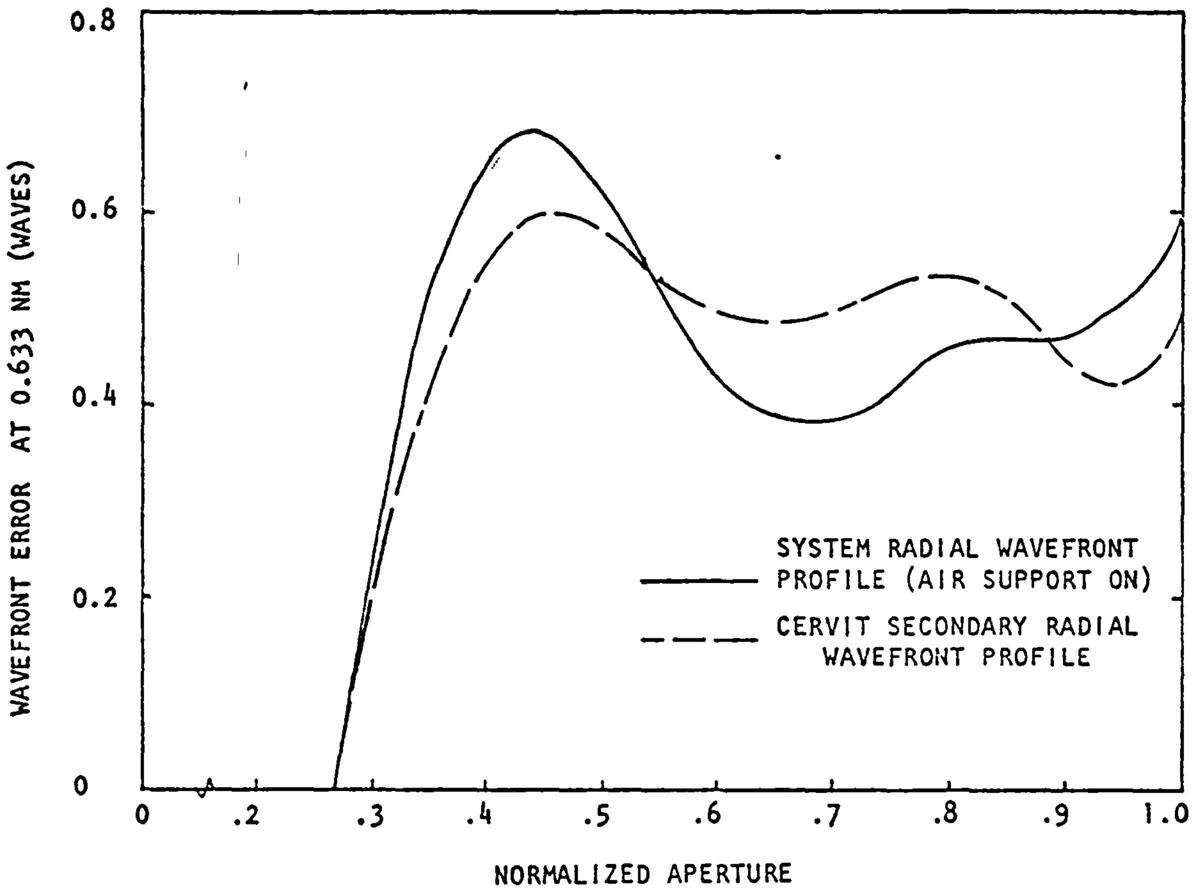


Fig. 7. Comparison of System and Cervit Secondary Average Radial Wavefront Profile.

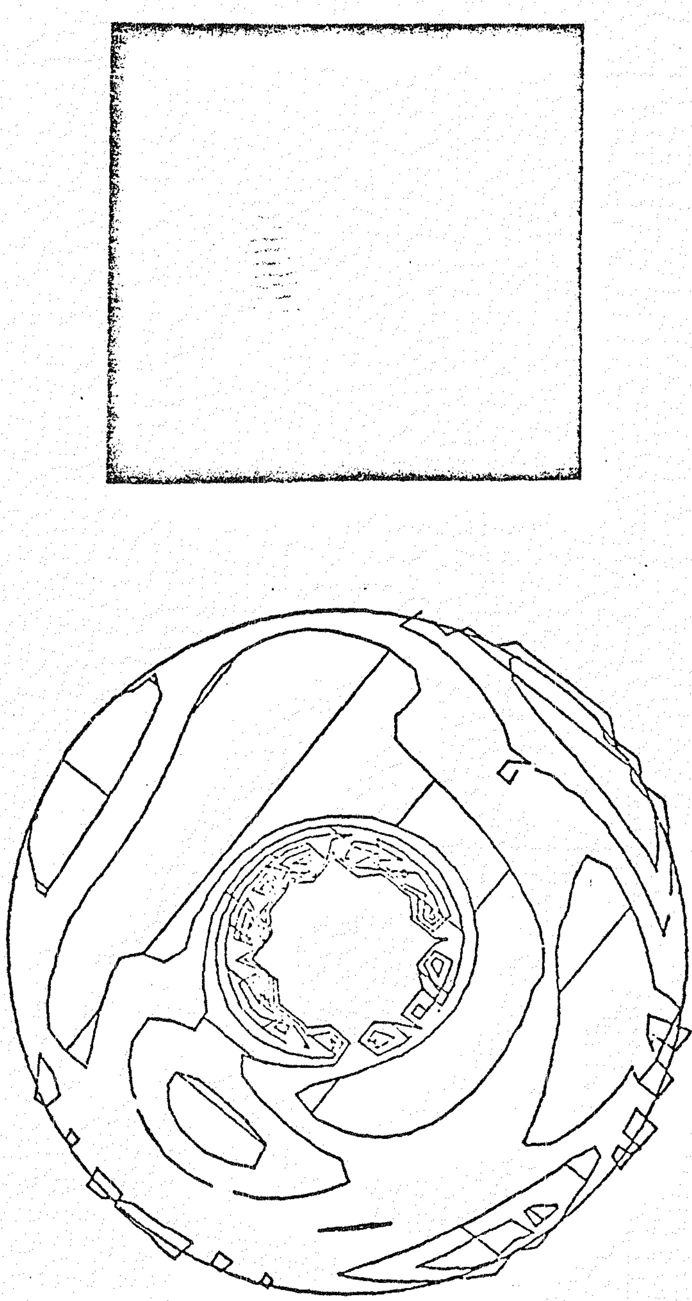


Fig. 8. Interferogram and Wavefront Contour Map of Cervit Secondary.

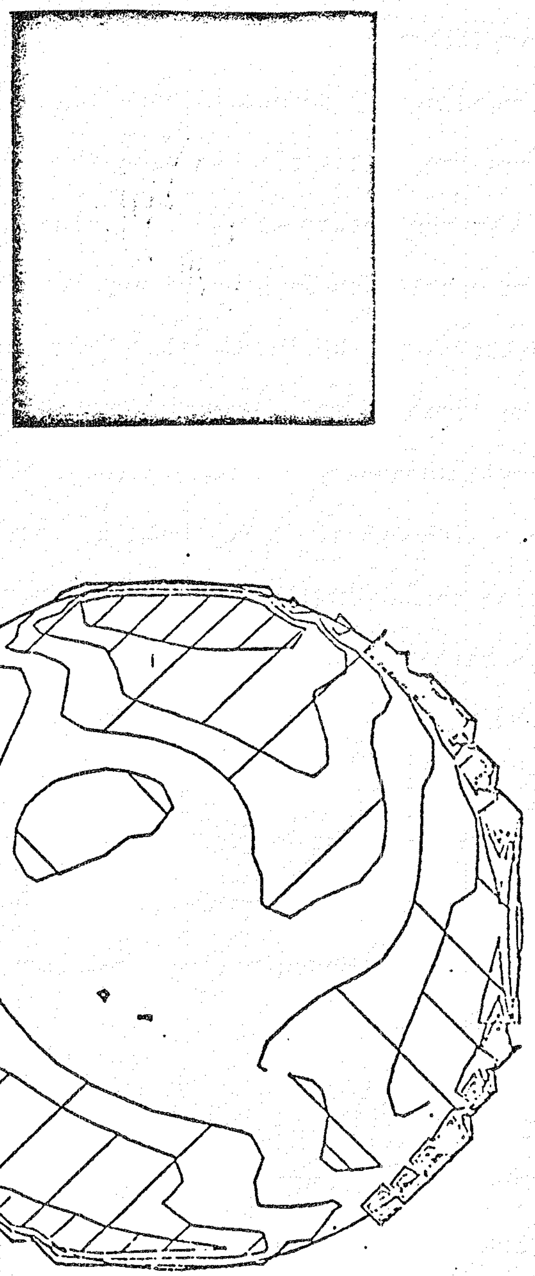


Fig. 9. Interferogram and Wavefront Contour Map of Fused Silica Secondary.

the center hole of the secondary mirrors. This was done to insure that the difference in error was not caused by the method of mounting the secondary mirrors and that the fairly large amount of astigmatism was not induced by any defect in mounting. Another reason for repeating the tests was that there had been some confusion as to which secondary mirror was the better of the two. The repetition of the test led to the same conclusion as before that the Cervit secondary mirror was somewhat better than the fused silica mirror.

The final matter regarding the secondaries concerns whether or not the Cervit secondary was manufactured to a tolerance of 2 arc seconds or better. Although it is somewhat difficult to find the radial energy distribution for a single component, we have used the fringe reduction program to calculate the effect of the wavefront errors shown in Figs. 8 and 9 on the radial energy distribution produced by these mirrors. Figure 10 shows the energy distribution produced by the secondaries on the system assuming that other components were perfect. This analysis shows than the Cervit secondary was made to better than the 2 arc second specification and the fused silica secondary is not as good but still better that 2 arc seconds.

Primary Mirror Test

The next component to be tested was the primary mirror. The mirror was taken out of the cell and slung in a specially designed sling mount so that its axis would be horizontal. The sling mount did not interfere with the mounting pads on the edge of the primary mirror. The schematic of the primary mirror test is shown in Fig. 11. A flat mirror was

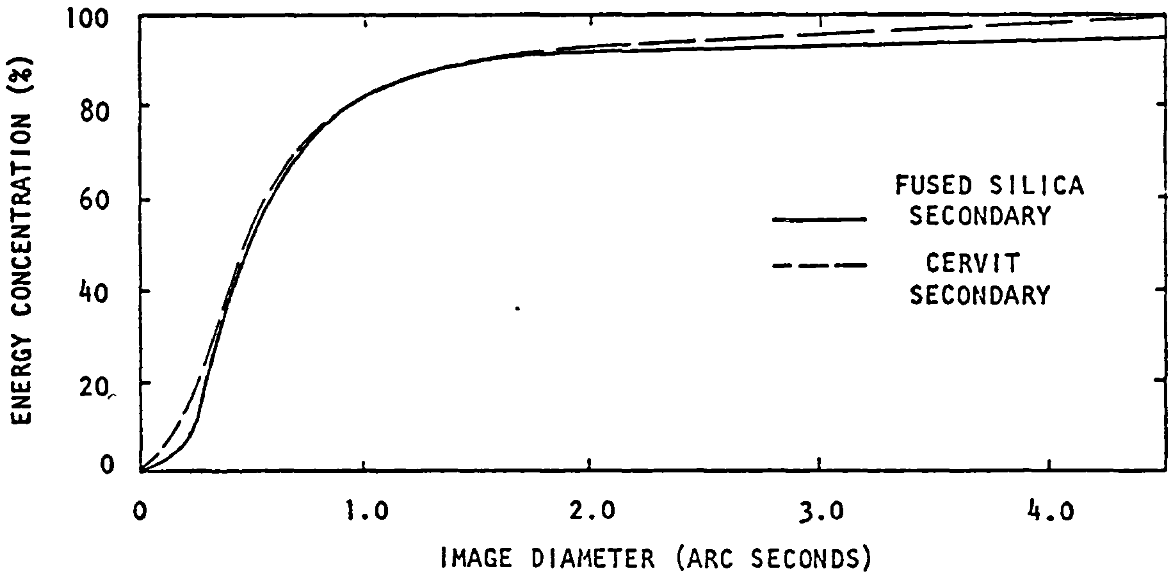


Fig. 10. Energy Concentration vs Image Diameter for the Fused Silica and Cervit Secondary Mirrors.

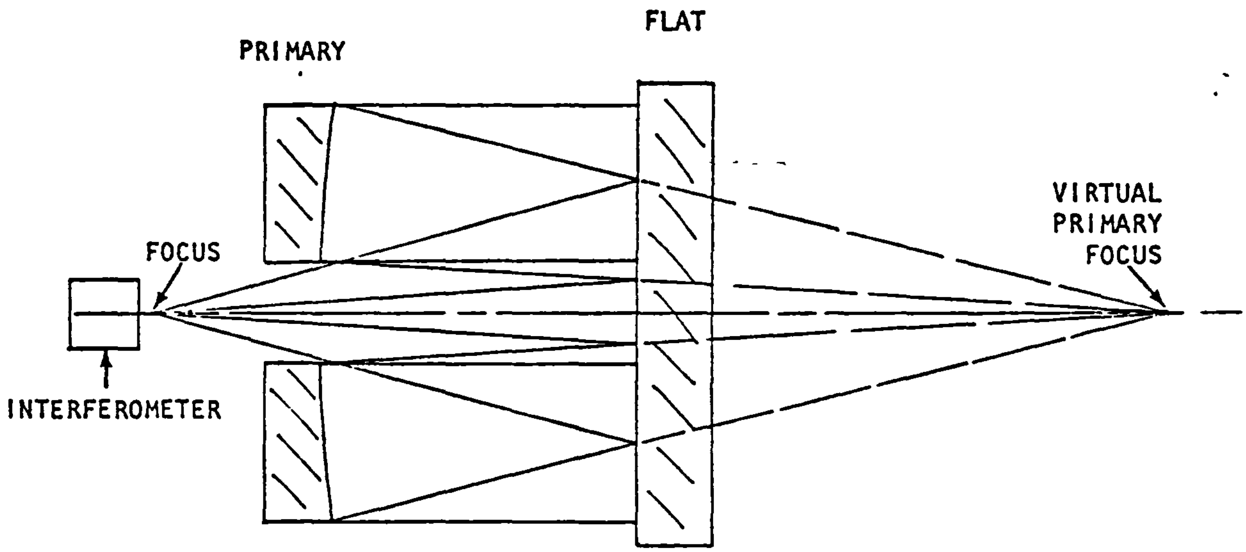


Fig. 11. Primary Mirror Test Against a Flat Mirror.

positioned at a little less than half the focal length from the primary so that there was easy access to the focus of the primary. The interferometer was placed at the focus of the primary as reflected in the plane mirror. Light from the interferometer diverged up to the flat and continued to diverge into the primary mirror. The primary mirror collimated the light and directed it toward the flat where it struck at normal incidence. The light then retraced its path back from the flat to the parabola and finally to the interferometer. This test was compact and allowed us to test the primary mirror with no larger obscuration than that due to the hole in the primary itself.

The data taken from the interferometer were divided by two because this is a double pass test and were analyzed by the FRINGE reduction program. Figure 12 shows the average radial profile of the primary mirror. As is immediately obvious, the departure from the correct curve affects the wavefront by less than a tenth wave. Thus the mirror surface has a radial profile of better than 1.20 wave. This represents an extremely small manufacturing error on a mirror of this speed. Figure 13 shows the contour map of the wavefront produced by this mirror. The wavefront has a peak-to-valley error of 0.46 wave. The surface of the mirror is better than a quarter wave, an extremely fine primary mirror. In Fig. 14 we show the radial energy distribution in the image assuming that all the other components in the telescope are perfect and that only the primary mirror is contributing to the spread in the radial energy distribution. As can be seen from the figure, the primary mirror is superior in performance to the secondary mirrors. Both the radial energy distrbution of the primary in Fig. 14 and that for the secondary

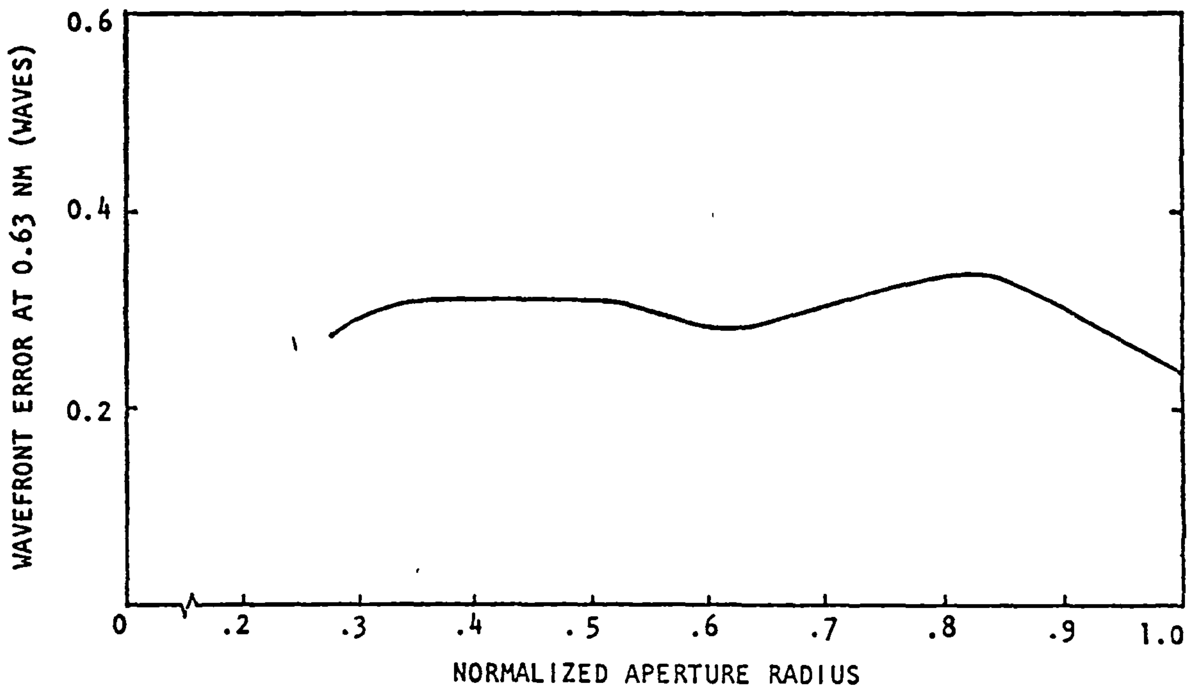


Fig. 12. Average Radial Wavefront Profile of Primary Mirror.

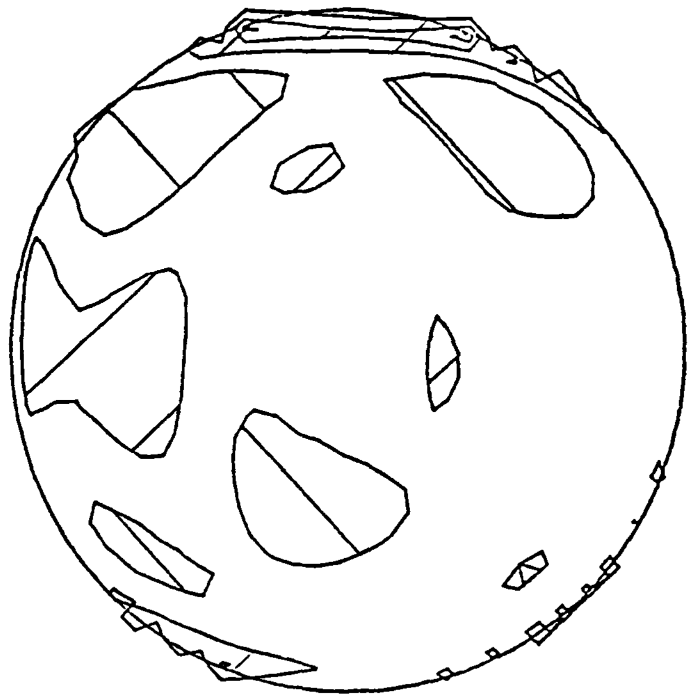


Fig. 13. Contour Map of Wavefront Produced by Primary Mirror.

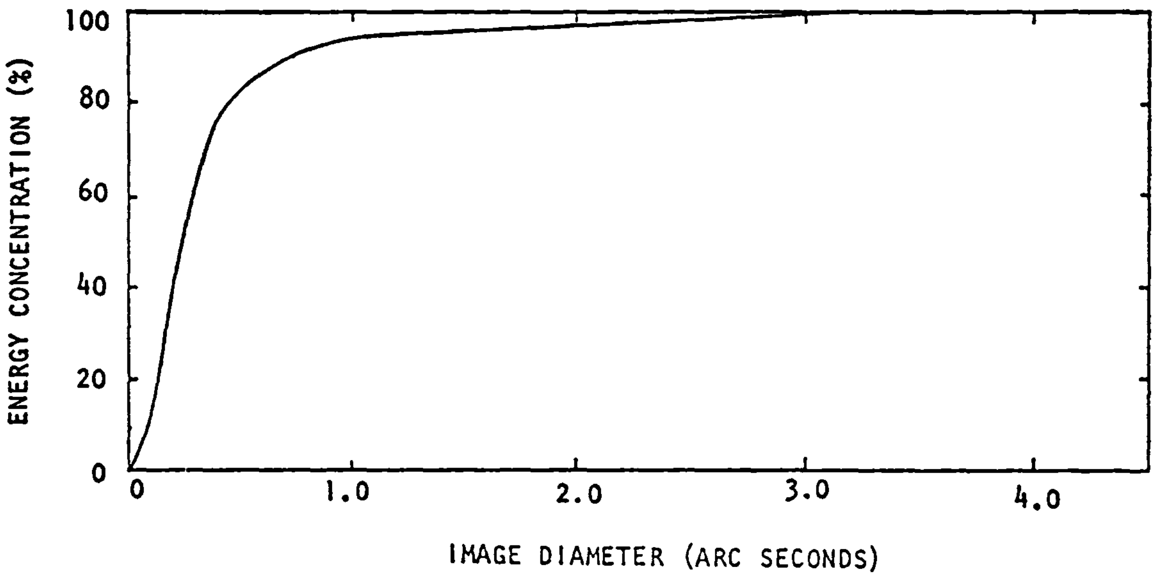


Fig. 14. Energy Concentration vs Image Diameter for the Primary Mirror.

mirrors in Fig. 10 are plotted to the same scale. Clearly, the primary mirror is close to perfect, and if one wished to make the system better, an obvious place to begin would be with work on the Cervit secondary mirror.

Tertiary Mirror Test

The final component of the system that was tested was the tertiary mirror. This plano mirror was tested in the classical fashion using the Ritchey-Common Test shown in Fig. 15. The advantage of using this test is that the mirror is tested at a 45° angle of incidence just as it is used in the telescope. Thus the wavefront produced by the mirror gives a one-to-one correlation with its effect on the telescope. The result of this test showed that the tertiary mirror had almost exactly one half wave of pure astigmatism. This amount of astigmatism in the tertiary mirror would be itself contribute a 0.33 arc second blur to the image. Figure 16 shows the radial energy distribution calculated for the tertiary mirror assuming the primary and secondary of the system are perfect.

We were surprised that the tertiary mirror had this large a figure error. It should be pointed out that these tests were run after the tertiary mirror had been coated. We ran a very cursory check on the tertiary mirror over a portion of the aperture prior to coating and the mirror looked at that time to be flat, certainly less than a quarter wave. Thus we were surprised to find after coating that the mirror did appear to have about a half wave of astigmatism. This led us to believe, as will be pointed out below, that there may be a certain problem

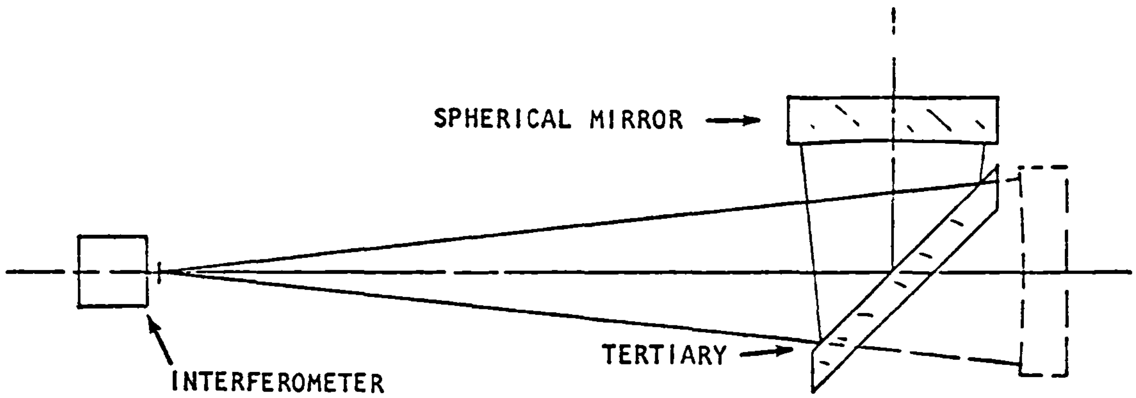


Fig. 15. Ritchey-Common Test of the Tertiary Mirror.

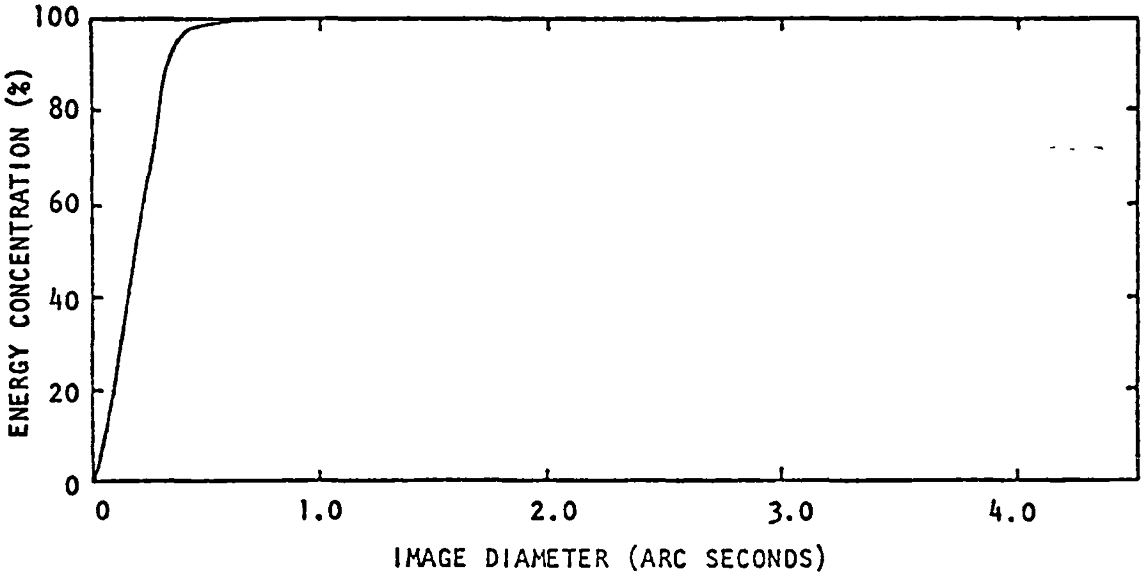


Fig. 16. Energy Concentration vs Image Diameter for the Tertiary Mirror.

with the exact method of mounting the tertiary mirror. Because of its placement in the telescope system, a rather small figure error in this mirror will have an effect on the angular diameter of the final image of the telescope. Thus it is imperative that this mirror be properly mounted.

Conclusions from Optical Systems and Components Testing

The primary conclusion we reach after testing the system and the three principal components is that the system in an unchopped mode is capable of producing images approximately 1.5 arc seconds in diameter for 80% energy concentration. Second, we conclude that the primary mirror is an excellent optic having an overall surface error of less than a quarter wave. Third, we see that the air support system for the primary mirror appears to be working properly but that the primary mirror is stiff enough that the pneumatic support system is probably unnecessary. Fourth, the secondary mirror is better than the specifications to which it was made but is several times worse than the primary mirror. If one wished to make the basic system better, the secondary mirror should be improved. Fifth, the tertiary mirror is not totally flat. Because of its size and shape and the environmental changes it had gone through prior to testing it, it is reasonably apparent that the problems with the tertiary mirror are in its mount or method of mounting rather than with the mirror itself. Sixth, it is obvious that the major problem with the system lies in the chopping secondary mechanism. There are three principal errors: (1) a minor error is that the secondary has a jitter even at zero offset although small enough not to affect image size, (2) at certain chopping frequencies there is a large resonance in some part of the chopping secondary mechanism, a resonance large enough to produce images with an apparent 10 arc second elongation in one direction, (3) there is a cross coupling in alignment in the secondary chopping mechanism. However, the cross coupling factors are large enough to produce alignment errors that could produce images on the order of 10 arc seconds in diameter. Certainly the conclusion from these tests is that effort should be put into improving the chopping mechanism for the secondary mirror.

4. METHOD OF SYSTEM ALIGNMENT

The method of system alignment is presented here so that it may be used independently from this report as a procedure for alignment of the telescope should that become necessary in the future. The instruments required for aligning the telescope are an alignment telescope such as the D300 available from Davidson Optronics and a point source. A point source microscope would be an ideal source. The alignment telescope must be located roughly 3 ft beyond the focal plane of the telescope and aligned so that it is boresighted with the trunion axis. The point source must be placed at the center of curvature of the primary mirror. The alignment procedure then goes as follows:

(1) Remove the secondary mirror and chopping mechanism.

(2) Establish that the head ring is square to the primary cell (this will be the case unless the metering truss has been removed or tampered with).

(3) Apply centered cross hairs to the primary cell and to the primary mirror. These cross hairs will be used to mechanically insure that the primary mirror is centered within its cell.

(4) View the primary mirror from its center of curvature and shift the mirror laterally to square the primary in its cell. Use the cross hairs applied in step 3 for guidance. (This procedure will insure that the axis of the primary mirror lies on the axis of the trunions. If the primary mirror axis does not lie on the trunion axis, the image in the focal plane of the telescope will appear to move as the telescope

changes elevation.

(5) Center the secondary mirror spider so that the adjustment screws on the spider are mid-range. Then place cross hairs over the secondary mirror mounting ring.

(6) Place the point source at the center of curvature of the primary mirror and then tilt the primary mirror using the three axial defining points until the center of curvature of the primary mirror lies in line with the cross hairs placed on the secondary ring. Readjust the centering of the primary mirror if ncessary after doing the tilt procedure on the primary. Repeat the tilt and centering process until the primary is both centered in its cell and the center of curvature lies on the cross hairs on the secondary mounting ring. (The primary mirror is now free of tilt and decenter relative to the telescope structure. The center of curvature of the primary, the secondary mount, and the vertex of the primary mirror will now all be collinear. This reference system can now be used as the reference for the balance of the alignment).

(7) Boresight the alignment telescope on cross hairs placed at either end of the trunion axis. (Set up the alignment telescope at least 91 cm (3 ft) beyond the focal plane of the telescope).

(8) Install the tertiary mirror and adjust the tertiary in two degrees of tilt and one degree of vertical translation. These three degrees of freedom will allow the tertiary mirror to be adjusted such that the cross hair on the secondary ring, the cross hairs on the primary cell, and the point source at the center of curvature of the primary all lie on the axis of the alignment telescope. When this is the case, the tertiary mirror will be correctly adjusted so that it transfers the optical axis

of the telescope structure collinearly down the axis of the trunion.

(9) Install the secondary mirror chopping mechanism and the secondary mirror. Set the chop offset to zero. Use the alignment telescope to center the secondary mirror laterally. The alignment telescope should be focused on the mounting stud for the secondary mirror.

This completes the basic alignment procedure for the telescope. The one additional adjustment that could be made but for which there is no auxiliary equipment at the moment is to set the zero chop offset so that there is no tilt of the secondary mirror. A special jig for this purpose could be made the next time the telescope is down for service. We had the advantage when the telescope was in the Optical Shop that the large plano mirror used to test the telescope could be used to determine when the secondary mirror was free of tilt. An auxiliary flat could be made which would attach to the telescope head ring. This would have a built-in reference so that the secondary mirror zero offset position could be corrected at any time.

5. SYSTEM MECHANICAL PROBLEMS

In the following section we list some of the mechanical problems we encountered with the telescope. Most of these problems will ultimately affect the performance of the telescope. Although none of the problems was particularly bad except those to do with the chopping secondary mechanism, all contribute to a degradation of performance.

The first problem we encountered was that the primary mirror was decentered in its cell by some 3 mm. At first glance, this does not appear to be a particular problem because the telescope could be aligned relative to the decentered primary. However, because the line of sight is turned 90° by the tertiary mirror, it is impossible to make the axis of the system collinear with the trunion axis. This will cause an apparent boresighting error as the telescope tracks an elevation. We felt it was imperative to correct this situation.

We were at somewhat of a loss to explain how the primary mirror became decentered within its cell because it is constrained to stay centered by three radial defining pads. In order to center the mirror, we had to manufacture three new spacer blocks because there was insufficient adjustment in the existing blocks to permit the mirror to be centered. One thought that did occur was that the mirror, during a coating, had become rotated by 120° from its original position. This could have caused the decentering because the radial defining points are not attached to the mirror at precisely 120° intervals. One other thought was that the mirror perhaps was never perfectly centered in its cell although this is very hard to believe. The only other explanation we have is that some part of the radial defining mechanism had actually become fatigued with time and that this had permitted the mirror to sag some 3 mm from its centered position. The decentration of the mirror was in the direction that gravity could have pulled it. In any case, the radial defining points were adjusted with the help of new spacer blocks to reposition the primary in its cell to an accuracy of better than 0.5 mm.

A second area of mechanical problems arose with the secondary mirror. There was approximately 0.75 mm clearance between the hole in the secondary mirror and the stud on which it was mounted. Thus every time the secondary mirror was removed and replaced on the study, the centration of the mirror could have changed as much as 0.75 mm. Figure 17 shows the impact on image quality of this type of decentration of the secondary mirror.

Clearly, this large a decentration made it difficult to obtain proper alignment of the telescope. Therefore, we had a new Invar mounting stud manufactured in our shop with a clearance of 0.05 mm. With this new stud, the secondary mirror can be removed and replaced with minimal effect on the alignment of the telescope.

Another area with which we found some problem was the primary mirror pneumatic support system. The first time we tried to use the system for some of our tests, we found that the regulator was improperly installed. When we thought we had the pneumatic support system working, in fact, it was not. This problem was quickly cleared up. However, when we went to adjust the centration of the primary mirror on itself,

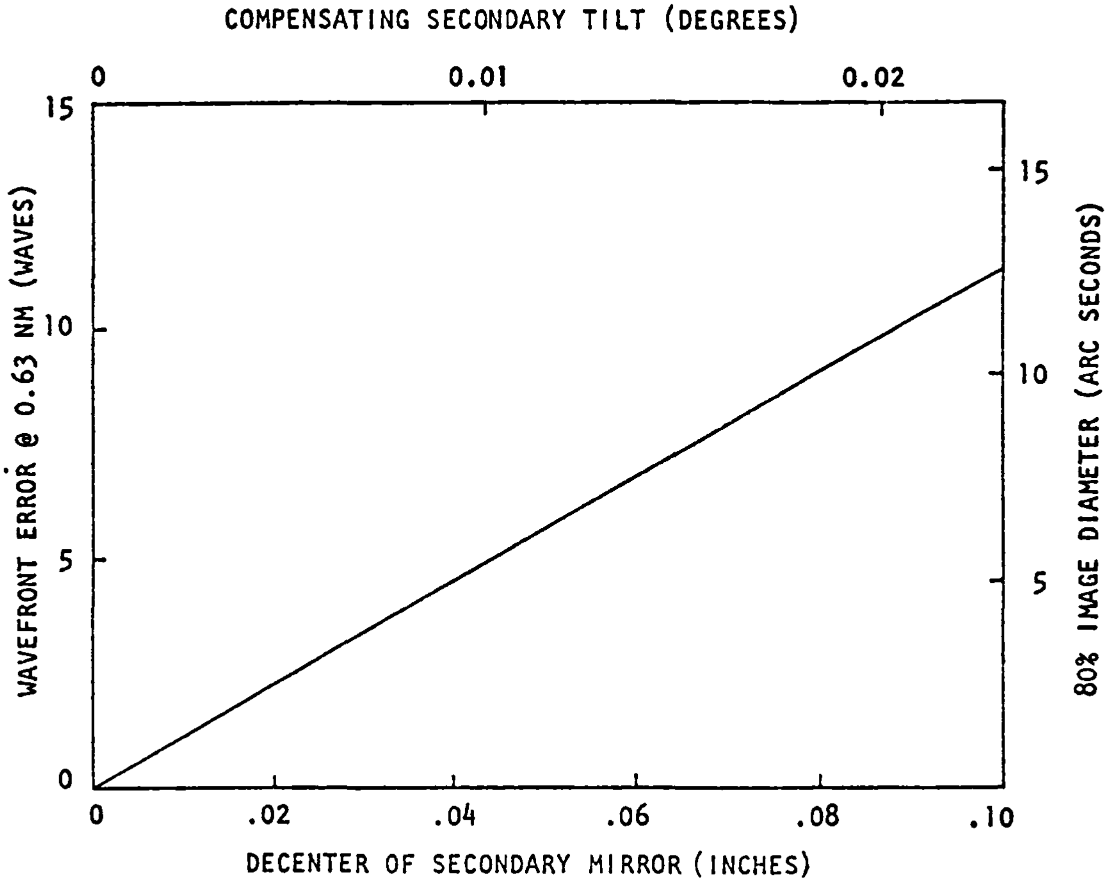


Fig. 17. Coma Introduced by Decenter of Secondary Mirror.

we also discovered that the primary mirror may have been resting on the three axial defining points independent of whether the pneumatic support system was turned on or off. It may have been this problem that led some people to believe that there was a problem with the operation of the pneumatic support system. We found that with the axial defining points properly adjusted, the pneumatic support system appeared to work satisfactorily.

Another area where we had mechanical problems was with the secondary spider support. It was adjusted to the limits of travel, and when we tried to line up the telescope, there was no further travel in one direction. It turned out that the need for this adjustment was caused by a misadjustment of the tertiary mirror. This tertiary mirror adjustment had been incorrectly made because one of the adjustment screws on the mirror had a stripped thread that made it feel as though the screw had come to the end of its limits. The tertiary mirror adjustment was completely disassembled, and the threads on the adjustment screws were chased, and the system was reassembled. Once this was done, the tertiary mirror could be aligned into its proper position. This allowed the secondary support spider to be adjusted to its mid-range allowing the entire system to be put into proper alignment.

Finally, we had several problems with the chopping secondary mechanism to which we have already alluded. The first of these relates to the focus mechanism. Attempts to focus the secondary mirror cause the image to move laterally in the image plane. This problems appears to be caused by excessive clearance in the linear bearings of the mechanism.

Second, the axis of rotation of the chopper assembly is not perpendicular to the chop axis. For purposes of the system test only one position of the chop axis was tested. However, during final alignment the system could be aligned only for either of two positions of the chop axis or one position with minimum deviation at other rotations. Since we knew that experimenters rotate the chop axis for different experiments, we found best alignment for one position and then minimum deviation for other rotations. This does mean, however, that in all positions the telescope is aligned in a less than perfect condition. Third, it is our opinion that the placement of the linear bearings at a 45° angle to the chop axis serves only to maximize the cross coupling between the chopped and the unchopped axis.

One final item concerns the tertiary minor and its method of mounting to the Invar pedestal. The mirror appears to be bonded to the Invar base at four places by use of .050 thick silicon rubber adhesive pads. It appears that as the environment changes (perhaps with humidity), the silicon rubber materials couples a moment into the mirror and causes a slight warp. We would suggest that the mount be studied carefully to find a better mounting configuration.

Clearly, from this list of mechanical problems the balance of the unsolved problems lie with the chopping mechanism for the secondary mirror. We believe that we have found a solution and have fixed the mechanical problems in the other portions of the telescope leaving only those concerning the chopping mechanism and the tertiary mount still to be addressed. We felt we were in no position to remedy these particular problems.

6. SYSTEM DESIGN ASPECTS

In this part of the report we discuss briefly the effects of secondary misalignment and improper spacing between the primary and secondary mirror on image size. The first topic we discuss is misalignment of the secondary mirror.

Typically, during alignment one attempts to keep the image in the focal plane on axis. Therefore, if the secondary mirror is decentered by some small amount, it is common practice to tilt the secondary mirror to compensate for the image shift produced by decentering the secondary. The tilt brings the image back on the axis of the instrument. In Fig. 17, we illustrate what happens to the image quality as a function of the amount of decentration. As an example we use a 0.75 mm clearance in the hub of the secondary mirror relative to the mounting stud. If the system is perfectly aligned with the secondary mirror toward one edge of the stud and the mirror is removed and replaced so that is is now pushed to the opposite edge of the stud and thus is decentered by 0.75 mm, we find that the image has grown from its nominal diffraction-limited size to a spot 4 arc seconds in diameter. Clearly, this has a major impact on system performance if the instrument is being used in a diffraction-limited situation. Also note from the graph that the image size grows linearly with the amount of decenter and compensating tilt. The curve also shows the criticality and necessity for good alignment if diffraction-limited performance is desired from the telescope.

The second area concerns mis-spacing between the primary and secondary mirrors. With the Cervit secondary mirror, the nominal design distance between the secondary mirror and the focal plane is ∿3 m (124 in.). This gives the instrument a magnification of 8 with an f/17 output beam. It turns out that some experimenters' packages do not mate with the telescope so as to use the focal plane at this position. In Fig. 18 we show the effect on image size as the focal plane is shifted from its designed location of ∿3 m (124 in.). If the image plane should be shifted 36 cm (14 in.) farther back or away from the telescope, it will introduce roughly 0.75 of a wave of spherical aberration that will produce and 80% spot diameter of 1.8 arc seconds. Again, it is obvious from the curve in Fig. 18 that this is a linear effect and the farther one gets from the nominal focal plane of the instrument the worse matters become. For experimenters working into the IR region this is probably no detriment, but to persons working in or near the visible, in the absence of other image defects, this can be a problem.

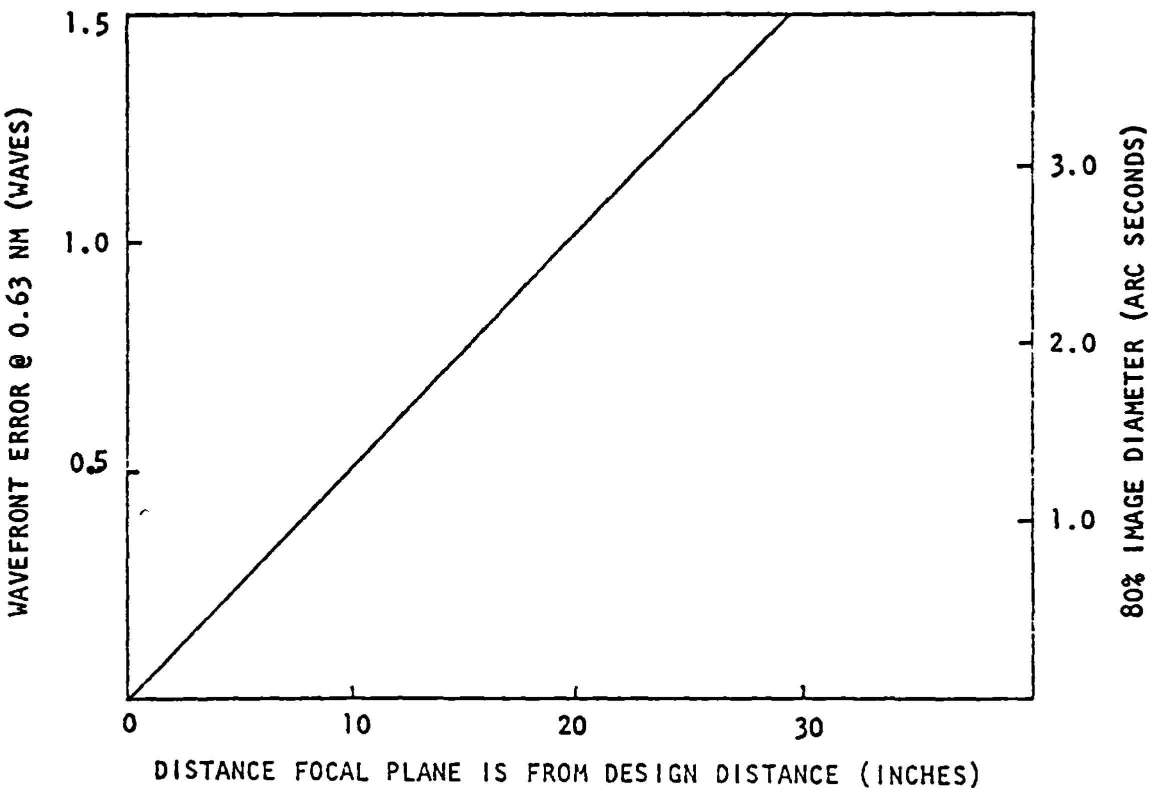


Fig. 18. Spherical Aberration Introduced by Using Telescope at Focal Plane Other Than That It Was Designed for.

7. CONCLUSIONS

Based on our tests and analysis of the Kuiper 91-cm telescope we have shown that the static system is capable of producing 80% energy images at 1.5 arc seconds when the system is properly aligned independent of whether the pneumatic support on the primary mirror is working or not. Further, we have shown in our dynamic tests that image diameters from 2 to 10 arc seconds are possible during chopping modes. It appears that at the higher frequencies of around 34 to 38 Hz it is possible to obtain ∿2 arc second images in the chopping mode. From evidence of misalignment when the instrument was delivered to Optical Sciences and because of the play in the secondary mirror relative to its mounting stud, we feel that during typical operation there may have been sufficient misalignment to account for image diameters of from 2 to 5 arc seconds. From these observations it is clear that work may need to be done on the chopping secondary mirror so that at any reasonable chopping frequency the bounce at the end of the chop can be reduced, thereby insuring 2 to 3 arc second images as a routine matter. Furthermore, we feel that we have eliminated most of the obvious misalignment errors and that image defects due to this cause should be able to be held to ∿2 or 3 arc seconds. Obviously, too, the errors due to chopping, the static system, and misalignment add up to yield an image quality of ∿4 or 5 arc seconds in the worst case, assuming the chopping secondary mechanism has been corrected.

Clearly, however, the 8 to 10 arc second images observed in flight point to another source of error even greater than those associated with the telescope. This was clearly the case when we went on a test flight of the Kuiper Observatory. There can be no doubt that air turbulence is the major cause of image degradation with the Kuiper Observatory. Until something can be done to reduce this major cause of image degradation, it does not make a great deal of sense to spend too much time or money on other aspects of the telescope. We certainly feel that some improvement ought to be made in the chopping secondary mechanism, but we do believe that to worry about the figure quality of any of the optical elements in the telescope would not be an effective way to improve the telescope performance.

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15. Supplementary Notes
Technical Monitor· Louis C. Haughney, Mail Stop 211-12, NASA Ames Research Center, Moffett Field, CA 94035 (415) 965-5339 or FTS 448-5339

16 Abstract Testing of the Kuiper Airborne Observatory 91-CM Telescope was performed. A static system test with the secondary mirror not oscillating followed by a dynamic system test with secondary chopping were conducted. The system was tested both with the air support for the primary mirror turned off and with this air support system turned on. Further, all separate optical components were separately tested in their own null configuration. This included the primary mirror, the tertiary folding flat, the Cervit secondary mirror, which was installed in the telescope when it was received at Optical Sciences, and the auxiliary fused silica secondary. A brief look was also given at the guide scope and CRT camera system.

The report contains the results of the static and dynamic tests; a scheme for system alignment; a discussion of the system mechanical problems including the primary mirror decentering in its cell; problems with the air flotation system for the primary mirror, the chopping mechanism for the secondary mirror, and the large amount of clearance in the mounting of the secondary on its mounting stud; and problems with the method of mounting the tertiary mirror. The final section of the report discusses system optical design aspects of problems such as the amount of optical aberration induced by various amounts of misalignment of the secondary mirror and optical degradation due to using the telescope at the improper conjugates or or with an improperly positioned focal plane.

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