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OPTICAL AND MECHANICAL PERFORMANCE OF THE TILLINGHAST 60-INCH REFLECTOR, MT. HOPKINS OBSERVATORY

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1. INTRODUCTION

Numerous optical properties of cassegrain reflectors are best determined through actual field testing. Among these are the location along the optical axis of the best (smallest) image, the image scale and focal length for this image, and the image quality. Some parameters are calculated in the course of telescope design and manufacture but should be verified by field performance. These include periodic error of both the sidereal tracking worm and the tube flexure. The results of numerous tests on the Tillinghast 60-inch reflector, together with reasonably detailed notes about the procedures by which the data were acquired, are given in the body of this report. They are expected to be of value to others designing auxiliary instruments for the telescope and to provide first epoch performance against which the results of future modifications can be compared. A table of mechanical and optical parameters are included as Appendix A; these should be useful to those planning instruments or experiments for the telescope.

As of this writing, the telescope's optics consist of a 60-inch F:2.5 spherical primary and secondaries corrected to cancel the spherical abberation of the primary. This produces satisfactory images on the optical axis, as described in subsequent sections, but images off the optical axis become comatic. No measurements or ray traces of off-axis images are currently available.

2. RESOLUTION TESTS

Resolution was tested on July 17 and 19, 1970, through the observation of double stars. Both nights had moderately good seeing after clouds from the preceding afternoon's storms had cleared. Observations of double stars were made by using the alignment telescope, which has a 32-mm F. L. Erfle eyepiece.

It must be emphasized that double-star observations are most useful in assessing the effects of small-scale irregularities in the two mirrors. This is because such irregularities (sometimes called "orange peel" to describe the appearance behind a knife-edge) scatter light and cause image enlargement that cannot be focused away. This is in contrast to the situation when the optics are slightly astigmatic or are slightly overcorrected or undercorrected, overall. In either of the last two cases, a focus position can usually be found where a sharp image is surrounded by a very bright halo of scattered light; nevertheless, double stars can be resolved because of the eye's ability to distinguish the star images from the bright background.

Double star $\Sigma 2173$ = ADS 10598, with components 6.0 and 6.1 mag separated by 0.8 sec, was easily resolved. The core images were judged to be 0.5 to 0.6 sec in diameter. A first-year graduate student with no observing experience made the comment that the two images were surprisingly easy to resolve and was able to identify correctly the position angle of the secondary.

A more significant test was λ Cas = ADS 434, having 5.5- and 5.8-mag components separated by 0.6 sec. The two components were readily resolved in moments of good seeing, but seemed to be in contact. This essentially confirms the previous estimate that, apart from errors in the overall curvatures of the mirrors, the intrinsic image size for the telescope is about 0.6 sec.

3. CASSEGRAIN IMAGE LOCATION

A knife-edge was used to examine star images of the Cassegrain focus in order to determine image size and the location of the best focus along the optical axis. The technique adopted was to measure the size of the image containing an estimated 80% of the light. In spite of seeing effects, the eye can readily observe when the image is locally fainter by averaging the effects of seeing fluctuations over a few seconds. Except on a night of extremely good seeing, the knife-edge does not reveal small-scale irregularities (orange peel) of the mirror surface, which are formed in figuring with subdiameter tools; however, the knife-edge permits the overall curvature to be evaluated rather quickly, even on a night of imperfect seeing.

In the following paragraphs, distances are measured along the optical axis from the original instrument mounting plate. A rotating counterweight/secondary-instrument mounting plate (SAO drawing 60T-080) has since been added to the telescope. Its thickness is 2.5 inches, and most auxiliary instruments are mounted to it.

The optimum image was found on a night of mediocre seeing (1.25 sec) to be 19.25 ± 0.25 inches back of the primary-instrument mounting plate. The position of best focus was surprisingly well defined: At a position 20 inches back, the mirror illumination looked decidedly worse. The measured image size, determined as described above to minimize effects of seeing, was 0.0030 inch, corresponding to 1.0 sec. This value is probably only a pessimistic indication of the true image size. At best focus, the image showed no zonal irregularities nor astigmatism on a scale larger than the seeing elements. In particular, it appears that the turned-down edge noticed at the factory acceptance tests in Pittsburgh is adequately diaphragmed.

The above tests indicated that instrument location is important if seeing limited images is desired. At a position along the optical axis 6 inches behind the optimum focus given above, micrometric knife-edge measurements indicated that the image is roughly twice the diameter of the optimum image if a telescope focus is chosen that gives a uniformly illuminated spot.

4. CASSEGRAIN IMAGE SCALE AND EFFECTIVE FOCAL LENGTH

By use of the micrometer screws on the offset guider attached to the image-tube spectrograph, the image scale at a position 19.25 inches back of the primary-instrument mounting surface (optimum location) was measured on September 8, 1972. The linear distance between the two components of ϵ Lyr and that between 21 and 22 Tau (Pleiades members) were measured and compared to the star positions listed in the Smithsonian Astrophysical Observatory Star Catalog (U.S. Government Printing Office, 1966). An image scale of 13.7 ± 0.1 arcsec/mm was established in the comparison. (Attempting to use this number to make large blind offsets may lead to problems with the telescope's small field of view, since the location of the very asymmetrical (comatic) off-axis images may depend on magnitude and on seeing.)

The telescope's effective focal length corresponding to this image scale is 593 inches, and the focal ratio is F:9.9.

5. DAYTIME VISIBILITY OF STARS

Tests were made to determine daytime visibility of stars at the Cassegrain focus. It was found that the position encoders must be fairly accurately set so that the object always appears near the center of the field of view. This is quite easily done, since first-magnitude stars can be seen in the finder telescope.

On the morning of September 6, 1972, numerous Pleiades stars, all with $B - V \approx 0.0$, were observed with a rather dirty primary mirror. About 1.5 hours after sunrise, 22 Tau ($V = 6.41$) was observed, but it was estimated that a star half a magnitude fainter would not be seen. A red plexiglass filter did not seem to increase the visibility of the star.

Extreme care must be exercised in daytime observing to ensure that the sun does not shine directly on the primary mirror; the solar image thus formed can damage equipment in the dome.

6. COUDÉ IMAGE LOCATION

A knife-edge was set up at the coudé focus on August 18, 1970, to locate the optimum coudé focus and to look for imperfections in the coudé optics. Procedures were similar to those noted in Section 3. Distances along the optical axis are referred to the final coudé window as a zero point. The night was 80% cirrus cloudy; seeing was only fair.

Knife-edge tests showed the best coudé image to be 92 ± 3 inches back from the coudé window. A noticeably worse image was found at 97 inches. The optimum image showed some indication of a slightly turned-down edge, presumably in the coudé secondary. The measured size of the best image was 0.013 ± 0.002 inch.

Image scale was not measured at the location of the optimum coudé focus. However, Dr. Nathaniel Carleton reports that the scale is 4.85 arcsec/mm at a distance of 102 inches from the final coudé window.

7. PERIODIC ERROR OF SIDEREAL TRACKING DRIVE

The bright binary ϵ Lyr was observed on July 28, 1970, to look for periodic error in the right-ascension drive worm. The image was observed in a comfortable position, by using the illuminated reticle and eyepiece of the alignment telescope. The full amplitude of the periodic error was estimated to be somewhat less than 0.25 arcsec, and possibly as small as 0.17 arcsec. The full period of rotation of the worm is 2 min.

8. MECHANICAL DEFLECTION OF THE TELESCOPE TRUSS

Tests were made of the mechanical deflection of the telescope head ring under various loadings on August 26, 1971. A Taylor-Hobson universal alignment telescope was attached to the instrument mounting plate of the telescope. This attachment permits linear displacements to be directly read to 0.001 inch, and interpolation is possible for greater accuracy. The alignment telescope was focused on the fine scratch mark at the center of the coudé secondary, and the cross hairs in the alignment telescope were aligned along the cross in the secondary. With oblique illumination of the scratch mark, settings to 0.0002 inch could be made consistently.

It is assumed that when weight is attached to the head ring, to generate the loading designated W_1 in Figure 1, stress is not transmitted to the mirror cell via the strains in the central weldment; this was an early design specification for the telescope. With this assumption, the vertical deflection of the head ring to the loading W_1 could be readily measured and is shown in Figure 2. The data of Figure 2 suggest that the deflection of the head ring with the telescope tube horizontal is only 0.0008 inch per hundred pounds of load W_1.

A second test of the mechanical tube deflections was made to determine the tilt of the telescope's mechanical center line as the telescope is tilted from zenith to horizon. The tests were made with the Taylor-Hobson alignment telescope firmly mounted to the instrument mounting plate. The fixture attaching the alignment telescope is designed to remain rigid to a second of arc as the telescope is turned, so the measured linear deflection is the difference between the deflection of the head ring and that of the mirror cell (with attached instrument mounting plate). In other words, both the head ring and the mirror cell deflect an unknown amount; it is the difference between their deflections that is of interest for the assessment of mechanical alignment changes for different orientations of the telescope.

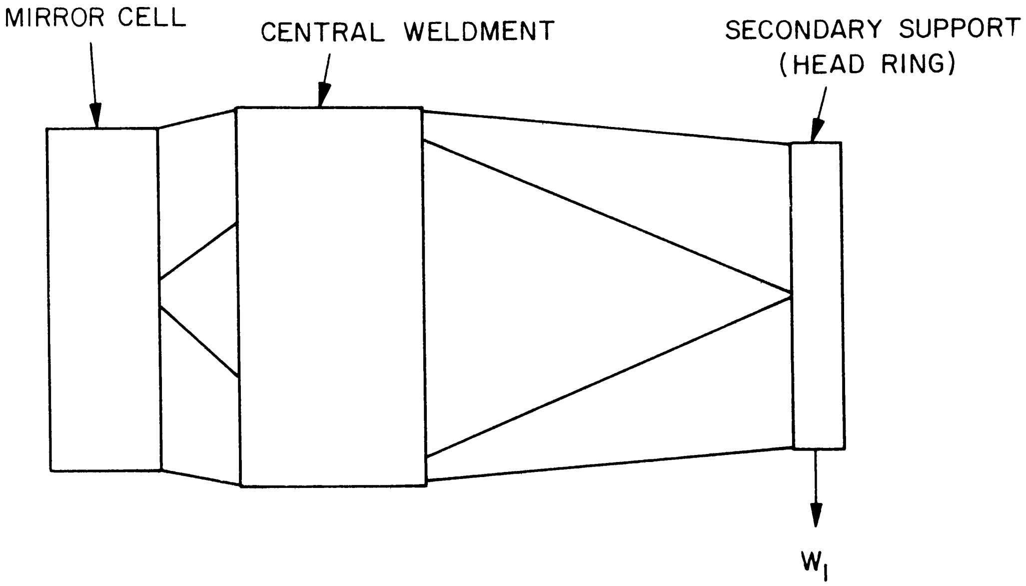

Figure 1a. Schematic diagram of telescope tube structure, showing location of principal members and the load W_1.

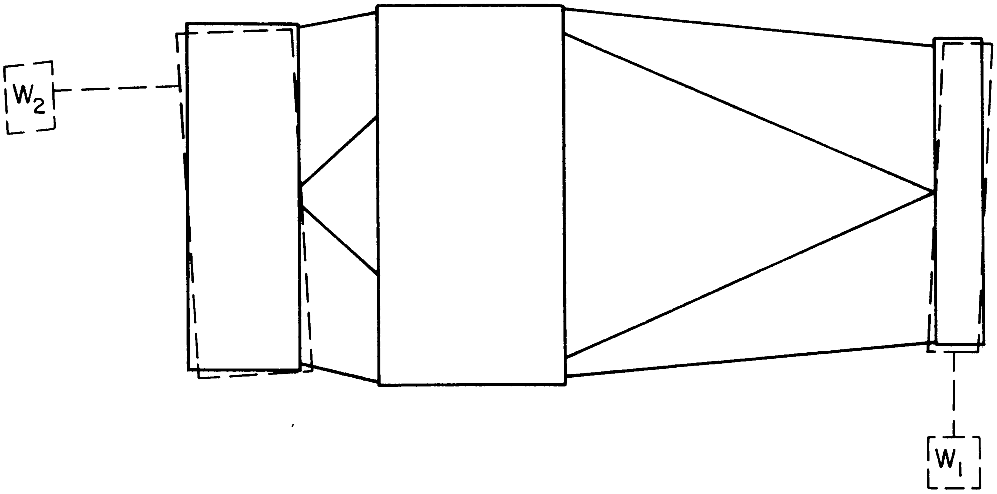

Figure 1b. Schematic diagram to show response of telescope tube truss to two loading situations, as revealed in autocollimator tests detailed in the text.

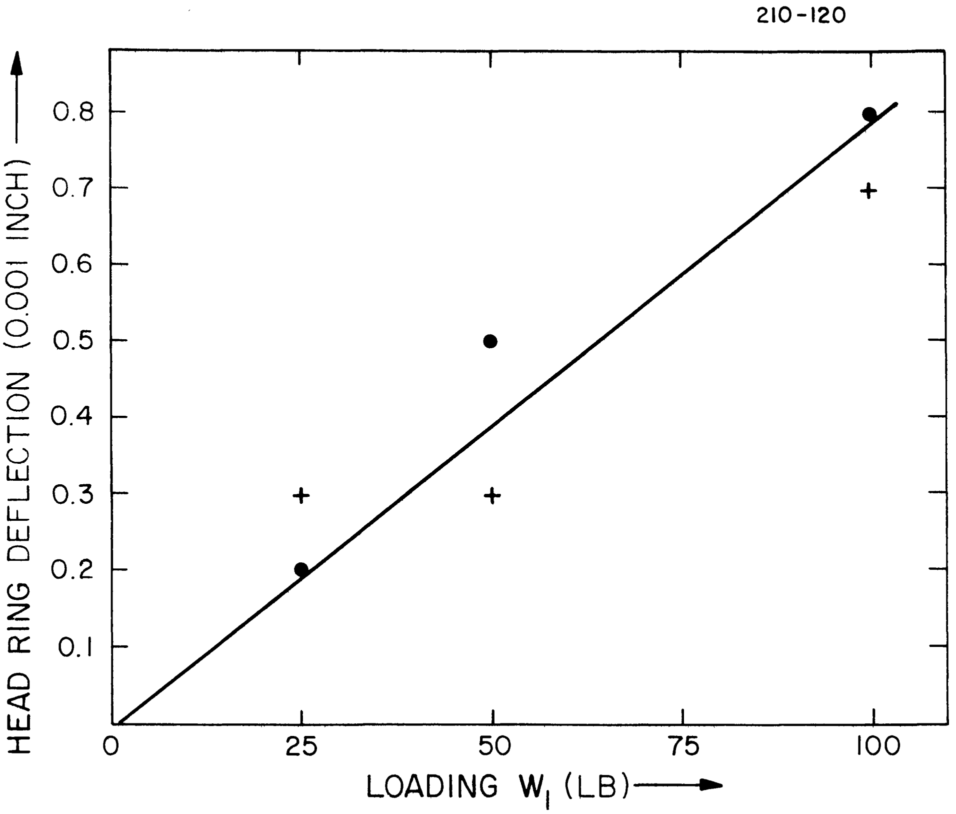

Figure 2. Sag in upper telescope truss, measured as deflection of telescope's head ring, as a function of load W_1.

The net displacement of the head ring with respect to the mirror cell is shown in Figure 3, where the data fit a cosine law as expected. The data show that, relative to the alignment when the telescope is vertical, the mirror cell sags more than the head ring by 0.001 inch. This test was made on August 29, 1971, with the rotating instrument mounting plate in place, and with the telescope balanced with several of the round weights on threaded shafts. Had all the weight been on the threaded shafts (i.e., no rotating instrument mounting plate), the net displacement would have been even smaller.

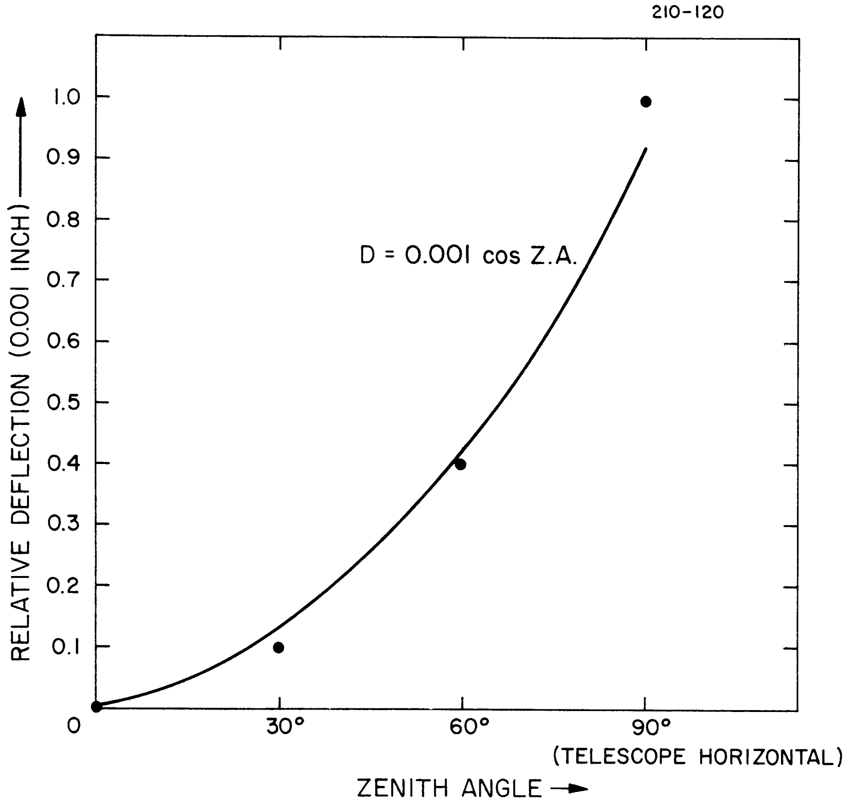

Figure 3. Difference between sag of upper and lower trusses, measured by alignment telescope rigidly attached to the instrument mounting plate, as a function of zenith angle for telescope motion along the meridian.

9. OPTICAL ALIGNMENT CHANGES

A Leitz autocollimator, which reads to 0.1 arcsec, was firmly mounted to the instrument mounting plate to measure tilt of the telescope's optical components under loading. A small autocollimating flat was attached to the dummy secondary installed at the secondary mounting point. The dummy secondary was supplied by the telescope's manufacturer, and weighs as much as the Cassegrain secondary. Tests were made on August 27, 1971, with the rotating instrument mounting plate in place.

Figure 4 shows the response of the optical axis to increased loading of the mirror cell. Weight was added in 100-lb increments. The weights were attached to the threaded rods supplied by the manufacturer, so that the effective load point is 24 inches back of the instrument mounting plate. This is, of course, the typical location of the center of gravity of an auxiliary instrument. The data of Figure 4 suggest that a load of 100 lb produces a deflection of slightly more than 1 arcsec, in the sense that the loaded configuration points to a higher point on the secondary. This behavior is schematically shown in Figure 1b.

The same autocollimator setup was used to measure the angular deflection of the head ring under loadings of up to 100 lb. However, these tests revealed a nonlinearity of response of the upper tube structure, which had a hysteresis-like character. To investigate the cause of this, alternate methods of attaching the weights were tried, and the best results were obtained when weight was applied to a cable tied to the telescope's upper struts at the point where they attach to the head rings. Mechanical deflection of the head ring may have spoiled the first measurements.

Results in Figure 5 still show a hysteresis loop pattern and seem to indicate that the response of the head ring is about 1 arcsec/100 lb. The sense of the deflection is that a flat mirror attached to the loaded head ring deflects the beam upward. This is shown schematically in Figure 1b.

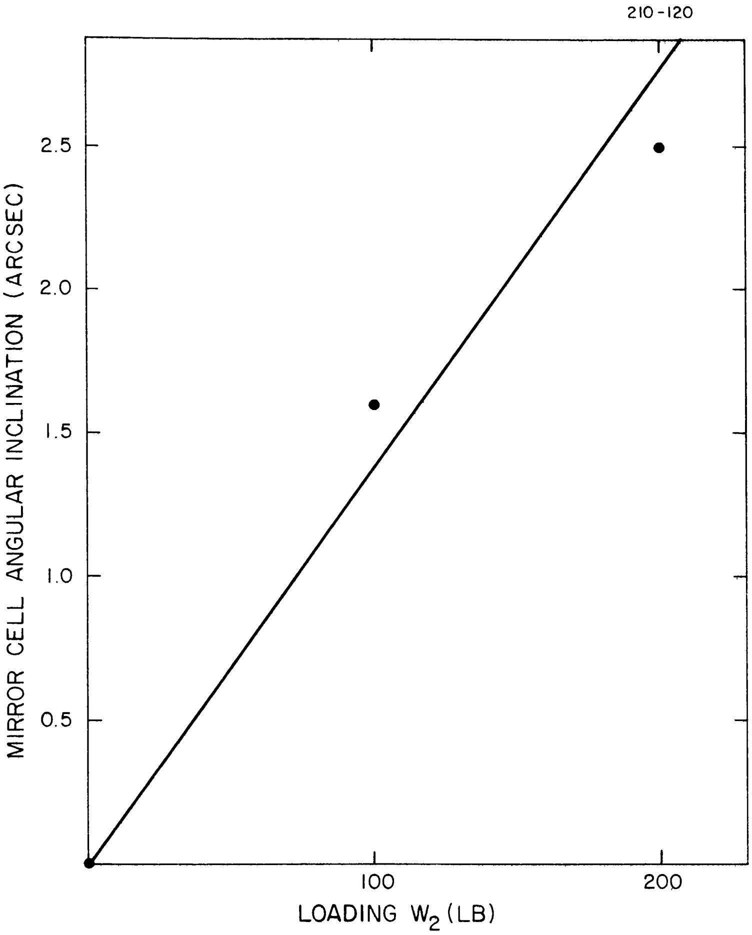

Figure 4. Angular tilt of primary mirror with cell in response to loading W_2, as shown in Figure 1b.

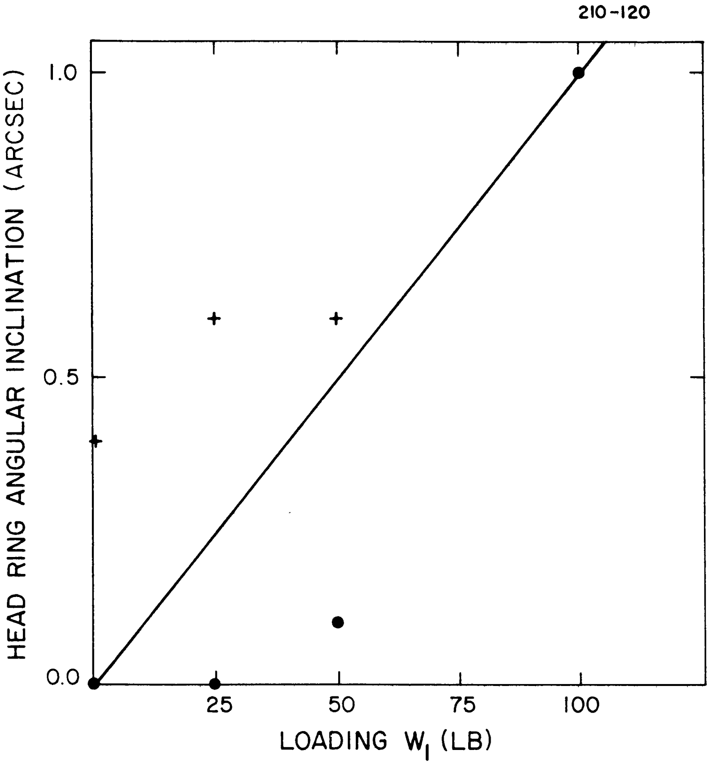

Figure 5. Angular tilt of head ring in response to loading W_1, as shown in Figure 1b. The dots are for measurements made as load W_1 was being increased, and the crosses correspond to data for decreasing load W_1. Data indicate that the response of the head ring is nonlinear.

10. FINDER TELESCOPE ALIGNMENT

The finder telescope is mounted in an 8-inch-diameter tube attached to the mirror cell and to the head ring. The optical components are all located near the bottom end, where it is securely fastened. The upper end is mounted to the head ring through a flexible coupling that transmits no torque to the tube. The tube itself is, for all practical purposes, rigid. The purpose of the above mounting scheme is to have the finder telescope partake of the same deflections as the upper and lower telescope trusses, so its alignment is preserved for all telescope pointings.

It was noted that this mounting scheme is very effective, at least for observations along the meridian. In particular, the finder was almost perfectly aligned with the main telescope when observations of α Ind at -47° were made, despite the fact that overall telescope flexure is rather large.

Tests of the finder's coalignment with the main telescope were made on September 4, 1971, by observing stars along the meridian. These tests verified that when a star is centered in the finder telescope's cross hair, it will be near the center of the field of a 32-mm E. F. L. Erfle eyepiece, at least for stars along the meridian. This was true even for the star α Ind at declination -47°, for which the zenith angle was 79°.

BIOGRAPHICAL NOTE

RUDOLPH E. SCHILD received his B.S. in physics in 1962 and his Ph.D. in astronomy in 1966 from the University of Chicago.

He was a research fellow at Mount Wilson and Palomar Observatories from 1966 to 1969, at which time he joined the Smithsonian Astrophysical Observatory as Scientific Director of the Mount Hopkins 60-inch Telescope Program.

His fields of special interest include stellar spectroscopy and spectrophotometry.

APPENDIX A

ADDITIONAL OPTICAL AND MECHANICAL PARAMETERS

A. Optical Element Parameters

1. Primary mirror (ref. Owens Illinois drawing 245-1000)

Diameter = 61.17 ± 0.03 inches

Thickness at edge = $8.16^{+0.00}_{-0.06}$ inches

Hole diameter = $9.275^{+0.060}_{-0.000}$ inches

Material = Duran 50

Radius of curvature = 300 ± 1 inches

Clear aperture = 60.0 inches

Edges = optical surface edges have 0.125 inch × 45° chamfer

= rear surface edges have 0.250 inch × 45° chamfer

Coating = Liberty Mirror Coating 749

2. Cassegrain secondary (ref. Owens Illinois drawing 245-1025)

Diameter = 17.0 inches

Thickness at center = 2.5 inches

Hole diameter = 3.0 inches

Material = Duran 50

Radius of curvature = -103.726 inches

Clear aperture = 16.0 inches

Edges = all edges have 0.060 inch × 45° chamfer

Coating = Liberty Mirror Coating 749

3. Coudé secondary (ref. Owens Illinois drawing 245-1026)

Diameter = 17 inches

Thickness at center = 2.5 inches

Material = Duran 50

Radius of curvature = -85.1548 inches

Clear aperture = 15.50 inches (updated from 245-1026)

Edges = 0.060 inch × 45° bevel

Coating = Liberty Mirror Coating 749

Note: Coudé secondary has cross mark engraved within ±0.003 inch of mechanical center. Full length of cross line is 3/16 inch.

4. First coudé flat

Diameter = 18.0 inches

Clear aperture = 12.5 inches

Thickness = 3.0 inches

Coating = Liberty Mirror Coating 749

5. Second coudé flat

Diameter = 14.0 inches

Clear aperture = 9.5 × 13.5 inches

Thickness = 2.00 inches

Material = Duran 50

Coating = Liberty Mirror Coating 749

B. Telescope Optical System Parameters

1. Cassegrain

Spacing of Cassegrain secondary reflective surface from primary, measured along optical axis (telescope mechanical center line) = 111.597 inches for nominal focus 16 inches back of primary-instrument mounting plate.

Spacing of primary mirror surface, at center, from primary-instrument mounting plate = 20.375 inches

Distance from Cassegrain secondary to nominal instrument location, 16 inches back of primary-instrument mounting plate = 147.972 inches

Movement of secondary mirror by 0.1 inch will change focal-plane location by 1.575 inches.

Nominal unvignetted field diameter = 2.515 inches (0°25)

with shield = 2.0 inches (0°20)

Image scale = 13.7 sec/mm

Location of best image = 19.25 ± 0.25 inches back of primary-instrument mounting plate

2. Cassegrain shield tube

Outer diameter = 11.50 inches

Clear aperture = 10.75 inches

Length (overall) = 53.25 inches

3. Coudé

Spacing of coudé secondary reflective surface from primary mirror, measured along telescope optical axis (telescope mechanical center line) = 111.597 inches for nominal focus 228.1 inches from second coudé flat, or 391.7 inches from secondary surface at center.

Spacing of first coudé flat from coudé secondary = 91.6 inches (to be coincident with declination-axis center line).

Movement of coudé secondary by 0.1 inch will change nominal coudé focal plane 9.70 inches.

Nominal unvignetted coudé field diameter = 1 inch

Optimum coudé focus location = 92 ± 3 inches back of final coudé window

C. Finder Telescope

Objective diameter = 5.062 inches

Working aperture = 4.88 inches

Objective focal length = 24.75 inches

Tube outer diameter = 8 inches

wall thickness = 0.072 inch

length = 141 inches

Field of view = 1°7 (approximately)

Magnification = 22×

Exit pupil = 5.8 mm

D. Miscellaneous

Periodic error of drive worm ≤ 0.25 arcsec full amplitude

Maximum slew rate α = 90°/min

Maximum slew rate δ = 120°/min

Alignment laser (in focus drive) = Electro Nuclear Lab model LS-32 (HeNe, 6328 Å red)

Through clear aperture on optical axis at instrument mounting plate = 7.000-inch-diameter pilot bore concentric with plate, but reduced to 6.75 inches when Cassegrain shield is in place. (ref. Owens Illinois drawing 245-1041).

Rotation of rotating instrument mounting plate = full 360° rotation about optical axis.

Bolt circles in secondary (rotating) instrument mounting = 6 tapped, equally spaced holes on 20-inch-diameter circle, 0.75-inch depth

= 6 tapped, equally spaced holes on 16-inch-diameter circle, 0.75-inch depth

= 6 tapped, equally spaced holes on 10.5-inch-diameter circle, 0.75-inch depth

Instrument mounting bolt size = 3/8-24 (see SAO drawing 60T-040-A)

Primary mirror cell truss tubes = 2-inch OD × 1/8 wall seamless cold drawn steel

Head ring truss tubes = 2-inch OD × 5/16 wall seamless cold drawn steel

Telescope dome diameter = 30 feet

Dome opening (clear) = 120 inches, by lateral biparting shutters with adjustable lower windscreen

Dome material = aluminum, noninsulated, TiO$_2$ white exterior paint