No. 111 THE DESIGN OF LOW-COST PHOTOMETRIC TELESCOPES*

by Harold L. Johnson

1. *Introduction*

The design and construction of astronomical telescopes intended specifically for photometric work has never been discussed in great detail. It is usually assumed that telescopes designed for general astronomical work also are suitable for photometry. To a considerable extent this is true, and much good photometry has been done with telescopes whose designers had other applications in mind. On the other hand, no general-purpose telescope I have used is capable of providing maximum efficiency for all types of photometric work. For example, no telescopes of moderate or large aperture (except those to be discussed in this article) are capable of slewing rapidly from one part of the sky to another.

A further limitation of the general-purpose telescope, imposed not by the design of the telescope itself but by the fact that it is used for general purposes by many astronomers, is the relatively small amount of telescope time that is available; and even this limited time usually is broken into many short runs of a few days, making it difficult to establish and to maintain proper photometric systems.

Our recent work in the far infrared has brought to light a number of serious problems, such as the very large long-wavelength background radiation from the telescope itself, whose solutions dictate telescope designs not normally considered.

We have found it necessary to design and build our own photometric telescopes, so that we can satisfy our requirements for special telescope designs and for large amounts of uninterrupted observing time. Since we want special purpose telescopes that will not be available for general use, it is difficult to justify the large budgets needed for modern general-purpose telescope designs. As a result, there is an additional design requirement; namely, that our telescopes must be built at relatively low cost, while meeting our other requirements.

2. *Design Requirements for a Photometric Telescope*

The performance specifications for an astronomical telescope that will be used exclusively for photoelectric photometry differ in certain important respects from those for telescopes that will be used for general astronomical work. Since we deal, so far as the photometer is concerned, with essentially on-

---

*Reprinted with permission from Vistas in Ast., Vol. 10, 1968.

axis images, rapid deterioration of the images with distance from the optical axis is unimportant; therefore, cassegrain systems with easily produced primary mirror figures, such as ellipsoids or spheres, are acceptable. Furthermore, it is permissable that the quality of the on-axis images be significantly poorer than is needed for many other applications.

On the other hand, the rigidity of the entire telescope and the precision of the right ascension and declination drives should be at least equal to those expected from the best telescopes. We have found that, for the maximum observing efficiency, the photometric telescope should be included as a component in the measuring and data-recording system, with control of the telescope slow motions for moving back and forth between star and sky regions vested in the data-recording system, rather than under the direct control of the observer. Provision for offset guiding is essential, both for measuring stars too faint to be set on visually and for making long exposures in infrared wavelengths.

The design of a low-cost photometric telescope represents a compromise between cost and precision. If we are to minimize the cost and at the same time satisfy the requirements of the photometry, we must be very clear about the degree of precision needed at every point in the telescope design. Every specification must be examined thoroughly to be sure that the minimum precision that will accomplish the job actually is specified.

The first requirement of the design is that the telescope shall be capable of very rapid slewing from one part of the sky to another. We shall specify that the telescope can be slewed from four hours east hour angle to four hours west hour angle, or from declination −30° to +60°, in less than 30 seconds of time. In a low-cost telescope, this requirement necessarily implies that the telescope is hand-slewed, with hand-operated clamps; the cost of electro-mechanical drives capable of driving and stopping the telescope safely at these rates is incompatible with our budgets. Thus, our first specification is that the photometric telescope is to be hand-slewed, with hand-operated clamps.

As is often the case, further specifications follow from the first one. Since we wish to make photometric telescopes of apertures as great as 60 inches, we must keep the moving mass of the telescope as low as possible; if we do not, the observers will not be able to slew it by hand. Telescope mountings of the symmetrical equatorial class, such as fork or English yoke types, do not require counterweights and, therefore, have minimum mass and inertia for a given telescope aperture.

The requirement of low telescope-cost restricts our choice of polar-axle bearings to standard self-aligning roller or ball bearings (i.e., costly oil-pad bearings, etc., are prohibited). These two bearings should be as far apart as possible in order to minimize bearing loads and the effects of inaccuracies in bearing construction.

Thus, our choice of telescope mounting has been narrowed down to the English yoke type. This mounting has the disadvantage that, as is the case of Mount Wilson 100-inch telescope, the region of the North (or South) celestial pole is not accessible. The area of the sky north of declination +65° or +70° (or south of −65 or −70°) is not large, however, and in our experience this restriction seems not to be serious. The complete symmetry of the English yoke makes for a rigid structure that minimizes gravitational deflections and their effects upon the observations. It is especially important that a photometric telescope be rigidly constructed and that it be as free as possible of the lightly damped oscillations that are excited, in most large telescopes, by high-speed setting and guiding motions. A photometric observer makes many setting and guiding motions during a night's observations and rapid, accurate, setting and guiding is essential for efficient work.

The overall length of the telescope tube should be short, in order to minimize inertia and cost. A short tube also is more rigid than a long one. On the other hand, a short telescope tube means a small primary focal-ratio and, consequently, more difficulty for the optician who must figure the mirrors. We can, however, reduce the optician's problems by relaxing the specification on image size; images two or three seconds in diameter are satisfactory for almost all photometric work. The use of an ellipsoidal or spherical figure on the primary mirror makes the optician's work much simpler; this is particularly true for the spherical primary, even though the secondary mirror must then have a strongly aspheric surface. The resultant small field of good image definition does not restrict significantly the use of the telescope for photometry.

While it is possible to relax the specifications on image quality and field of view of a photometric telescope, the specifications on setting, guiding and sidereal tracking motions cannot be greatly different from those for general-purpose telescopes; in fact, as mentioned earlier, the setting and guiding motions should be more precise in some respects than many such telescopes exhibit. Not only should the motions be rapid (15 seconds of arc per second of time for guiding; ten times this rate for setting) but the telescope must stop immediately upon release of the push button, with no significant coast or oscillation. Since we wish to move the telescope back and forth between star and sky regions, under the control of the data-recording system, the backlash in the drive system must be very small, less than about one second of arc. Most astronomical telescopes can meet this requirement in the right ascension drive (because the gears are pre-loaded and driven continuously in one direction), but very few have declination drives of the necessary precision. We have found a tangent arm assembly for the declination drive coupled with a relatively fine-pitch screw to be good, low-cost, means of obtaining the required precision.

While the precision required of the right-ascension tracking drive is about the same as that required from a standard optical telescope (periodic and random errors less than about ±1 second of arc, if possible), our budgets do not permit us to buy the expensive, precision, worm and gear sets that are installed on high-precision general-purpose telescopes. We have found, however, that standard-precision worms and gears will produce the required drive accuracy (periodic errors of one or two second amplitude), provided that very careful attention is paid to the concentricity of the worm and its shaft, and to the design of the end-thrust bearings for the worm shaft. The worm teeth must be concentric with the shaft ±0.0002 inch and the runout of the end-thrust bearings must be less than 0.0001 inch, for a 30-inch diameter worm gear.

In order to keep the total cost as low as possible, all other specifications must be examined to be certain that no greater precision than is absolutely necessary is specified. For example, the absolute pointing accuracy should not be specified to be better than about ±6 minutes of arc (but note that the English yoke is the best mounting for minimum pointing error). This precision is quite satisfactory for use with a finding telescope of 1° field. We use right-ascension and declination circles attached to the telescope, instead of shaft encoders and readout dials, not only because they are cheaper but also because they are simpler and, therefore, less likely to get out of order. The requirement of low cost means that no frills, such as filling and grinding of weldments, can be included. No machine work can be done that does not contribute directly to the performance of the telescope for its intended purpose.

The type of building in which the telescope is installed must also be considered as part of the problem. Most rotating domes, especially those of the larger sizes, move quite slowly compared with our specifications. Thus a roll-off roof structure, which leaves the telescope open to the sky, is indicated for a photometric telescope. Such buildings also meet the requirement of minimum cost. The only significant problem posed by this design is the effect of wind upon the relatively unshielded telescope; our experience indicates, however, that simple wind screens can provide a satisfactory solution to this problem.

3. *The 28-inch Photometric Telescope*

The result of our first attempt to apply the design principles outlined above is the 28-inch telescope at the Catalina Station of the Lunar and Planetary Laboratory. The telescope is shown in Fig. 1 and the roll-off-roof building is shown in Fig. 2. The primary mirror focal ratio is 2.7, and the cassegrain focal-ratio is 15. The primary mirror is ellipsoidal; the secondary, spherical. The mirrors are Pyrex and the mirror supporting mechanisms are conventional.

The right-ascension and declination drives are powered by Superior Electric Company Slo-Syn stepping motors. The very large range of synchronous speeds provided by these motors makes it unnecessary to change gears between setting, guiding and sidereal tracking motions; all speeds are provided by these motors, in conjunction with the electronic drive circuits. These same motors are coupled to the photometric data-recording system, so that the telescope "wobbles" automatically between the star and sky regions, under the control of the photometer. With this system it is convenient to make photoelectric exposures as long as several hours while "wobbling" at 15 second intervals back and forth between star and sky. Very frequent comparison of star and sky regions is essential in long-wavelength (5μ, 10μ, 20μ) photometry, because of the very bright, variable background.

The 28-inch telescope was put into operation in July 1963; the total cost of the installation, telescope and roll-off building, was approximately forty thousand dollars. Since its installation, the telescope has been used continuously for photometric observations in ultraviolet, visible and infrared wavelengths. The first stellar and planetary observations at 20 μ were made with the 28-inch telescope by Dr. F. J. Low. Almost all of the published JKL observations of the bright stars, and many of the UBVRI observations

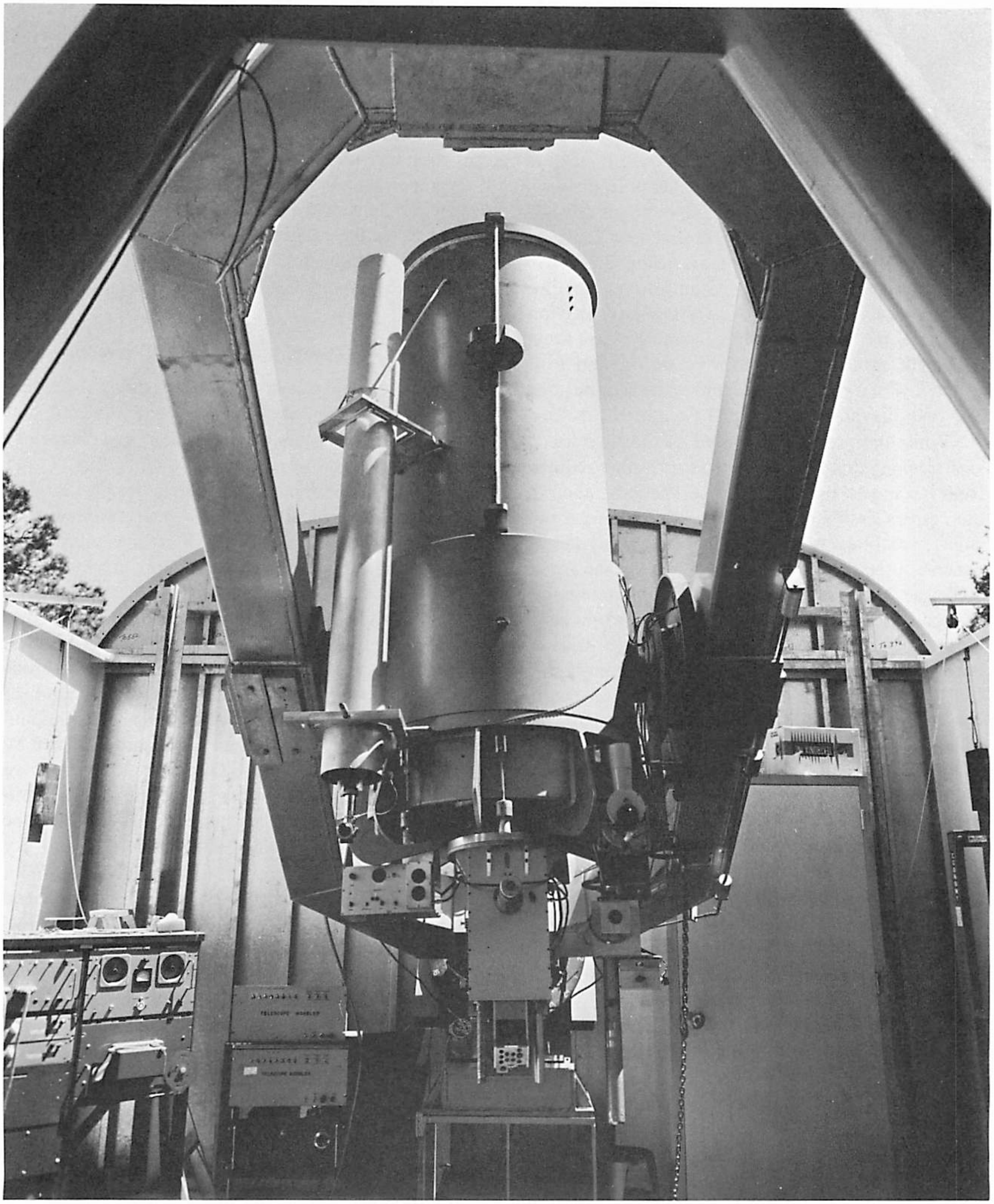

Fig. 1 The 28-inch photometric telescope from the north, inside the building. The JKL photometer is shown attached to the telescope. The 6-inch finder, mounted on the left side of the main telescope tube, can be offset ±1° from the main telescope and has high-power eyepieces for guiding long exposures. The photometric data recording and automatic telescope-"wobble" systems are housed in the cabinets in the lower left corner of this photograph. The telescope was constructed by Astro Mechanics, Inc., of Austin Texas. The optics were figured by Mr. Don Loomis, of Tucson, Arizona.

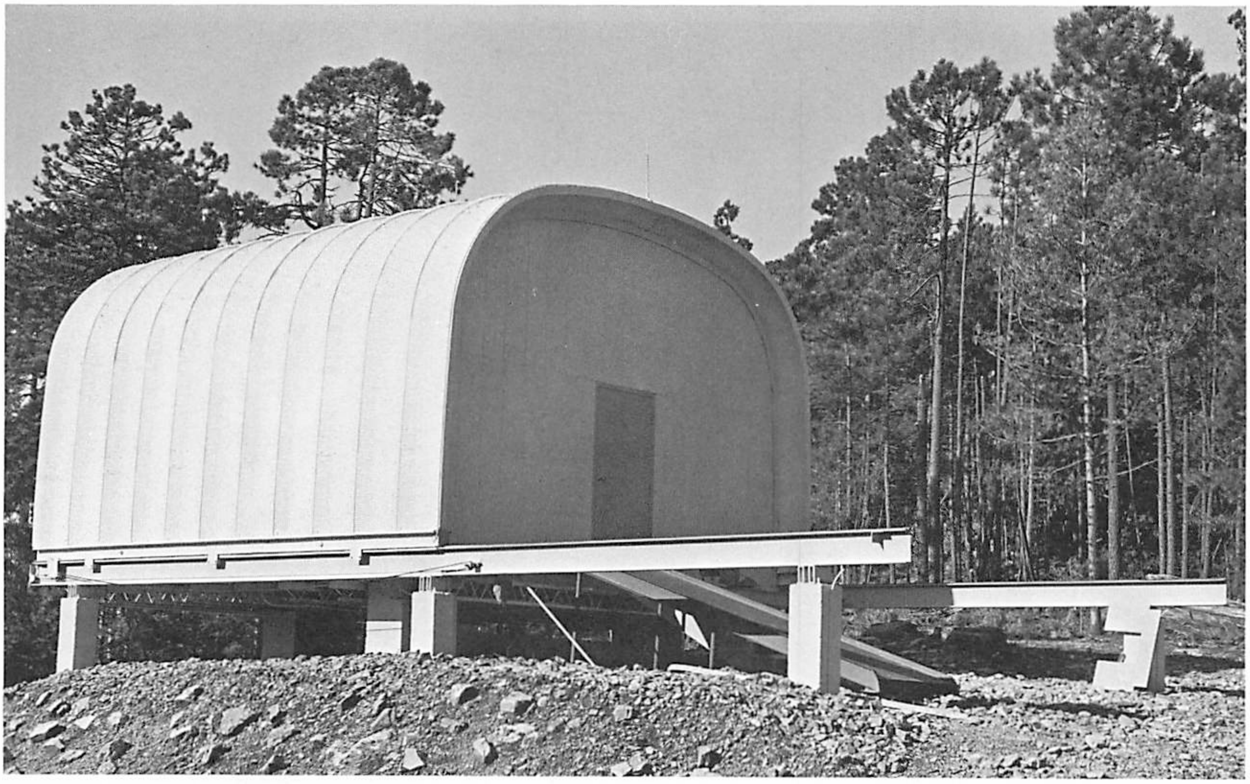

Fig. 2 The roll-off-roof building which houses the 28-inch telescope. The south wall of the building (at left) is hinged and folds down for observations of southern stars.

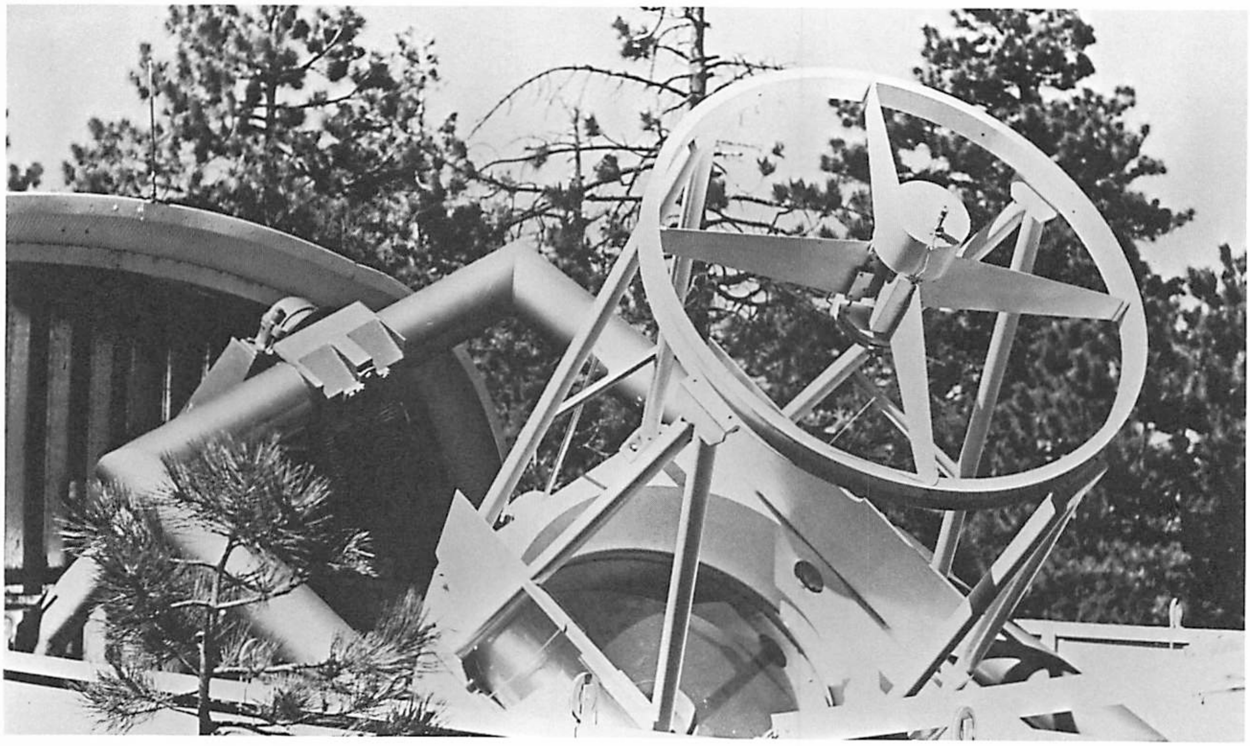

Fig. 3 The 60-inch telescope from the west. The details of the north end of the yoke and polar-axle are visible in this photograph, which was taken before the finders and sky baffler had been installed. The telescope was constructed by Astro Mechanics, Inc., of Austin, Texas. The mirrors were figured by Mr. Robert L. Waland of the Lunar and Planetary Laboratory.

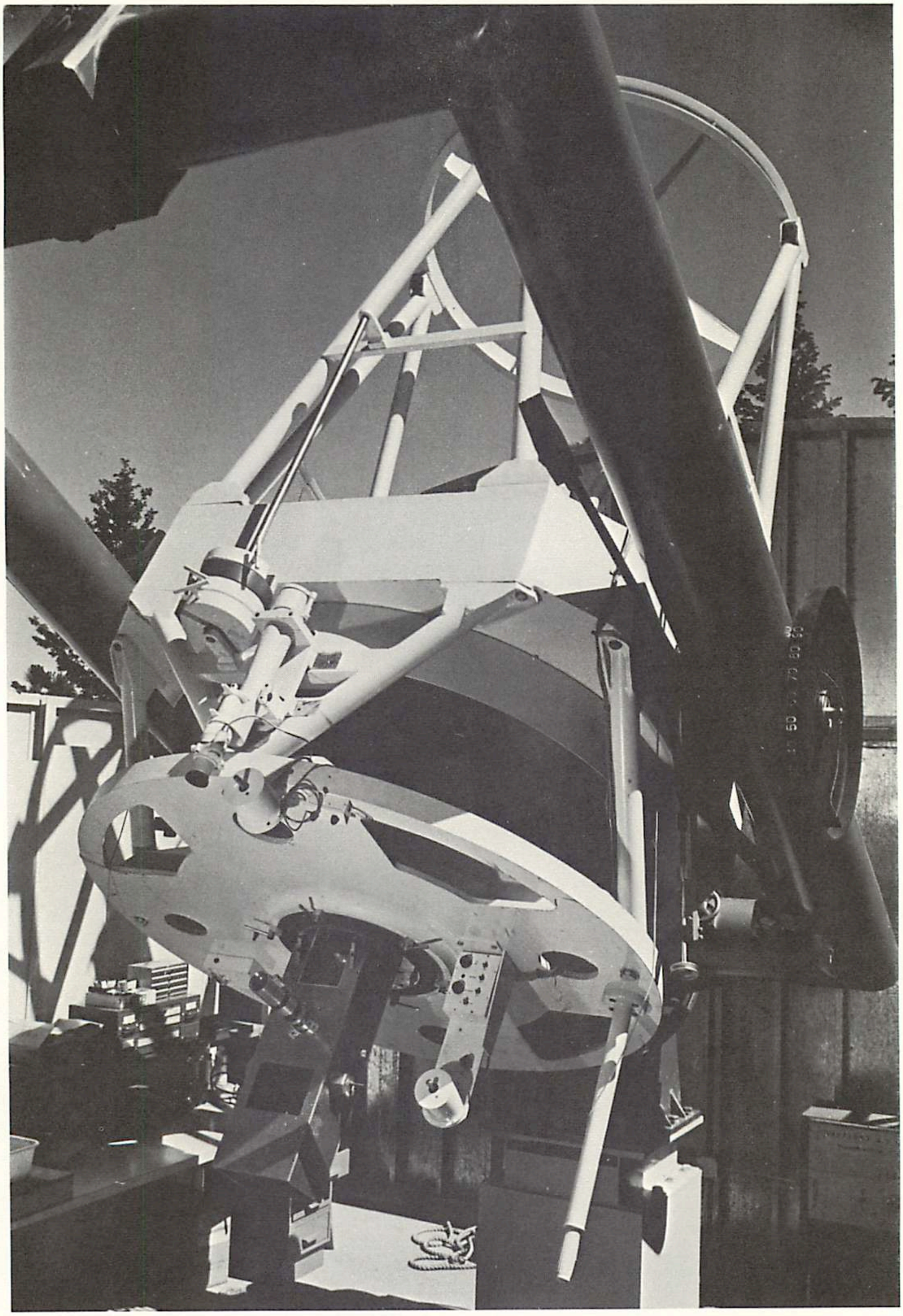

Fig. 4 The 60-inch telescope from the north, inside the roll-off-roof building. The back of the all-aluminum primary mirror is visible in this photograph, which was taken before the 6-inch finder (shown in Fig. 7) was installed. All photographs for this article are by Dennis Milon or Fred Forbes, Lunar and Planetary Laboratory.

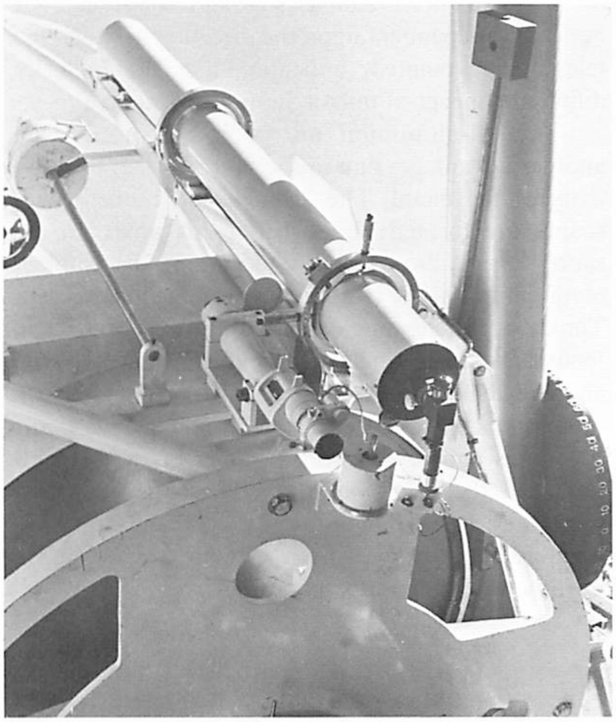

Fig. 5 The 3-inch and 6-inch finders, mounted on the 60-inch telescope. The 6-inch finder can be offset +1° from the main telescope and has high-power eyepieces for guiding long exposures.

(Johnson, Mitchell, Iriarte and Wisniewski 1966), were made by this telescope. It has shown itself to be an excellent photometric instrument, fully capable of satisfactory performance for the most critical applications.

4. The 60-inch Photometric Telescope

Our next step was to design and construct a 60-inch photometric telescope, based upon the design principles we have outlined, and the experience with the 28-inch. Views of this telescope are shown in Fig. 3, 4, 5, 6 and 7; the roll-off building, which is quite similar to that of the 28-inch, is shown in Fig. 8.

This telescope differs from the 28-inch in that the primary mirror is an all-aluminum casting (following a design by the Kitt Peak National Observatory). The primary mirror is about nine inches thick in the center, tapering to a thickness of one-fourth inch at the edge. It is bolted firmly into the telescope, with no other support mechanism. The figure of the primary mirror is spherical, with a focal-ratio of 2. The Pyrex secondary mirror produces a focal-ratio of 14 at the Cassegrain focus. The image produced by the 60-inch telescope is approximately 4 seconds

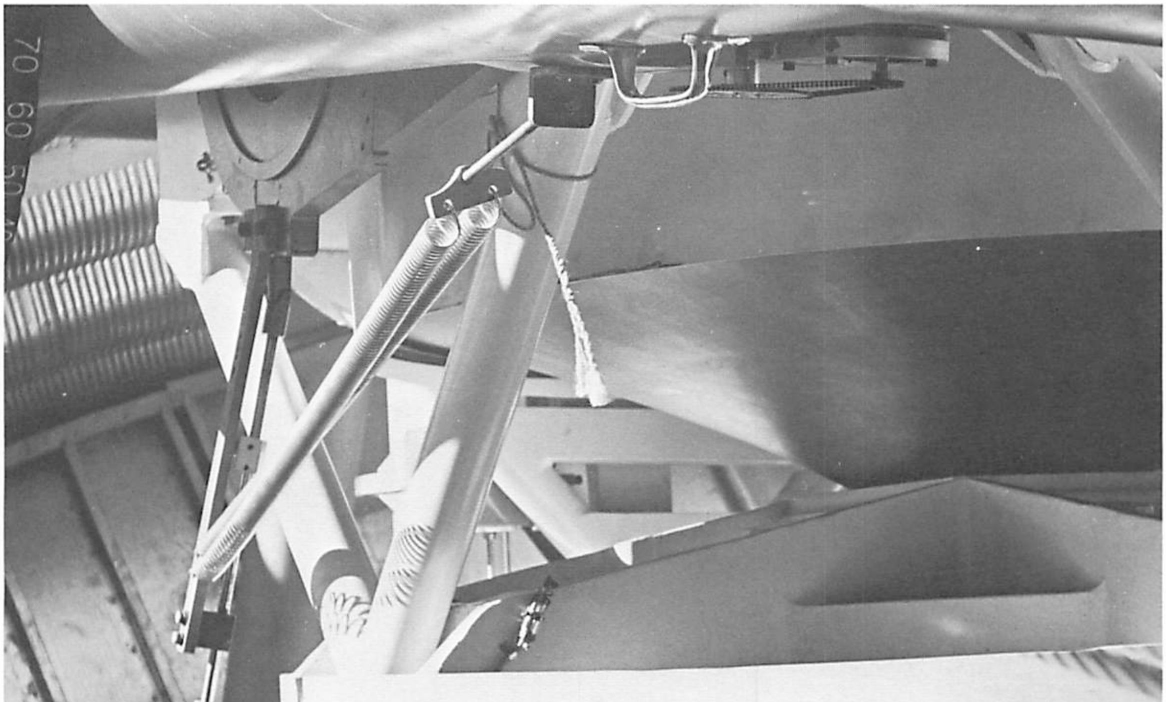

Fig. 6 A view from the side of the 60-inch telescope, showing the conical back of the primary mirror. This all-aluminum mirror is bolted solidly to the backing plate.

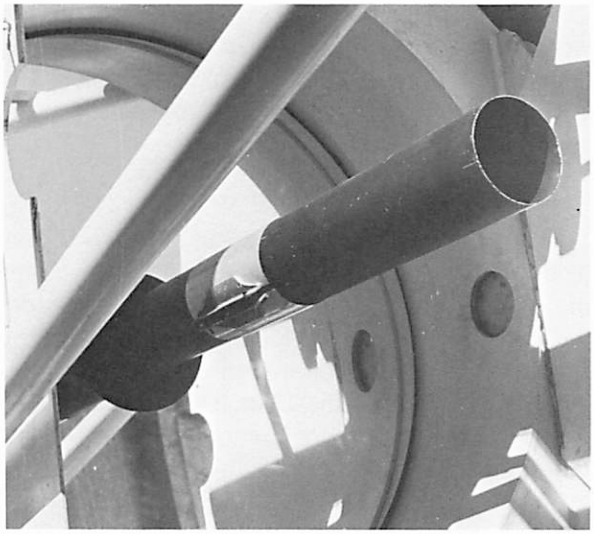

Fig. 7 A view of the front surface of the 60-inch all-aluminum primary mirror. The long tube protruding from the center of the mirror is part of the sky-baffling system.

of arc in diameter and its size and shape are not noticeably dependent upon the direction in which the telescope is pointed, indicating that the radically different concept of mirror support is sound.

The all-aluminum mirror has demonstrated another advantage, due to the high thermal conductivity of the metal. The 28-inch and 60-inch telescopes are located about 100 yards apart on the same ridge at the Catalina Station and the ambient temperatures at the two sites are practically identical. The 28-inch telescope exhibits the usual changes in focus and image quality caused by changes in the ambient temperature. Because of the low temperature-conductivity of Pyrex, the 28-inch primary mirror warps appreciably with changes in air temperature. On the other hand, the 60-inch telescope's image and focus remain almost constant with temperature changes, even over the extreme range from daytime to nightime temperatures.

Fig. 8 The roll-off-roof building which houses the 60-inch photometric telescope. The telescope is shown in its rest position. The south wall of the building (at left) is hinged and folds down for observations of southern stars. The hanging weights counterbalance the wind screens.

Following the practice at the Kitt Peak National Observatory, the 60-inch primary mirror was Kanigen coated prior to the optical figuring. Unfortunately, the Kanigen coat was not entirely satisfactory, and we were not able to reduce the telescope images below about 3 or 4 seconds in diameter. With a good Kanigen coating, however, it is possible to make a 60-inch aluminum-mirror telescope which produces images one or two seconds in diameter. We are, in fact, now making a second telescope of the same design from which we expect images about one second in diameter. The primary mirror of the first 60-inch telescope will be reworked after the completion of the second one.

The construction of the setting, guiding and sidereal-tracking motions was copied from those developed for the 28-inch telescope. Thus, the 60-inch also is integrated with the data recording apparatus and it wobbles automatically between star and sky regions.

The 60-inch photometric telescope was put into operation in September 1965; the total cost of the project (telescope, roll-off roof building, and the necessary experimental and developmental work) was approximately $130,000.

It has not been in use as long as the 28-inch, but the 60-inch has already produced significant observational contribution to astronomical knowledge. For example, UBVRIJK observations on two 13th magnitude giant star members of the globular cluster M3 have been obtained with this telescope, thus making possible the first observational determination of the bolometric corrections and effective temperatures of individual globular cluster stars.

REFERENCES

Johnson, H. L., Mitchell, R. I., Iriarte, B. and Wiśniewski, W. Z. (1966) *Comm. LPL,* 4, 99.

TABLE OF CONTENTS