Sky and TELESCOPE

Dome of new 61-inch telescope

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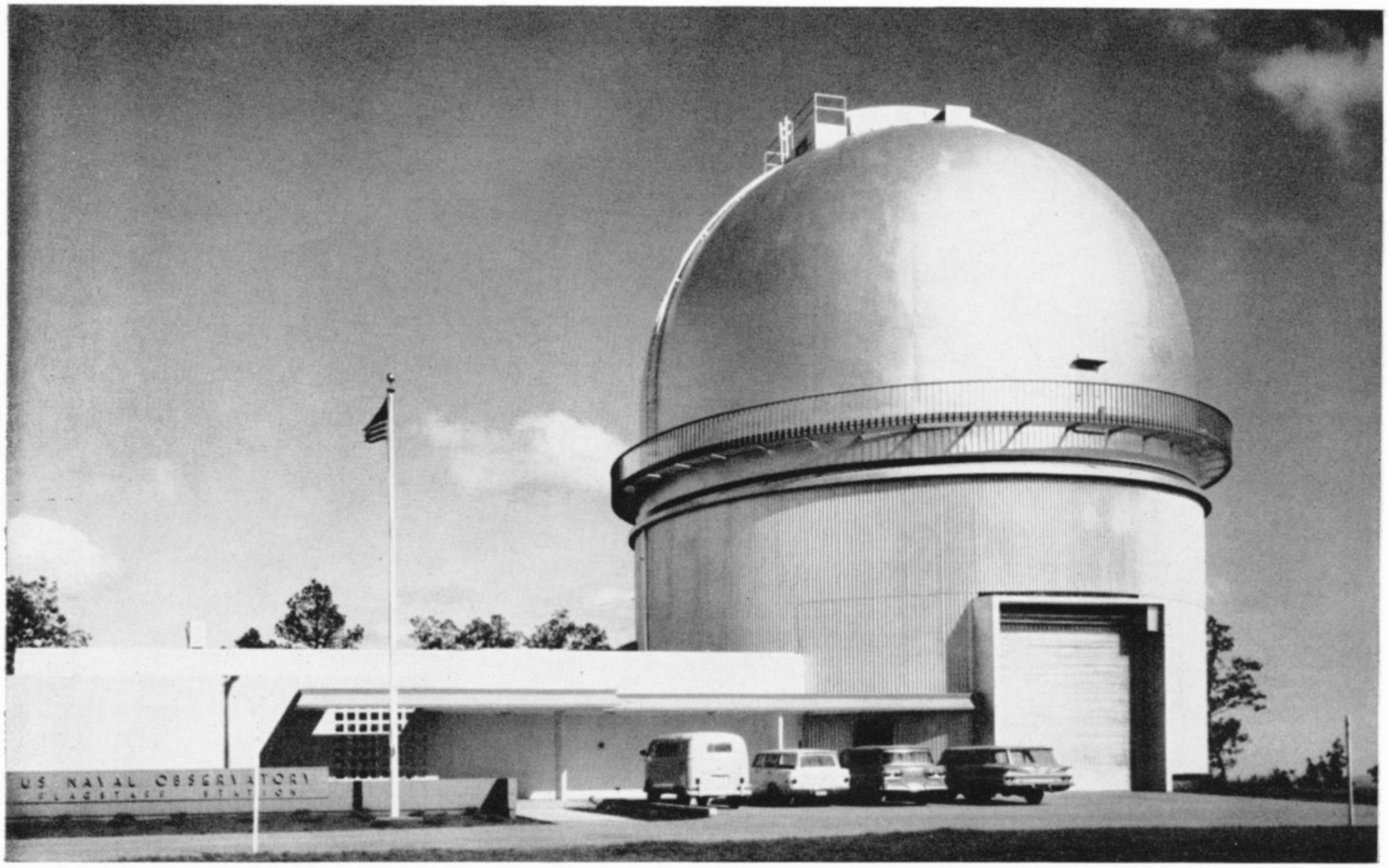


The new 61-inch reflector's dome, with its laboratories, offices, and library, as seen from the west. Built by Allison Steel Co., Phoenix, Arizona, the dome weighs 150 tons, is 65 feet in diameter and 82 feet high. It turns on 20 carriages with 18-inch truck wheels by means of a pair of two-horsepower motors. Inside the dome are insulation panels for temperature control, consisting of 2½-inch trays filled with four double layers of crumpled aluminum foil. C. W. Jones of Los Angeles was the engineering and architectural contractor, with subcontractors Rochlin and Baran (architect) and Murray J. Schiff, Inc. (builder). Official U. S. Navy photograph.

The New 61-inch Astrometric Reflector

K. Aa. Strand, *U. S. Naval Observatory*

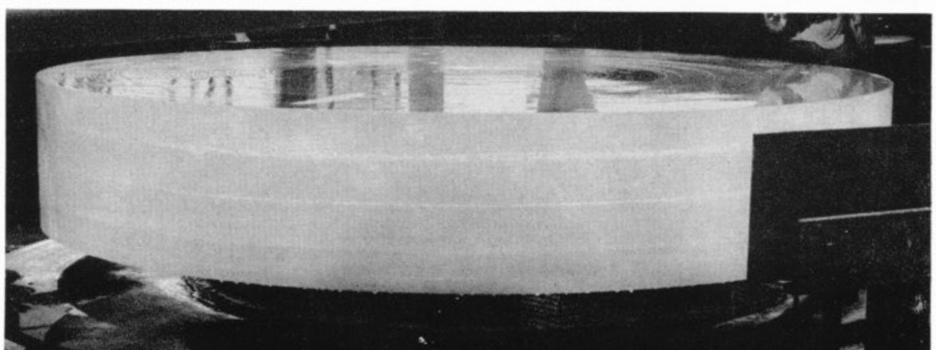
During December, 1963, the U. S. Naval Observatory began testing a large telescope of unique design. The new instrument is located on a hilltop five miles west of Flagstaff, Arizona, where the observatory's 40-inch reflector has been in operation since 1955.

Astronomers have learned that there is no such thing as an all-purpose reflector. Instruments like the 200-inch on Palomar Mountain and the 84-inch at Kitt Peak were designed primarily to be very efficient light collectors for spectrographs or photometers. The new 61-inch, on the other hand, is the world's first big reflector specifically planned for the utmost accuracy in positional measurements.

The Parallax Problem

Surprisingly, this very modern telescope is the ultimate result of a 17th-century proposal, made independently by Galileo and Huygens, of a method for measuring stellar distances. Imagine two stars of very unequal brightness adjacent to each other on the sky. Presumably they would be at very different distances from the sun. The orbital revolution of the earth causes both objects to describe tiny ellipses on the celestial sphere, larger for the nearer star and smaller for the more distant one.

Galileo and Huygens proposed measuring the difference between these parallactic displacements. If the more distant star is so remote that its parallax shift is negligible, the observed displacement will provide the distance of the nearer star. The advantage of this method is that it involves measurement of relatively small angles on the sky, a much simpler problem than measuring widely separated stars.



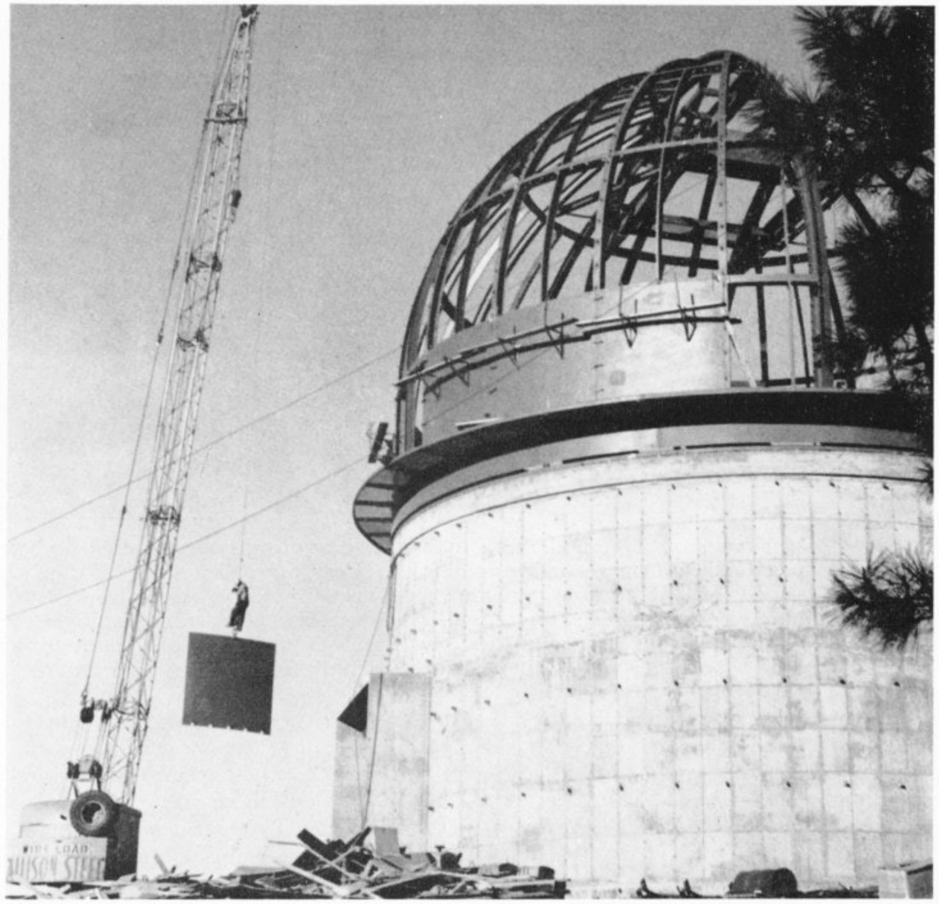
The quartz disk for the primary mirror is the largest ever manufactured successfully. To attain the required thickness, four layers were laminated together, each more than 2½ inches thick. Davidson Optronics photograph.

The suggestion appeared so promising that at the end of the 18th century William Herschel began a systematic survey of visual double stars, as the first step toward a parallax program. He did not succeed in measuring a stellar parallax; instead he discovered that many double stars are actually binary systems, whose components are at almost the same distance from us.

Of course, some doubles are optical pairs for which the method can serve, and they were used in some of the first successful determinations of stellar parallaxes. In 1837-39, the distances of 61 Cygni, Vega, and Alpha Centauri were measured by F. W. Bessel, Wilhelm Struve, and T. Henderson, respectively (Sky and Telescope, November, 1956, page 9, and December, page 69).

These pioneer successes spurred many 19th-century astronomers to attempt visual parallax measurements with heliometers, meridian circles, and filar micrometers. Photographic work began near the end of the century, but it was affected by even larger systematic errors than were the visual results. By 1900 only a few hundred parallaxes had been obtained, many of them with gross errors, and all of them now superseded by later work.

The modern era began with Frank Schlesinger's photographic observations with the 40-inch Yerkes refractor in 1903-05. He devised techniques of observing, measuring, and calculating that produced parallaxes of unprecedented quality. Essentially, his method was to take one to two dozen photographs of the star on the meridian, divided among three epochs at roughly half-year intervals when the parallactic displacement was a maximum. The star's position was then measured against three or four faint and presumably much more distant comparison stars.



Contoured to fit the cylindrical part of the dome, one of the skin panels is here being hoisted into place (January, 1962). Made of $\frac{1}{4}$-inch steel, each plate was welded to the rib framework and to adjacent plates. The dome turns on a circular rail that has been adjusted for concentricity within $\frac{1}{4}$ inch and leveled within 1/16 inch. Official U. S. Navy photograph.

The central core of the primary mirror blank was cut out with this diamond-studded biscuit cutter and natural diamond grit of 40/60 mesh, held in heavy-duty bond. This water-cooled drill turned 250 revolutions per minute as hand pressure controlled its cutting rate through the hard silica. After being smooth ground, the blank was $61\frac{3}{4}$ inches in diameter and $10\frac{1}{4}$ inches thick. Davidson Optronics photo.

Many forms of systematic error were avoided by having the telescope in the same position for all photographs. Schlesinger laid down carefully planned rules for the number of exposures per plate, for the number and arrangement of the comparison stars, and devised a labor-saving yet precise procedure of plate reduction (the dependence method). The whole procedure masterfully combined highest precision with utmost economy of effort.

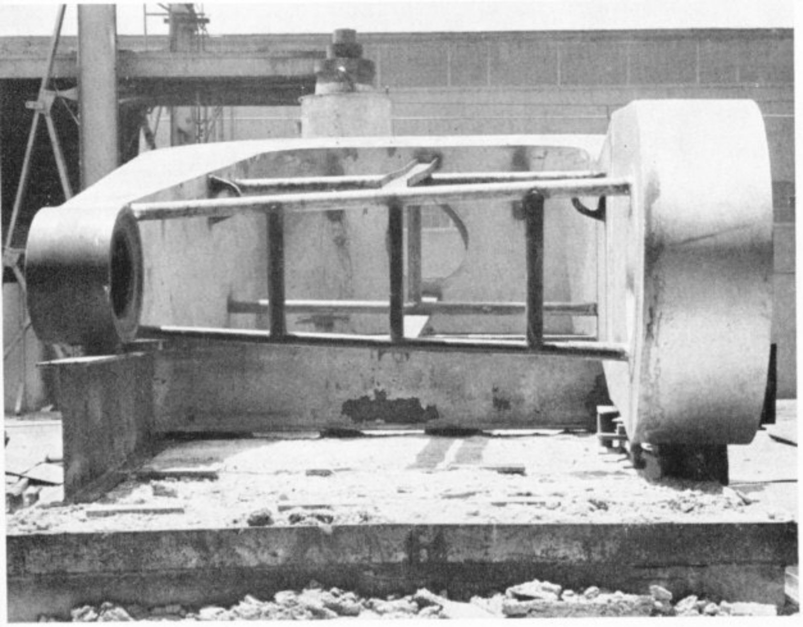
So effective were Schlesinger's techniques that they are still in use today with little change, and long-focus refractors have remained the primary instruments for parallax determinations. After leaving Yerkes Observatory, Schlesinger continued this work, first at Allegheny Observatory, then at the South African station of Yale Observatory. Major parallax programs were also carried out at the Cape, McCormick, Greenwich, Mount Wilson, and Sproul observatories.

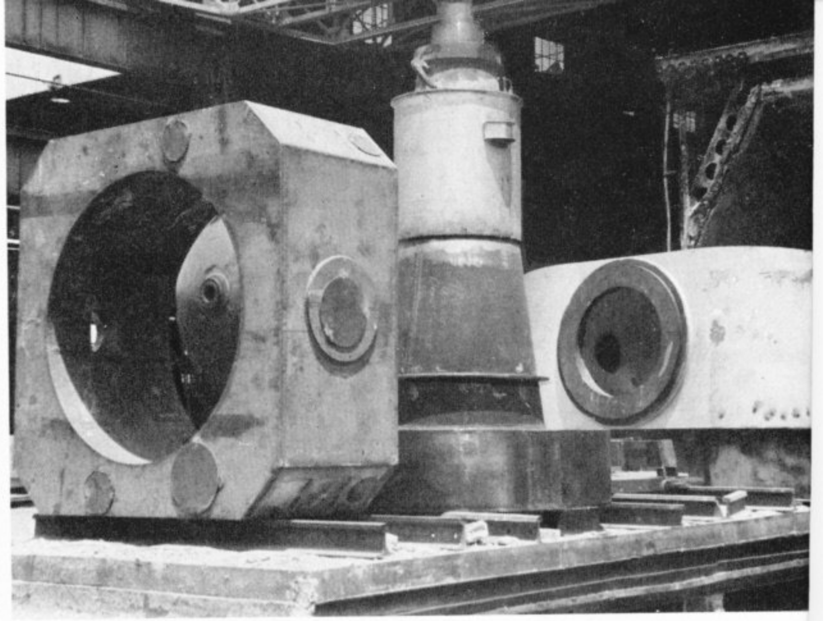
The impressive joint effort of these relatively few institutions can be judged from Louise Jenkins' 1952 *General Catalogue of Trigonometric Parallaxes,* which contains parallaxes of 5,822 stars based on about 10,000 determinations. Progress during the past 10 years has been much slower, because some observatories have discontinued this work. Furthermore, to improve accuracy, such observatories as Allegheny and Sproul have greatly increased the number of plates and the time span required for each parallax determination.

Emphasis must be put on the extreme delicacy of these observations. Often a star's parallactic shift corresponds to only a few microns (1 micron = 0.00004 inch) on the photographic plate. Hence the error with which differential coordinates can be obtained is of critical importance, and in particular, variations in this error may cause troublesome systematic errors when plates from different nights, seasons, or years are combined.

Telescopes for Parallax Work

Refractors of long focus were early found to be well suited for these exacting requirements. They provide large plate scales, sizable fields of good definition (usually about half a degree in diameter), and relative freedom from spherical aber-



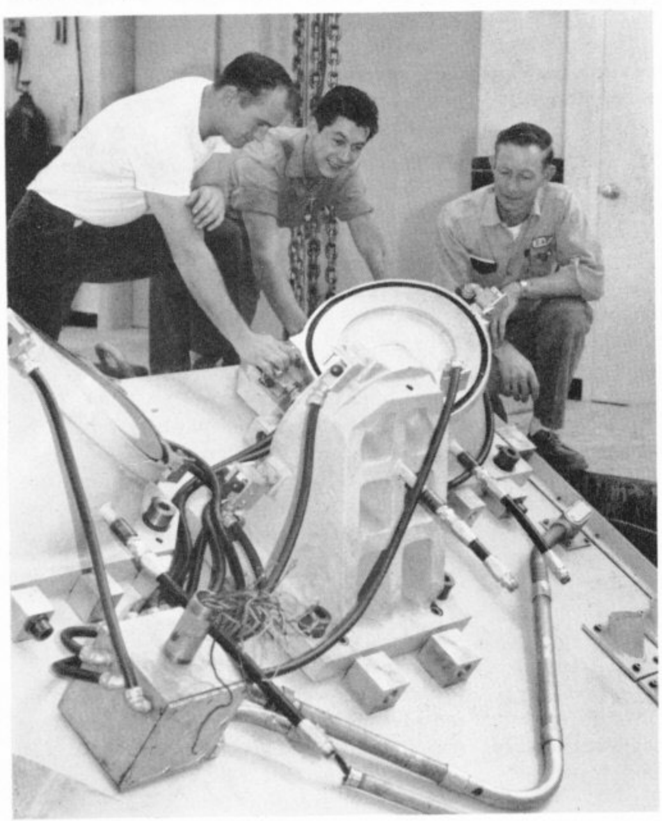


Two views show main parts of the new telescope's mounting being readied for stress relieving at 1,200° Fahrenheit in the large furnace (extreme right) at Consolidated Western Steel Co. At left is the 24,625-pound fork, made of one-inch welded steel plates, stiffened by internal partitions, and here braced by piping to prevent deformation in the furnace. At right are the declination box, eight feet square by 3½ feet, and the polar-axis assembly, 12 feet high and seven feet in diameter at the bottom (north bearing). Photographs from L and F Machine Co., Huntington Park, California, which with Boller and Chivens, Inc., South Pasadena, manufactured the telescope.

ration, astigmatism, and field curvature. These old-fashioned telescopes also have great mechanical stability, affording good control over the scale of the plates and permanency of the optical adjustments. It is no wonder 95 percent of the 11,000 trigonometric parallax determinations to date have been made with long-focus refractors.

In comparison, conventional reflectors have several disadvantages. They are sensitive to flexure changes, which affect optical alignment. They are more susceptible to air turbulence in the tube, stray light, and rapid loss in quality of off-axis images due to coma. Nevertheless, in the 1920's A. van Maanen was able to measure about 550 parallaxes with the 60-inch and 100-inch Mount Wilson reflectors. The writer recently made a critical comparison of those results with refractor parallaxes, and found that both reflectors are in fact suitable for high-precision astrometric work, provided it is confined to small fields with coma-free images. In the case of the 100-inch, the field-diameter limit is only seven minutes of arc at the Newtonian focus.

The solution to the problem of fully adapting the reflecting telescope to parallax work is therefore clear. Choose a sufficiently large focal ratio to obtain a coma-free field of desired size; use modern engineering techniques to minimize flexure in both the tube structure and the optics.



Each of three oil pads for the north polar bearing has a recessed cavity half the pad diameter. Oil under high pressure fills the cavity and flows outward against the bearing and into the collection channel along the pad's periphery. Examining these components are Bill Boykin, Danny Garcia, and Jud Massey of L and F Machine Co.

It is indeed fortunate that with their great light-gathering power reflectors are suitable for parallax programs, because there are many hundreds of intrinsically faint stars discovered in recent years whose apparent magnitudes are below the limits of even the largest refractors. The stars in question are red dwarfs, white dwarfs, and subdwarfs, all of great interest to astrophysicists. Their properties cannot be fully evaluated, however, without knowledge of their distances.

This problem requires a reflector with sufficient light-gathering power to permit photographing stars from magnitude 13½ to 18 with exposure times of less than 15 minutes. Such a telescope should have a long focal length, 10 meters or more, to give a generous plate scale. Moreover, its optics must remain stable over periods of several years.

The U. S. Navy 61-inch astrometric reflector (pictured on page 232) was designed to meet these requirements. Its paraboloidal primary mirror has a nominal focal length of 15 meters (49 feet) and its secondary is flat, like a Newtonian's. However, the optics are arranged as in a Cassegrain, with the secondary reflecting the light through the perforation of the primary to a focus behind it. The large focal ratio (f/10) results in a coma-free field of five inches (29 minutes of arc diameter); compare this with the half-inch (2.9 minutes of arc) field of the 200-inch Palomar telescope, which is f/3.3.

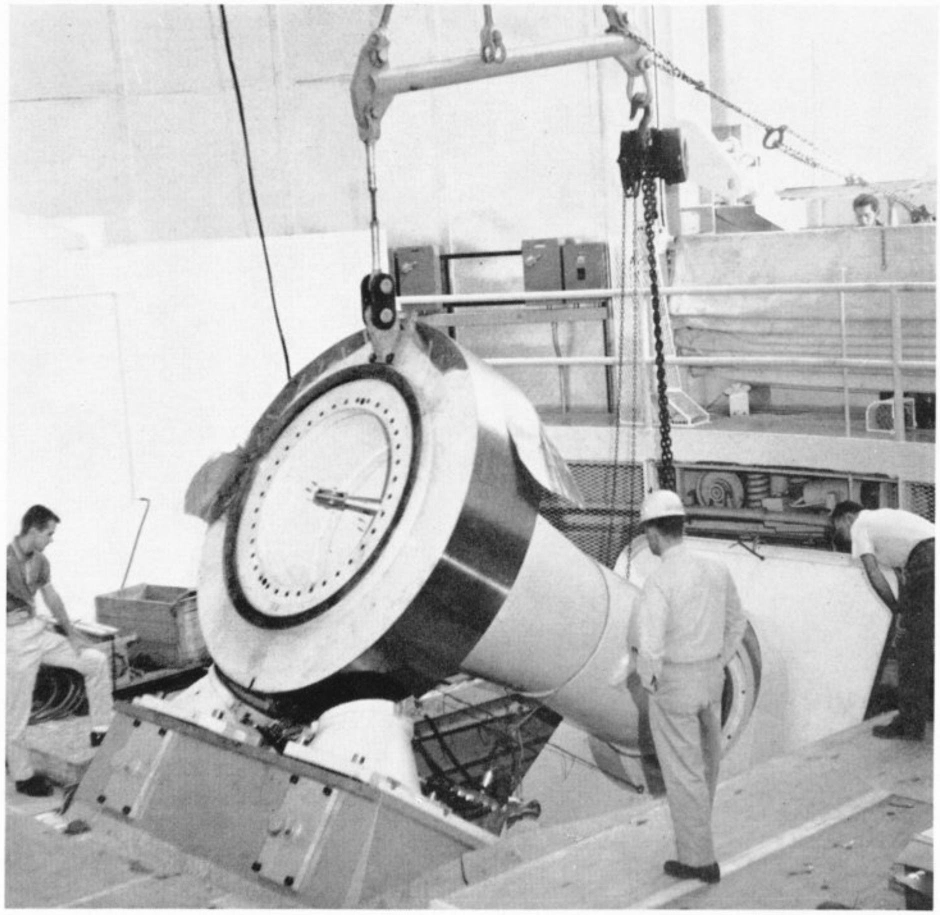
Of course, a conventional Cassegrain secondary can give a long effective focal length, but collimating the optics becomes increasingly difficult with decreasing primary focal ratio and increasing amplification. A flat secondary makes the collimation relatively simple, because the only requirement is that the secondary be normal to the optical axis of the primary. Vignetting effects, which would be caused by major shifts of the secondary with respect to the primary, are avoided by the designs of the telescope tube and mirror cells.

The Mirrors and Their Supports

To obtain the maximum parallactic shift between observing epochs, the plates of a parallax series should ideally be obtained with the field on the meridian and the sun setting in the west or rising in the east. Although this can never be realized, the early evening hours and the late night hours before dawn are essential in a parallax program.

Yet it is precisely during these times that rapid temperature changes take place which produce distortion in the optical figure of a mirror. This makes it essential to use mirror materials with a low coefficient of expansion, such as pyrex, which was adopted for the 200-inch telescope after attempts to produce quartz blanks of sufficient size and quality had failed. But the coefficient of expansion of quartz (6×10^{-7} per degree centigrade) is only about one fifth that of pyrex. Increasing demand for quartz in fairly large pieces, for electronics applications, has revived interest in producing quartz blanks.

The process developed by Corning Glass Works of fusing quartz from gaseous silica appears at the present time to be the most successful of the various methods, at least for large mirror elements. Liquid silicon tetrachloride ($SiCl_4$) and water are sprayed on a rotating platform inside a furnace at 1700° centigrade, molten silica (SiO_2) being formed. Cooling of the molten mass becomes critical in the range 1040° C. to 940° C., because of possible devitrification of the silica.



The polar axis assembly being lowered into position on the base pedestal. The highly machined cylinder of the north polar bearing, made of steel plate five inches thick, will rest on the radial oil pads. A third oil pad, which is hidden from view, bears against the flat back face of the cylindrical section. Wearing the helmet is Lt. R. A. Easton, resident officer in charge of construction of the telescope, appointed by the Southwest Division, U. S. Navy Bureau of Yards and Docks. This agency managed the engineering, contracting, and construction of instrument and building.

In May, 1960, Corning agreed to make the blanks for the telescope, the primary to be much larger than any previous disk made by this method, at a cost of about $250,000. Weighing close to 3,000 pounds as cast, the disk's weight was reduced to 2,200 pounds by finishing all the surfaces and removing the 16-inch central plug. The coring, grinding, and polishing were carried out at the plant of Davidson Optronics, Inc., West Covina, California.

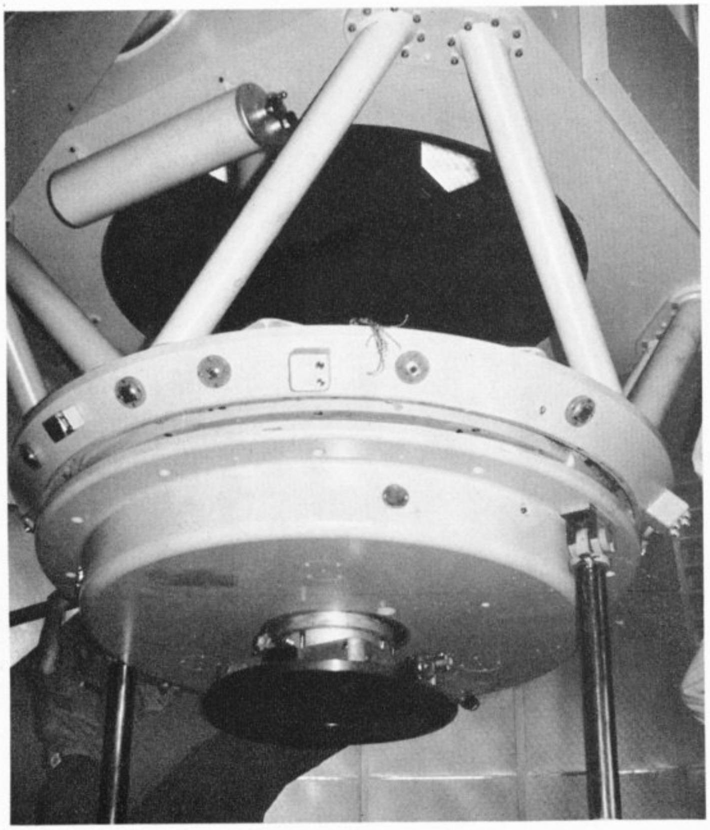
In February the primary mirror was coated in an aluminizing tank manufactured by F. J. Stokes Co. of Philadelphia. In this operation, aluminum filaments were fired for three to five seconds at 2,600 amperes at a pressure of 0.00007 millimeter of mercury. Hartmann tests show that the paraboloidal figure is accurate within 1/30 wavelength of light. Standing beside the mirror are D. Davidson and the author (at right). U. S. Navy photograph.

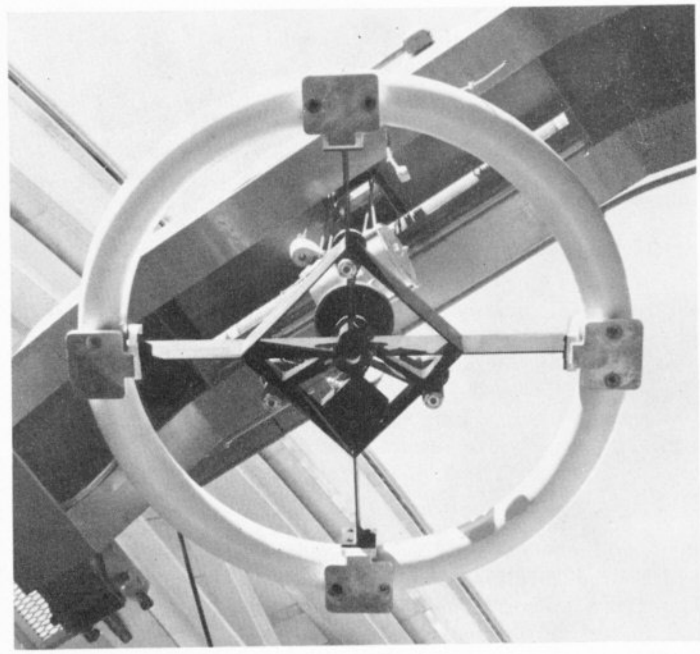
After the preliminary grinding the blank was examined for stresses. The late Donald Hendrix, who had worked on both the 200-inch mirror and the 120-inch for Lick Observatory, checked the photographs of the polarimeter test. He remarked that he had never seen a large telescope blank with such a uniform strain pattern and with such low strain in it.

The final top surface of the mirror exposed to starlight has some 25 bubbles with maximum diameters of 0.01 inch. In this respect, too, the primary exceeds in quality most existing mirrors of similar size or larger.

The 35-inch secondary mirror, six inches thick, came out extremely well, with less than one third of the maximum strain allowed by the specifications.

To preserve their optical figures as the telescope position changes during observing, the mirrors must each have proper





Above: Looking upward at the support ring and struts for the cage that will hold the secondary mirror. The ring is a tube eight inches in diameter with 3/16-inch walls.

Left: The cell of the primary mirror is being attached to its supporting ring, on which are electrical outlets; below the cell is the instrument mounting plate.

back (axial) support and edge (radial) support. For the 61-inch primary we employ an old idea first put into practice by Leon Foucault, who used a pig's bladder to carry the mirror axially. We utilize a buoyant neoprene bag, filled with air at a pressure that changes with the attitude of the telescope. The clearance between the mirror and the cell is $\frac{1}{4}$ inch. Axially, the mirror position is defined by three Teflon pads in the rear of the cell carrying a fraction of the mirror's weight. Radially, the support is provided by a buoyant neoprene tube filled with mercury, sealing off the space between the mirror edge and the inside of the cell.

The system for the secondary is similar to that for the primary, except that a vacuum is applied to hold the mirror against the pull of gravity. When the secondary is horizontal the vacuum-induced pressure equals the mirror's weight, and it is zero when the mirror is in a vertical position. The pressures and vacuums supplied by the regulating apparatus cancel the weights of the mirrors very closely.

The telescope has a built-in collimator which checks the alignment of the two mirrors.

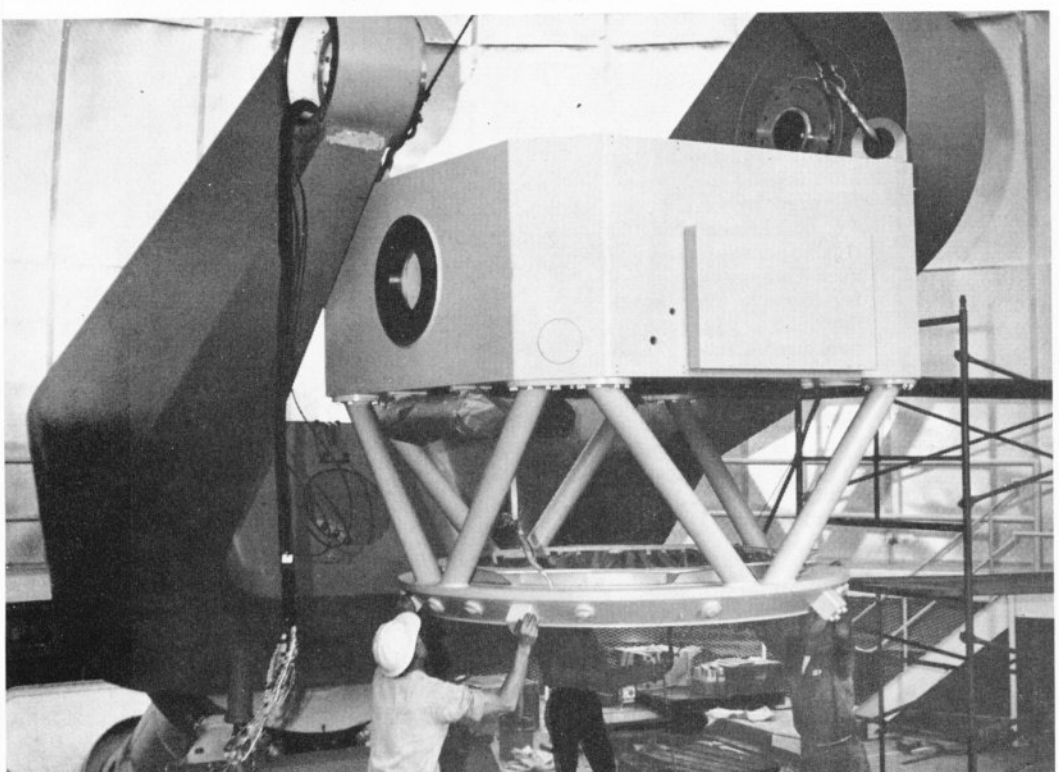
Telescope and Building

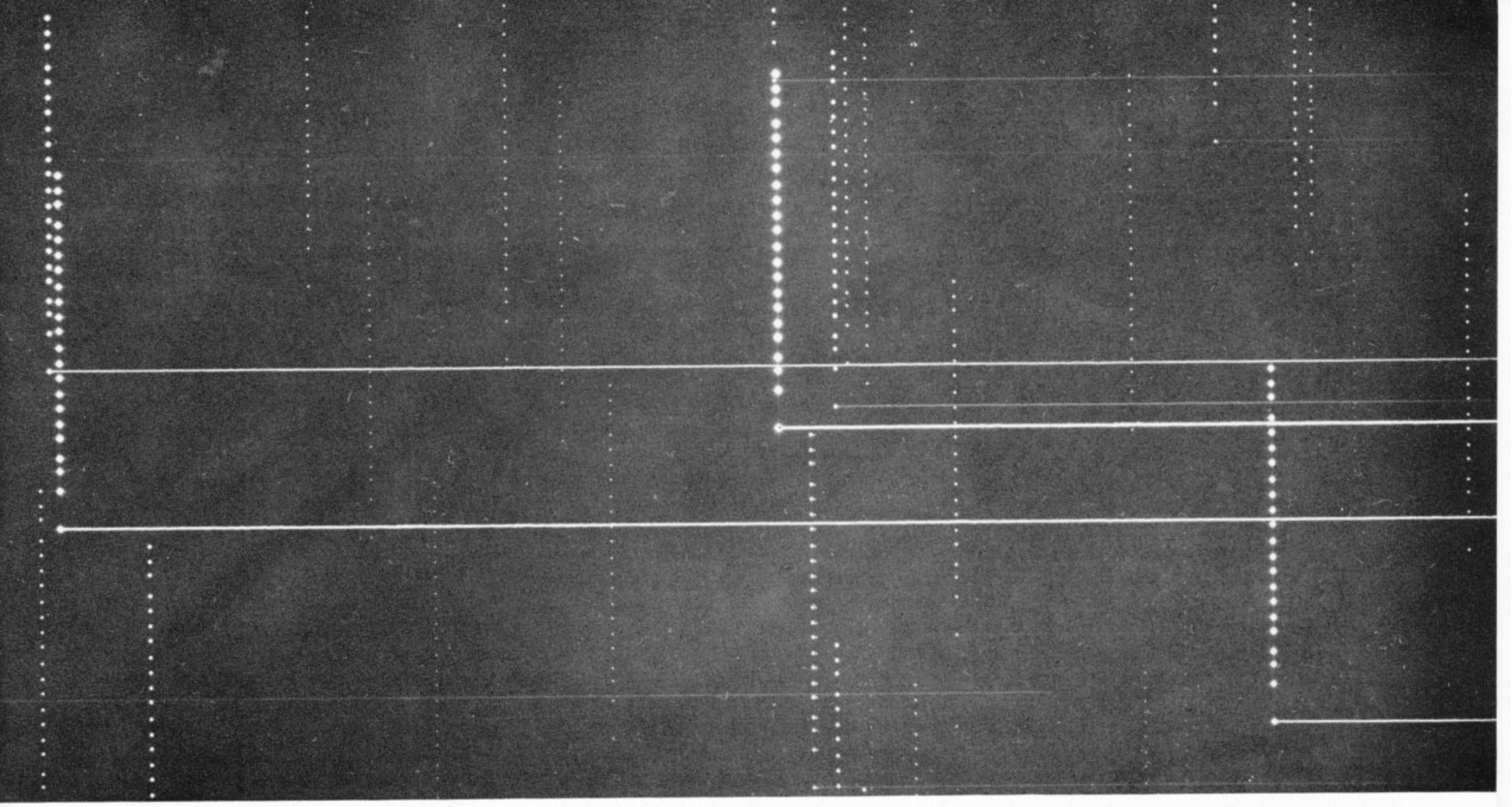
As the pictures of its construction show, the 61-inch reflector has a massive fork mounting, designed to have much less flexure of its arms than any previous instrument of its size. The main tube is a structure of the Serrurier type, whose compensated truss pattern allows the primary cell to deflect under gravity by the same amount as the secondary cell. Thus the alignment of the two mirrors remains unchanged when the telescope is moved.

The primary-mirror support struts are seamless steel tubing four feet long, with $\frac{1}{2}$-inch walls five inches in diameter. Secondary struts are 17 feet long, eight inches in diameter, with 3/16-inch walls. The total weight around the declination axis of the finished telescope is $16\frac{1}{4}$ tons

The distances from the center of the declination axis to the mirror cells are six feet for the primary and 19 feet for the secondary. (Refer to the picture on the facing page.) With their support sys-

Here, in October, 1963, the lower tube section is being raised into position between the arms of the giant fork, which is $15\frac{1}{2}$ feet deep from its lower end to the center of the declination axis. The fork is asymmetric because the west arm (upper right) contains the declination driving mechanism. Attached to the $1\frac{1}{2}$-inch steel base of the declination box frame are tubular struts carrying the ring casting (held by the workmen) on which the primary mirror cell will be mounted. All pictures on these pages are from the U. S. Naval Observatory.





One of the test plates taken December 23-24, 1963, by Arthur Hoag, director of the Arizona station, and his staff. It contains 22 exposures of the central Pleiades, to check the driving mechanism.

tems, the two mirrors weigh about 11,000 and 1,650 pounds, respectively.

The rotating weight around the polar axis is 36 tons, and is carried by a combination of oil-pad and standard ball bearings. The north polar bearing consists of three oil pads which support most of the telescope weight, both radially and axially. Each pad's surface matches the journal surface, against which oil flows at an average pressure of 770 pounds per square inch. The oil film between pad and journal is only 0.003 to 0.005 of an inch thick.

Low friction at the north polar bearing, achieved by means of the oil pads, permits using a single worm and gear wheel for all three kinds of telescope motion around the polar axis. These are fast motion (slewing), setting on a star field, and tracking at the sidereal rate. The wheel, 7½ feet in diameter and weighing nearly a ton, was manufactured with utmost precision. Its 720 teeth were machined with a maximum tooth-to-tooth composite error of 0.0002 inch. Similar accuracy has been achieved for the declination drive, which is housed in the west arm of the main fork.

Fast motions of the telescope in right ascension or declination are carried out with 1/3 horsepower motors, while 1/20 horsepower motors do setting and tracking. During an exposure, corrections to the tracking of the telescope are made by 1/70 horsepower motors that act directly through the right ascension and declination drives.

These corrections can be controlled by an automatic photoelectric guider of the Weitbrecht type, which employs a four-sided pyramidal prism as position indicator. If the guide star strays from the apex of the pyramid, light is reflected from one or more prism faces and actuates photocells in the control circuit. This guider can scan a field 25 by 60 minutes of arc in search of a suitable guide star.

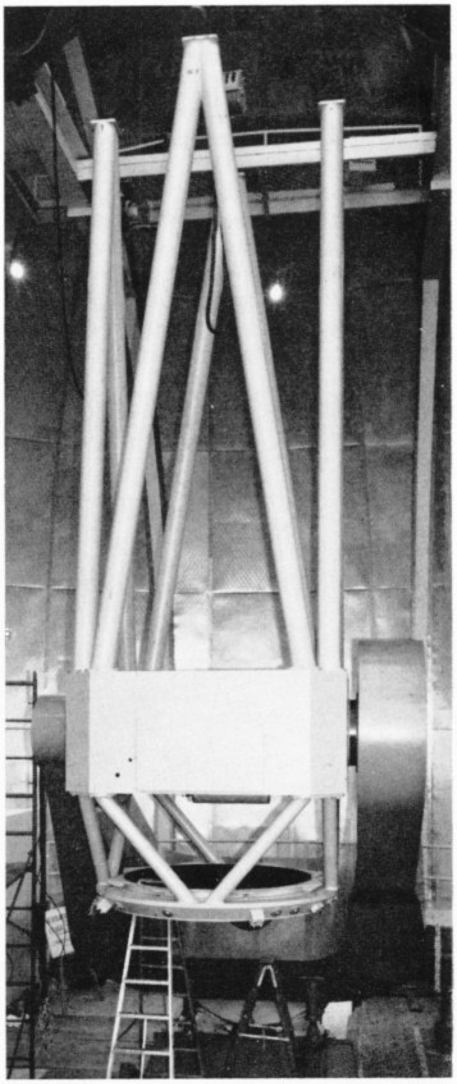
Designed for parallax observations, the camera of the 61-inch telescope is fully automatic. Exposure times from 10 seconds to one hour can be preset, and selector switches choose any or all of six positions on the plate for a sequence of exposures. Between exposures the plate is shifted automatically.

The test plate above was made before the primary mirror was aluminized, and bears a series of 30-second exposures taken with the automatic camera. Between exposures the telescope was shifted in declination southward about half a minute of arc, the last exposure being trailed to furnish an east-west line.

Alcyone, brightest of the Pleiades, is the central star; at the left are 27 and 28 Tauri and at lower right 23 Tauri; plate scale is reproduced unchanged. The straightness of each row of images and other tests indicate that the 61-inch telescope's sidereal driving mechanism has no measurable periodic error.

To insure mechanical and optical stability of the astrometric reflector, careful temperature control is necessary. The dome building has been designed, like those for the 200-inch and 120-inch reflectors, to minimize the harmful effect of high daytime temperatures upon the nighttime operation of the telescope.

(Continued on page 232)



The partially assembled main tube.

THE NEW 61-INCH ASTROMETRIC REFLECTOR

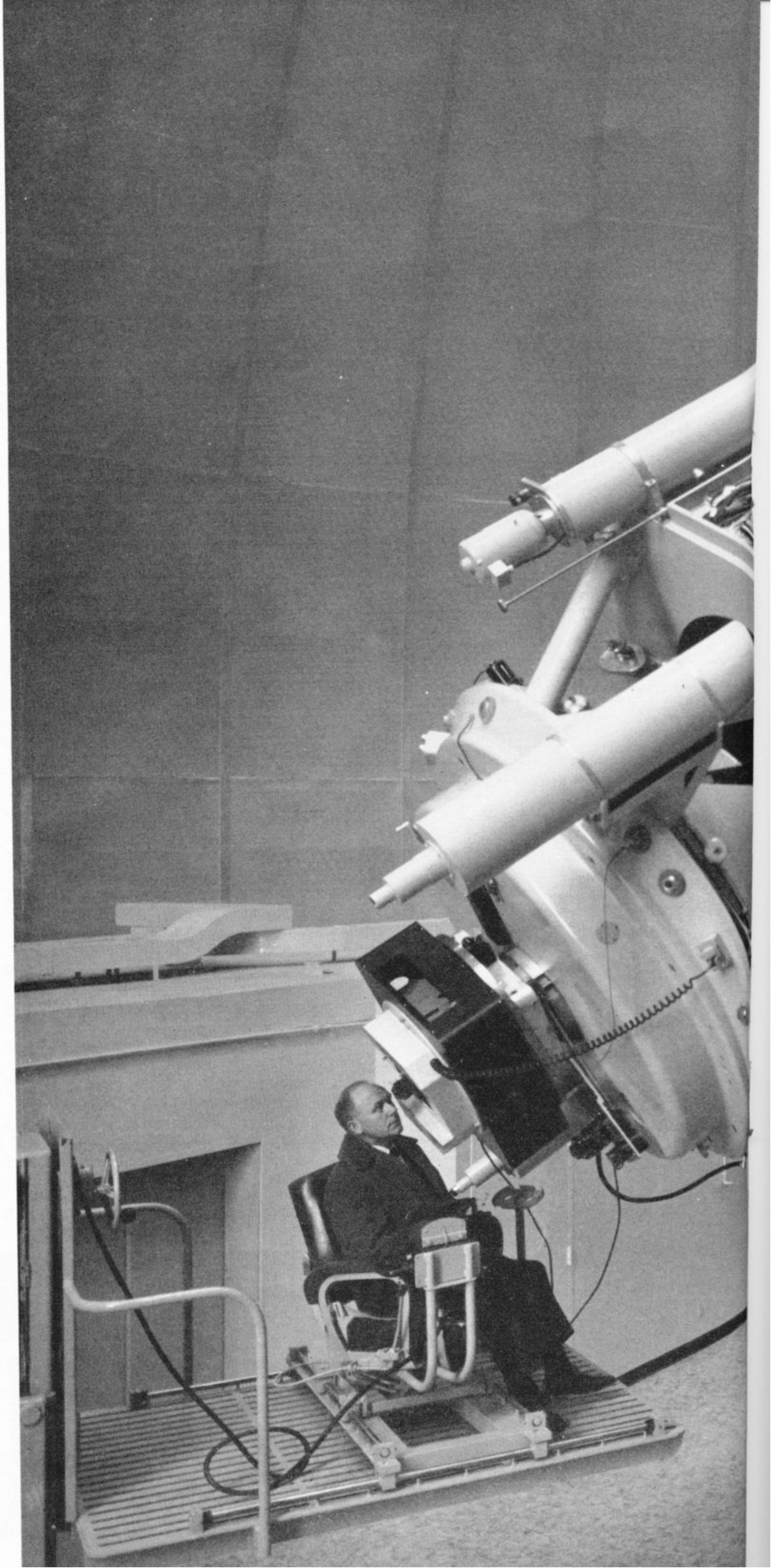
(Continued from page 209)

The stationary part of the building is reinforced concrete, with cellular glass insulation and an aluminum shield six inches outside the wall that allows free flow of air. The movable dome has double walls with a one-foot space and a 2½-inch layer of crumpled aluminum foil. By these means, the temperature inside the dome can be kept unchanged within one or two degrees centigrade even when the temperature outside rises 10 degrees. Incidentally, special needle valves allow adjustment of the oil-pad bearings so that the film thickness is appropriate for the particular temperature at the time of observation.

Observing conditions are known to be excellent at the site of the 61-inch telescope, 7,600 feet above sea level, with the observing floor about 33 feet above ground. Our experience with the nearby 40-inch telescope during the past eight years has been very satisfactory in regard to number of clear nights, sky transparency, and seeing.

We expect that the highly efficient 61-inch reflector will produce so many photographs that modern automatic methods of plate measuring will be necessary. Currently we are having built an automatic plate-measuring engine which will record the coordinates of star images on punched cards. The first plate of each parallax series will be measured manually, to provide instructions on punched cards for the engine to select the images on the remaining plates of the series.

Usually the planning, funding, and construction of a large astronomical instrument extend over many years. This was not the case for the astrometric reflector. Preliminary engineering for cost estimates started in the fall of 1959, and the following July Congress appropriated the funds. The first on-site tests of the telescope were carried out last autumn, and actual parallax observing began this March.



Seated on the observing platform of the 61-inch astrometric reflector is the author, who is scientific director of the U. S. Naval Observatory. The platform is a converted fork lift that allows the observer to raise and lower himself and to move across the floor to any position of the guiding eyepiece. At lower right is the control console, which contains all the necessary indicators for operating the telescope, including readout of right ascension and declination. Note the partly opened leaves of the sectored cover for the primary mirror, also the black baffle tubes that shield the primary and secondary mirrors from stray light. Left of center is an 8-inch f/7 finder, and the long tube on top is one of two containing movable counterweights for balancing the telescope about its declination axis. Official U. S. Navy photograph.