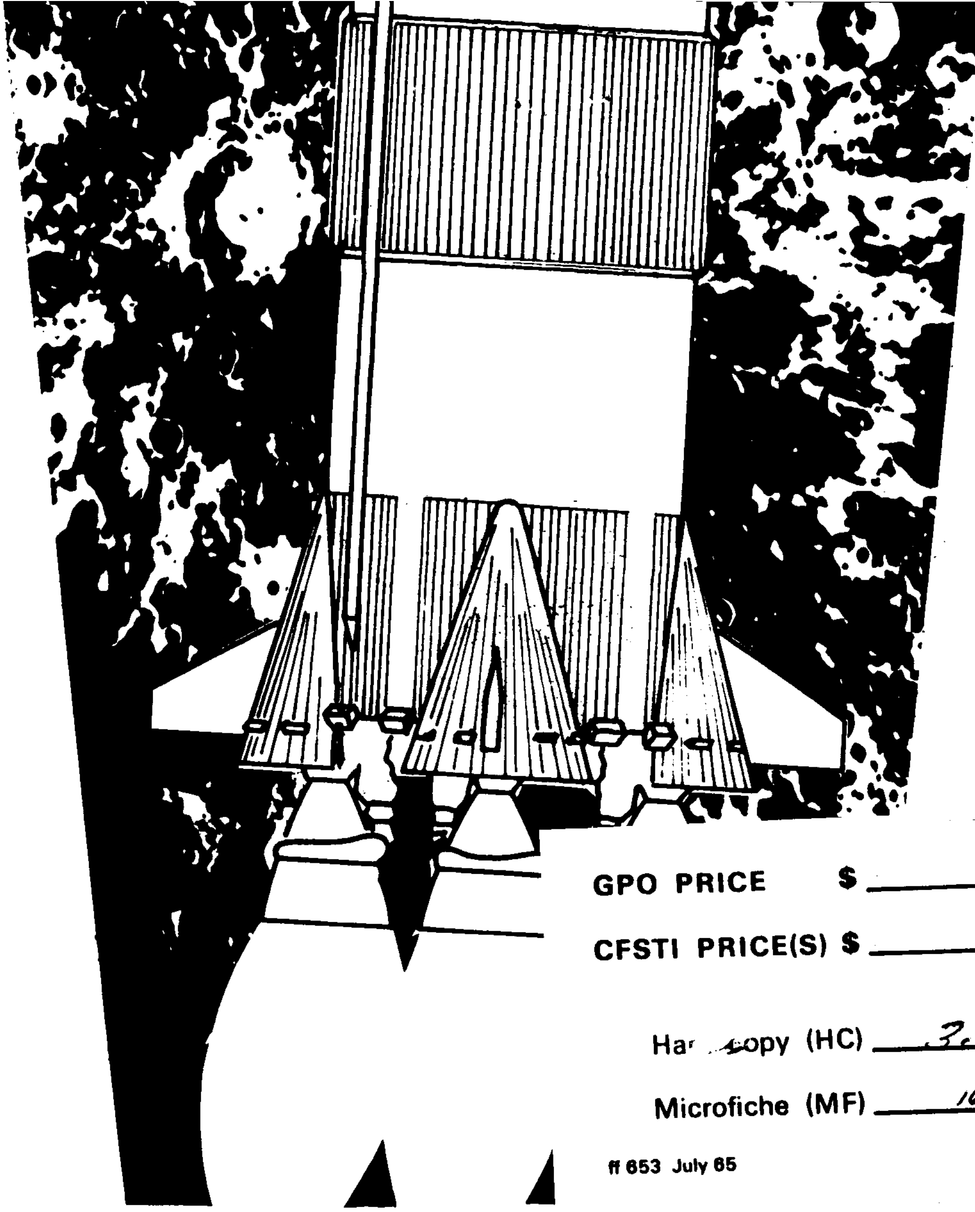


space science seminar

GEORGE C. MARSHALL SPACE FLIGHT CENTER
NATIONAL AERONAUTICS and SPACE ADMINISTRATION

ACCURATE GUIDANCE WITH LARGE OPTICAL EQUIPMENT

By Bruce H. Rule

1967

Report No. SSS-67-78

NASA - GEORGE C. MARSHALL SPACE FLIGHT CENTER

Report No. SSS-67-78

ACCURATE GUIDANCE WITH LARGE OPTICAL EQUIPMENT

By

Bruce H. Rule

Chief Engineer, Mount Wilson and Palomar Observatories
and
Director, Central Engineering Services
California Institute of Technology
Pasadena, California

RESEARCH PROJECTS LABORATORY
RESEARCH AND DEVELOPMENT OPERATIONS

ACCURATE GUIDANCE WITH LARGE OPTICAL EQUIPMENT

By

Bruce H. Rule

ABSTRACT

There are several classes of large optical instruments including optical tooling and gaging, surveying and analysis, search and communicating, solar and stellar telescopes, and now tracking and space telescopes. The best example of sophistication and finesse in meeting high accuracy requirements is the astronomical telescope.

Presented herein is a review of the advance of telescope accuracy technique and a discussion of the criteria of excellence for large ground-based optical telescopes. The criteria of excellence discussed are based on those required for the largest, most well known ground-based telescope, the 200-in. (508-cm) Hale telescope at Mt. Wilson and Palomar Observatories. The main factors of these criteria could apply equally well to the criteria for space telescopes.

NASA - GEORGE C. MARSHALL SPACE FLIGHT CENTER

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

FOREWORD

This report is an edited review of material presented by Mr. Bruce H. Rule at a Space Science Seminar at the Marshall Space Flight Center on December 8, 1966.


CENTRAL
ENGINEERING

BIOGRAPHICAL NOTE

Mr. Bruce H. Rule has been project engineer of the Hale 200-in. (508-cm) telescope and the chief engineer of the Mt. Wilson and Palomar Observatories for over 25 years. He has also served as chief engineer for the Institute's High Energy Physics Synchtotron Laboratory. He is currently a staff member of California Institute of Technology and the Carnegie Institution of Washington.

Mr. Rule received his B. S. degree in engineering from CalTech and his teaching credentials from UCLA. At CalTech he has continued his studies in engineering, management, and industrial relations. Mr. Rule is consultant for the National Science Foundation, science and engineering advisory panels, and other national observatory groups for large observatory projects.

His technical experience is varied, running the gamut in engineering development and construction from laboratory apparatus to large generating power plants; in defense research equipment from low-temperature liquid air apparatus to high-temperature solar furnace equipment; in optical instruments from aerial survey cameras to some of the world's largest telescopes; and in microwave development from electron particle accelerator and high-energy experimental equipment to large radio astronomy antennas. In addition, Mr. Rule is engaged in the activities of his institution, serving with various committees, employees groups, and the Management Club, as well as other community programs, college groups, National Education Association, and local school projects.

Mr. Rule is a Registered Professional Engineer, California, in both EE and ME fields. He actively participates in several professional groups, including Sigma Xi, the American Institute of Electrical and Electronic Engineers, American Society of Mechanical Engineers, American Astronomical Society, International Astronomical Union, and the Astronomical Society of the Pacific.

ACCURATE GUIDANCE WITH LARGE OPTICAL EQUIPMENT

SUMMARY

Involved in the space program are several classes of large optical instruments. Among these are optical tooling and gaging instruments, survey and analysis equipment, search and communicating equipment, solar and stellar telescopes, and now tracking and space telescopes. The best example of sophistication and finesse in meeting the high accuracy requirements of optical equipment is the astronomical telescope.

The pace of astronomy has increased rapidly in the last 25 years because of instrumental improvements and the rapid pace in the general physical sciences. Radio astronomy and efforts in space science technology have provided more recent advances. It would be prudent, therefore, to review the advance of telescope accuracy technique and discuss what the criteria of excellence are for large ground-based telescopes.

CONTINUING NEED FOR LARGE ASTRONOMICAL TELESCOPES

Astronomers are devoted to their space quest, not only for its passing contribution to science; they are totally dedicated to obtaining basic knowledge about the universe as we see it, and, in general, they don't care which tool they use as long as it's the best one.

There are over 220 observatories in all countries, but very few have adequately large instruments. About 12 have diameters of 36 in. (91 cm) or larger. There are 10 with 48-in. (122-cm) or larger diameters, and there are only 3 with 100-in. (254-cm) or larger diameters, although there are a half dozen or so large telescopes being planned or constructed, many of them outside of this country.

At the present time, looking out through 5×10^9 light years (50×10^{24} m) we can see about 10^{12} stars much like our own sun, but some of these are 10^{18} times brighter. This means that in our normal light fields on photographic plates like the 48-in. (122-cm) Schmidt we see in one square inch of the plate well over 10 000 objects.

The higher demands on astronomy are caused by a number of things. First, there is a total commitment to the pursuit of the basic science of astronomy as a result of our increased curiosity; second, the specific positions and transitions of stars, galaxies, and planets need to be known for research, navigation, and space guidance. Third, we need to continue observations for a detailed look at the energy process taking place in the vast laboratory of stars where we have extremes of pressure, temperature, and size. We need to determine facts about the abundance of elements, their origins, something about the nuclear processes involved, and information about the radio, otpical, and X-ray emission sources.

The extent of the growth of our curiosity and the growth rate of scientists has been no less than the growth of the general population, with unfulfilled demands going up 6 to 7 percent a year. Much of the needed instrumentation is limited by the number of precise ground-based or space facilities that can be provided in a given time. A large ground-based telescope, for example, will keep about 25 astronomer-scientists and their technical assistants busy on observation programs. Of course it takes many more to plan and build such facilities.

THE SPECTRAL RANGE OF TELESCOPES

We talk about the broad range accuracy of a telescope in terms of the wavelength that is observed. There is no one optical instrument that can completely cover the broad spectrum of emission energy received in the form of visible light, infrared, radio, X-ray, and other long-wavelength radiation. There are very definite transparent "windows" for viewing different ranges of these wavelengths from ground-based instruments. For example, the visible optical range is about 1 or 2 octaves wide at a wavelength of about 20×10^{-6} in. (50×10^{-6} cm). The radio window is about 12 octaves wide, or more than 6 times wider. There are several infrared windows which extend on out some 13 octaves up to the millimeter wavelength range. More recently, there has been a considerable amount of work done, particularly in rocket package experiments, in the X-ray region. This extends the older methods for studying gamma rays and high-energy cosmic sources from the ground.

You will notice from all of these comments about the viewing windows from the ground that there are obvious benefits of space viewing that are becoming more and more apparent; these are, namely, freedom from atmospheric "seeing" problems, from the sky background "noise" source within our atmosphere, and from absorption. There is another advantage derived from space experiments, that of being able to view the planets, at least in our own planetary system, at close range from flyby satellites. There is nothing like being able to zoom in on an object to look at it. These limits of good seeing as restricted to the regions between these transparent windows, for the ground-based astronomer, we hope will be covered by newly developing and precise space telescopes that will extend our vision to cover the entire spectral range.

INSTRUMENT ACCURACY DEVELOPMENT FACTORS

The accuracy development factors required for precise observations involve not only the highest quality optical system and operating techniques, but some control of the environmental effects as well, by design or compensation. The major problem is designing the mount with stiffness and guiding accuracy compatible with the optics and the high-quality detecting instrumentation.

A considerable amount of integrated engineering and fabrication skill is required to meet the user needs of anticipated programs with long-life reliability, safe and easy operation, and at reasonable cost. All of this, however, must include providing great stability and guiding accuracy, and these factors will be similar for either ground- or space-based requirements.

Good technical planning is required, and no ground-based instruments are ever quite satisfactorily constructed in as short a time or with as great an accuracy and universality as the observing group would like. The major ground-based telescopes, for example, usually require from five to eight years to be designed and fabricated and have an expected full-time operating life of about 50 years or more. I say "about" because most of the younger ones have yet to exist this long and all of the older ones have gone way beyond 50 years.

I understand that the space science requirements provide no exception. It would appear to require from four to six years to develop, test, successfully debug, and launch a modest-sized telescope with a space instrument lifetime of perhaps a half to one year at a cost that may be 100 times that of equal ground-based apertures. However, the current techniques, component improvements, and the knowhow available from these space efforts is of ever increasing value to augment the output and utilization of all existing ground-based facilities.

EFFECT OF INSTRUMENT SIZE

Why can't we build our instruments larger and larger? There is no cook-book recipe for determining the optimum telescope size because the scaling is not linear. Large mirrors in general are not diffraction limited, but, for atmospheric reasons, they are limited by what some astronomers call the "frustration limit." Moderately large optics now being made have as much as 2/50 accuracy in surface figure, but we are frustrated by the material through which we must look. These large optics can easily resolve 22nd magnitude stars that require surfaces corresponding to perhaps quarter or fifth wavelength. Theoretically it is possible to resolve 0.025 arc sec (or more briefly 0.″025). Because of seeing problems, however, we are limited to about 0.″25 most of the time, although in rare intervals and in some carefully selected locations, we may have 0.″1.

There are several general effects of size on limiting brightness. For example, for photometry it would improve with the square of the aperture; for spectroscopic work it would improve directly with the aperture; and for detailed surface photography it is proportional to the "f" ratio of the optical system. However, there are other mechanical limitations on accuracy and guidance, and these tend to become very restrictive because of the limitations of materials, environment, and our system accuracy.

The situation is similar for radio astronomy telescopes except that the wavelength ratio and the tolerances involved for optics are from 100 to 1000 times greater. Thus a similar wavelength-to-aperture ratio for a radio telescope would require a dish diameter of several miles with impossibly large mounting and driving requirements if it were to be classified as having the same resolution accuracy as an optical telescope.

ACCURACY PROBLEMS FOR ORBITING ASTRONOMICAL OBSERVATORIES

There are plans to launch several Orbiting Astronomical Observatories in the next four years with telescope sizes up to 40 in. (100 cm) in diameter for various observations in the optical, infrared, and X-ray regions. The pointing accuracy requirements for these programs will start out in the range of something better than a minute of arc (or 1.′0) [this accuracy is about 1/500 of the accuracy of the 200-in. 508-cm Hale telescope] with about 50 minutes

(50^m) exposure time. The plan is to use short exposure times to reduce camera holding requirements. Later, perhaps, the refinements may permit fine pointing to about 0".01 to 0".001 with correspondingly longer exposure times.

With such orbiting telescopes above our atmosphere, the limiting magnitude of the stars that we view will then be extended from the present ground-based limit of about 22nd magnitude out to perhaps the 26th or fainter. This will enormously increase the number of faint star objects that we will be able to view. Instead of 10 000 objects per square inch on a particular plate, depending on the camera, there may now be thousands more.

This will lead to immeasurably more difficult viewing field selection problems and will require even more critical guidance with much more delicate equipment. There is, too, the problem of regulating these components in space to maintain them in this very sensitive operation. These factors add to the reasons for planning future manned telescope vehicles, or possible lunar- or planetary-based observing systems, in which experienced astronaut-astronomers operate the equipment. There are tremendous problems in the on-board logistics required for photo processing, spectroscopy, field selection, detector equipment functions, and readout systems.

One of the largest problems is to maintain the optical quality and alignment of the telescope for critical observations. The slightest movement of the astronaut can have an effect of arcseconds or arcminutes on the angle of orientation of the capsule on even the largest vehicles. Similar changes can occur from power or servo equipment in addition to deflections from reasonably sudden thermal changes or thermal balance of the craft. Even a man's respiration could produce about an arc second deviation that would adversely affect the holding accuracy. Therefore, initially at least, the programs being planned will limit the short range exposure to 10^s or under for fairly bright objects (about 14th magnitude) and will use telescopes up to 36 or 40 in. (91 or 102 cm) in diameter.

Great technical strides have been made in space guidance systems, particularly in accuracies, trajectory, and the logistics of trajectory computations. Many of these techniques have been either directly or indirectly applicable to ground-based stations and have been quite useful. The necessary improvement of guidance and control of the space telescope attitude, even from the excellent closed-loop gain of the Orbiting Astronomical Observatory (OAO) image formed by the telescope optics, leads to a system-pointing response required to be at least equal to the resolution of the telescope itself. A 0".1 image requires an approximate 0".1 guiding accuracy or better.

Generally the problem does not involve the absolute position of the telescope itself but rather the stability of the desired sky direction, ability to scan for density, and precise return to a given position. Techniques of telescope guidance are continually being upgraded, although perhaps at a slower rate for ground-based astronomy than for radio or space astronomy. Although astronomers are somewhat reluctant to change their fine existing instruments which are expensive and worked out with a great deal of care and long familiarity, there is a gradual build-up of good understanding on the adaptation of many new techniques.

CRITERIA OF EXCELLENCE FOR LARGE OPTICAL INSTRUMENTS

We can use, for the criterion of excellence, the world's largest ground-based telescope, the Hale 200-in. (508-cm) at Palomar. It is now in its 18th year of successful operation. (It has actually been operating 20 years, the first 2 years having been used for improving the mirror and the drive system.)

The rotating dome, which weighs 1000 tons, has a diameter of about 135 ft and is 135 ft high. The observatory has three foundations: one supports the telescope; one supports the dome; and the third supports the Coudé spectrograph instruments. The dome biparting shutter is, incidentally, part of the "thermal control" system. It houses the telescope to maintain the average daytime temperatures usually within 2° C of the nighttime temperatures. Contrary to most buildings, the interior of the dome is kept at average nighttime temperature. The shutters open at night and equalization occurs with surroundings in about a half hour or more. We attempt in some cases to program or to anticipate the forthcoming night temperature by opening the shutters slightly before or after sunset. To date we have found it has not been necessary to regulate the temperature very much during the daytime because we have a very well insulated system.

The telescope mount is 550 tons (500,000 kg) of moving steel and instruments. The support itself is the conventional equatorial mount. The rotation must be unwound on a system that has a polar axis of rotation parallel to the earth's axis. The other rotation element, the declination axis, is used to find a particular position (north-south) in the sky. With these two coordinates one can point to any region.

The other elements have to do with the mount, the hydrostatic bearing, the horseshoe yoke which provides a north bearing, the cage at the top tube end, and the elevator on which a man rides. (We can have a "captive astronaut" up there for some time each night. He is in a capsule that moves around in ground space, except that we have no way of removing gravity. We move his seat around so he is always in a comfortable position.)

The telescope has a field size of about $0^\circ.25$, and the field is rather limited when used strictly as a parabolic mirror. With a series of optical corrector plates we can enlarge this field to a more useful size of 8 in. (20 cm) or so. The 48-in. (122-cm) Schmidt survey telescope has a much wider field of $7^\circ \times 7^\circ$. It has been very excellent for the sky survey work done under the sponsorship of the National Geographic Society that produced many volumes of the blue and red sky survey plates used all over the world. These fields are very good down to the 21st magnitude. New types do more specific work in the photometry field with image tubes for high dispersion spectroscopy. There are new telescope cameras that are being built, including our new 60-in. (152-cm) Polaroid photometric camera.

The bottom end of the telescope (Fig. 1) shows a little bit of what is done about the thermal problem. Looking up from the bottom of the telescope, one can see where the support systems show through the holes in the bottom plate of the cell. The central hole, which goes up through the center mirror, contains the Cassegrain support tube. The observer can ride below this opening. Some of the main factors that constitute the criteria of excellence of the large telescope could apply equally as well, with modifications, to space-borne telescopes. Five of these general factors are discussed below.

The first one is the image viewing quality, as determined by seeing through the earth's atmosphere or no atmosphere at all, as in the case of a vacuum spectrograph or space telescope. This also applies to effects of gases or other scattering or thermal effects in the system.

The second factor is the optical system quality and alignment. Excellent optics that are free of distortions either on the ground or in space are required.

The third is the mounting structural rigidity. Although rigidity applies to a 1-g field for ground-based stiffness, the space frame stiffness requirements for acceleration and drive forces for thermals and other environments are similar.

The fourth factor concerns the drive stability, the smoothness over a wide range of rates and the holding stability for reasonably long exposures. Whether for space-borne or ground-based telescopes, this stability has to be on

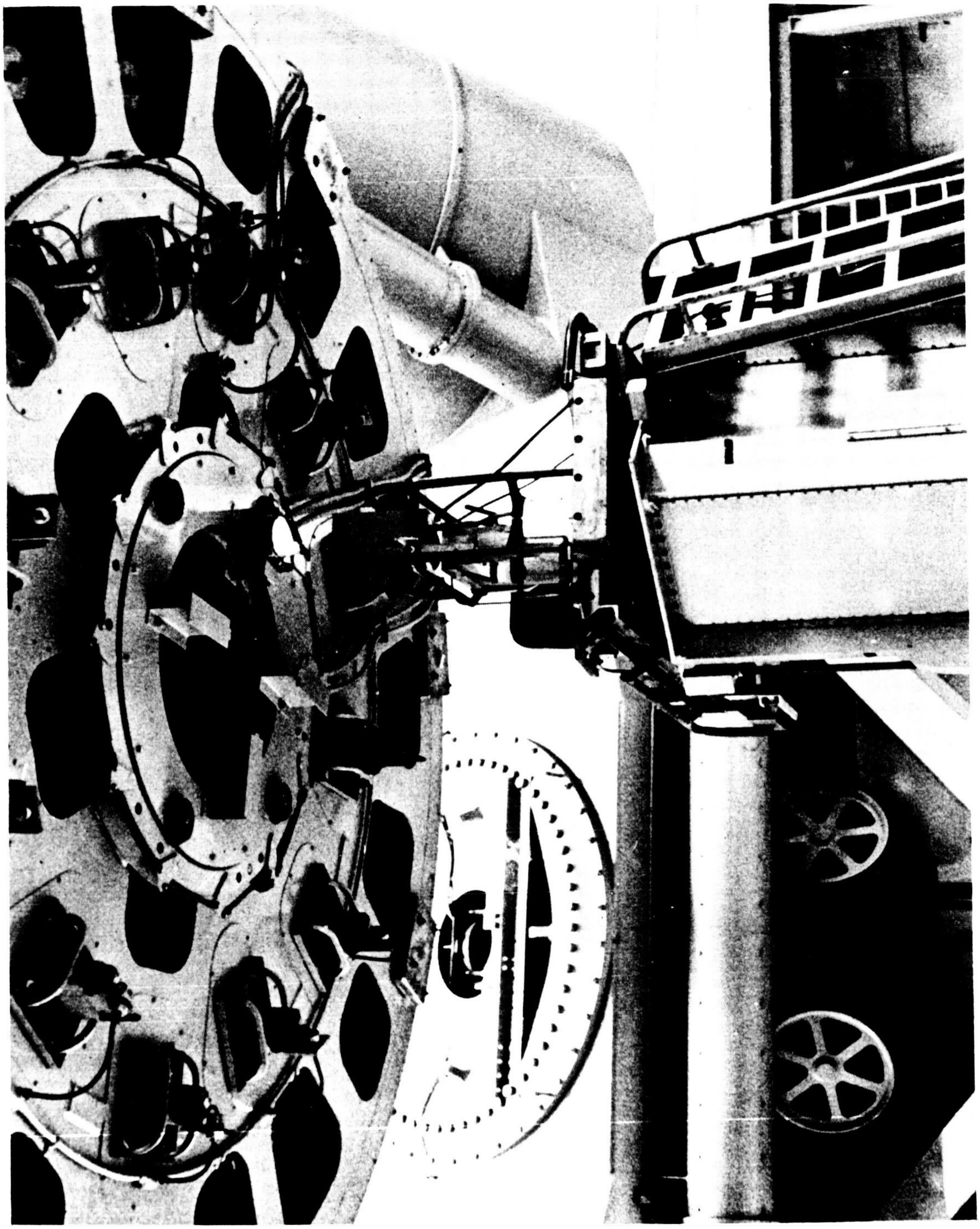


FIGURE 1. LOWER END OF 200-IN. (508-cm) TUBE

the order of about 1" or less per hour, and this is 0°.0003/hr. Tracking velocity for guiding, setting, and scanning, which may go up to as high as 48 000"/hr (this would be on the order of 10" to 15"/sec) has to be achieved without telescope oscillations or perturbations beyond the optical resolution of the system.

The fifth criterion is based on the control logistics, the data and readout system required by the operation program. Ground-based systems are quite similar. Providing readout techniques, telemetering, and data reduction directly on cards, as in the case of the Hale's IBM cards, for computing and computer programs, has been a great adaptation.

THE CRITERIA IN MORE DETAIL

Atmospheric Seeing Quality

Little more will be said about the atmospheric criteria, which are determined by the location of the ground telescope or space environment, and not necessarily by any design parameters. Great efforts are made to locate ground-based observatories at the best possible seeing locations, which are generally in the northern and southern latitudes from 25° to 35° and in regions that are generally free of clouds, rainfall, and other disturbances. Elevations may be up to 6000 or 8000 ft (1800 or 2400 m), and in some recent efforts (being supported by NASA) up to 13 000 ft (4000 m), which is a difficult elevation in which to operate.

Optical Quality

The excellence of the optical system is determined mainly by the geometrical parameters that are adopted and the quality of the surface finish, which is diffraction-limited to about 1/20 of a wavelength or better. This surface accuracy is affected, however, by the particular conditions under which the mirror is used; i.e., gravity, the support system function, or accelerating or thermal forces.

The stability of the optical surface is determined by the mirror material, its physical properties, and its homogeneity. The homogeneity is important, and most designers don't even look into homogeneity of materials. It is normally assumed that a thermal coefficient, a Young's modulus, a Poisson's ratio, or thermal conductivity are constants. However, none of these are really constants. The rate of change of these values is important in the optical system design. For example, in most quartz and other materials even Young's modulus varies some 1% per 10°C, whereas most of the effects of the mirror have to be kept to well under 0.1%.

The material also must be suitable for applications of a high reflecting surface, and it must have lower thermal effects with low gradients. It must be precisely supported and aligned; for example, if these effects exceed the minimum limits (which in most cases they do), one needs to provide some sort of support and aligning system to either eliminate these or to provide compensation for them.

Because of these limitations in the physical constants, the environmental effects are important, especially in the case of ground-based telescopes. The effects of gravity loads, the thermal variations, the wind loads, and the support forces are relatively high. In the case of space optics, the environmental effects include the higher thermals and the lower defining reactions and drive forces.

The optical components on ground-based systems must have anti-gravity support systems to compensate for gravity. These may also be required to some extent for space forces or accelerations, transportation, or even as supports in the original mirror production with gravity forces. In the original producti such an optical surface for space has to be supported either here on earth or in an optics lab in space. This has brought into the foreground recently a lot of ideas about "active optics," i.e., optics which obviously recognize all these shortcomings and provide a system of adjustments to compensate for these deformations.

Structural Stiffness

The structural design is primarily for the fixed instrument geometry required and the support forces involved (gravity forces in the case of ground-based instruments, or launching and drive forces in the case of space-based).

The structural stiffness and the dynamic stability have to withstand the forces of acceleration and all of the variable drive rates. This means that the region in which the auxiliaries (e.g., cameras, photometers, spectrographs) are mounted, effects of these forces on the drive systems, and their effect on the optical system are very important. In the Hale telescope, involving 550 tons (4 500 000 kg), we worry about small forces on the order of 10 lb (45N). Normally such a system in most commercial machinery might involve hundreds of horsepower; the Hale is driven by a small, 0.01-hp (7.46-W) motor. We also worry about thermal inputs that exceed 100 BTU (105 500 J) an hour. Only one observer is permitted on the telescope at one time; it can carry more, but the thermal radiation of a man is disturbing to this optical system, and to pump this heat away from the telescope is a problem.

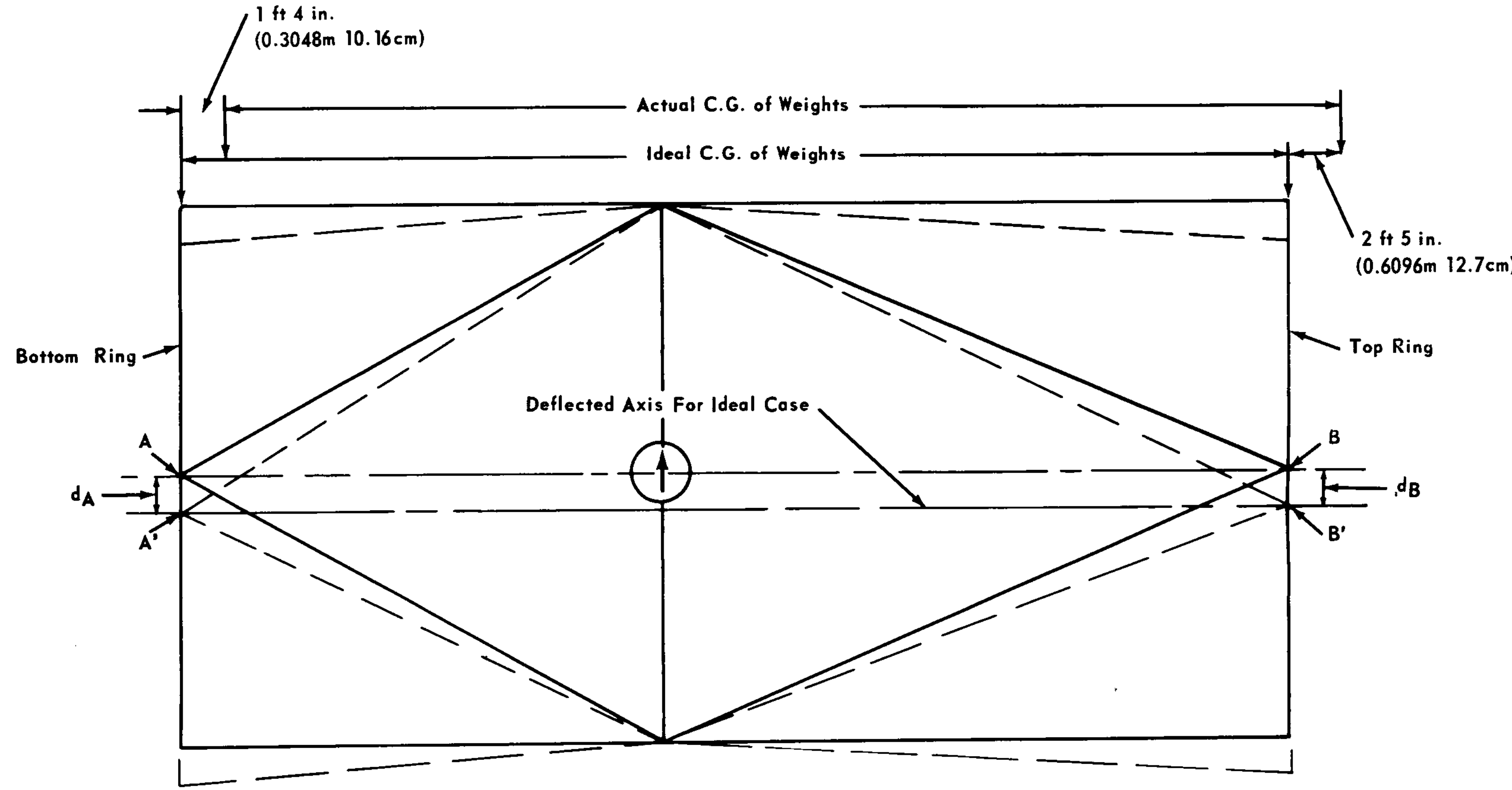
The structural materials must have a high Young's modulus and must be uniform throughout. In a less severe way, the structural material properties have to be pretty well known, with no high modulus rates as a function of temperature. Simply, it should be a very stiff high "Q" structure. No hysteresis effects can be afforded, because they tend to produce deflections that will be extremely difficult to stabilize either by optics or other control measures. Thus, there have to be a few redundant members and many excellent joints.

Mounting surfaces must provide adequate heat sink and heat transfer time constants for the redistribution of thermal gradients produced by diurnal ambient changes and air heat-transfer equilization in the case of ground-based, or by solar thermals in the case of space instruments. It is necessary to maintain the same ambient condition or some steady-state condition during the time of observation. In the case of ground-based telescopes the use of the additional parameter is air convection cooling. These effects are about equal on ground-based and on the spacecraft because there is radiation and conduction of the members themselves.

For the foundation or base stabilization, it should be noted that with land-based large instruments, soil bearing gravity problems are the limiting ones, but there is effectively a large base (earth) to work from, whereas with a space vehicle with very little mass or gravity, the space structure involves problems of low base mass, low inertia, low thermal capacity, low damping, and consequently low perturbation forces, which can disturb the pointing accuracy.

When the absolute structural rigidity cannot be obtained in a very large instrument such as the 200-in. (508-cm) with larger steel members, other tricks or methods of avoiding excessive deflections must be used, such as using the parallelogram tube-bending compensation. This permits the actual deflection of the tube on the order of a centimeter or more at the ends, yet it only allows the misalignment of the optical axis tube less than 0.1 mm for most observations at the horizon.

The parallelogram tube-bending compensation is diagrammed in Figure 2. A cage goes on the upper end and a cell goes on the lower end of the main tube section. This actually has a slot down one side to bring the Coudé beam out and down the axis. The center section is a square box section with a large declination spider and ball bearing that permits freedom of flexure but maintains the exact polar axis. The unique thing about this structure is that these four panels make up a parallelogram so that when this system is tipped from the zenith "look" position to the horizon "look" position the ends that do deflect on the tube structure deflect parallel to the axes. An optical element at the bottom end and an



East and West Faces of Tube

Design diagonals so that $d_A = d_B$. Then in ideal case there is no relative deflection between the ends of the tube

FIGURE 2. DEFLECTION-IDEALIZED TUBE

optical element at the top end then deflect equal amounts and remain parallel so the optical axis remains precisely the same.

The diagram in Figure 2 shows an idealized structural deflection represented by two parallelogram ends without the center. If the framework is supported in the center, both ends would deflect equally. It is also possible to design the members on the side without constraining the center line so that the deflecion d_A and the deflection d_B are designed in the structure to be equal. This is sometimes known as the Surrurier tube design that has been used very successfully on a number of telescope structures and other frame elements. This design can also be used for other ratios of tube lengths. The two ends are approximately equal in case of the Hale telescope, but it is used with ratios of up to 5 to 1 on others by changing the cross section of the member walls, making them thin-walled, very short members at the lower end. The deflection ratio can be made perhaps 5 times greater than the upper end to match.

There are a number of similar designs on the polar mount. The problem here is to prevent torque windup. This prevents deflections in the main tube structure, which supports the 250-ton (230 000 kg) tube in the center, with deflections allowed in such a direction that this angle would always remain exactly 90 deg (Fig. 3). Deflections parallel to sight axis on any instrument are not serious; it is only the angular deviations that count,. as they do in any spacecraft. The illustrated Hale horseshoe yoke (Fig. 3) is supported on oil hydrostatic bearings and is made in the form of a horseshoe so that the tube can reach the polar region. At the bottom end is the spherical pad bearing which takes care of the thrust on the other vertical component of load.

The Young's modulus, E, determines the stiffness of most large structures and the design section geometry. From existing telescope data, a curve can be made to show the distribution of the assembly and the polar axis assembly weights for all modern large telescopes (Fig. 4). Although space telescopes are nearly gravity-free and designed for better lightweight efficiency, the general weight curve required for optical and drive stiffness would still follow such a power function of the aperture size.

The general weight curve in Figure 4 is a recent plot of some of the data of weights accumulated from various telescopes. The solid curve is the total telescope tube weight, the moving tube weight on a declination axis or any other axis which mounts the optical system. The dashed curve, which is of more interest for ground-based telescopes, is the total polar axis mounting. The interesting thing is, for optically very small apertures or very large apertures, these weights seem to fit a curve drawn to a 2.4 power of the aperture, so they seem

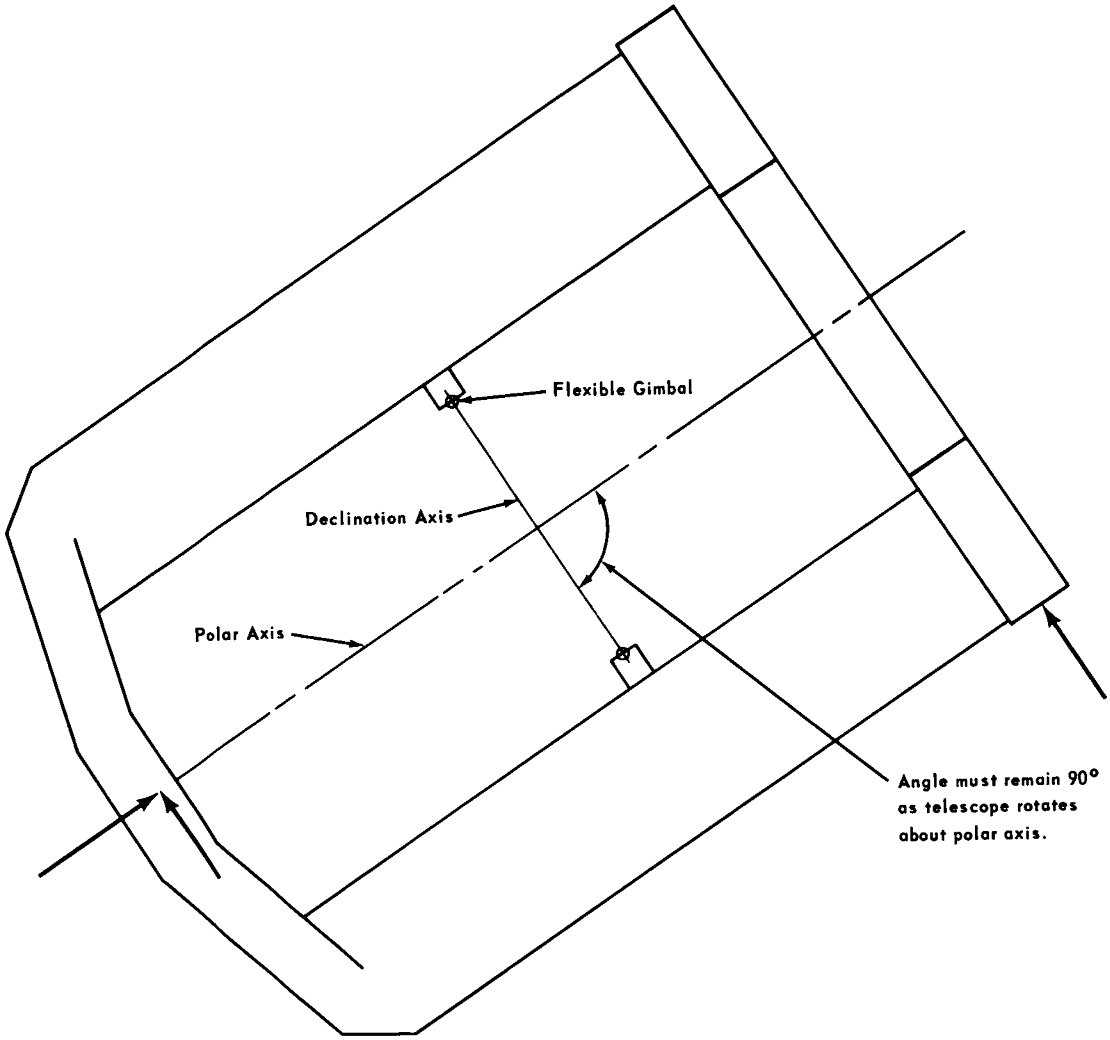


FIGURE 3. DEFLECTION OF YOKE

to follow the 2.5 power curve for the weight, which is the weight curve required for spacecraft for good pointing stiffness. Most optical systems require this sort of stiffness for proper support.

Drive Stability and Guidance

The drive requirements are for very high angular resolution over limited angular fields, if fields can be identified. It is one thing to make a trajectory

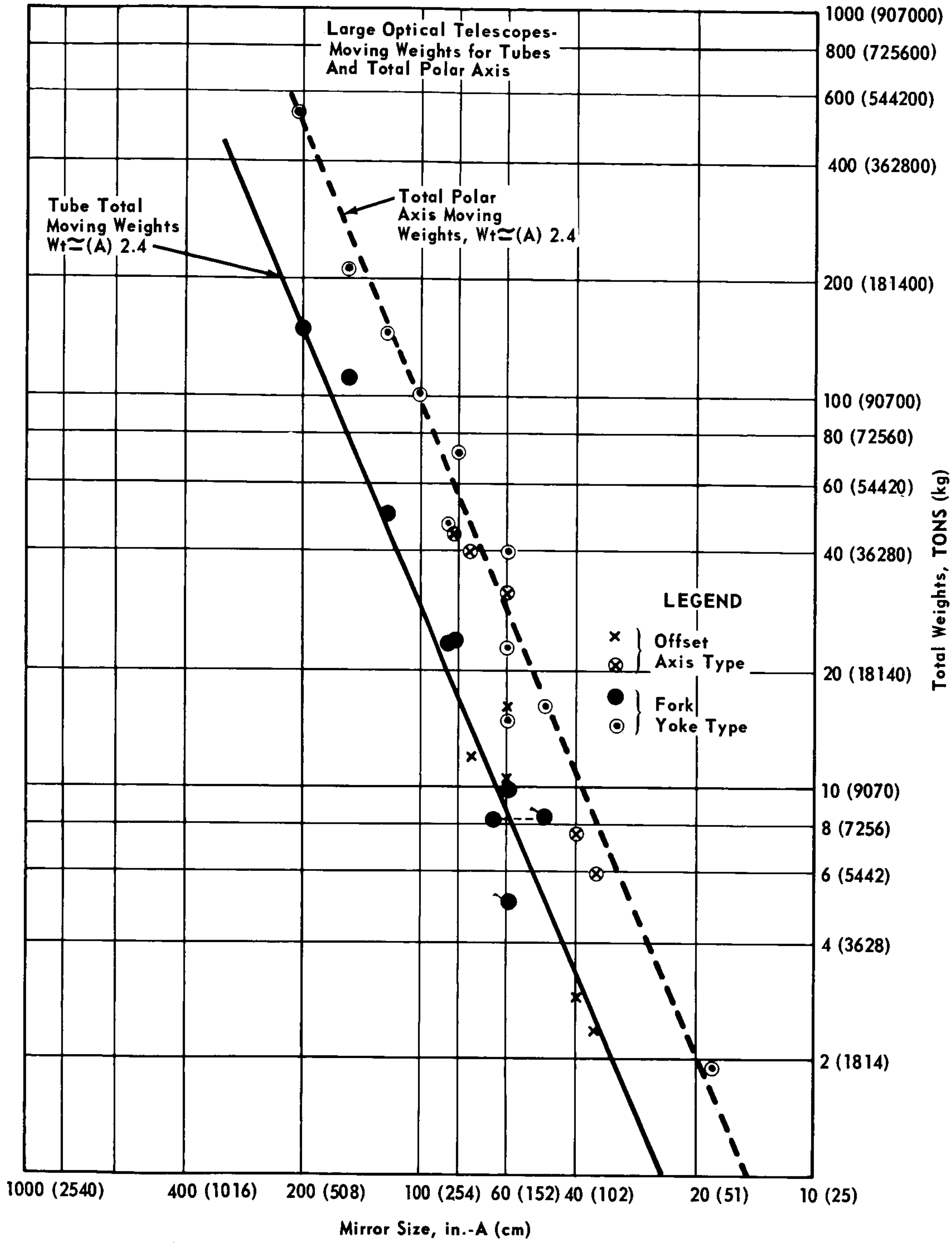


FIGURE 4. WEIGHT DISTRIBUTION FOR LARGE TELESCOPES

plot or something that is moving, but to hold the exact line of sight continuously is another. With a photographic or spectroscopic device, one must aim and hold for the length of time required to get the entire exposure without the image jittering or moving. If one is taking a photodensity measurement, for example, the star image must not be lost from the slit even for a short length of time because it would affect the total exposure time. The accuracy drive requirements are usually at very low rates. The mechanical background jitter effects of variable torques or friction must be small to operate over a fairly wide range of limits. (See Figure 5 showing Right Ascension worm of the 200-in. (508-cm) telescope - west view.)

The guidance reference system for astronomical objects need only be of high relative accuracy with respect to identifiable field areas. Identifications, positions, and observational data, however, are usually referred differentially with respect to celestial right ascension and declination coordinates of known stars.

The drive, for high accuracy, must consider the environmental effects of mechanical reactions, thermal gradients, friction, viscosity effects, and deflection dispalcements due to other component mounting motions.

For the highest image tracking accuracy, it is essential that the mounting structure and the drive system mechanical axis agree very precisely with the real optical image axis. These axes do not coincide very well in most telescope systems and usually vary with pointing position. We are always faced, at one time or another, with the problem of reconciling errors of these three differences.

In addition to these drive stability factors, the overall dynamics of the system must be very carefully considered to allow for all of the effects noted above, in addition to those dynamic periods of the main structure and optics, or any of the coupled vibration modes. One may theorize about the simple bending mode of the tube or the vibrational mode of the mirrors, the fundamental period of the drive system, or the thermal time constants, but it is inevitable that when all these are combined one finds that the coupling vibration modes turn out to be combinations of these frequencies which are sometimes lower than even the lowest separate mode.

As an example of these factors, let us consider several problems in a ground-based telescope. The function of the polar axis drive is to "unwind" the earth's rotation by a sidereal clock rate opposite to the rotation. Other superposed rates in right ascension and declination are then introduced to compensate for mechanical, optical, environmental, and refraction seeing perturbations. Such corrections can be introduced in a stiff open-loop displacement servo system, or programmed from some closed-loop of velocity or rate-type correcting system, only if all errors are <u>within</u> the error-correction servo loop.

For example, with the Hale 200-in. (508-cm) telescope the tracking and rate correcting system is shown in schematic form in Figure 6, does not require pointing accuracy much better than a few seconds of arc for field centering, although the drive is good to 0.''25. Precise track and scan rates are required to about 0.''1/5 sec (this is 0.''02/sec) to take advantage of the unusual times of excellent atmospheric seeing. Stability of this drive must be repeatable and be good to about 10^{-6} over several hours for long exposures.

Table I shows the angular ranges of the Hale telescope. These are the fast setting or slew rates that are associated with the various angles of which the motions are switched out when in the sidereal tracking mode of 15''/sec. The low guiding velocity, which is actually a measure for the optical quality of the system, was originally prescribed at 0.''5 /sec. It was felt at that time that seeing could not be better than 1''. We now have bettered this, and other telescopes also have reduced this requirement down to on the order of 0.''2/sec. These are the very low guiding motions required to take out seeing perturbation motions, oscillations, etc.

Setting velocities are usually established at a factor of 10 to 50 times above guiding rates. The setting velocities are sometimes used for fast scanning rates, and the velocity is 45°/min.

We have provided for systematic corrections for tube deflections, but because the structural compensation was so good we didn't have to use it. There is a maximum velocity rate correction of about 270''/hr. These are for atmopsheric refraction, deflection, or other corrections. For varying the rates for lunar-planetary objects, a range of ten times greater is provided. To track the moon from the earth, for example, requires rates up to about 2700''/hr, but for very slow drift rates we can go down actually to one second per hour. Thus, that range extends 10 000 to 1.

The maximum accumulative errors (and we are well under this now) is about 1''/hr, although in the extreme limits of the horizon look the refraction error is so much larger than this that it really doesn't matter.

The overall accuracy for gear drives required by original specifications is about 5'' for overall setting, but it is now good for about 0.''33. The Hale has

TABLE I. TELESCOPE DRIVE CONSTANTS

	RIGHT ASCENSION	DECLINATION
ANGULAR LIMITS (deg.)		
Polar Axis Mounting	±105	N + 91
Tube--arch-crane down		S - 57
Tube--arch-crane up		S - 43
Tube--above horizon slew limit	5	5
Tube--above horizon final limit	2	2
Phantom limits (artificial horizon)	5	5
MOVEMENTS		
Tracking velocity, arc sec/sec.	15	
Guiding velocity, arc sec/sec.	1.5	1.5
Setting velocity, arc sec/sec	40	40
Slewing velocity, deg/min	45	45
Slewing acceleration and deceleration, deg/min/sec	4.5	4.5
CORRECTIONS		
Limits, arc sec		+ 50 -100
Maximum velocity, arc sec/hr	270	270
Time constant, sec	15	15
Maximum superposed rate, arc sec/hr	2700	1000
SPEED RANGE		
Manual, low to high	1/1800	1/1800
Automatic, low to high	1/36 000	1/36 000
RATE OF DRIVE		
Maximum accumulated errors, arc sec/hr	1.0	1.0
Maximum momentary error, arc sec/5 sec	0.1	0.1
Overall setting accuracy, seconds of arc (within 45 degrees of zenith)	5.0	5.0

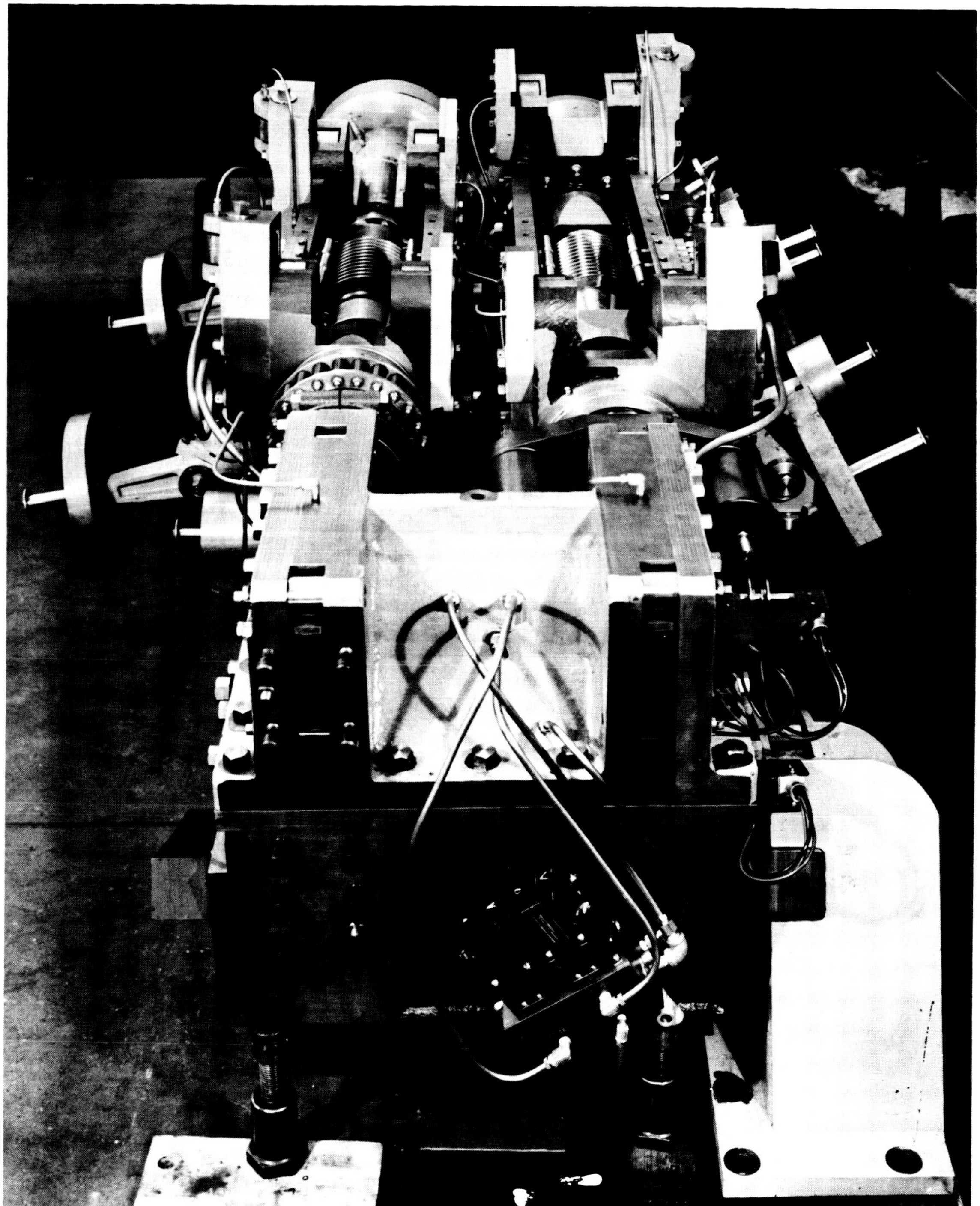


FIGURE 5. RIGHT ASCENSION WORM UNIT OF THE 200-in. (508-cm) TELESCOPE

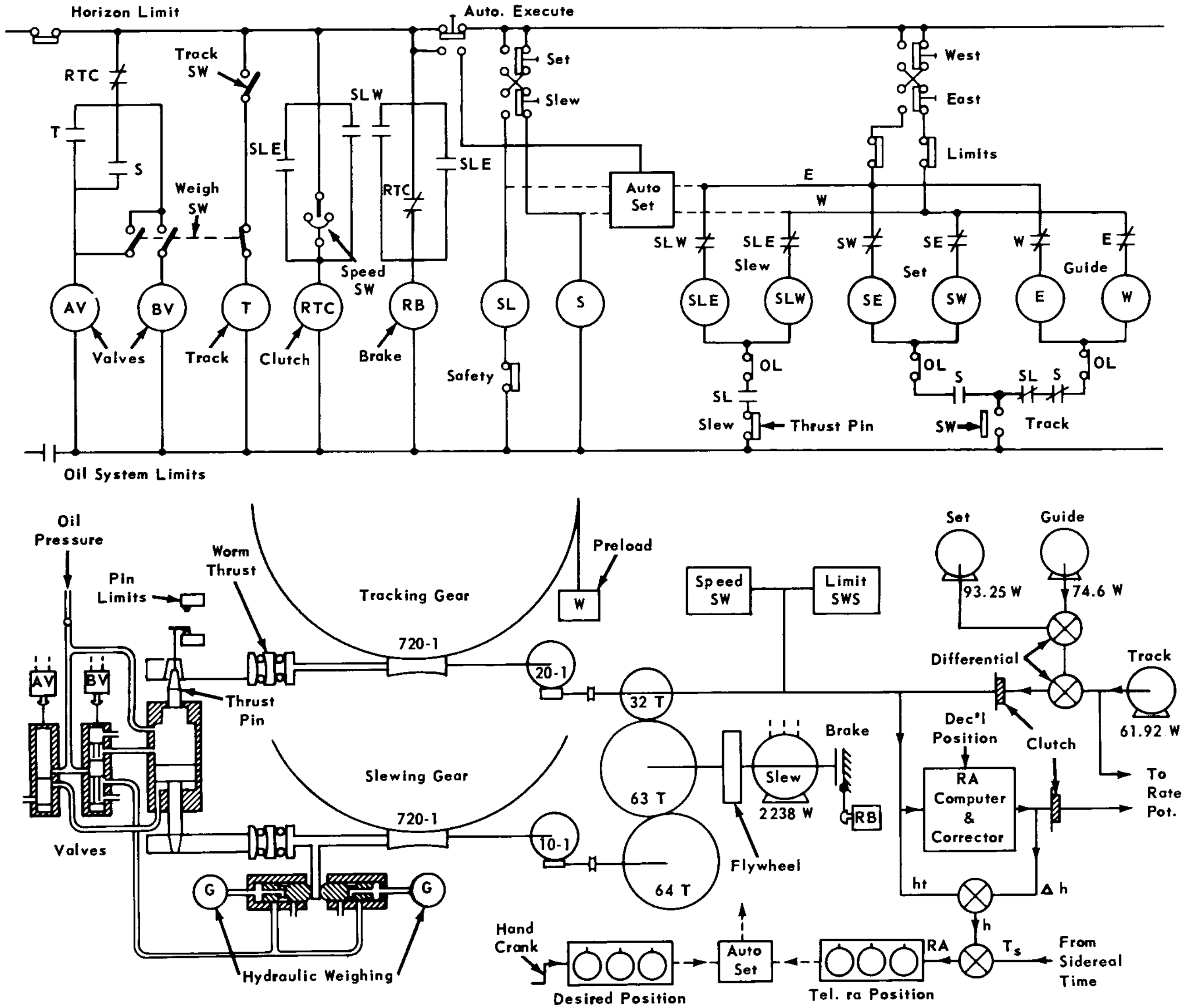


FIGURE 6. TRACKING AND RATE CORRECTING SYSTEM (Schematic)

two gears, the slewing gear (for fast motion) and the fine tracking gear (for slow motion), each of which is driven by a precisely mounted worm (Fig. 5). The reason for two gears is to control loads and wear rates. Each is a very precise gear with a 14-ft (4-m) diameter and a tooth-to-tooth gear error of less than 0.0002 in. (0.0005 cm). For the Hale and Schmidt telescopes, we built all our own gears. We ground them to locations by optical methods in a constant temperature room.

Because the slewing forces of acceleration are 50 times what they are for general tracking, we wanted to protect the fine tracking rate worm. We built two gears alike, picked the best one for fine tracking and used the other one for slewing rates.

One might ask, how do you load worm wheels that are permanently geared together? For this system two gears are connected. If any shaft in this system is operated, both worms turn but nothing happens to the worm wheel unless end thrust is taken up on one of the two worms. Either one can be chosen to be driven if a fixed end thrust is provided on the one desired. This end thrust is in the form of a fixed pin driven by a hydraulic ram with a tapered surface, which is in nominal position for failure of oil, power, or anything else. This always puts it down in the safe slewing drive position. Even if there is a total loss of power, it is automatically put within the deceleration region down on the slewing drive. When this pin ram is in the upper position, the end thrust on this fine worm is fixed so the tracking drive is engaged. If the ram is left in the intermediate position both ends are free, to a limited degree. This freedom allows one to weigh it or use it like a beam balance for actually weighing the unbalance of the telescope, which is usually kept down to about a man's weight of 200 lb (80 kg). The tube weighs 250 tons (200 000 kg) and is balanced to ± 100 lb (50 kg).

The rest of the gear train is rather conventional. There is a constant rate tracking drive to provide the sidereal rate and the correction side rates that are put in differentially.

Figure 5 shows an entire carriage which is supported entirely free of the base of the telescope. In a circular track there are slide members, which are held by the slip damper ram at the other end for motion impact from accidents. If the whole carriage shifts by accident, the center position in the reference system, which is good to about 10", shifts the alarm until it is reset.

The horseshoe polar mount, diagrammed in Figure 3, is supported on hydrostatic oil bearings. The oil pads on each side of the horseshoe are 30°

from the vertical. Each carries some 60 000 lb (27 000 kg), and on each there is a little roller microswitch. The microswitch reads out the oil film thickness to about 0.0002 in. (0.0006 cm). The film operates normally at about this thickness; if it drops below this level, it automatically shuts the telescope system down. The south bearing is quite similar to the north.

The unusual feature about this whole system is the vibration damper. The moving weight of the Hale telescope has a moment of inertia of 10^9 lb ft^2 ($4 \times 10^8 \, . \mathrm{m}^2 = \mathrm{N} . \mathrm{m}^2$) and an absurdly low coefficient of friction of 10^{-6} for its hydrostatic bearings, which is about 1000 times lower than the best ball bearings. Initially there was very little damping for this low friction until a viscous-type damper was added to the polar axis (Fig. 7). The axis requires only 50-ft lb (70 m.N) torque to move the telescope, and without such a damper the telescope freely oscillates at its lowest coupled torsion mode period of 1.4 sec with an amplitude exceeding 15'' or 20'' at the prime focus. This undamped oscillation lasts for several minutes or longer, but with the viscous damper coupled at the north horseshoe, these oscillations can be brought down to 1/e or to 0.''25 in about 1.3 sec of time (or $1\overset{s}{.}3$), and maintained to less than this only if the observer is careful how he moves.

For space telescopes one must consider the local effects of manned personnel including the varying stress, deflections, heat, and momentum changes and also possible other similar effects of power drive units. These effects are annoyingly present and affect all of the above items of optics, structure, drive, and guidance techniques.

Control and Readout

There are obviously many other problems concerning the integration of required detection instruments with their associated readout and telemetry facilities, together with technical problems of data readout transmission and reduction that are being carried out to effectively upgrade the Hale and other telescopes in process. New techniques include visual readout and modernizing in all of the Palomar-Mt. Wilson telescopes and include new third generation detector instruments. For our future systems we supplement these analog components with digital readouts and pulse count techniques on instrument readout.

There are basically two time standards that are used by a number of observatories. One consists of a string vibrating in one mode. The string can be made to vibrate very precisely to one part in a million. What is even more

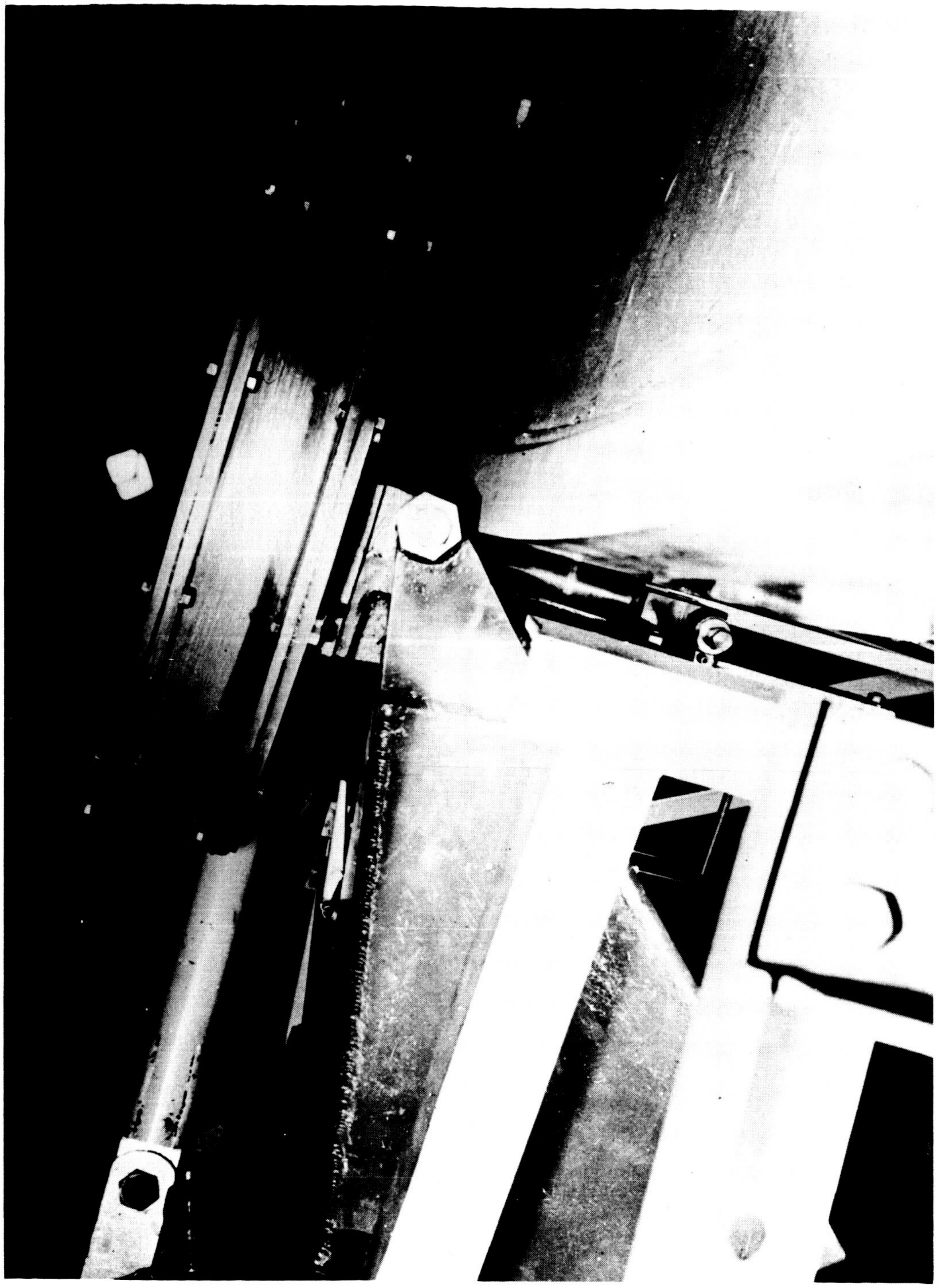


FIGURE 7. VISCOUS DAMPER AT THE 200-in. (508-cm) NORTH POLAR AXIS

interesting about the vibration standard properties is that one can then adjust the values on the weight on these strings and can put a glass housing over them to make them independent of barometric pressure.

It is very easy to change the right ascension standard by a small dc coil at the bottom of the string mass. This can be very precisely controlled from essentially 0 up to $\pm 1\%$ of the basic rate. Only 0.5% is required for corrected RA rates without disturbing the fundamental accuracy. Other methods of possible time standards are multivibrators or digital clocks. These were of particular concern to us 20 years ago because we could then feed into the clock system the analog correcting rates required for either refraction, deflections, or any other program errors, and this has been quite a valuable method.

The same system is used for manual control of rates, which are put in by the operator in most cases. The refraction errors caused by atmosphere don't become very large until you go beyond 3 or 4 hours from zenith.

We actually have three time standards; the one is used for the RA rate standard, another is used for sidereal constant rate, and the third is standby and can be switched either way. These are downstairs in a separated room and have been operating for 20 years.

DRIVE RATES AND STABILITY OF LARGE TELESCOPES

It may be of interest to report on the Hale telescope drive and guide rate status. The ultimate proof of optical telescope drive accuracy is in the quality of the photographs, spectrograms, or detector output. To assist in obtaining qualitative information on these rates and to test schemes of measuring such performance by mechanical-optical tests instead of the usual nighttime star photographs, supplemental tests were conducted a few years ago.

Most of our measurements are taken from the eyepiece in the telescope or from the photographic plates, which must be made at night, and which require developing and assessing. This is a slow process. To find some rapid way of measuring these rates, we set up a midarm grating device on the telescope to measure rates in the daytime (Fig. 8). Rates and vibration periods were measured at various places on the telescope.

The drive characteristics show less than a 0.2% deviation for long times at any set slow rate. Normal sidereal tracking is done at 15"/sec up to faster

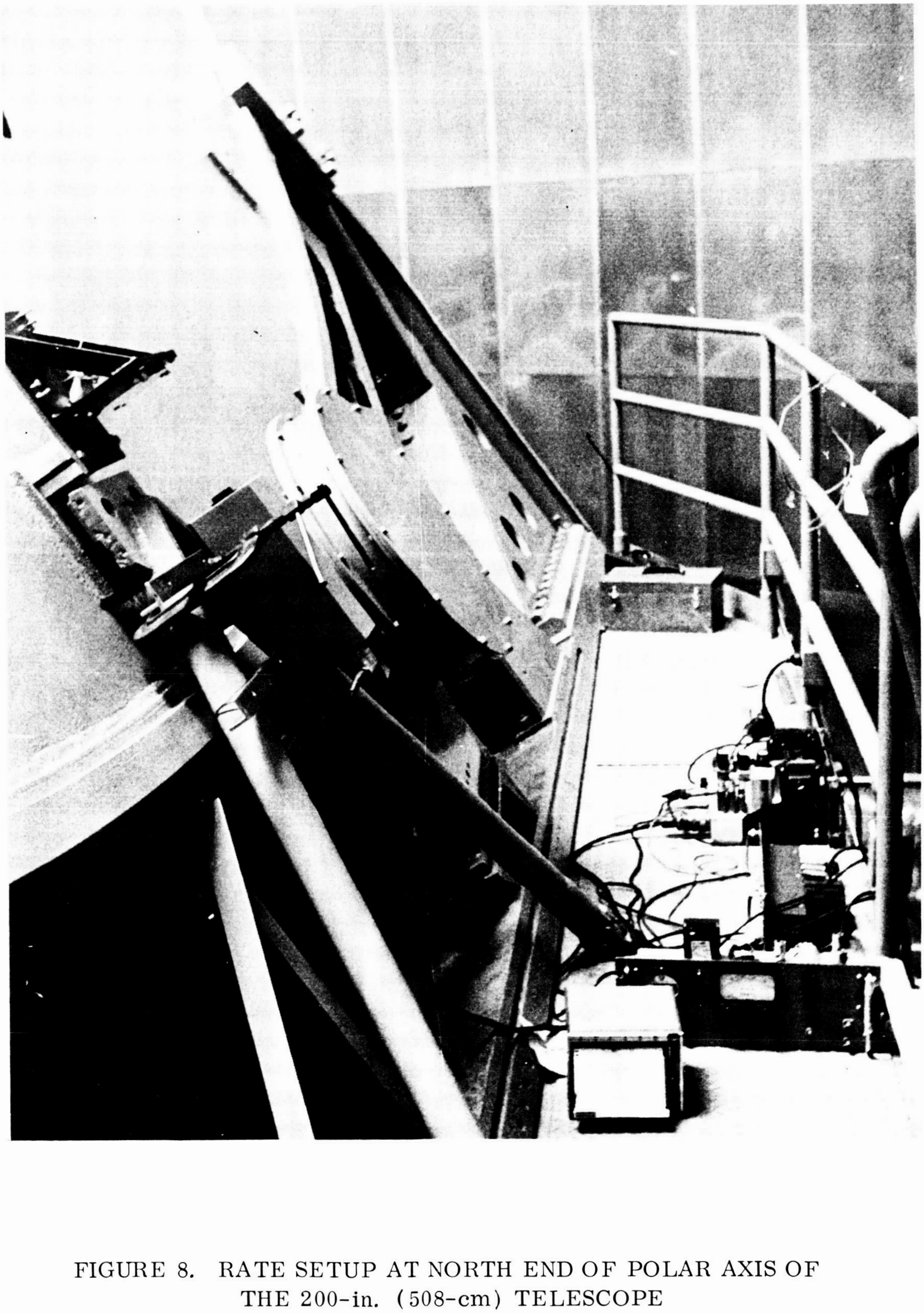


FIGURE 8. RATE SETUP AT NORTH END OF POLAR AXIS OF THE 200-in. (508-cm) TELESCOPE

guiding rates of 45''/sec. In addition to this, superposed rates are used for corrections, refraction, scan rates, etc., from 900''/hr down to 3''/hr (0.0008°/hr). Stability at these rates is better than one part in 10^{-5}. The range of these rates is 54 000 to 1 (3''/hr to 45''/sec). Added to this is the smooth, fast slewing rate having a range ratio of 10 800 above this (track 15''/sec to 1/8 rpm) for the full 550 tons (500 000 kg) of telescope moving weight.

APPENDIX, QUESTIONS AND ANSWERS

Q. Suppose you aim at some star in the sky before you opened up the dome, or at least before you looked out. How close to this star by means of the circles can you come? What arc distance can you get to a star starting at random in some part of the sky, say, at 45 deg elevation?

A. Although we don't require this capability in operating, usually it is within 5 sec. If you tune up the readout system and check out the calibration reference, this can be done to 0".25. If you are working through the night and had all these trackings continuously built into the drive equipment, and then you set to a new place in the sky to, say 30 deg off, you might come to 0".25. That is the readout accuracy. The mechanical accuracy could be somewhat better than that but with the servo system and analog readout our smallest dial division is one second. Thus, we read approximately one quarter of division, and that is about the backlash in the system. However, with the digital or some other type of better readout we presumably could do ten times better than this! For our purpose it is not required. The field identification is the real problem, and the tracking and the correct rate is the essential requirement. We must have very smooth rates to 0".1.

Q. Is this true of quite a number of other observatories, or are relatively few this far advanced?

A. I think there are relatively few that are this good, although the KPNO Kitt Peak group is gradually getting these same parameters. Optically they are as good. The 84-in. (213-cm) at Kitt Peak is still undergoing some optical adjustments. They are trying to introduce better drives by going to torque drive or combination stepmotor and torque drives. There are quite a number of attempts being made to do the servo-problems better. We are hoping it will be a big step forward for Palomar. We hope to make our new 60-in. (152-cm) photometric telescope as good as the 200-in. (508-cm), and this will be quite a feat. To do this with a support and mechanical system, it requires usually a very large base line like the 200-in. (508-cm). A 60-in. (152-cm) diameter means that you know a lot more about the problems.

Q. You said that you maintain the nighttime temperature in the day. Is this true in all seasons?

A. We actually don't maintain it; we stabilize it at the average nighttime temperature. The temperature varies throughout the year. The outside temperature varies diurnally from day to night, and we have an insulated space in the dome. This inside variation is kept very small. We let this come to equilibrium at whatever the long range deviation of this temperature is, seasonally. It just depends on the heat transfer time. If you have a sudden change in weather, you end up with perhaps a higher temperature inside and have to ventilate more to bring it down faster. When we observe, the temperature will usually be within say 2 deg of the previous night's temperature. The rate of change of the night temperature is small. The mirror, which is exposed to the night sky, sees a different set of temperatures. We have to equalize this as well by insulation and fans.

Q. If you operate 364 days out of a year, approximately how much of that time do you shut down for maintenance?

A. Speaking as an engineer, the telescope has to be available every night of the year except once every few years. We take the mirror out for two days to realuminize it, and one day every six months we take it out during the day to wash it. For the latter, we have it back for the night's run. Mechanically, the statement is true; it is operable throughout the year, but daytime adjustments can be made. Spectroscopy can be done under immensely worse seeing conditions than can direct observation. If you include all nights of observation, roughly 70 percent of the year is usable. This is one of the site selection problems, to pick a location which is sky transparent and clear enough to use many nights. If you talk about the available number of seeing nights at prime focus, it is considerably lower. All astronomers have a series of priority programs on which they can operate under different weather conditions. Observation time is assigned to different astronomers and different institutions. You take your weather luck along with anyone else.

Q. How does the midarm rating device work?

A. If you have an axis which is rotating, you can put a grating or a picket fence ruled grating on the end of it, look at it with an optical system, and measure the rate at which the fringes go by. This particular one (Razdow Midarm Type) had a sensitivity that will show up 12" for one cycle of the picket fence period, so by timing this with a clock or digital timer you could then produce the rate of rotating very precisely. We could actually determine the rates of rotation to something like 0.008°/hr, which is $0\overset{''}{.}01$/sec. This means that we could determine rates to essentially the factor of 20 below what our system could resolve.