SCLERA: an Astrometric Telescope for Experimental Relativity

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An $f/100$, 12.2-m focal length photoelectric telescope designed specifically for daytime astrometry of objects near the sun is now operative at its Tucson, Arizona, site. The design goal was to achieve accuracies of order 0.001 sec of arc in field position measurements of stars. To accomplish this, many features reducing systematic and random errors are employed, including Schupmann medial telescope optics, compensation for lateral color aberration, apodization for reduction of diffracted light, and use of an accurately measured solar diameter for calibrating the field.

Introduction

Using an astrometric telescope specifically designed to achieve accuracies of 0.001 sec of arc, Zanoni[1] proposed to measure the gravitational deflection of light to 1% by photoelectrically determining the positions of stars relative to the sun as they made a solar transit. Actual construction of the telescope was begun in 1966, supported by the facilities of Wesleyan University and the University of Arizona. This description of the recently completed instrument will emphasize techniques that have been developed to reduce or eliminate systematic and random errors in the star position measurements.

Although highly specialized for this primary experiment, the telescope is ideally suited for other small field precision astrometry including solar oblateness measurements, nighttime stellar parallax and proper motion studies, planetary perihelia advance measurements, and determination of the secular variation of the Newtonian gravitational constant.

Before discussing aspects of the telescope in detail, it may be helpful to remark that most design specifications have derived from three requirements: (1) Symmetric images must be formed so that center of the image can be unambiguously defined. This led to specification of low coma and correction for lateral color introduced by wavelength dependent refraction in the atmosphere.[2] (2) Low scattered and diffracted light levels must be produced to reduce background shot noise and gradients in background intensity. This requirement influenced the site selection as well as the objective apodization technique,[3] choice of a singlet objective, and specification of coronographic optical surfaces, i.e., surfaces producing scattered light intensities of the order 10^{-6} times that of the solar image at a distance of one solar diameter from the image.[4] Calculations indicated that with this level of instrumental background and a 10-cm aperture, shot noise from sky light was the factor limiting the accuracy to which star position could be determined. (3) The scale of the field must be known precisely. To remove gross scale changes, the separation between the nodal point of the objective and the image detector is controlled to 1 part in 10^7. In addition, the solar diameter is used to normalize sun-star separations. This corrects for remaining first order scale changes resulting from optical aberrations and from differential atmospheric refraction. For reasons related to all three requirements, the telescope is also evacuated, and only the first surface of an entrance window is exposed to air.

General Description

The basic configuration of the telescope, shown in cross section in Fig. 1, is that of an elevation-azimuth (El–Az) mirror pair that directs light vertically downward through a singlet BK-7 objective having a 12.2-cm aperture and 12.2-m focal length. Light reaching the primary focus passes through a color-correcting folded Mangin optics system extending 2.4 m downward from the primary focus. The achromatic secondary image is formed by the Mangin system near the primary focus at $\lambda = 486.1$ nm. This is a variation of the Schupmann medial telescope discussed by Baker.[5] The entire optical system is mounted to a structural steel cage enclosed by a separate concentric vacuum chamber. The telescope is

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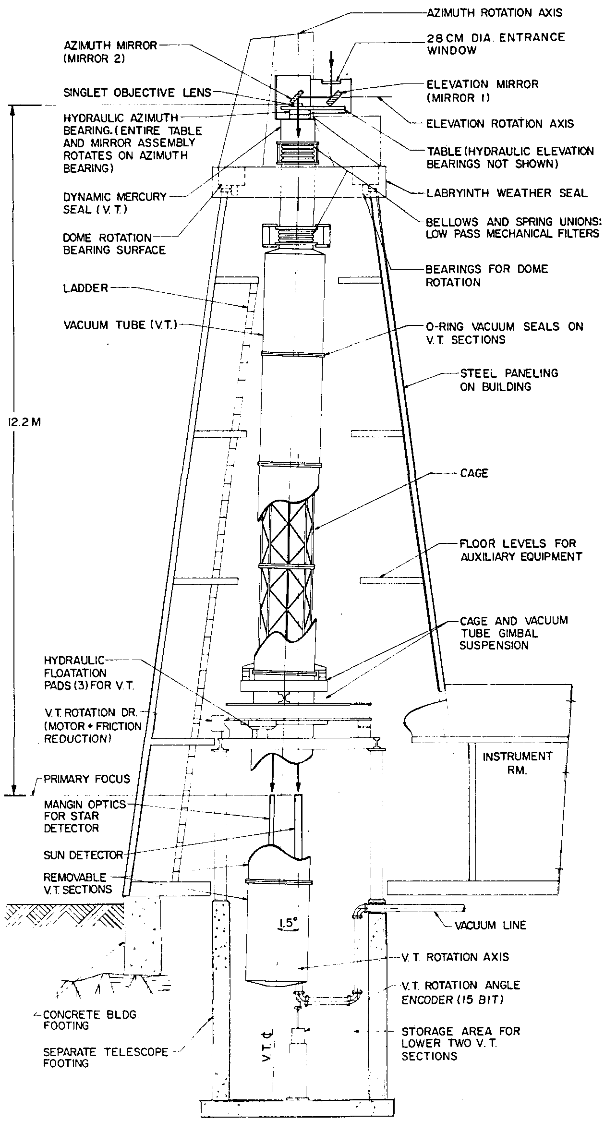

Fig. 1. Cross section of the telescope.

further enclosed in an eight-sided tower providing a thermally controlled environment and protection from the elements. Contiguous to the tower are rooms for electronic instrumentation, heating and air conditioning plants, and a room for cleaning and testing optics. The building, shown in Fig. 2, is in a pine forest at 2960-m elevation in the Santa Catalina Mountains 61 km by road northeast of Tucson, Arizona. (The acronym for the project is SCLERA: Santa Catalina Laboratory for Experimental Relativity by Astrometry.)

Primary Optical System

Although the achromatism of a reflecting system is a desirable property for broadband measurements, there is a basic difficulty when using a mirror to form the primary focus of a field containing the sun. For a coma-free field, the aperture stop must be located at the center of curvature of the mirror. This placement of the aperture, however, insures that the solar flux illuminates the mirror nonuniformly. It is unlikely that one could compensate for the resulting thermal distortion of the mirror figure to the degree required for astrometry, and this conclusion led to consideration of refracting systems. Achromatic multiplet objectives rely upon cancellation of intrinsically large spherical aberrations from each surface, and multiple reflections from each surface contribute to background light.

A singlet objective avoids these problems and has the advantage that with spherical surfaces and a large f number, detectors can move on a spherical surface of radius F equal to the focal length and yet remain in focus. This property is important in the scheme discussed below for controlling the distance between the detectors and the nodal point of the objective. Consideration also of resolution, seeing dependence upon aperture size, and physical scale of the instrument led to the choice of a 12.2-cm diam,

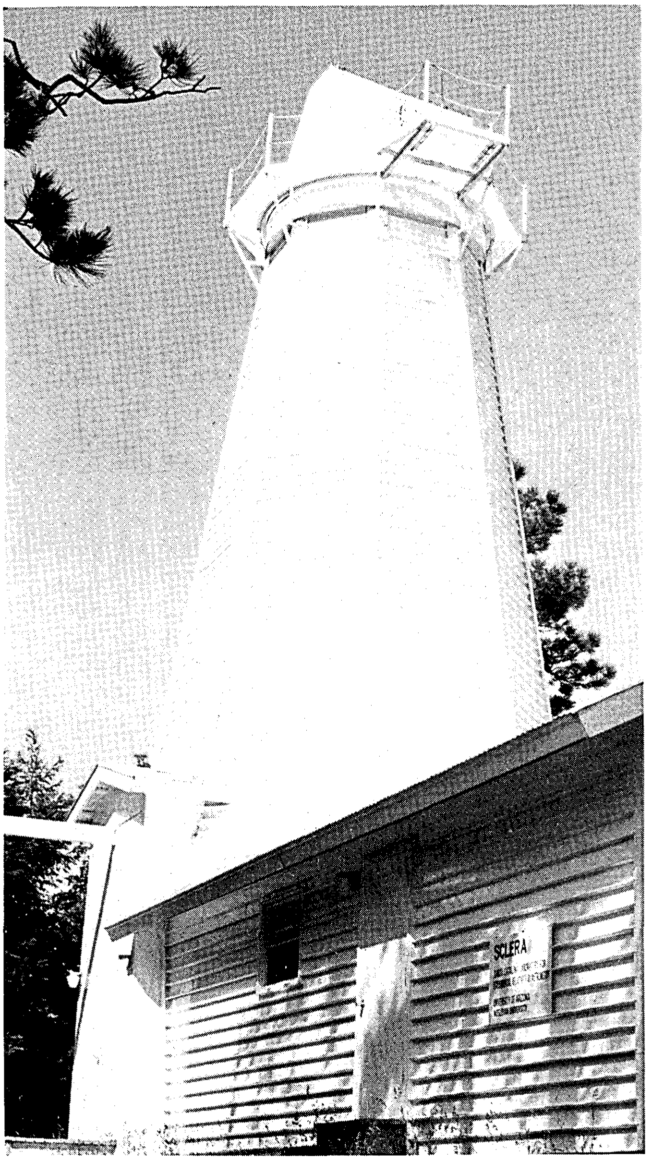

Fig. 2. The telescope at SCLERA.

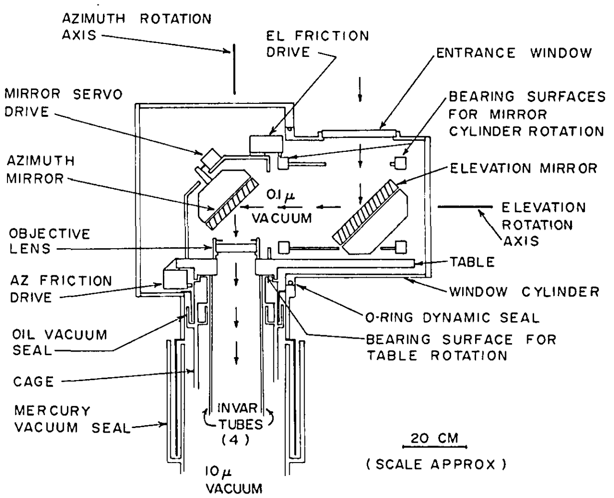

Fig. 3. Detail of primary optics system in dome.

12.2-m focal length objective made of Schott BK-7 borosilicate crown. The shape factor of the lens was chosen to produce zero third-order coma at 500 nm, and 0.010 sec of arc of coma per 100-nm bandwidth results. In the case of the objective lens as well as the vacuum window, the $\lambda/20$ figuring tolerance could produce as much as 1 sec of arc of coma; however, the variation of this coma with field angle produces the important contribution to systematic error, and this variation is only 0.001 sec of arc over the 3° field of the telescope.

A square aperature is fixed to the objective lens. Zanoni and Hill[3] have shown that this apodization reduces the diffracted light below that from a circular aperture by a factor of 10^4 for one-half of the azimuthal field and for distances greater than 400 sec of arc from the solar limb. This apodization technique is an improvement over the usual Lyot coronograph technique in which stops separated from the objective are used to occult light from the solar disk and from diffraction maxima produced by the entrance pupil. Uncontrolled motion of the stops orthogonal to the optical axis is difficult to avoid and results in changes in the instrumental aberrations.

Specification of the objective lens essentially determined the remainder of the telescope design. With a 12.2-m focal length it is desirable to have a vertical instrument to prevent flexure of the structural members under gravitational forces. A vertical instrument requires a mirror system for directing light through the lens, and the El–Az tracking configuration chosen provides a means of precisely determining the aberrations in the field, as discussed in the section on Scale Determination.

The El–Az mirrors are aluminized blanks of quartz and are flat to $\lambda/10$. They are mounted at 45° to the optic axis, as shown in Fig. 3. Quartz was originally chosen in preference to other materials such as Cervit to minimize flexure under solar heating and to provide a material that could be given a coronographic polish. Polishing techniques on Cervit have improved greatly in the meantime, and installation of a Cervit pair is anticipated in the near future.

Consistent with uniform illumination and smallest possible surface area (in order to minimize the overall physical size of the mirror mountings and enclosures), the flat surfaced mirrors have an elliptical circumference. Heat transfer through the mirrors is controlled by containing the mirrors in a 0.1-μ vacuum and providing cooling coils close to each mirror back. Oil that fills the chamber containing the mirror suspension provides thermal contact between the mirror and cooling coils. With these arrangements the thermal gradient is perpendicular to the front and back surfaces and produces a spherical bending of the mirror. The radius of curvature can be calculated from the measured temperature gradient, and hence the aberrations caused by the curved mirrors may be calculated as well as measured by the principle to be discussed below.

The mirror mounting is designed to permit flexure of the mirror without constraint as well as to prevent dimensional changes in the mirror cell from deforming the mirror. Eighty conical brass pads are epoxied onto the mirror back in a grid pattern. Soldered to each brass pad is a steel wire that has its other end pressed into a shaft. The eighty shafts connect to a system of spring-loaded lever arms that ultimately transfer the mirror's weight to a kinematic three-point connection with the magnesium mirror cell. The system of levers has balanced moment arms so that motion of the mirrors, as in El–Az tracking, will not produce torques in the suspension. A similar suspension set on a side of the mirror constrains motions of the mirror parallel to its reflecting surface.

The elevation mirror cell is mounted in a cylinder having precision-ground bearing surfaces around each end. The cylinder rests in a cradle formed by a pair of hydraulic bearing pads engaging each bearing surface. Rotation of the cylinder in the cradle defines the elevation rotation axis.

The azimuth mirror cell is suspended with leaf spring pivots on a gimbal inside a steel frame that rests upon the table in common with the elevation mirror assembly. A 25-cm lever arm extending from the back of this mirror cell connects to a leaf spring arrangement that permits two loudspeaker voice coils with orthogonal axes to rotate the mirror cell in its gimbal. The voice coils are driven by servoerror signals produced by lack of solar image centering upon four silicon photovoltaic cells located in the primary focal plane. This image centering servosystem is called the primary tracker. The primary tracker servo has a low frequency pole at 0.2 Hz and has unity open loop gain at centering error frequencies of 40 Hz. Thus the azimuth mirror compensates in part for seeing disturbances affecting the whole image.

The filtered outputs of linear position transducers attached to each voice coil are combined with the El–Az tracking rate signals calculated to 1% by an on-line computer, and these signals drive the El–Az servomotors. By this means, very small position errors are sufficient to correct the 1% error in the rate

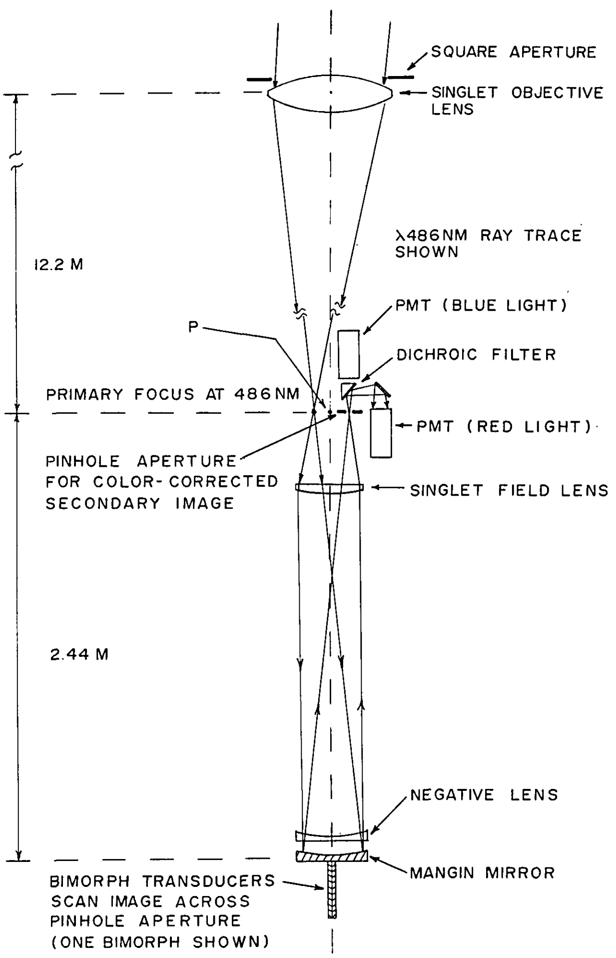

Fig. 4. A simplified drawing, not to scale, of the modified Schupmann medial telescope as used for star tracking. Rotation of the Mangin optical system about point P compensates for lateral color aberration.

calculation. The resulting amplitude of solar image motion on a fractional-second time scale is below 0.25 sec of arc.

The objective lens cell is mounted on the table below the azimuth mirror, and rotation of the whole table on three hydraulic bearing pads defines the azimuthal rotation axis. The entire load upon these bearings is approximately 270 kg.

Hydraulic bearings and friction reduction drives are used for the El-Az rotations as well as the vacuum tube rotation to produce a low mechanical noise, low friction tracking system.

Secondary Optical System

The nominal 12.2-m focal length of the singlet objective varies by 20 cm/λ100 nm. Tracking accuracies required for measurement of the deflection of starlight necessitate a broadband detection scheme, and it is therefore important to correct for this longitudinal color dispersion. The correction is accomplished, as mentioned, by using a type of Schupmann Mangin that will be described in detail in a separate paper.

Briefly, the Mangin designed has a singlet BK-7 field lens located 91.5 cm below the primary focus at λ_0 = 486.1 nm. The field lens images the objective stop onto a BK-7 negative lens-concave mirror pair located 244 cm below the λ_0 focus. The reflected light passes again through the negative lens and field lens and forms the secondary focus of the image that has been color corrected through cancellation of the powers of the objective lens and negative lens. The secondary image is conjugate to the λ_0 primary image and is displaced 12.7 mm from it.

At no point is an image formed on a lens surface, and problems caused by dust or surface imperfections are thus greatly reduced, in contrast to Mangin designs having a primary focus at the field lens.[2,5] The color correction achieved is a variation of secondary focus of ±2 mm from λ365 nm to λ768 nm. The depth of focus of the objective lens is ±1 cm.

A very important property in addition to longitudinal color correction derives from use of the Mangin.[2] The Mangin can be rotated about the point P on its optic axis in the λ_0 image plane to reduce lateral color in the primary image by a factor of 100. This lateral color results from wavelength dependent refraction in the earth's atmosphere, in the vacuum window (which has a 15-sec of arc wedge to separate multiple reflections), and in the singlet field lens. The separation of the extreme red and blue images of a star may thus be reduced from the 1 sec of arc typical at a 45° zenith angle and 3-km elevation to 0.01 sec of arc. A servosystem is used to rotate the tube holding the Mangin optics until the red and blue images of a star are superimposed.

Still another modification of the Mangin system has proved to be invaluable, but to describe this a digression is necessary to explain the nature of the image detection method used with this telescope.

By scanning across a secondary star image with a pinhole aperture, or across the solar limb with a slit aperture, the light passing through the aperture into photomultipliers is converted from a spatial distribution into a signal in the time domain. The phase of certain harmonics of the signal, relative to the scanning waveform, is related to the sense of the displacement of the aperture from the spatial center of the image, and phase sensitive detection of these harmonics thus provides error signals for a servoloop that centers the aperture. The separation of apertures in the field is then measured to 0.001 sec of arc or λ/8 by a He-Ne laser interferometer using polarized coincident beams in quadature and fringe counting electronics. Each distance to be measured, sun-star separation or solar diameter, is thus one arm of an interferometer.

To reduce the time response of the fringe counting electronics and the centering servo and to eliminate motion of the exit pupil at the scanning frequency on the photomultiplier, images are scanned across the apertures. The modification of the Mangin that accomplishes this is the mounting of the Mangin mirror on a bimorph,[6] a slab consisting of a cemented pair of poled piezoelectric crystals that bend through an angle accurately proportional to the voltage applied across the slab. Thus the bimorph is a convenient, linear, voltage-to-position transducer used to rotate the small Mangin mirror, resulting in scanning of the image across the pinhole aperture. Since two orthogonal scanning directions are required to define the center of the star image, two appropriately mounted bimorphs are actually used, and each is driven at a different frequency. The pinhole aperture, together with the relatively massive optics attached to it, is centered by a servo having a response time approximately ten times greater than the period of the scanning waveform.

This technique, of course, requires that the average alignment of the Mangin mirror with respect to the primary star image be controlled to 10^{-8} rad if the secondary image is to be measured to 0.001-sec of arc accuracy. An auxiliary optical system that will not be described here accomplishes this.

Motion of the solar image across slits on opposite limbs of the image is obtained in a somewhat different manner. Detection of the solar limb is performed using λ10-nm bandpass filters, and consequently no color correction is required on the limb. It is important that both limbs of the image move together across their respective slits, however.

The azimuth mirror and its fast servosystem are used to scan the primary image of the sun across the limb slits. Four Mangin systems placed symmetrically around the limb of the image focus light from four areas of the limb onto the photovoltaic cells that provide the primary tracker centering error signals. Applying a sinusoidal voltage to a bimorph supporting each Mangin mirror moves the secondary limb image on the photovoltaic cell, and the azimuth mirror must rotate to null this displacement of the secondary image. Servoing the azimuth mirror to track the linear bimorph transducers in this manner produces the desired primary image scan.

Principle of Scale Determination

Consider first the problem of controlling field scale changes that result from variations in the separation F of image detectors and the nodal point of the objective and the problem of moving the detector on a spherical surface of radius F. A pair of 6.25-mm diam Invar tubes extends from near the nodal point to each detector. A servosystem adjusts the vertical position of each detector so that each aperture lies along a line joining the lower ends of respective pairs of tubes. Circulating through each tube is a fluid, temperature controlled to 0.1°C. This keeps $\delta F/F < 1 \times 10^{-7}$, and thus scale changes from this source are smaller than 0.001 sec of arc. Moreover, the relative scale for the sun and star detectors is even more precise since both detectors tend to move together with temperature changes in the Invar tubes. Observed changes in the solar diameter, which is measured to 0.001 sec of arc, are thus due to differential atmospheric refraction which is primarily linear in field angle and to third-order aberrations in the primary optics which are considered next.

The spherical bending of the quartz mirrors produced by solar heating and figuring tolerance of $\lambda/10$ on each mirror combine to produce displacements of the images from the ideal image positions.

The systematic error produced in the star position measurement resulting from image displacement linear in field angle is removed by normalizing the sun-star distance with the simultaneously measured solar diameter directed along the sun-star line.

A difference in the scale along orthogonal directions of the field results from spherical bending of the mirrors and enters directly into the solar oblateness measurement. The difference is determined in the same manner as is the small residual ($\sim$0.003 sec of arc) of star position error caused by scale changes quadratic in field angle. The principle used in removing the latter instrumental contributions is quite simple. The solar image, for example, rotates daily with respect to the surface of every primary optical element, resulting in a rotation of the instrumental aberrations in the field relative to the solar pole. Hence analysis of the observed oblateness in terms of an intrinsic solar oblateness and an instrumental oblateness rotating with respect to the solar image with known time dependence determines this instrumental contribution.

In practice, changes in the variance of atmospheric seeing systematically change the apparent solar diameter by as much as 0.04 sec of arc. On-line correction of the measured diameter by an amount proportional to the variance of seeing is therefore an important technique which will be described in a forthcoming paper.

Use of the measured solar diameter in eliminating significant effects of instrumental aberrations and differential atmospheric refraction is thus seen to be fundamental to use of this telescope as an astrometric instrument.

Vacuum System

An important feature of the telescope is that except for the first surface of the entrance window the optical systems are entirely enclosed in a vacuum chamber. The El–Az mirrors, objective lens, and inside surface of the window are in a chamber that may be evacuated to 0.1 μ with an oil diffusion pump. The lower part of the telescope containing the secondary optical systems is kept at a forepump vacuum of 10 μ. A dynamic oil seal located at the top of the cage separates the two vacuum regions. There are several reasons for the vacuum design:

(1) Differential atmospheric refraction is reduced by a factor of $\sin^2$ (zenith angle) along a meridian and is zero orthogonal to a meridian for a plane, laminar atmosphere.[1]

(2) Seeing within the telescope is eliminated.

(3) Convective and conductive heat transfer from the mirrors into surrounding air are minimized, so thermal gradients in the mirrors can be controlled.

(4) Optical surfaces may be kept free of dust, reducing scattered light intensities.

(5) Index of refraction changes along the arms of

interferometers essential to the field measurements are avoided.

The cylindrical vacuum chamber concentric with the elevation mirror cylinder and supporting the entrance window is servoed to rotate with the mirror. Similarly, the dome and vacuum chamber surrounding the aximuth mirror are servoed to track azimuthal rotation of the table. A mercury seal between the upper part of the vacuum tube fixed to the dome and the lower part of the tube allows independent rotation of these two sections. The lower section is supported on hydraulic bearings and is driven with a motor and friction reduction drive to follow the daily field rotations produced by the El–Az tracking system and the relative sun-star motion.

The cage and vacuum tube each have a gimbal suspension that connects to the circular frame forming the bearing surface. The cage gimbal allows a servosystem to keep the cage aligned vertically, correcting alignment errors resulting from irregularities on the bearing surface and thermal effects in the cage structure. Vertical alignment errors of 80 sec of arc could produce errors in field rotation angle of 4 sec of arc, complicating the initial acquisition of a star.

Operation and Performance

The star detector is positioned by a set of precision lead screws, and rotating the encoded lead screws moves the star detector radially across the field with respect to the solar image.

In operation, then, the upper section of vacuum tube follows the El–Az motions of the tracking mirrors. Rotation of the lower section of the vacuum tube and cage, together with rotation of the lead screws, moves the star detector in a polar coordinate system centered on the solar image. These degrees of freedom are used to place a pinhole aperture in the star detector to within about 5 sec of arc of the star image. Fine centering of the pinhole aperture on the image by means of the phase sensitive detection methods previously mentioned completes the star tracking operation.

An on-line computer calculates the tracking rates for both the sun and star, processes and stores data for later analysis, and is used in several hybrid analog-digital servoloops for phase-sensitive detection and digital filtering.

Initial solar oblateness studies (unpublished) provide several measures of performance of the telescope. The aberrations produced by the $(1/10)\lambda$ figuring tolerance and spherical dishing of the mirrors result in a 0.007% maximum difference in scale along orthogonal directions of the fields. This results in an instrumental contribution to the solar oblateness of amplitude 0.14 sec of arc, and the contribution can be reproducibly determined to about 0.030 sec of arc in a single 3-h oblateness observation.

As previously mentioned, centering errors in the primary tracker are less than 0.25 sec of arc. A solar diameter may be measured to 0.030 sec of arc in 4 min of time, and improvements upon this accuracy may be possible. The standard deviation in atmospheric seeing inferred from the data is about 2 sec of arc on the average.

These initial results indicate that the telescope performance will meet the design objective of providing accuracies of order 0.001 sec of arc in field position measurements.

Important contributions have been made by W. E. Rosing and J. Bach, who designed and constructed the on-line computer; by J. Sugameli who has produced countless engineering drawings of the telescope and its instrumentation; and by B. Cardon, R. T. Stebbins, and G. R. Hostetter, who have given much time and talent to the development of the telescope.

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5. J. G. Baker, Astron. J. **59**, 74 (1954).
6. Bimorph is a registered trade name of Clevite Corporation, Bedford, Ohio.

Finally, if a long, talky, involved, tortuous sentence has sneaked in, as it will once in a while and should, since we all recognize that the New York *Daily News* cannot be regarded as the sole exemplar of good style, then it is well very soon thereafter to provide relief from its intricacy of structure, a welcome contrast, and reassuring proof that the communicator is one's friend rather than enemy by making the following sentence very short. Cools the brain.

WALTER LITTEN
Eastman Kodak Company