Coaxial, Dual-Field Optics For a Space Sextant

H. E. Brunelle, Jr., and R. R. Willey, Jr.

A telescope having a 2° field of view and an optical system with a 165° inside-out, quasi-stigmatic field of view, which has been axially integrated to be mutually nonobscuring and confocal, is described. Navigation and guidance application requirements of space vehicles from which the optical specifications have been derived are discussed. The narrow-field system is a Schmidt-Cassegrain telescope of unusually short length as dictated by the requirements. A semiautomatic lens design program for the IBM 7090 computer developed by coauthor Willey was used in the optimization of the optical design. The final optical performance predictions are shown and have been essentially supported by the performance of the prototype unit which was constructed.

The Problem

Among the earliest developed, and still most fundamental, techniques in the art and science of navigation and guidance is the determination of present position and true bearing. The first mariner, who deliberately ventured far from the sight of land, must have relied on the constancy of the stars and planets and on his ability to determine from them his navigational needs.

The astronaut with his self-contained navigation system, venturing into the solar system beyond the domination of the earth's gravity, must rely on the same ultimate frame of reference to obtain the same navigational fix. He must have the means to perform a particular sequence of measurements related to a suitable coordinate system.[1] Each measurement, when reduced, constrains his position to a locus of points constituting a surface in three-dimensional space.

By measuring the angle between a planet (or moon) and a known star, a position locus in the form of a cone is established. Measurement of the angle between two planets (or one planet and the sun or moon) determines a locus in space called a navoid which has the form of an arc of a circle rotated about its chord. Observing and timing an occultation of a known star by the moon (or a planet) establishes a cylindrical locus. By measuring the angle subtended by a planet (or moon) disk, a positional locus in the form of a spherical shell provides range or altitude usable within a few diameters of the planet. A good approximation to the local vertical is also provided by aligning an optical axis on the center of the disk.

Proposed Solution

The present state of the art for obtaining positional fix measurements on a lunar mission might require an earth horizon tracker, a moon tracker, two or more star trackers, and a sun seeker. The extended source nature of the moon and earth (or planet), especially when viewed at a range of a few diameters, requires the use of a continuous mechanical scan technique for horizon tracking, which is, from reliability considerations, undesirable for long duration use in space. Two or more sets of gimbals, with drive mechanisms and angle readout transducers, are required to provide relative motion between earth tracker, moon tracker, and star trackers; and between star trackers, if other than preselected stars at fixed angles are to be tracked.

The problem of obtaining these measurements is greatly simplified and accuracy is increased through the use of the advanced optical-inertial space sextant.[2] A space sextant is any instrument capable of making measurements of the orientation of celestial bodies relative to some reference. This advanced instrumentation concept eliminates the multiple telescopes and duplicated gimbals and angle transducers for a single integrated optical system combined with an inertial reference system and mounted on a single gimbal system. This basic configuration is shown in Fig. 1. The two gyros, operated with their spin axes mutually orthogonal, are mounted with the tracker optics on a common gimbaled platform. Two precision two-

H. E. Brunelle, Jr., is with the Armament and Control Products Section, Light Military Electronics Department, General Electric Company, Johnson City, New York. R. R. Willey, Jr., is with Willey Optical Research Lab and Development Service, Farmington, Connecticut, now a division of the Instrument Corporation of Florida, Melbourne, Florida.

Received 1 May 1963.

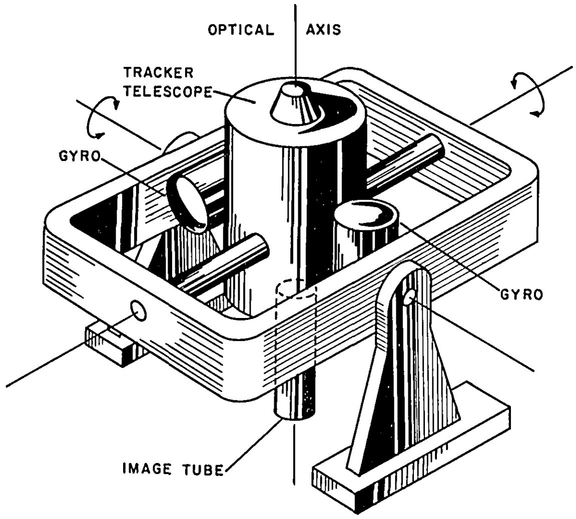

Fig. 1. Optical-inertial space sextant.

degree-of-freedom free rotor gyros, body-bound to the telescope, provide basic three-axis inertial reference during the sighting operation. The single telescope performs the desired sightings in sequence. For each sighting, alignment of the optical axis, relative to the inertial reference, is read directly by the precision gyro pickoff. The need for precision gimbaling and high-gain gimbal drives precisely to track and null targets is eliminated through the use of a high-resolution image tube. The tube electronically scans and resolves angular offsets between the optical boresight axis and the line of sight to a target at any point in the optical field of view imaged on its photoactive surface. An extremely wide field-of-view optical mode images extended disks for stadiametric ranging and local vertical determination, while a narrow field-of-view optical mode consistent with the image tube resolution capabilities is used for precise sightings on point sources.

Wide-Field Optics

The requirements of the wide-field system for planetary horizon tracking are appreciably different from those for which conventional extreme wide-angle lenses are developed. Typically, for these lenses, the center of the field of view is presented with little or no radial distortion in the central two-thirds of the image plane. Radial compression in the image is present at an ever-increasing degree for objects whose position in the field of view moves farther off-axis. It is obvious that, with these lenses, the region of interest to the horizon tracker is nonlinearly compressed into a narrow band at the periphery of the image while the bulk of the planetary disk dominates the center of the image.

Since the wide-field system will be used chiefly to look at planetary disks at close distances, it is optimized for large subtended angles up to 165° between horizons. It is desirable to provide a system which will exclude light from an area of no interest by obscuring a central 50° cone in the field of view, and, at the same time, to displace the image field radially inward toward the optical center so that a maximum of the central image area is used.

It is also desirable to reverse the image field boundaries so that the outer edge of the field $82^1/_2$° off-axis will be near the center of the image, and the central boundary 25° off-axis will appear at the outer edge of the image. The "inside-out" field images the horizon of a planetary disk near the center of the image plane as the horizon subtends a larger angle. Since the central region of the photoactive surface of an image tube provides better resolution than the edges, the horizon can be more accurately determined in approach situations where resolution of stadiametric altitude and local vertical are critical.

Distortion is expected in the wide-field optical system. For accurate horizon location distortion must be axially symmetrical. The system is optimized at the tangential focus to minimize sagittal image smear so that a sharp horizon line can be obtained. Tangential smear is permissible if it is concentric about the axis, otherwise a sharp horizon line cannot be obtained.

The basic system chosen to satisfy the wide-field requirements consists primarily of a toroidal element which resembles the bell of a horn. Figure 2 shows the wide-field system schematically. The horn element serves almost exclusively as a device to produce the desired "inside-out" field distortion and appropriate angular expansion of the annular field. Modifications had to be made in the usual ray tracing equations in order to investigate this unusual horn surface.

The heavy inherent astigmatism of the horn element is rendered relatively harmless in the present application by making its scale large with respect to the aperture of the beam impinging upon it. The resolution of the wide-field system at $f/8$ closely matches the resolution of the image tube. The image is not only inside-out as in the device described by Killpatrick[3] for a similar application, but it is also stigmatic as Fig. 3 shows. There is point to point imaging of the object plane onto the image plane.

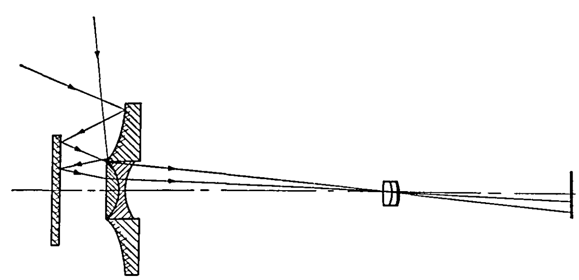

Fig. 2. Annular wide-field system.

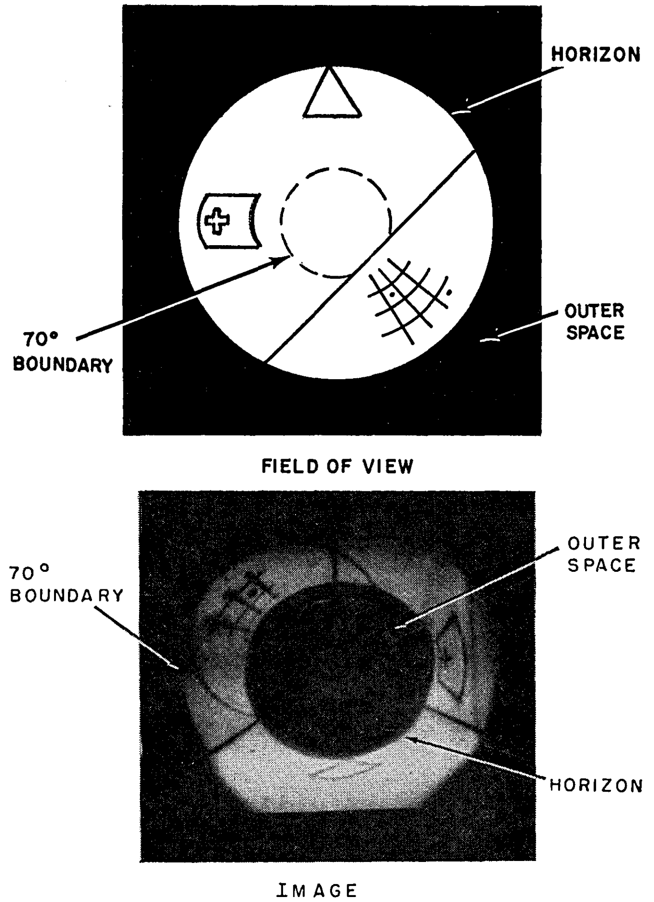

Fig. 3. Space sextant monitor display of field of view as seen by image tube through the wide-field system.

Narrow-Field Optics

Functionally the narrow-field system field of view is dictated by the usable diameter of the photoactive surface of the image tube and the number of elements or lines which can be resolved in this diameter. If, for example, an angular resolution of 1 sec of arc is desired, the field of view imaged on the photoactive surface of the image tube must not subtend more seconds of arc than the number of resolvable lines. The aperture real diameter must also be large enough so that the limit of angular resolution imposed by diffraction is less than that imposed by the image tube resolution. For a selected image tube and brightness of the dimmest star of interest, an effective aperture of the system necessary to give a desired signal/noise ratio can be determined.

Consideration of the space sextant application requirements emphasizes the desirability of the shortest folded system functionally practical. The short tube length reduces the weight of the structure necessary to ensure maintenance of proper optical alignment and adjustment; allows the use of a lighter, more compact gimbal; and reduces the size of any enclosure within which the sextant must be articulated.

The general class of system usually considered for a short telescope application is the Cassegrain telescope. Since the clear aperture and focal length are predetermined by the application and image tube characteristics, the problem is to design the shortest system which is consistent with the image quality requirements, and that can be produced to the necessary accuracy with a finite amount of effort.

The true Cassegrain[4] with parabolic primary mirror and hyperbolic secondary mirror has inherent coma to a degree which cannot be tolerated in this application. The Ritchey–Chretien modified form of Cassegrain corrects for coma by a different aspheric figuring of the mirrors. Astigmatism is still uncorrected and is the limiting aberration. The Schmidt–Cassegrain and Maksutov–Cassegrain forms offer advantages over the Ritchey–Chretien form in that the stop position and aspheric figuring are moved toward the center of curvature of the primary mirror, and the corrector can be used to support the secondary mirror. The Schmidt–Cassegrain form was chosen for this application because the corrector plate is less massive and occupies less space than the Maksutov corrector.

Since, to achieve compactness, the corrector plate of the Schmidt–Cassegrain is at a distance from the center of curvature of the primary mirror, astigmatism is not fully eliminated. The system is shortened until the residual astigmatism brings the image size up to the maximum tolerable amount as defined by the image tube characteristics. Although the Petzval sum is approximately zero, the residual astigmatism causes the field to be curved, and a field flattener is introduced adjacent to the focal plane. The resulting design has a spherical primary mirror, and aspheric corrector plate and secondary mirror.

The design of this system was carried out entirely (except for slide-rule calculations) on an IBM 7090 computer and much of the optimization was done by a semiautomatic lens design program.

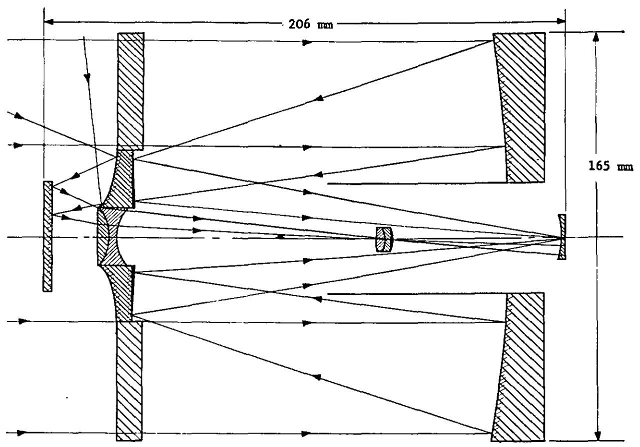

Fig. 4. Combined optical system.

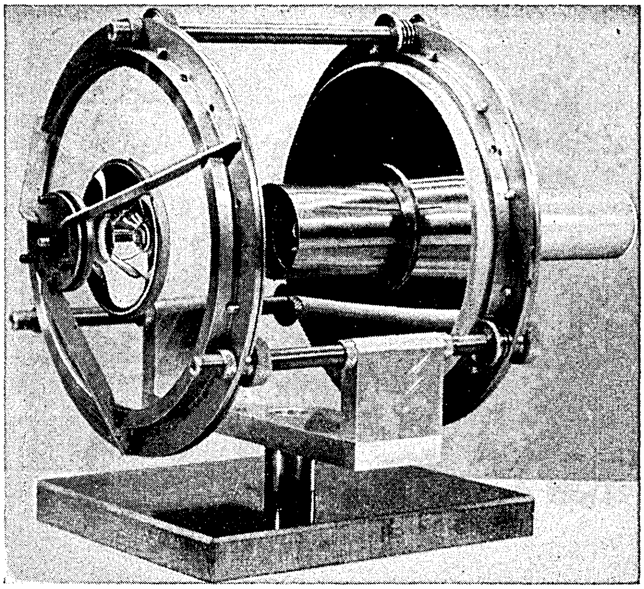

Fig. 5. Dual-field star tracker with image tube shield.

The lens optimization program was very useful in finding the best division of asphericity between the corrector and the secondary mirror of the Schmidt–Cassegrain. Although this is a relatively simple problem, the optimization program further reduced its difficulty. The eccentricity of the secondary mirror (conic section figuring) was allowed to vary while the corrector was figured to maintain axial stigmatism. Heaviest weighting was placed on obtaining the smallest possible images at the edge of the field. Although the only aberration appreciably controlled by this process was coma, the optimal solution was not the exact elimination of coma, but a balance between a small amount of coma and the residual astigmatism of the system. The Schmidt–Cassegrain was then shortened until the optimized system gave images at the edge of the field that just matched the tolerances. The optimization of the division figuring in any one case, would typically take from 1 to 2 min of computer time because of the extensive number of rays examined (45).

Combined Optical Systems

The problems of gimbaling the optical axes of the wide- and narrow-field systems in a space sextant application emphasize the desirability of coaxial combination and mechanical symmetry. Any fixed astrodome or window traversed by rays incoming to the systems should present a symmetrical and invariant aspect relative to the optical axes of the system, for any orientation permitted by the gimbal system. In a Cassegrain system the central zone of the aperture is blocked by the secondary mirror whose center, in turn, sees only its own shadow in the center of the primary. The wide-field system is arranged to occupy this vacant core with its aperture located just in front of the correcting plate, as shown in Fig. 4. With the two systems coaxial and the intersection of the gimbal motion axes located on this common optical centerline close to the plane of the rear surface of the corrector plate, the effect of an astrodome whose center of curvature also coincides with this common center will be symmetrical; and the optical axis will be normal to its surfaces in any gimbaled position.

An optical relay is provided to transfer the image, formed by the short focus wide-field system, to the image tube photoactive surface which is coincident with the narrow-field system focal plane.

Mode selection is accomplished by alternate insertion of masks in a plane just behind the optical relay where the ray bundle from the narrow-field aperture is small but still separate from the wide-field ray bundle passing through the relay lens. No optical elements are moved in a changeover. Thus, the danger of loss of alignment or adjustments is eliminated, and the masks located near the image plane are small and low in mass.

Performance

To verify the performance predicted for the system as a result of the optimization programs on the computer, a set of optical elements were constructed and assembled in a mount of laboratory breadboard construction. The dual-field star tracker with image tube shield is shown in Fig. 5 and has the following characteristics:

Narrow-Field System

Type	Schmidt–Cassegrain
Field of view	2°
Clear aperture	165-mm (6.25-in.) diam
Effective aperture	143-mm (5.62-in.) diam (equivalent)
Focal length	437 mm (17.2 in.)
Image plane	15.25-mm (0.6-in.) diam

Wide-Field System

Type	Annular field, "inside out"
Field of view	Solid angle included between two concentric cones with apex angles of 70° and 165°
f/number	f/8 average
Image plane	15.25-mm (0.6-in.) diam

Tests were conducted on the wide-field system to demonstrate the inside-out, point-to-point mapping of the annular toric reflector (Fig. 3). A plot of the angle transfer from object space to the image plane also demonstrated a very close-to-linear relationship.

It was expected that the nature of the toric reflector might result in an appreciable change in both focal length and effective aperture as a function of off-axis angular position. Measurements to determine this variation in terms of f/number ratio showed the system to have an average value of $f/8$ with a variation of less than $0.5f$ stop between points anywhere in the field of view.

The resolution of a point source onto the image plane was found to have a radial width of 0.025 mm and a tangential length of approximately 0.125 mm. This held true for any off-axis position within the field of view.

Tests were conducted to establish the linearity of the narrow-field system. Angular position in the field of view was determined to within 2 arc-sec, and the image position was measured to within 0.013 mm. Within the accuracy of the measurements, the system was linear which indicates a linearity of better than 0.1% full field. The image of a point source was less than 0.025 mm in diameter and of high quality throughout the field, showing only a trace of astigmatism at the extreme field edges.

The design and fabrication of the optical elements of the dual-field star tracker telescope was performed by the Willey Optical Research Lab and Development Service, Farmington, Connecticut, for the Armament and Control Products Section of the Light Military Electronics Department, General Electric Company, Johnson City, New York. Mounting, integration with the electron optics, and performance testing and evaluation were performed by Advance Engineering of the Armament and Control Products Section.

The automatic lens design program was developed by R. R. Willey, Jr., while at the Research Laboratories of United Aircraft Corporation. Continuation of the work reported in this paper is now being carried out under a National Aeronautics and Space Administration contract.

References

1. H. B. Haake and J. D. Welch, IRE Trans. Aerospace Navigational Electron. **ANE 8**, 28 (1961).
2. J. D. Welch, "Advanced Optical-Inertial Space Navigation System", paper presented at AIAA, Summer Meeting, 17 June 1963.
3. J. Killpatrick, Appl. Opt. **1**, 147 (1962).
4. R. R. Willey, Jr., Sky and Telescope **23**, 191 (1962).

Applied Optics Patents

The patents reviewed below have been issued by the U.S. Patent Office on the dates quoted except where otherwise mentioned. The patent number, date of issuance, and classification number are quoted in the first line. The filing date is that of the earliest patent application. The opinions stated in the reviews are those of the reviewers and are not meant to express the thinking either of the organizations with which members of the panel are associated, of the Optical Society of America, or of this journal. Normally, statements of fact are based upon the patents and not independently verified. Printed copies of American patents may be ordered from the Commissioner of Patents, Washington 25, D.C., for 25¢ each. A weekly subscription service to any selected subclass is also available from the Patent Office.

3,021,751 20 Feb. 1962 (Cl. 88-20)
Tachistoscopes.
G. C. Barnette. Assigned to Learning Through Seeing, Inc. Filed 26 May 1960.

Mechanical and electrical details of a projection tachistoscope to test reading ability are given. W.L.H.

3,021,754 20 Feb. 1962 (Cl. 88-61)
Light-polarizing apparatus or the like.
B. Ross. Assigned to Hoffman Electronics Corporation. Filed 26 Sept. 1956.

The light reflected from a semiconductor at oblique incidence is polarized, and Ross points out that the polarization can be varied by injecting free carriers electrically or optically into the material. No quantitative results are given. W.L.H.

3,038,368 12 June 1962 (Cl. 88-1)
Co-ordinate theodolite.
L. Fialovszky. Assigned to Gamma Optikai Muvek. Filed 8 Sept. 1959 (in Hungary 10 Sept. 1958).

A mechanical and optical arrangement is described that provides simple and direct data reduction when surveying by traversing. W.L.H.

3,039,356 19 June 1962 (Cl. 88-15)
Kaleidoscopes.
R. E. Knittel. Filed 4 Nov. 1959.

New and exotic kaleidoscopes complete with flowing liquids are revealed. W.L.H.

3,041,922 3 July 1962 (Cl. 88-14)
Optical device for a correct adjustment and reading of the slidable displacement of a carriage in a machine.
K. Rantsch. Assigned to M. Hensoldt und Söhne Optische Werke, A. G. Filed 5 Mar. 1959 (in Germany 8 Mar. 1958).

This is a complex patent with 33 drawings showing optical systems that allow a tool to be positioned accurately on inaccurate ways. The position of the tool (or the work) is observed with reference to an accurate grid, and the optical systems are devised so that linear and angular errors in the optical train do not introduce reading errors. W.L.H.

3,041,923 3 July 1962 (Cl. 88-14)
Stress photometer.
F. T. Geyling. Assigned to Bell Telephone Laboratories, Inc. Filed 14 Dec. 1959.

Describes a means for scanning photoelastic stress patterns along circular contours and measuring light intensity values therein to facilitate gathering of data from a photoelastic model under stress. The data so obtained are particularly suited to a new mathematical method of stress calculation developed for its compatibility with modern high-speed digital computers. R.D.A.

3,042,805 3 July 1962 (Cl. 250-207)
Light measuring apparatus.
S. L. Boersma. Assigned to N. V. Optische Industrie de Oude Delft. Filed 18 Apr. 1960 (in Netherlands 22 Apr. 1959).

A light-measuring device is described particularly suited to low illuminations encountered in x-ray photofluorography, wherein a photoelectric cell circuit is automatically standardized during brief periods (less than 0.1 sec) using a reference light source. This procedure yields a capacitor charged to a reference voltage which, in turn, permits accurate measurement of the