Optical System for Measuring Position in Space

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Summary

There exist certain distinct advantages in accuracy and economy in the use of systems to measure vehicle position which operate at optical wavelengths. The positions measured are usually of critical importance to the success of a space mission.

There are several types of navigational and tracking systems which produce data in an immediately usable form. Such "real time" systems, however, sacrifice some relative accuracy to gain speed of data availability.

Stellar metric camera systems presently offer the most accurate means of determining position in space; however, there is an unavoidable time delay in reducing the data to a usable form.

There is room for significant improvement in the errors of presently used stellar metric cameras, particularly in the geometrical optical characteristics of the lenses in both design and fabrication. The usefulness of such cameras can be extended by daylight use with the proper designs and techniques. Lunar-based cameras should also offer several advantages over Earth-based systems, but only at a high price.

Recent developments in optical design techniques using high speed digital computers have brought far greater sophistication and economy than had previously been possible. Vastly improved new optical designs are just waiting to be executed for application to the problems of Measuring Positions in Space.

Introduction

One of the major factors effecting the success or failure of missions in space is the determination of position as a function of time. To navigate, it is necessary to know the position of the vehicle at a given time. From position as a function of time it is then possible to determine the velocity and acceleration components of the vehicle's travel.

When one contemplates navigation in space, it becomes imperative that measurements of position be made by beams of electromagnetic radiation using either active or passive systems. When one further contemplates navigation at some distance from other bodies in space, active electromagnetic systems such as radar and opdar become impractical due to power requirements. One finds also that the shorter the wavelength of radiation used in observation, the smaller the instrumentation can be for a given accuracy. This area of technology is what is referred to as diffraction effects in optics or beam or lobe pattern in microwave propagation.

What are some of the positions in space which are of interest? Let us first concern ourselves with the navigation of a vehicle from one planet to another or from a planet to a satellite of
some planet. At least three different measurements are generally required to determine the position of the vehicle within the solar system. These measurements must include as a reference two sightings on bodies of known position within the solar system, such as the sun, a planet, or a satellite of one of the planets. The best solar system reference is usually the one nearest at hand. It is not our intention to discuss the geometry of the problem beyond what is necessary to identify the types of measurements to be made. Another class of positions of interest are geodetic positions of the surface features of various bodies and the actual trajectories of bodies influenced by the forces of these bodies. At least two applications of this latter class of positions are of importance: one is the calibration of various measuring instrumentation; another is the determination of geophysical characteristics of the major bodies of influence. These various applications have been described elsewhere.

Depending on the application, one may need to know the positional information almost immediately, i.e., in "real time", or one may be able to wait some reasonable length of time for documentary positional information. The question of "is the data available in "real time"?", is a matter of degree; no data is usable at the instant that it occurs. However, there are generally two widely different classes of data when we consider the time between the event and the availability of the data concerning the event. The "real time" class of data system is limited primarily by electronic response time, whereas, the other class of data system is limited by human and mechanical response time in reducing the data to a usable form. Radar and opdar are examples of "real time" systems while ballistic and geodetic cameras are examples of "non-real time" systems.

The "real time" optical systems are generally required when it is desired or necessary to guide the vehicle on the basis of optical data. However, due to the usual sacrifices required in the precision of "real time" systems, photogrammetric techniques of documentation are usually used for precise calibration of real time optical and electronic position sensing systems.

Real Time Systems

Navigation Systems

There are many navigational optical systems in existence or under development today. There are several ways that these can be classed. We shall divide these systems into tracking and off-boresight classes, and this class we will divide into sequential and simultaneous sighting types.

Many systems exist which track on an object such as a star and readings of angle from some reference are made which assume that the system is pointing exactly at the object. There are a few systems, one of which we will describe in some detail, which are capable of reading the position of the object anywhere within a field of view (usually of a few degrees in size). Members of the latter class are off-boresight systems.

Most systems take a sighting on an object and measure the object's coordinates in some reference system, usually inertial. Sightings on various objects are taken successively and the relation of the object coordinate system to the coordinate system of the navigation system can be computed. Such a system must take its sightings sequentially and refer to a "fixed" coordinate system. Another type of device which can be used would have two sighting devices which simultaneously observe two objects and measure the angle between them. The angle between two objects is determined simultaneously but one must read the angle between other pairs of objects sequentially. If the system has three sighting devices and can measure the angle between each, three objects can be sighted simultaneously and position can be determined.
continuously, in "real time" so to speak. All the navigational systems except this last "TRISECTOR" method require a significant time lag for the successive sightings which are required and therefore are somewhat short of being truly "real-time" systems.

**Dual-Field Space Sextant**

We would like to describe here the optics of one navigational system which we have designed and built. The system is designed to be used in an off-boresight, sequential mode of operation. The instrument has been referred to as a "Dual-Field Space Sextant", but the term sextant is actually not as appropriate in this case as it would be for the simultaneous two sighting system described above. This system has been described elsewhere in great detail. The first model (see figure 1) consisted of a telescope having a two-degree field of view and an optical system with a 165-degree, inside-out, quasi-stigmatic field-of-view, which were axially concentric and integrated to be mutually non-obscurong and confocal.

The wide field system was designed to look at planetary disks at close distances for determination of local vertical and stadiametric ranging. The field of view was turned "inside-out" to cause the image of the horizon of a planetary disk to shrink from the edge of the format toward the center as the planet is approached and the horizon subtends a larger angle. The black sky background appears in the center of the field. The "inside-out" field of view, therefore, allows the center of the receiver, a vidicon or orthocon television tube, which has higher resolution than the edges to be utilized when the stadiametric ranging and local vertical determinations are most critical at very close approach, to the planet. The utilization of the best resolution portion of the receiver at the most critical phases of navigation is the only motivation for the "inside-out" optical system.

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. The flat mirror, the negative achromat, and the positive achromat in the wide-field system serve only to transfer the image to the focal plane with appropriate magnification. The effective focal length of this total system is approximately three-tenths of an inch.

Let us consider what a field of view would appear to be when turned inside-out. Figure 3 shows diagramatically a potential field of view and what that field of view would appear to be when seen through the inside-out optical system. If one was to position this system with its axis pointed at the horizon, and observe a vehicle traveling down a highway in front of the instrument, the vehicle would appear to start from the center of the format as it appeared at the extreme edge of the field of view in actuality, and travel toward the edge of the format at which point it would disappear and reappear at the opposite edge, travel toward the center and disappear at the center as it actually disappeared from the field of view on the real horizon.

The narrow field of view optics is essentially a telescope with a small field of view. The receiver is a television vidicon tube or image orthocon. Functionally, the narrow field system of view is dictated by the usable diameter of the photo-active 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 one second of arc is desired, the field of view when imaged on the photo-active surface of the image tube must not subtend more seconds of arc than the number
of resolvable lines. The aperture's 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, the effective aperture of the system necessary to give the desired signal-to-noise ratio can be determined. Consideration of the space sextant application requirements emphasizes the desirability of the shortest folded system functionally practical.

The specific optical system chosen for the first model produced was that of the Schmidt-Cassegrain form of telescope. Figure 4 is a scale drawing of the combined optical systems including the Schmidt-Cassegrain System and the wide field optical system. The design of this system was carried out entirely, except for sliderule calculations, on the IBM 7090 Computer, and much of the optimization was done by a semi-automatic lens design program. Figure 5 shows the feasibility model of this design which was fabricated. Figure 6 shows a second instrument which has been produced with slightly different specifications such as: a one degree field of view at higher resolution; and an inside-out optical system with a smaller dead space in the center of the format. The second model has a functioning mechanical change-over system from one field of view to the other. One of the objectives of this design is to allow changing from one field of view to the other without the movement of any optical component. This feature should reduce any danger of misalignments in the course of field changeovers. In the second model, the change-over is accomplished by sliding a baffle tube down from the focal plane to obstruct the beam coming from the telescope primary mirror to the secondary mirror. As this tube reaches the end of its travel, it activates a shutter mechanism within the wide field system to open these optics and allow light from the wide field system to reach the focal plane while the narrow field system is obstructed. A simple one quarter turn of a crank shaft accomplishes this in practice. Figure 7 is a photograph of the second model produced which has an outside diameter of 6 inches. It will be noted in Figure 6 that the second model is not a Schmidt-Cassegrain System but more nearly resembles the Maksutov-Cassegrain System. In actuality, however, the system is neither a Schmidt nor a Maksutov System but intermediate between the two with a curved corrector as in the Maksutov but with heavy aspheric figuring as with the Schmidt corrector. We have, therefore, chosen to call this system a Maksutov-Schmidt Cassegrain design.

**Real-Time Tracker**

There exists a desire in the missile field and in some other applications for a real-time tracking optical system of the theodolite type. Photographic-recording theodolites have the disadvantage of the time required to reduce the data. Electronic or radar-type tracking systems have the disadvantage that the wave-lengths used are long and therefore the resolution is inherently low. One of the few existing real-time trackers with which we have some familiarity by virtue of designing the optical system may be considered to be equivalent to a passive radar system operating at very much shorter wavelengths or higher frequencies. The actual aperture of this system is 6 inches. The absolute tracking accuracy of this system is expected to be less than 10 seconds of arc. The resolution of this system on the other hand, is anticipated to be a few seconds of arc. The problem in the optical design of this system was not particularly one of image quality for the field of view is essentially a very few minutes of arc. The design problem here was one of trying to optimize the various opto-mechanical parameters of the system to reduce bore-sight drift to a minimum under the conditions of the thermal environment anticipated. The actual optical system was a simple Cassegrain telescope, but the relative magnifications used and the positions of the element were studied in great detail to minimize the bore-sight drift. The focal length of the system was 200 inches. The design study consisted primarily of considering the effects of tilts.
and decentrations of the various elements of the system with respect to their effect on the bore-
sight of the system. In this case, the tilts and decentrations anticipated were not of a magnitude
to significantly effect the image quality of the system. This characteristic is essentially similar
to the stellar-geodetic cameras that we will describe subsequently. Real-time tracking theo-
dolites of this type and other types have distinct advantages when data is required immediately.
However, they contain inherent difficulties mechanically, electronically, and optically that
cause a reduction in the precision and accuracy of these systems as compared to some of the
photogrammetric methods to be described next.

**Stellar Metric Cameras**

**Ballistic Cameras**

The type of ballistic cameras to which we refer are essentially photogrammetric or aerial
cameras pointed at the sky. In the most accurate application of such cameras, a background of
stars is photographed and the vehicle of interest passes through the field of view emitting or
reflecting light of its own or of a beacon attached to it, and the stars and the beacon are
photographed with appropriate shuttering sequences to identify the times at which the stars and
the vehicle were at given positions. The procedures used are essentially similar to the pro-
cedures of astrometry used for many years by astronomers determining the positions of various
stars and various celestial bodies passing across a background of stars. Astronomers, however,
have very long focal length instruments and ordinarily track the star background. In ballistic
camera work, the cameras are fixed with respect to the earth on most applications and the trails
of stars are recorded on the photographic plates with time breaks for identification of position
as a function of time. Most of the early work with ballistic cameras was done with very short
focal lengths of from 100 to 200 mm. This afforded a wide angular coverage when a standard
photographic plate was used, and this had definite advantages in the work with short range
missiles and aircraft. However, the severe limitations of positional accuracy due to the short
focal length or small scale ratio resulting therefrom have made it desirable in many applications
to have longer focal length systems. The Atlantic Missile Range at the present time has systems
of 300, 600, and 1000 mm focal lengths for this reason. The Instrument Corporation of Florida
is quite intimately familiar with this instrumentation since we have built the 1000 mm cameras
and have also produced 600 mm and shorter focal length cameras.

Brown\(^2\) has shown the error budget for the PC 1000 cameras as they exist today under normal
conditions. Figure 8 shows a table of the various errors taken after the work of Brown with our
own additions. The figures to note at this moment are that under normal conditions today the
orientation of the camera is known with an error of less than one arc second and that under the
improvements that are being made daily, it is anticipated that within a short time, approxi-
mately .6 arc seconds accuracy can be obtained. The determination of the direction of flashes
from a beacon, such as the ANNA satellite, can be made to essentially equivalent accuracy.
Figure 9 and Figure 10 show an operating 1000 mm Camera System inside a dome with a radial
louver shutter. This particular shutter was developed by the Instrument Corporation of Florida
and is capable of a chopping sequence at a maximum rate of 55 chops per second with a transfer
time from close to open or vice versa of 5 milliseconds and a shutter position pick-off for
precise measurement of the actual times of the opening and closing. The electronics associated
with the systems for timing and shutter actuation are not shown in the figures.

**Geodetic Cameras**

Ballistic cameras can be applied to the measurement of position of orbiting satellites or flares.
exploded at high altitudes. If a network of three or more cameras at known positions on the surface of the earth can determine the accurate positions with respect to the network of the flares or satellites at a given time, cameras at other sites whose positions are not accurately known can be accurately located by resection. This is essentially the same procedure used at the known sites to locate the satellite except that in the latter case we know the position of the satellite or flares and we determine the position of the camera by photographing the satellite against a star background. These procedures can determine with extreme accuracy the positions of points on the surface of the earth. When sufficient numbers of accurate positions have been determined, it then becomes possible to determine the precise orbits of various bodies, satellites, etc., that encircle the earth. From the perturbations of these orbits, it is possible to determine various other geodetic data such as mass distribution of the earth, atmosphere density at high altitudes, etc.

Future Improvements of Geodetic and Ballistic Cameras

Referring to the table in Figure 8, we have indicated the possible improvements which can be expected with an earth-based 1000 mm focal length camera in the near future. One major improvement being worked on at the present time is the reduction of star catalog errors. Another error which is being attached from both the analytical and the fabrication point of view is the residual tangential distortion of lens systems. Most of the other errors contributing to the error budget can be reduced by small amounts through improved equipment and techniques.

We also show in Figure 8 the anticipated error budget from a 2000 mm land-based geodetic camera and this is expected to have about one half the error of a 1000 mm camera.

Another area of future improvement in the use of geodetic and ballistic cameras is being pursued at the present time and this is usage of stellar geodetic cameras. It can be shown that the relative merit of various cameras with respect to producing high contrast images of point sources against a continuous sky background is directly proportional to the square of the focal length. It is at first surprising that the contrast is not also a function of the aperture. This indicates then that a 1000 mm camera would have relative contrast eleven times greater than a 300 mm camera when photographing the same object under the same conditions. Because of the fourth power law of scattering in the blue sky, it is fairly obvious that it is necessary to work in the longest wave length region possible, and that would be the red or near infrared region of the spectrum. The limitations placed on the focal length which can be used are primarily due to the field of view desired and the format which can be used, the standard ballistic camera plate format at the present time being about 180 mm square. This gives, for example, a field of view of 10° by 10° at 1000 mm focal length. At 2000 mm, this would be cut to about 5° by 5° square. Various daylight systems currently are under study including laser source systems and other optical beacons to be placed on the vehicle to be tracked.

Another vast new area in the field of geodetic cameras may be opened up by taking cameras outside of the earth's shimmering sea of atmosphere. In determining the direction of flashes from a strobe satellite such as ANNA, the largest error is introduced by the high frequency atmospheric shimmer as we have shown in Figure 8. Another error contributed by the atmosphere is residual paralactic refraction error. Simply by removing these two factors, it is possible to improve the accuracy and determination of the flashes on the order of 60%. Lunar based geodetic cameras or ballistic cameras may show great potential because of the unlimited weather conditions, perpetual night sky, and slow diurnal rate. It is not inconceivable that such cameras would be useful in the guidance of vehicles in inter-planetary space because of
their extended range of usefulness and the very high angular resolution obtainable. Such systems will probably be of great focal length and approach very closely the more classical application of astrometry. Lunar-based cameras, however, are confronted with several rather formidable problems such as radiation, heat, cold, and high energy particles which would tend to expose the plate unless very careful shielding is done. There would have to be a rather complete lunar-based timing and communication system to determine time from astronomical constants. The photographic plates would have to be maintained at some temperature at which they are useful. The cameras would have to be protected from the effects of meteorites and there is apt to be operator's problems in that the clumsiness of probable protective clothing for the human will not allow precise work and he would have trouble viewing through conventional finder telescopes. Complete plate development and plate reduction facilities will have to exist on the moon for the data to be practically useful. It is clear that automation would have to be used extensively to make a lunar geodetic camera station functional.

Stellar geodetic cameras would be quite useful in determining details of the lunar surface positions, shape, and mass distribution as they would be determined on the earth. In fact, photogrammetry and stereo photogrammetry would seem to be the only reasonable first approach to a general survey of the moon. If the moon were 1/4 the diameter of the earth, the surface therefore would be only 1/16 that of the earth. However, photogrammetrists only have 1/4 of the earth's surface in land to be measured. This means that the lunar surface consists of about 1/4 the land area of the earth and photogrammetrists know how many man-hours it has taken to arrive at our present state of geographic knowledge of the earth, and they further know how slow the rate of progress was before the advent of photogrammetry when only the conventional theodolite survey was performed.

Lunar photogrammetry is a vast new world which has only become of interest to many in the past decade. The most thoroughly distributed publication in the field today is probably the Air Force's Lunar Chart series available from the Government Printing Office. The scale is the same as that of the World Aeronautical Charts and the price is only twice that of a WAC.

Optical Design

The instruments used in photogrammetry including stellar geodetic and ballistic cameras depend very heavily on the quality of the optical design of the system and its execution by fabrication. There have been many advances in the past decade in the field of optical design which should allow considerable improvement in the various photogrammetric instruments. However, very limited use has been made, to date, of these advances.

One area of advance has been promoted by the advent of the high-speed, high-capacity digital computer. The pioneering work of Dr. James Baker in the era containing the Second World War would have made unbelievable strides if performed on the computers available today. The computers of today offer tremendous economy in both time and money to the design of optical systems. Whereas relatively simple photographic lenses would take years to design in the past, much more complex designs can now be achieved in months or even weeks. Semi-automatic design programs have been developed which take almost all of the burden from the designer and allow him to think only the most penetrating thoughts required for the optical design and not be bothered with mundane and tiresome tasks. Although all these programs are still in the very early stages of development; they are already proving to be invaluable tools, and the organization which attempts to pursue this business without such capabilities is sure to find that its designs are not competitive in either price or quality. Another advantage of the computer era of lens design
is that much more thorough work can be done in the optimization of designs and many more factors can be practically included in the design rather than considered by only a cursory inspection.

Another major area of improvement is that of optical materials both for refraction as in glasses and other transparent media and reflection as in metallic mirrors and other types of mirrors. One should also comment on the advances in coating technology for high reflection, anti-reflection, and spectrally selective coatings for filters. Not only have there been improvements in the available materials and material processing techniques, but also there have been very significant improvements in the methods of selecting appropriate materials for color correction. Hertzberger\(^3\) and others\(^4\) have made great strides in developing the selection techniques. It has been shown that using only refracting elements it is possible to design lenses which would not be detectably different from mirrors with respect to color correction. Color correction has been one of the most serious faults of stellar geodetic systems. We have done extensive theoretical and experimental investigations in this area recently to show the extent to which these difficulties exist. The useful spectral range of even the best stellar geodetic systems is only from 1000 to 1500 Angstroms wide. However, the sensitivity of the plates used is more than 3000 Angstroms wide and in the night operation of stellar geodetic cameras there is no difficulty with the blue sky background. It should therefore be possible to use all of the visible spectrum and perhaps some of the radiation in the near ultra-violet and infrared to advantage. If this were accomplished, a given aperture would collect on the order of two to three times as much usable energy and therefore be more than one f-stop faster than present systems at the same aperture. This is definitely one of the fertile areas which should be pursued next in the field of stellar geodetic cameras.

The new techniques have, of course, had considerable advantage in the development of all types of optical systems. Navigational systems and real-time tracking systems have benefited from these new techniques somewhat already. The two dual field star trackers described earlier were designed exclusively on high-speed digital computers and much of the optimization was done by semi-automatic lens design programs. The two systems described also included 4 and 2 aspheric surfaces respectively. Such surfaces are very difficult to design and evaluate by other than digital computation\(^5\). The two systems described were designed in their entirety, including the telescopic and inside-out optical system, in less than one hour of computer time per system. The time between conception of the system and the final detailed working design was only a few weeks, although we must admit that these were designed on an "as soon as possible" basis.

The techniques and tools of the optical design field and the optical industry in general are ready to provide the instrumentation necessary for all of the many far-reaching programs in the measurement of positions in space, such as navigation, tracking, photogrammetry, and geodesy.
Footnotes


Figure 1. DUAL FIELD SPACE SEXTANT
Figure 2. Annular Wide Field System
Figure 3. Space Sextant Monitor Display of Field of View as seen by Image Tube Through the Wide Field System
Figure 4. Combined Optical System
Figure 5. COMBINED OPTICAL SYSTEM ASSEMBLY
Figure 6. Second Model Optical System
Figure 7. SECOND MODEL ASSEMBLY
### Geodetic Cameras

**RMS Error Contributions**

**Under "Normal" Conditions**

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Figure 9. 1000 mm GEODETIC CAMERA SYSTEM WITH SHUTTER AND DOME AS SEEN IN USE

Figure 10. 1000 mm GEODETIC CAMERA SYSTEM WITH SHUTTER AND DOME, CUTAWAY VIEW