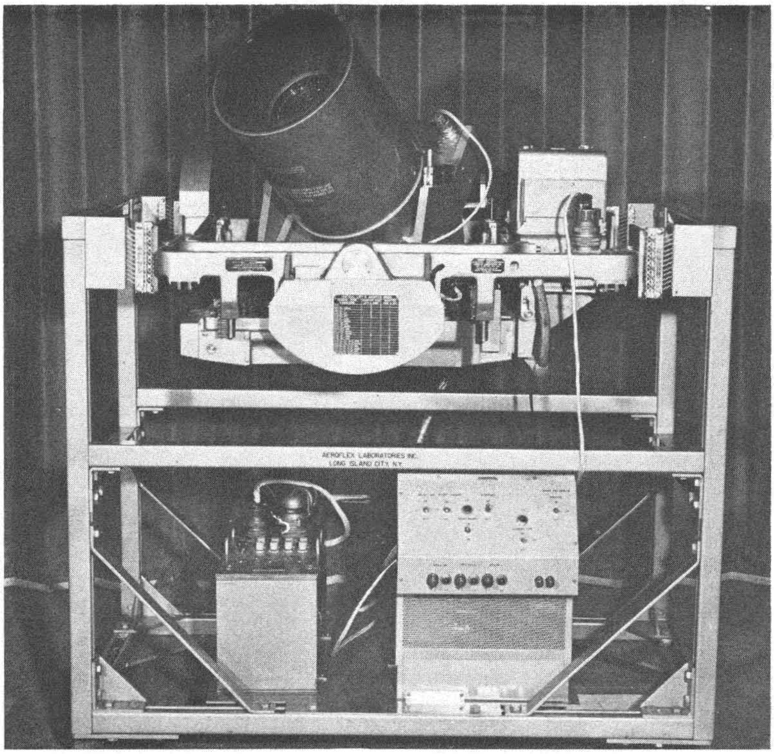

FIG. 1. Gyrostabilized camera mount with K-37 camera.

NELSON C. VANCE
U. S. Naval Oceanographic Office
Washington, D. C.

A Photo-Astro Ship Locating System

A method is developed and tested for determining the position of a vessel at sea from a passing satellite using a gyrostabilized camera.

INTRODUCTION

THE METHODS OF GEODESY employed for establishing control and mapping terrestrial masses of the earth are well known and adequately documented. However, when the earth's surface is considered "in-total," one cannot fail to observe that the oceans, which comprise about 72% of the earth's surface, are virtually a "geodetic desert" from both informational and observational viewpoints. With the exception of stations on some widely spaced islands, the ocean areas are void of geodetic control.

When one considers the problem of mapping the surface of the ocean floor, it soon becomes apparent that the traditional methods of observational geodesy are, in general, not usable at sea. Even the most basic and independent of classical geodetic survey techniques—that of establishing astronomic positions by multiple stellar observations with a precise theodolite—is not practical since one could not hope to establish a satisfactory vertical reference for each of several observations taken from the moving deck of a ship.

One might ask the question, why not use electronic positioning systems? Actually there are presently in use several electronic ship positioning systems which have the advantage of operating in all types of weather and are capable of providing real time positions. Most of these, however, are still subject to errors caused by a lack of knowledge of the exact values for the propagation of radio waves. The system described in this paper was designed to complement these systems by establishing precise geodetic positions at sea. In addition, it could be used as a standard with which to calibrate and evaluate electronic systems.

Four years ago, at which time oceanographic technology was expanding rapidly, geodesists were examining optical satellite geodesy as a method for improving geodetic nets within one land mass and for making long intercontinental ties with accuracies commensurate with geodetic work. The outstanding advantages of optical satellite geodesy, as compared with classical geodetic methods, are: (1) it is independent of errors caused by deflection of the vertical and (2), the satellite is high enough above the earth's surface to provide a common observation point from the vertices of extremely large triangles. Both of these factors are intriguing to those interested in accurately positioning a ship at sea. A system free from deflection of the vertical errors and capable of participating in triangulation schemes with far-distant land-based positions was promising indeed! It thus appeared that the Ballistic Camera approach offered a means of establishing a geodetic control net for mapping the ocean floor.

It is the intent of this paper to present a brief background description of optical satellite geodesy and then to describe, in the main text, the details of developing and testing the equipment. The various phases will be discussed as follows:

A. Preliminary Planning
B. Development of Hardware
C. Preliminary Testing
D. A Miniaturized Test of the System Using a Ship Motion Simulator
E. A Miniaturized Test of the System Aboard Ship
F. A Shipboard Test Utilizing the Satellite ECHO I

ABSTRACT: *The purpose, design, fabrication, and testing of a prototype Photo-Astro Ship Positioning System are described. Results of Atlantic Missile Range and U. S. Naval Oceanographic Office tests of a gyrostabilized ballistic camera system indicated that a ship at sea was positioned within two feet of its true location. The test involved an aircraft-borne flashing light observed against a stellar background. Extrapolation of the test data indicates that if an active or passive satellite at an altitude of, say, 600 nautical miles, were substituted for the aircraft, the ship could be positioned to within 100 to 150 feet using more sophisticated equipment, assuming all other parameters are comparable to those of the reference test. These conclusions are borne out by a concurrent theoretical study conducted by The Massachusetts Institute of Technology under contract to the U. S. Naval Oceanographic Office.*

BACKGROUND

Ballistic cameras have been used in Germany for many years, and more recently the United States, to track missiles and accurately determine the time correlated spatial coordinates of selected points along the missiles' trajectory. Basically, the technique used is simple. Ballistic cameras (cameras with high precision optics and suitably large apertures for recording several magnitudes of stars) are positioned at known geodetic positions in such a manner as to provide good geometry for triangulation of the anticipated path of the missile. A series of short, time correlated exposures is taken prior to and after the missile tracking event to provide a reference star field on the photographic plate.

As the camera remains in a fixed position, images are formed by the apparent motion of the stars across the plate. The reference star field serves as the basis for the determination, for each camera, of the absolute orientation with respect to any chosen celestial coordinate system. During the tracking event, all camera shutters are open and simultaneously record the images of flares ejected from the missile in flight. Measurement of the coordinates of the flare images on each plate provide data to yield direction cosines from each station to each flare and provide a means of triangulating the spatial coordinates of each flare. It follows that if one of the several camera stations be treated as an unknown location, it is possible to determine the direction from the flares back to the earth's surface to locate this station. Thus, we have the basis for photogrammetric flare triangulation or optical satellite geodesy. In recent years, however, geodesists have been working more with passive satellites than with active satellites and missiles. In observing passive satellites the flares or flashes are replaced by a series of short, time-correlated images of the satellite in reflected sunlight. The images are produced by synchronously opening and closing the shutters on all cameras.

A. PRELIMINARY PLANNING

When the U. S. Naval Oceanographic Office examined the possibility of locating a ship by means of observing satellites against a stellar background, it was fortunate that methods and techniques-established for land based cameras could be drawn upon. As mentioned previously, cameras used in terrestrial observations are normally stationary (i.e., without sidereal mounting). Pre- and post-event stellar exposures provide a means of determining camera orientation and stability, from which directions to the flares, flashing light, or shutter chopped portions of a passive satellite orbit can be computed to provide secondary control points whose spatial coordinates can finally be determined.

If one considers utilizing the terrestrial method aboard ship, he notes that the camera must be presumed to have remained in a fixed orientation between the pre- and post-event star calibration exposures. That is, it would require that the camera be stabilized to a second of arc over a period of, say, 10 minutes. This was not considered practical. Very early in the development program, it was indicated that the camera would not only have to be somewhat stabilized, but also that it would be necessary to develop an observing technique that would provide for computation of an instantaneous orientation of the camera at the time of each flash rather than to employ the pre- and post-event calibration exposures normally used for still cameras.

One method of accomplishing this instantaneous orientation was suggested by Duane C. Brown while he was with RCA at the Eastern Test Range. Basically, the idea was to rotate the camera at a constant angular rate during exposure. The rate would be rapid as compared to the sidereal rotation but slow enough to permit the stars to create a good quality photographic image on the plate. By introducing such a motion, small irregularities in the star trails, resulting from imperfect stabilization, could be elongated in the direction of rotation and the breaks in the images programmed from the closing and opening of the shutter could be measured. During the data reduction process, it would be possible to use the coordinates of these time correlated breaks in each star trail to fit a mathematical description of the curve formed by the star's path across the plate. The problem would then be reduced to one of interpolation along the curve to find the time correlated coordinates of the stars at the corresponding times of each flash.

As will be discussed later, this concept of observation was eventually abandoned. However, it was a good beginning and was abandoned because the availability of improved equipment in the field of timing permitted the use of a system more suitable for data reduction.

After formulating these preliminary system concepts, it appeared that the most practical means of evaluation would be to assemble a prototype system and examine its performance at sea.

B. DEVELOPMENT OF HARDWARE

The preliminary approach was to assemble and test a prototype system in order to verify its feasibility and investigate design parameters for an optimum system. Accordingly, available components were used when possible. A two axis (pitch and roll) gyrostabilized aerial camera mount and an aerial camera with an $f2.6$ aperture and 300 mm. focal-length lens were obtained with very little effort. The particular type of camera that was obtained had been used during the early days of the missile ranges as a ballistic camera with some degree of success. Camera modification was relatively simple. The shutter mechanism was replaced with a solenoid arrangement to provide for opening and closing the lens according to any desired program. In addition, an adapter was made for the camera back which would accommodate plate holders designed to accept standard glass ballistic camera plates.

The gyrostabilized mount, on the other hand, required more modification. It had been designed for use in an aircraft to support an aerial camera in a vertical position. Consequently, adaptation was necessary to make it suitable for shipboard application in stabilizing a stellar camera. Figure 1 (shown on first page of article), which shows the equipment after assembly, will be a convenient reference in describing the various components.

The stand was constructed to support the camera and mount at a convenient working level above the deck. The shock mounts, which can be seen between the stand and the gyrostabilized mount, were installed to eliminate vibration from the ship's engines and screws. These particular shock mounts were removed later and replaced by shock mounts between the deck and the bottom of the stand. The reason for this change was that, although the original shock mounts absorbed the vibrations, they allowed the mount to swing in azimuth as the ship rolled and pitched.

The stabilized mount, as it appears in Figure 1, required no physical changes to its configuration other than the addition of weights to balance the completed system. An adapter was designed and constructed, however, to support the camera in the mount. The top portion of this adapter can be seen supporting the camera trunnions. Designed to attach to an existing gimbal ring, the adapter, in addition to supporting the camera, provides for azimuth settings through 360° and elevation settings from 0° to the zenith. As can be seen, the camera was nestled as low as possible in the mount in order to keep the center of gravity of the stabilized weight close to the intersection of the gimbal axes. This limited the minimum elevation angle to between 20° and 40°, depending on azimuth setting, but reduced the size of the massive counter balance which was later installed below the gimbals. Perfect balance, regardless of azimuth and elevation setting, is essential for this system as the stabilizing "torquers" produce very little torque. The center of gravity of all stabilized weight must be at the intersection of the gimbal axes. Below the camera and mount, on the left, can be seen the power supply. On the right is the control panel and electronic equipment which was added to provide for an induced angular rotation of the camera through either the pitch or roll "torquer."

C. PRELIMINARY TESTING

After the system was assembled and operating, it was taken to sea on the USNS *Richfield*, a Pacific Missile Range tracking ship, for preliminary testing. The purpose of these tests was to obtain stellar photography to ascertain the quality of star images which could be obtained, and at the same time to evaluate the performance of this particular gyrostabilized mount.

These tests showed that use of this equipment for test purposes was feasible if it were used aboard a large ship in a fairly calm sea. This was satisfactory, for it was believed that good test results under these conditions would provide an indication of what could be expected of a more sophisticated system under normal operating conditions.

D. A MINIATURIZED TEST OF THE SYSTEM UTILIZING A SHIP MOTION SIMULATOR

Starting in 1962, a series of tests was conducted at the Atlantic Missile Range. These tests, a joint effort by the Atlantic Missile Range and the U. S. Naval Oceanographic Office, were performed utilizing Navy equipment with the exception of the camera. The original camera was removed and replaced with a Wild B-C4, 210 mm.-fl. camera furnished by Atlantic Missile Range. This was considered desirable for several reasons: first, the calibration constants for the lens were known; second, the shutter was compatible with range timing and sequencing; third, many plate holders were already available for use with this camera; and fourth, the missile range ballistic camera operators were familiar with its operation. Necessary modifications for the camera change-over were done at the AMR.

Although the primary objective was to test the system aboard ship, it developed that much could be learned by testing it on a ship motion simulator first.

The first tests aboard the simulator, Figure 2, were designed to determine an optimum shutter sequence and induced angular rotation rate.

While modifications to camera and mount were being made, plans were formulated for the simulator and shipboard tests. One of the most important problem areas that required a decision was that of timing and sequencing the camera. It was decided that the curve fitting technique previously planned for data reduction of stellar images would be rather difficult and that it would be better to synchronize the shutter with the flashing

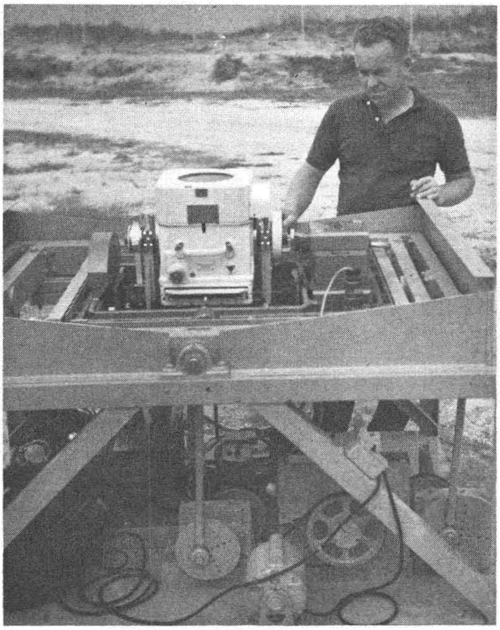

FIG. 2. Gyrostabilized camera mount with Wild BC-4 camera on ship motion simulator.

light to be carried by a high altitude aircraft to supply secondary control points for these tests. This would have the advantage of providing a short, discrete image of each star for each flash and eliminate the need for interpolation in data reduction. However, the camera would still be driven through an angular displacement in order to stretch out the star trails and smooth out some of the stabilization errors.

For the actual test, the cameras were deployed as depicted in Figure 3. The flashing light was carried by an aircraft at an altitude of 20,000 feet. Light flashes were commanded from the ground and synchronized to the mean time of the shutter opening for the gyrostabilized camera. Supporting cameras operated in the normal mode, i.e., a pre- and post-event star calibration and an open shutter to record the event.

Results of this test, according to a report by H. L. Jury of Pan American World Airways at AMR, showed that the stabilized camera was positioned to 1.22 feet Circular Probable Error with respect to the known geodetic position of the station. Had a satellite been observed at a slant range of 1,000 nautical miles, the error probably would have been about 300 feet.

E. A MINIATURIZED TEST OF THE SYSTEM ABOARD SHIP

The results of the motion simulator test were extremely encouraging and plans were made to proceed with the shipboard test. As will be noticed by comparing Figures 3 and 4, the geometry of the two tests was quite similar. Two additional problems, however, needed to be considered in conducting the shipboard test which should be noted. First, as the ship could not sail any closer than three miles off shore, the distances between cameras were greater and it was necessary to fly the aircraft carrying the flashing light at an altitude of 40,000 feet in order to obtain orientation conducive to reliable geo-

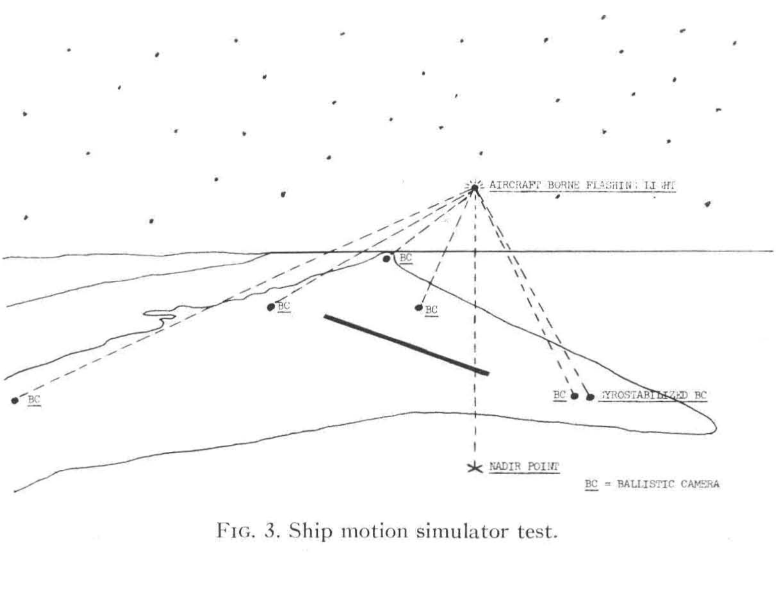

FIG. 3. Ship motion simulator test.

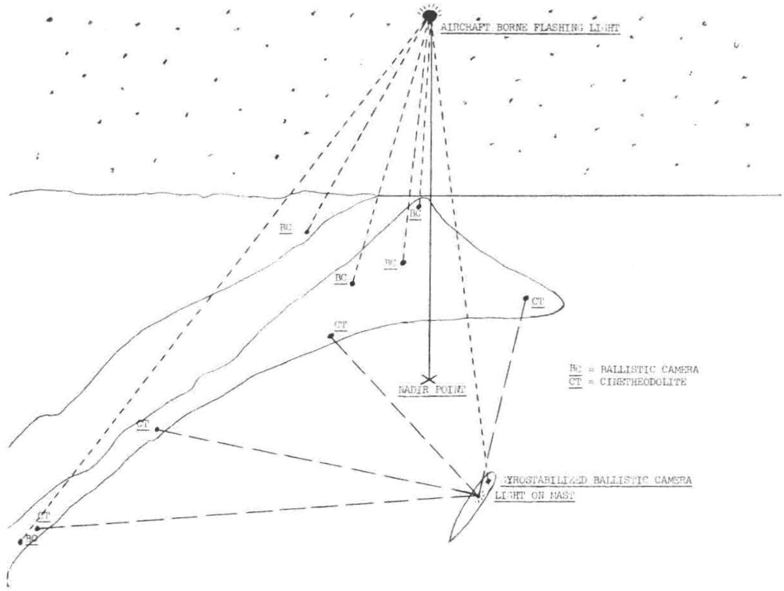

FIG. 4. Shipboard test.

metrical solution. Second, the ship was moving slowly in order to maintain a heading (the gyrostabilized mount did not stabilize in yaw) and a method for accurately locating the ship was required in order to have a basis for evaluating results obtained by the system being tested. It was deduced that time-correlated positions to within ten feet could be acquired by tracking a light on the ship's mast with cine theolites positioned at first-order locations along the shore.

Fortunately, during the period of the test the sea was very calm. As mentioned earlier, the capabilities of the particular gyrostabilized mount were limited and a relatively calm sea was needed for a successful test. Everything went smoothly and only one change was made in the test plan. It had been planned that the ship would sail two consecutive courses (one normal to the other) and observe three passes of the aircraft on each course. This plan was abandoned in favor of sailing one course twice because the heading was such that natural sheltering of the camera from the wind by the ship's superstructure was extremely good on this course.

As in the previous test, all data were reduced at AMR. Results were very encouraging. According to a report by Messrs. J. E. French and C. H. Rosenfield of RCA, the ship was positioned with a CPE of 2.06 feet.

F. A SHIPBOARD TEST UTILIZING THE SATELLITE ECHO I

From favorable results on all previous tests, it was concluded only one additional test would be necessary to demonstrate conclusively the feasibility of the system. Early in 1964, the equipment was taken to sea again for a test using ECHO I. Cameras capable of synchronous shutter operation were spread out along the Atlantic Missile Range at known first-order positions which would provide good geometry to satellite orbits which passed over the ship. The ship was simultaneously located with respect to transponders which had been previously located by another method. Although the data have not yet been reduced, they have been examined, and it is believed that this test will further verify previous convictions.

CONCURRENT STUDIES

Early in 1963, a detailed theoretical feasibility study of the system was independently conducted under contract to the U. S. Naval Oceanographic Office by the Experimental Astronomy Laboratory of the Massachusetts Institute of Technology. The study was conducted by A. C. Conrod under the able guidance of the Laboratory Director, Professor Winston Markey. As a result of the study, the U. S. Naval Oceanographic Office was furnished with a complete report stating that

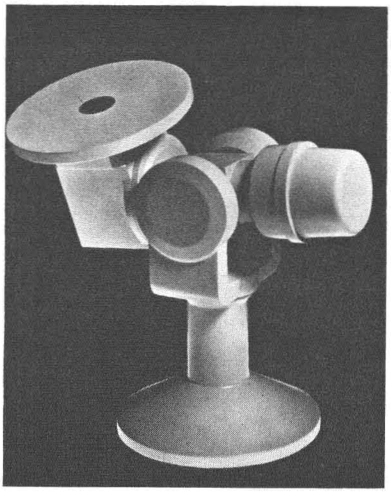

FIG. 5. Wooden mockup model of a shipboard gyrostabilized mount for 300 mm focal-length ballistic camera.

the system is feasible and detailing the design of an optimum system. The study concluded that a well designed and properly operated system should be capable of positioning a ship with accuracies approaching 100 feet.

Recommendations made in the report stated that an optimum system would consist of:

1. A ballistic camera with distortion uncertainties of less than 3 microns.
2. A timing system capable of time determination for shutter functions to 0.1 millisecond.
3. A stabilization system capable of stabilizing the camera to 2 arc seconds over a 5 second period of time.

Figure 5 shows a wooden model of the suggested system. The train (azimuth) stabilization torquers will be contained in the base of the pedestal, pitch torquers will be mounted on either side of the fork, and roll torquers will be mounted on the inner gimbal. The inner gimbal will support the camera at one end, counter balanced by the cylindrical housing at the other end which will house the three gyros. In actual use pointing angles for data acquisition would be established by rotating the camera in elevation about the roll axis and in azimuth about the train axis. As there is no need for an accurate vertical reference, the gyros will not be controlled by accelerometers, and consequently the camera will be standing still in inertial (stellar) space. In order to stretch out the star trails and produce measurable time-correlated star images, each of which can be identified with one of the satellite images, the camera will rotate through an angular displacement.

The system will be capable of use with either passive or active satellites and in either the intervisible or orbital mode.

ACKNOWLEDGMENTS

The U. S. Naval Oceanographic Office acknowledges the work done by all who participated in the development and testing of the system. The Office is particularly appreciative of support provided by the U. S. Air Force through the work done by H. L. Jury, Pan American World Airways, whose untiring efforts at the Atlantic Missile Range were largely responsible for the accomplishment of successful development and testing of the prototype system. In addition, the efforts of G. H. Rosenfield of the Radio Corporation of America in the field of data reduction, which involved the formulation of some new computer programs, were equally important.

BIBLIOGRAPHY

Brown, D. C. "The Precise Determination of the Location of Bermuda from Photogrammetric Observations of Flares Ejected from JUNO II," PHOTOGRAMMETRIC ENGINEERING, Vol. XXVI, No. 3, June 1960.

Brown, D. C., "Photogrammetric Flare Triangulation," *RCA Data Reduction Technical Report No. 46*, December 1958.

Schmid, H. H., "A General Solution to the Problem of Photogrammetry," *Ballistic Research Laboratories Report No. 1065*, July 1959.

French, J. E. and Rosenfield, G. H., "Project EGYPT, Data Reduction and Analysis Report (Evaluation of Gyrostabilized Photogrammetric Techniques)," *Range Geodetic Committee Report No. 1.*

Jury, H. L., "Photogrammetric Ocean Survey Equipment (POSE) Program," *Preliminary Report, Range Planning Department.*