"As to your question concerning a comparison of this system of aerial markers with that of other developments such as electronic and mechanical recordings, this can be said: A great deal of research is being carried out by a number of agencies to improve present snow survey methods. The telemetering of hydrologic data from remote locations as being studied by the University of Idaho Engineering Experiment Station is a case in point. As yet, these methods of obtaining snow data are not sufficiently developed for practical application. Installations and operating costs are much too high to be within the reach of most users. However, there is no doubt that in the future, perhaps only a few years from now, at least one or two stations in a basin will have some type of electronic telemetering equipment.

"2. In my own opinion, reading aerial markers as opposed to utilizing aerial photographs is a waste of time. Any data obtained by an on-the-spot reading would have to be substantiated with a photograph to have any value as a permanent record. Therefore, rather than using an engineer well versed in interpreting snow depths but not experienced in photographic methods, we have decided that the services of a professional photographer who is intent only on taking good photographs which can later be studied for accurate depth readings, is far more effective."

A Photogrammetric Ship-Positioning System

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ABSTRACT: *The possibility of using the photogrammetric flare triangulation technique for positioning a ship at sea for the purpose of accurately locating oceanographic data is considered. Results of tests of a prototype stabilized camera system conducted on a roll and pitch simulator and aboard ship are reported. It is concluded that use of a photogrammetric ship-positioning system, based upon the technique of photographing rocket flares or satellites against a star background from ashore and at sea, is feasible. A properly stabilized camera aboard ship should be capable of providing the same accuracy of position as is possible on land. Weather and sky brightness limit the use of the system to times when these conditions are suitable; but when maximum position accuracy is important, surveys could be scheduled at times when these conditions can be expected to be most favorable.*

INTRODUCTION

THE accurate positioning of features on the earth is a never-ending task that has challenged geodesists and cartographers for centuries. Fortunately, most of the tools and techniques needed for geodetic surveying have been developed. However, once the surveyor strays from shore and begins to map the three-fourths of the world that lies beneath the surface of the sea, his problems mount rapidly. Not only must he probe beneath the ocean's surface to the hidden mountains and valleys below, but once he has identified and mapped these topographic features he must locate them in relation to surrounding shores.

Numerous navigation systems have been devised to guide the mariner throughout the world. The most recent and most sophisticated of these is the Navy's *Transit* system. Developed for the Navy by the Applied Physics Laboratory of the Johns Hopkins University, the *Transit* system makes use of a measurable Doppler shift in signals transmitted from a satellite orbiting hundreds of miles above the earth. In operation, a ship

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will receive and record the Doppler shift of each of two frequencies transmitted from the satellite together with an accurate time signal. Using these data and an orbital ephemeris the ship's position will be determined.

Surveying the seas, however, calls for a degree of accuracy beyond that which is required for navigation. The *Transit* system is one of the most promising of navigation systems and may someday provide the accuracy required for hydrographic surveying. Other satellite systems such as the Army's *Secor* (Sequential Collation of Range) could possibly be adapted for ship positioning. Electronic systems such as *Transit* and *Secor* are appealing as possible ship positioning systems because of their all-weather capability. Optical systems, on the other hand, long used for navigation and surveying, are of little use at times when visibility is poor, and frequently require time-consuming multiple observations to obtain maximum accuracy. These limiting factors make one think twice before recommending an optical system for the precise positioning of a ship hundreds of miles from land.

As a navigator's function is normally to determine the position of a ship while underway, a system that requires days or even a few hours to compute a position is valueless for navigation. The surveyor, however, is seeking the position of a feature on the earth's surface, and accuracy, rather than time for data reduction, governs his choice of techniques and instruments. When surveying at sea, many situations exist where good relative positions can be obtained utilizing electronic navigation systems. What is needed is a way to adjust these relative positions to true positions. For this reason, an optical system, although not suitable for general navigation, may be useful for hydrographic surveying.

Nelson C. Vance, Jr.

Photogrammetric Flare Triangulation

The optical system for positioning a ship which is described in this paper is based upon the photogrammetric flare triangulation technique that has been used for many years to track missiles, and more recently to attempt to connect geodetic datums. Originally conceived with a balloon as the vehicle to carry the flares aloft, rockets now provide the geodesist a far higher light in the sky toward which to point his camera. This technique uses ballistic cameras of high-precision to photograph flares or a flashing light against a background of stars. The flares serve as relative control points, and the stars provide the absolute control from which camera orientation angles can be computed. As the camera orientation is determined from the stars, the system is independent from the deflection of the vertical. The theory behind this technique is relatively straightforward and is fully explained by Duane C. Brown in

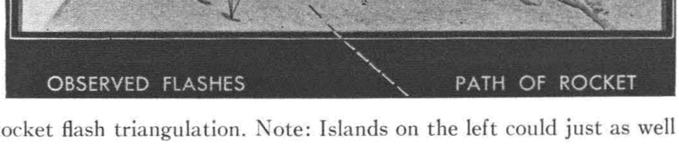

Fig. 1. Rocket flash triangulation. Note: Islands on the left could just as well be ships.

his report, "Photogrammetric Flare Triangulation."[1] The following from Brown's report briefly describes the technique.

> "Ballistic cameras are presently operated only at night. They function typically in the following manner. A few minutes before the missile-borne flashes are expected in the field of view, the precalibration star trace is recorded with the cameras firmly locked in a stationary orientation. In the precalibration, the camera shutter is opened and closed according to a sequence such as the following: opened 2 seconds, closed 30; opened 1 second, closed 30; opened $\frac{1}{2}$ second, closed 30; opened $\frac{1}{4}$ second, closed until next function. Each recorded star thus gives rise to a trace of four pointlike images of varying size and density . . . . At the appropriate time after the precalibration, the camera shutter is again opened and remains opened until the termination of the flashing sequence. The shutter is then closed for about 30 seconds to allow the stars to move a sufficient distance to permit the separation of the post-calibration exposures which are the same as the precalibration except that the order is reversed (i.e., $\frac{1}{4}$ second exposure is first and the 2 second exposure is last). The final plate thus consists of a series of flash images recorded against a background of hundreds of superb control points provided by star images."

The photogrammetric flare concept is shown in Figure 1.

The times of all the shutter functions are recorded against a precise time standard, such as the Naval Observatory time signal transmitted by station WWV, Washington, or the VLF station, NBA in Panama. With the time of the star exposures known, it is possible to determine the directions of any selected stars, and thus the rotational and interior orientation of the camera. The position of each missile flash is determined by spatial triangulation from two or more cameras at known locations.

In 1959, the Air Force Missile Test Center used the photogrammetric flare triangulation technique to determine the location of Bermuda on the North American Datum. According to Brown, the location of Bermuda was altered by 176.5 meters and was established to an accuracy of better than 20 meters.[2]

Since that time, the Air Force Cambridge Research Laboratories has attempted to use the technique in making other geodetic ties. Unfortunately, most of these attempts either failed or met with limited success. These failures did not occur because the technique is not theoretically sound, but because rockets have not always performed as supposed to and because mechanical devices such as flare ejectors have not always functioned as their designer intended.

Feasibility of a Photogrammetric Ship-Positioning System

It was the above-described technique and experiments that brought to mind a photogrammetric ship-positioning system. Because of the many problems that could be anticipated in the use of a ballistic camera aboard ship, it was decided that a feasibility study of moderate cost would be undertaken before commencing a full-scale development project. There are two major ways by which such an investigation could be conducted. One would be to conduct a purely theoretical investigation. The other would be to start taking pictures of stars from a ship and to examine the results. The technique decided upon was comprised of a limited theoretical investigation and as many tests with a camera ashore and at sea as could be arranged. The selection of this technique was influenced by the fact that the feasibility and accuracy of photogrammetric flare-triangulation had been demonstrated on land. It remained but to determine the feasibility of photographing stars from a ship with a ballistic camera that could chop the star trails in a way that would permit measuring their coordinates accurately on a photographic plate.

In an attempt to keep the cost of the investigation at a minimum, a search was begun for surplus equipment that could be used "as is" or modified at a reasonable cost. First a K-17 aerial camera with a 24-inch focal-length lens was obtained. The shutter was modified for electrical operation to permit recording the shutter functions along with a time standard on tape, Next a rigid, metal tripod was fabricated. This equipment was taken to the roof of the Naval Oceanographic Office and a series of star photos were taken on conventional panchromatic aerial film. Figure 2 shows the camera and tripod on the roof. The timing system consisted of a WWV receiver, amplifier, chronometer and recorder. Photographs obtained with the modified K-17 were used to investigate shutter performance, to practice star identification, to learn what effect the phases and location of the moon had on background density, and to determine the effect camera motion had upon the quality of star images. The later part of this investigation was conducted by photographing a star field while the camera rotated at different rates about its trunnions. Rates from 0.1 degree to 10 degrees per second were used. It was found that first-magnitude stars produced photographic traces at rates up to one degree-per-second. Lower magnitude stars became incapable of producing an image at the more rapid rates, but at 0.1 degree-per-second third magnitude stars made acceptable traces. These test results pertained to only one particular lens and emulsion combinations. From these data it is possible to predict the rates of camera motion that can be tolerated due to lack of perfect stabilization.

Other tests conducted during this period were primarily of different photographic emulsion and developer combinations. Most of that which was learned from such basic tests could have been predicted from information readily available, but it was found that opinions of authorities differ and some things are best learned first hand. Experience thus gained made it possible to subsequently conduct more sophisticated tests, and, in addition, these provided photographic negatives that would serve as controls for future work.

By February, project personnel had become quite proficient in camera operation and accustomed to spending long hours at night on the roof in temperatures well below freezing. The timing of the investigation was obviously poor as the beautiful fall months were spent in researching the literature, and the testing was carried on in mid-winter.

In addition to the personal inconveniences, the winter weather created problems with the camera. The auxiliary, before-the-lens shutter that worked so well in the shop required twice the normal voltage to operate and, during long exposures, frost formed on the lens. Similar experiences have been well documented by others in numerous reports, but frozen equipment and numb fingers impress the facts more firmly upon one's mind. On 14 February 1961, The Air Force Cambridge Research Laboratories attempted a rocket-flare triangulation experiment and invited the Oceanographic Office to participate. Unfortunately, clouds over the Washington area at the time of the rocket launch made it impossible to obtain any photographs.

In March the Air Force attempted another rocket-flare experiment. For this shot, arrangements were made to have the Navoceano camera mounted in a stabilized platform which was placed on a roll-and-pitch simulator. The weather was good for this launch, but the flares failed to ignite within the camera field of view. However, these photographs did include star traces that provided useful information regarding the performance of the stabilized platform, and indicated that it was possible to take star photos from a ship at sea. Based upon the information learned from this experiment, a breadboard model of the ship system was designed.

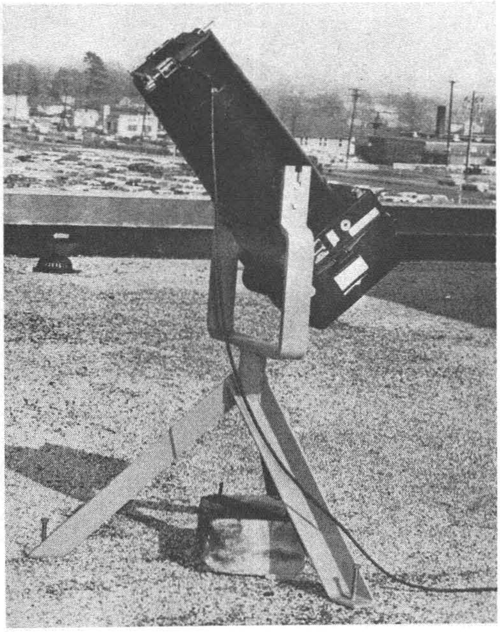

FIG. 2. Hydro's first ballistic camera. A K-17, 24 inch f.1. with capping shutter.

DEVELOPMENT OF A PROTOTYPE SYSTEM

To conserve the limited funds available, this prototype was assembled largely from surplus equipment. The stabilized platform was a modified ART-13 aerial camera mount. The camera was a K-37 aerial camera with a 12-inch, f 2.5 Aero Ektar lens. An adapter was made for the mount that permitted the camera to operate through a vertical angle of 45 to 90 degrees. Azimuth rotation through 360 degrees was also provided. The original 7 degree roll-and-pitch limit of the mount was not changed. The camera modification consisted of disassembling the shutter and installing a solenoid to permit electrical operation from a programmer. Plate holders were designed and made so that $\frac{1}{4}$-inch thick glass plates could be used in place of film.

As previously mentioned, test on the roll-and-pitch simulator had shown that the residual roll-and-pitch caused an erratic star trace in which the programmed breaks were difficult or impossible to measure, it was decided that the prototype ship system must be designed so that the position of each star on the plate could be determined at the exact time each flare was ignited. In this way, a

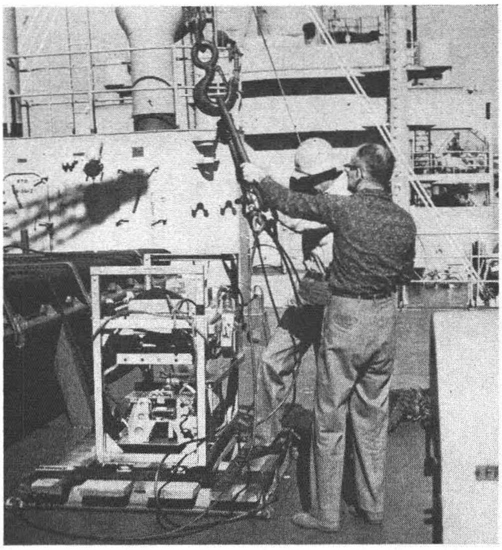

FIG. 3. System being hoisted aboard the USNS *Richfield*.

camera orientation could be determined for each flare. (The pre- and postcalibration exposures employed on land to obtain the camera orientation could not be used on board ship.) To be able to determine the location of the stars at the time of each flare, requires interpolation between programmed breaks in the star trails. As mentioned earlier, the residual roll-and-pitch made this impossible. One way of overcoming this was suggested by Duane C. Brown while he was with the RCA Missile Test Project, Air Force Missile Test Center. Brown's suggestion was to drive the camera at a constant angular rate during exposure. The rate would be rapid as compared to the Earth's rotation, but slow enough to permit the stars to produce a good quality photographic image. By introducing such a motion, the small irregularities in the star trails would be elongated in the direction of drive, and the position of the stars at the breaks caused by closing and opening the shutter could be measured. Brown's suggestion was adopted, and the ART-13 mount was modified to include such a drive mechanism. Work on the camera and mount was completed in three weeks so as to be ready to test during the Air Force's Project *Cambridge*. This project was to be an attempt to make the geodetic tie between Hawaii and the North American Datum by rocket flare triangulations.

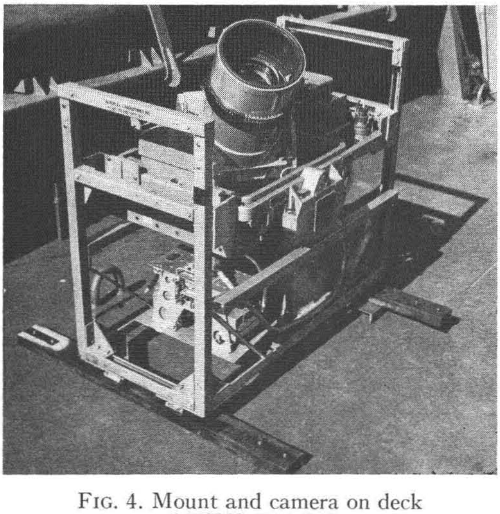

FIG. 4. Mount and camera on deck of USNS *Richfield*.

TESTS ABOARD SHIP

Project *Cambridge* called for four cameras to be located in North America between Alaska and California and two cameras to be in the Hawaiian Islands. The rocket was to be launched from the Pacific Missile Range Facility at Point Arguello, California, and was to reach an altitude of 1,500 miles approximately 900 miles down range. This project offered an opportunity to try out the prototype stabilized camera aboard ship.

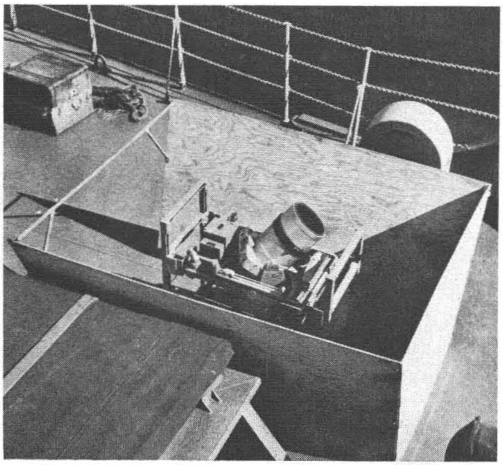

FIG. 5. Plywood shield to protect the camera from wind.

The cooperation of the Pacific Missile Range was solicited, and permission was obtained to place the camera on a range tracking ship that was to be stationed 900 miles at sea directly beneath the rocket's apogee. At this point in the trajectory, 7 flares were to be ejected from the rocket with an interval of 5 seconds between each flare. The camera

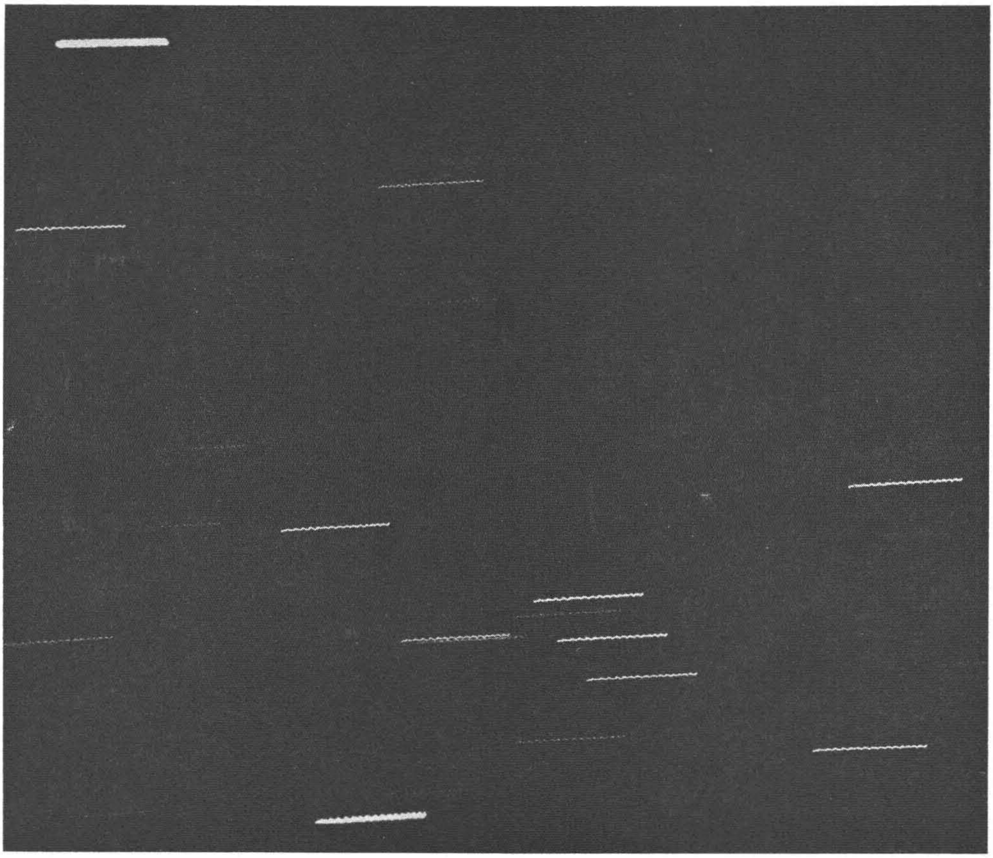

FIG. 6. Star exposures made ashore with simulated ship motion.

system and related timing equipment were shipped to Port Hueneme, California, and installed aboard the USNS *Range Recoverer*.

A trial run a few days before launch showed that the *Range Recoverer* rolled nearly 7 degrees, the limit of the mount, in a calm sea, and that a wind shield around the camera and mount was necessary.

Four days before the scheduled rocket launch for Project *Cambridge*, the *Range Recoverer* sailed from Port Hueneme for its station 900 miles at sea. It was planned to use this trip to test the camera and platform; however, only one night was clear enough for taking photographs of the stars. When these plates were developed aboard ship, it was learned that the camera was not properly stabilized. A day's work on the mount improved the stabilization somewhat, and the sea was calm and the sky clear when the ship arrived on station. By the time the rocket was finally launched the next night, the weather had changed, and 100% cloud cover made it impossible to obtain any photographs. Weather in Hawaii and North America was good, and, as the test of the camera on the ship was a secondary requirement, the launch could not be delayed. Immediately after the launch of the *Cambridge* rocket, the ship sailed back toward California. It had been hoped that the four nights of the return trip would make further testing of the camera system possible. Heavy cloud cover and rough seas, however, made it impossible to obtain photos on the return trip.

After this discouraging trip, it was decided to put the camera system on a roll-and-pitch simulator at the Pacific Missile Range and to attempt to improve the camera balance and stability. This was done during the past January, and by the first of February the breadboard model looked promising enough to attempt another sea trial. No flares would be available for this test, but as the primary purpose of the test was to obtain photographs of the stars from which the camera orientation could be derived, the rocket flares were really not necessary. The accuracy with which

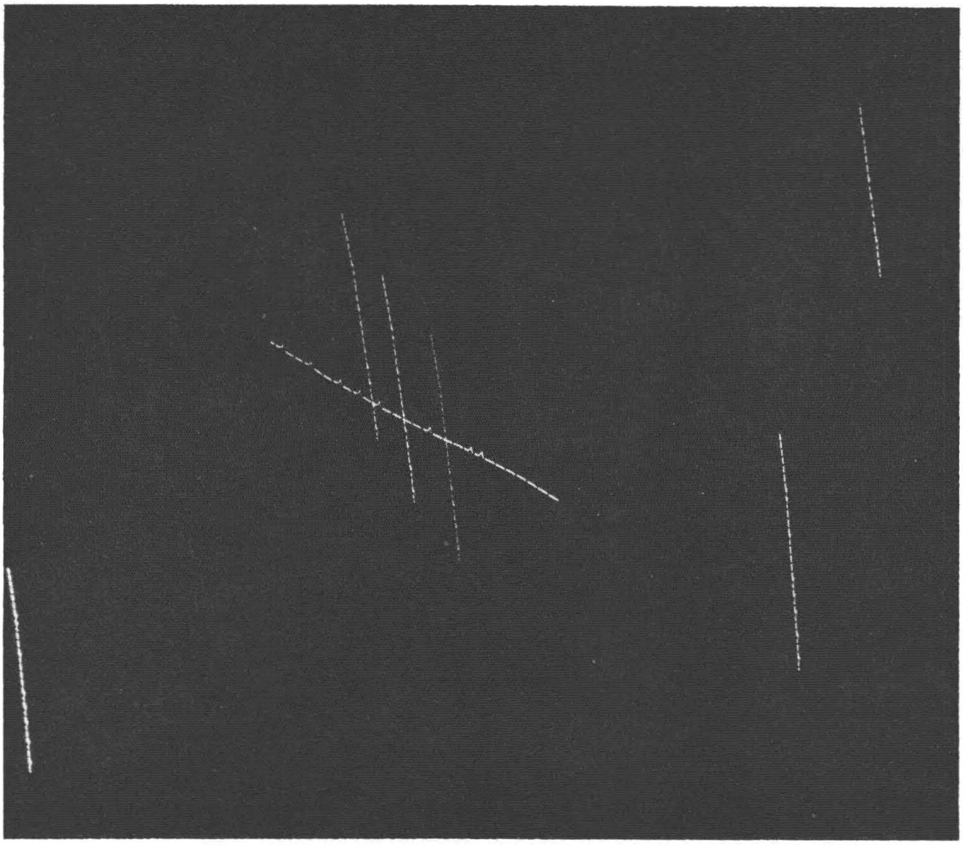

FIG. 7. Star exposure with echo imaged—exposure made aboard USNS *Richfield* in port.

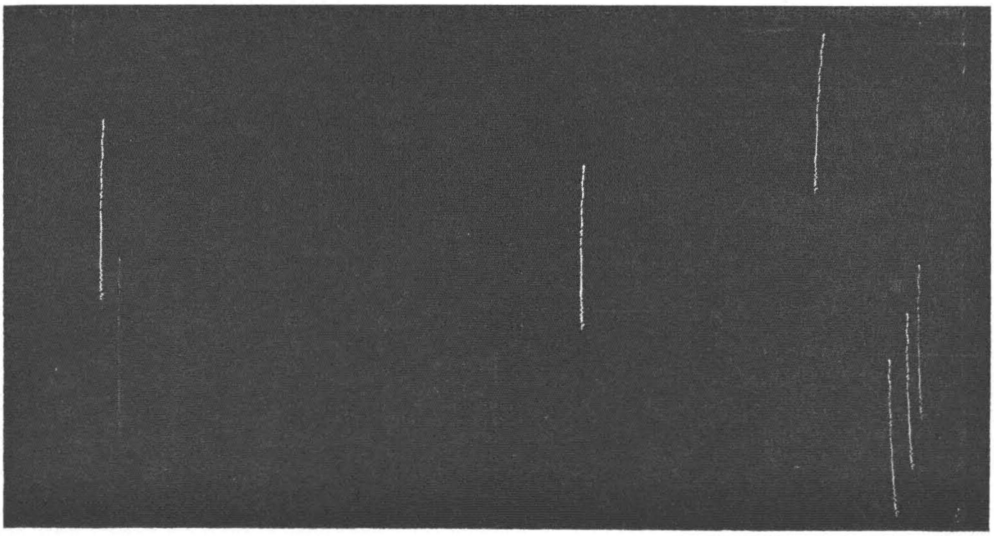

FIG. 8. Star exposure made aboard USNS *Richfield* at sea.

stars could be photographed must be demonstrated first. Flares could come later, and photographing them should present no real problems. Before placing the camera and mount on a ship, star photos were taken ashore while the system was being rapidly rocked in one direction. Figure 6 shows a photograph taken during this test. The residual motion shown by the excursions in the star trials, was about 5 minutes.

A second sea trial was scheduled during February at a time when the *Echo* satellite could be photographed near California. For this test, the camera and stabilized mount were placed aboard the USNS *Richfield.* (Figures 3, 4, 5.) The *Richfield*, a Victory ship converted for range use, provided a more suitable test platform for the prototype system than had the smaller *Range Recoverer* used during Project *Cambridge.* In spite of the unusually heavy rains that occurred in California during February, photographs of *Echo* were taken from the *Richfield* at sea and in port when the weather permitted. Figure 7 shows one of the photographs of *Echo* taken while the ship was in port. A similar photograph was attempted at sea soon after sunset, and was badly overexposed.

February 22 was the last night that *Echo* was visible in the area for several weeks. The *Richfield* went to sea again the following week, however, and star photos were taken (Figure 8). It has not been possible to fully evaluate these photographs in the short time available, but they do show the possibility of using ballistic-type cameras aboard ship to photograph satellites or rocket flares.

CONCLUSIONS

From the information obtained during this limited investigation it is concluded that a ship-positioning system, based upon the photogrammetric flare-triangulation technique, is feasible. A camera having a calibrated 12-inch focal-length, f 2.5 lens is suitable when mounted on a platform stabilized in roll, pitch and azimuth.

Such a system should provide a ship's position in mid-ocean with the same accuracy (50–100 ft.) as is now attainable using the photogrammetric flare triangulation technique ashore. The accuracy of the system when satellites are used in other than the intervisible mode is dependent upon the accuracy with which the orbit is determined.

The use of the system aboard ship or ashore is restricted by data reduction time, weather and sky brightness. However, in those instances when an accurate position is needed at sea and time is not critical, operations could be scheduled when the weather and the phase of the moon can be expected to be most favorable.

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