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Satellite Triangulation in the Coast and Geodetic Survey

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Technical Bulletin Series

This series of Technical Bulletins was inaugurated to present primarily to the personnel of the Coast and Geodetic Survey and incidentally to others technical information related to the Bureau's scientific and technical activities. Since many of the bulletins deal with new practices and new techniques, the views expressed are those of the authors and do not necessarily represent final Bureau policy.

Technical Bulletin No. 24 describes the present status of satellite triangulation in the Coast and Geodetic Survey. This hulletin, which is the work of many, is divided into four parts. The introduction contains tbe objectives and benefits of the subject and the basic principles. Under data acquisition are described the equipment, field operations, and quality control. The preliminary evaluation and computations, plate measurements and accuracy evaluation, and geometric reduction of data are found in the section on data reduction. The part on the satellite triangulation program deals with the results obtained on the first triangle, preliminary positioning of Bermuda, and planned continental and world networks.

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Satellite Triangulation in the Coast and Geodetic Survey

INTRODUCTION

Objectives and Benefits

With the advent of the space age, geodesists gained a valuable new tool: the artificial earth satellite. Geometric satellite geodesy, ordinarily referred to as "satellite triangulation," offers the first truly universal technique of accomplishing geodetic datum interconnections and establishing a valid world geodetic datum. The revolutionary importance of satellite triangulation is that a strictly geometric solution provides geodesy, for the first time in history, with the means of creating a three-dimensional, worldwide reference system that is independent of both the direction and magnitude of the force of gravity. The ultimate objective of the technique may be considered as the establishment of all points on the physical surface of the earth in terms of a universal three-dimensional coordinate system, the origin of which coincides with the center of mass of the earth, and one of whose axes coincides with the earth's rotational axis.

The primary purposes and benefits of satellite triangulation are as follows:

1. To provide a worldwide reference net to which all geodetic and topographic data can be related. Such a reference system would achieve economy and permanence in the collection and recording of data essential to the development of the earth sciences.

2. To replace the classic, time consuming, long arc triangulation methods of determining the size and shape of the earth by a more economical and theoretically superior approach. A knowledge of accurate earth parameters is necessary for the solution of modern geodetic problems and for meeting the requirements of modern astronomy and space research.

3. To produce unified, three-dimensional reference nets on all accessible land masses, thus eliminating the troublesome discontinuities in map and survey systems that occur over most national frontiers and which seriously hamper development in such areas.

These continental satellite triangulation nets will provide the necessary control for numerical photogrammetric aerial triangulation, executed from extremely high-flying aircraft or satellites to further intensify the geodetic control pattern in local areas in order to provide control density in accordance with specific topographic mapping requirements. The creation of such a control pattern will provide the most economical approach to worldwide mapping programs, and at the same time furnish the geodetic community with a data library for fast-response mapping capability.

4. To establish the necessary geometric fidelity for a worldwide system of satellite tracking stations for the accurate determination of satellite orbits, which will provide data ideally suited for analyzing gravimetric and related geophysical parameters. These parameters, in turn, are the necessary prerequisites for determining the position of the center of mass and the overall shape of the gravitational field of the earth.

Basic Principles

The geometrical triangulation of a selected number of non-intervisible points on the physical surface of the earth can be accomplished by a process of spatial triangulation, using auxiliary target points sufficiently elevated above the surface of the earth. Artificial satellites that can provide light signals visible over long distances are well suited for this purpose. Because of the unavoidable motion of a satellite, precise direction measurements can be carried out, at present, only by photographing the satellite against the star background and using the photogrammetric method as a tool of interpolation.

The reference system into which the direction to a satellite can be interpolated is the right-ascension declination system. This reference system is attractive from the geodetic standpoint because one of its axes is by definition parallel to the rotation axis of the earth. From a quantitative standpoint, a practically unlimited number of fixed stars are available as reference points. Since the stars are for all practical purposes at infinity, it follows that their direction coordinates are insensitive to translations, and, therefore, cannot be used for any scale determination.

Satellite triangulation by photogrammetric means gives promise of overcoming some of the basic difficulties encountered in classic geodetic triangulation. Foremost is the fact,

previously mentioned, that such a triangulation is independent of the direction of gravity, and, therefore, free of any a priori geophysical hypotheses. Because of the exceedingly large dimensions of its individual figures, satellite triangulation encompasses the entire earth, or parts of it, with a relatively small number of triangles and, closes its spatial triangulation in all three dimensions, thus providing sufficient geometrical strength to prevent unfavorable error propagation.

The use of the star background for orienting cameras in connection with the triangulation of auxiliary target points was applied for the first time during the 1930's by Hoppman and Lohman in Germany for trajectory measurements of shells and small rockets.

Professor Vaisala suggested the same principle in the *Sitzungsberichte der Finnischen Akademie der Wissenschaften*, 1946, under the title, "An Astronomical Method of Triangulation." The reasoning in Vaisala's paper is that two conjugate rays emerging from the end-points of a base line define a plane in space whose spatial orientation can be computed from the measured direction cosines of the two rays. If two such planes containing the base line are observed, the direction of the base line can be computed as the line in which the two planes intersect (fig. 1).

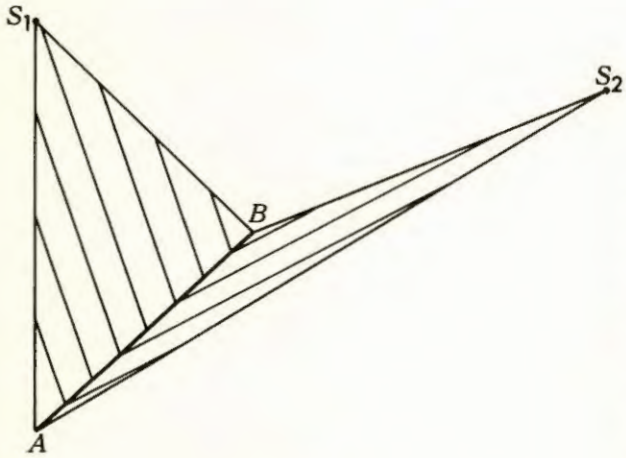

FIGURE 1.

It is now readily seen that two base lines originating from a specific station will form a spatially oriented triangle if the two lines under consideration are intersected with a plane that contains neither of the two lines and the orientation of which is known. As outlined before, each direction is determined from the intersection of two planes. Consequently, five planes are necessary and sufficient for establishing a unique solution for a spatially oriented triangle (fig. 2). Any one of these planes contains two

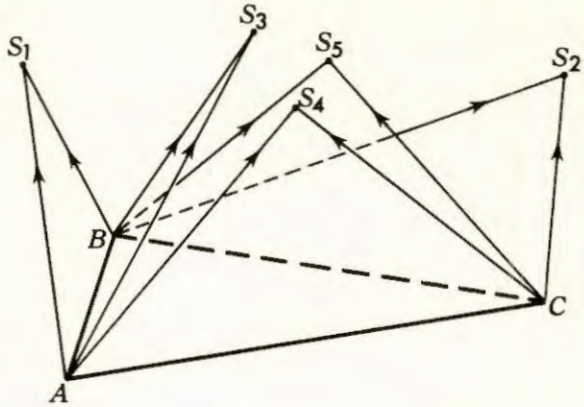

FIGURE 2.

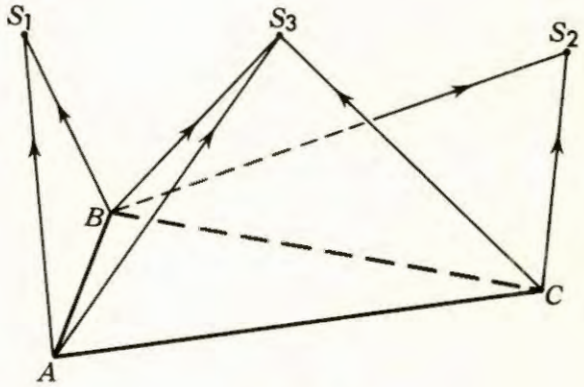

FIGURE 3.

stations and a specific satellite position. Of interest is the fact that three of the five planes can be formed with only one satellite position if the location of the satellite is such that its subpoint is approximately in the center of the triangle, as shown in figure 3. In this case, only three satellite positions are necessary.

In actual practice, a redundancy of observations is obtained by observing the satellite at many more positions than those shown in figures 2 and 3. It is desirable to obtain at least three planes intersecting along each line of the triangle. A satisfactory configuration is depicted in figure 4, where are shown, one three-station event over the center of the triangle, one two-station event approximately over each line, and one two-station event outside each line of the triangle. In lieu of the three-station event inside the triangle, three two-station observations could be substituted although the former configuration tends to provide greater geometrical strength.

The configuration of the spatial triangulation should preferably satisfy the following geometric conditions: first, the line of sight to the satellite must be at least 30° above the horizon in order

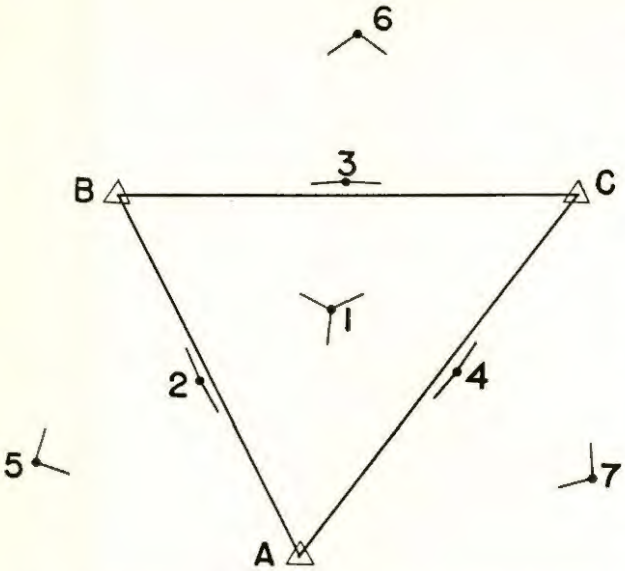

FIG. 4.—Desirable configuration of sub-satellite positions for one triangle.

to avoid disturbing refraction anomalies, second, the angle between two of the planes generating the spatial direction between two stations should be at least 60° in order to provide sufficient geometrical strength for the determination of the three-dimensional station positions, and third, the distance to the satellite should be about equal to the length of the line between stations in order to avoid scale degradation. Obviously, these conditions call for as much symmetry as possible with regard to the locations of the ground stations (fig. 5).

The feasibility of the practical execution of geometric solutions has been proven. The Coast and Geodetic Survey, using the balloon satellites *Echo I* and *Echo II*, has already performed satellite triangulation in North America over triangles with side lengths of approximately 900 miles.

DATA ACQUISITION

The basic problem in acquiring observational data in a geometrical satellite geodesy program is to accurately record time-correlated satellite and star images on photographic plates. From these plates the apparent direction to the satellite can be determined for a desired epoch in terms of the celestial right-ascension and declination system.

In the fixed-camera approach, such as used by the Coast and Geodetic Survey, the camera re-

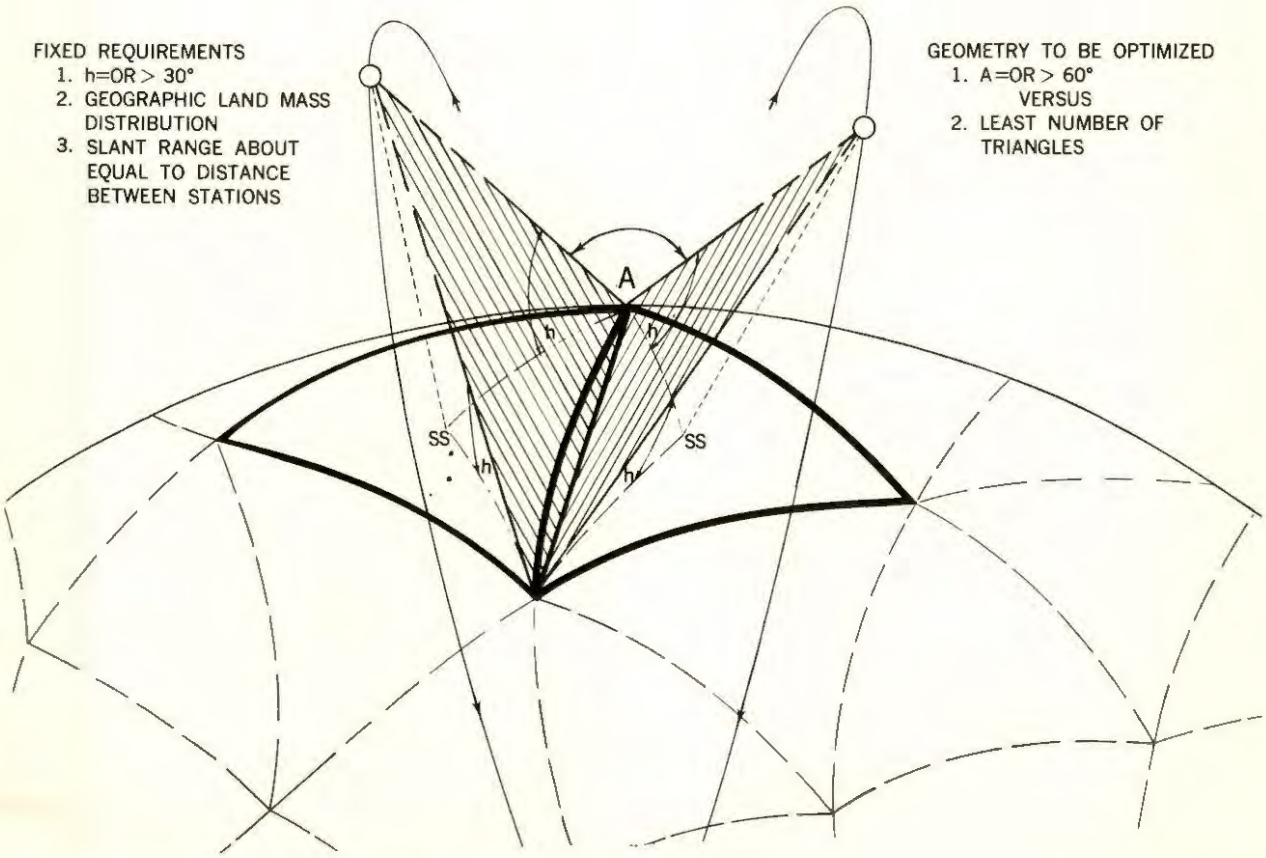

FIG. 5.—Satellite triangulation observation.

FIG. 6.—Wild BC-4 satellite tracking camera.

mains fixed in orientation during the entire observational period. Accurately timed shutters interrupt the star and satellite trails as they traverse across the field of view of the camera producing a photogrammetric record consisting of up to 1,000 stars and 800 satellite images across the entire plate. In the geometric approach it is necessary that the shutters which produce the satellite images be referenced to a time standard that is common to other camera systems involved in the simultaneous observation.

The BC-4 satellite tracking camera and electronic synchronization system described in this section were basically developed at the Aberdeen Proving Ground, Ballistic Research Laboratory after nearly ten years of research and development. Both of these components were developed concurrently to produce a completely integrated system specifically designed for missile tracking operations. By utilizing a slower chopping rate and eliminating the range-timing circuitry, the system was optimized for geodetic applications. Specifications were prepared by the Coast and Geodetic Survey prior to June 1961 and the first system was delivered in January 1962. The system was adapted for field operations by: developing a special timing system to enable widely separated field units to be essentially synchronized to ± 50 microseconds, designing mobile shelters for the camera and synchronization system, and developing all necessary field observing procedures.

Equipment

The BC-4 ballistic camera combines two well-known precision products: a modified lower part of the Wild T-4 astronomical theodolite consisting of the massive base and alidade with standards, and a modified Wild RC-5 aerial camera equipped with the Astrotar lens and a modified left-hand trunnion pivot holding a vertical circle and split-bubble vertical collimation level (fig. 6).

Orientation of the camera in azimuth prior to the observations is effected with a field adjustment frame by sighting through the principal point eyepiece to an azimuth light. Using this method, azimuth and elevation settings are made accurate to about 10 seconds of arc.

The Astrotar lens has a focal length of 305 mm., aperture of 117 mm., and an iris diaphragm that can be stepped down to f. 32. Exposures are taken on precision glass plates, 215 x 190 x 6 mm., with an effective picture size of 180 x 180 mm., corresponding to a field of view of 33° x 33°. Stars of magnitude 8 and 9 are easily identifiable on the plate, although stars of magnitude 6 or brighter are preferable because of the higher accuracy of the corresponding star-catalog information. The horizontal axis can be leveled with a striding level which has a sensitivity of 6 seconds per 2-mm. division.

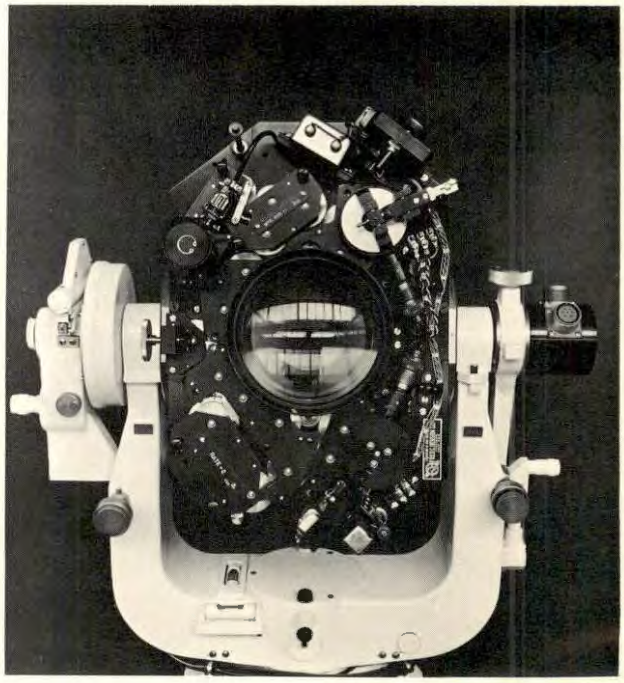

FIG. 7.—High precision shutter-drive mechanism.

Next to the plane of the iris diaphragm, and located between the lenses, are three rotating disks used for chopping satellite trails. Two of these counterrotate and constitute the high-speed exposure shutters, while the third, a slow disk is used as a capping disk to limit the exposure rate (fig. 7). The disks are driven by a high-precision gearing system. Constant speed is maintained by a 500 c.p.s. synchronous motor with the drive signal supplied by a time-code generator, which in turn is regulated by a high precision crystal quartz oscillator. Through reduction gearing, the exposure disks can be rotated at selected primary rates of 10, 5, or 2.5 times per second corresponding to exposure durations of 1/60, 1/30, and 1/15 of a second, respectively. The capping disk is synchronized with the exposure disks to reduce the exposure rate by ratios of 2 or 5. Further reduction of the exposure rate and coding of the satellite trail are accomplished by the auxiliary capping shutter mounted in front of the camera lens. This is an iris-type shutter which can be programmed to automatically subdivide the exposure rate by a selected factor.

The auxiliary capping shutter is used primarily to chop star trails before and after the satellite is tracked. This information is used to determine the orientation of the camera during the entire observational period. A normal star trail consists of groups of five images each. Different exposure times are used for each group to optimize the image size and quality depending upon the star's magnitude and declination. For star trail observations, the disk shutters are automatically locked in the wide-open position.

The electronic synchronization system provides means for:

1. determining corrections to the time-code generator with respect to a common time standard,
2. synchronizing the disk shutters with the timing pulses from the time-code generator,
3. programming camera operation on punched paper tape and controlling both the camera disks and auxiliary capping shutter,
4. exposing the fiducial marks and other camera identifying information, and
5. producing a detailed record of the observational program on ten channels of the paper recording tape (fig. 8).

While a satellite is being tracked, synchronization of the disk-type shutters to the accurately timed reference pulses from the time-code generators is accomplished in the following manner:

The desired disk-shutter rate for tracking a particular satellite pass is established electronically in the synchronization system by the programmer-selector switches and mechanically

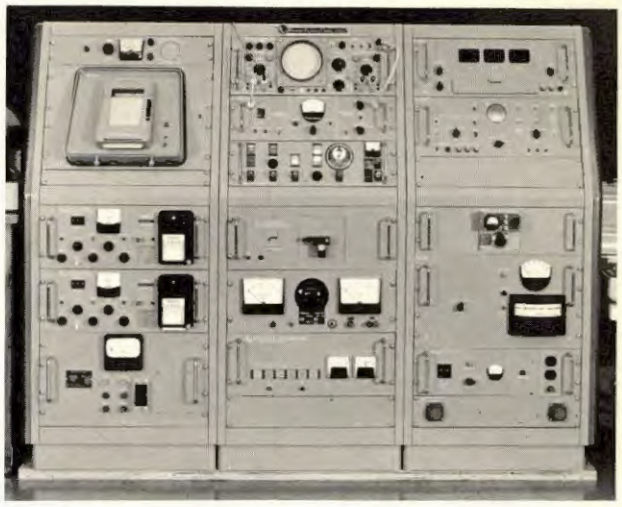

FIG. 8.—Electronic synchronization system.

in the camera by the selection of gear blocks. Program-timing pulses from the time-code generator trigger the oscilloscope at the rate established on the programmer unit. This rate must correspond with one of the following exposure rates established in the camera: 1p.p.2s. (1 pulse per 2 seconds), 1p.p.s., 1.25p.p.s., 2.5p.p.s., or 5p.p.s. The shutter-gate timing pulse, also from the time-code generator, is displayed on the oscilloscope and establishes the acceptable limits between which the midopen position of the shutters must occur. Pulses from the camera indicating the midopen positions are also displayed on the oscilloscope, and can be adjusted by means of the phase synchronizer to fall in the center of the gate. A gate width of ± 100 microseconds from the program-timing pulse is considered adequate for this program, but the gate can be widened or narrowed as desired.

Jitter caused by small mechanical and electronic disturbances in the gearing system results in slight variations in the intervals between the pulses from the camera. As long as the fast-disk, shutter-open pulses occur within the shutter gate, the system is considered to operate in synchronization and all exposures are acceptable. When any pulse occurs outside the shutter gate, the corresponding exposure is positively identified on the paper recording tape as being out of synchronization limits. Any such pulse will later be rejected in the data reduction. After prolonged testing, the jitter has been found to vary between ± 20 and ± 40 microseconds. The amount of jitter can be monitored on the oscilloscope during the observations.

The use of passive satellites for a spatial-triangulation program imposes rather stringent timing requirements. A timing accuracy for the

midopening of the satellite chopping shutters of ± 0.15 milliseconds would cause an uncertainty of ± 0.25 seconds of arc for a zenith observation of a 1,000-kilometer (621-mile) high satellite. When a number of cameras are tracking the same portion of the satellite orbit, usually termed simultaneous observations, their shutter midopening times must be known to a common time standard (not necessarily with respect to standard time) in order to represent homogeneous raw data for the triangulation.

Due to the finite time required for light to travel from the satellite to each camera, the image recorded on each photographic plate does not coincide with the corresponding satellite position in space. For each 300-kilometer difference in slant range from the satellite to each camera, there is a 1 millisecond difference in the image timing. This is accounted for in the data-reduction programs by correcting the midopen shutter times. For this reason, it is of no practical value to attempt to have the shutter mid-openings of all cameras exactly synchronized, or even to attempt to offset the local time standards by the anticipated traveltime of light to each station. The important consideration is to know accurately the corrections that must be applied to the shutter midopen times to refer them to a common time base. After applying the necessary corrections to the satellite image measurements, time-correlated, least square fitted polynominals are computed based on approximately 600 images from each plate. If this operation is conducted at various stations for the same specific time, the corresponding fictitious observations are synchronic.

FIG. 9.—Portable crystal clock.

In the Coast and Geodetic Survey tracking system, relative timing of the chopping shutters is essentially maintained to within ± 150 microseconds, which, practically speaking, eliminates the time error. The timing concept can be considered in three phases: (1) initial setting of the local time standard (station clock) of each camera station with respect to the common time standard (master clock), (2) determination of the daily drift rate of the station clock with respect to the master clock, and (3) determination of the relationship between the station clock and the shutter midopen times (jitter).

(1) The master clock presently used as a common time standard is a highly stable, quartz crystal oscillator maintained by the National Bureau of Standards at Beltsville, Md. This oscillator has a frequency stability of a few parts in 10^{-11} and is maintained to within -149.5×10^{-10} and $+150.5 \times 10^{-10}$ of the nominal frequency of cesium.

A portable crystal clock (fig. 9) is used to transport time from the master clock to set each of the station clocks. The portable clock is equipped with a stable oscillator having a frequency stability of better than $\pm 1 \times 10^{-10}$ and a frequency drift rate of less than 1×10^{-10}. To provide a check on the performance of this clock during a field trip, it is first synchronized to the master clock and checked immediately after return from each field trip. Experience has shown that the portable clock will normally have an uncertainty of less than ± 10 microseconds after a five day field trip. It is not unreasonable, therefore, to expect that the station clocks can be set to within ± 10 microseconds of the master clock.

(2) Each station clock is equipped with a time-code generator deriving 100-kilocycle-per-second frequency from a precise crystal oscillator having the same specifications as the portable clock. The performance of the oscillator and corresponding time corrections could conceivably be calculated from results of daily or weekly repeat trips of the portable clock, if this were practical, from a cost and logistic viewpoint.

The major disadvantage of very low frequency (VLF) for time pulse determinations is the inherent slow rise time of the VLF pulse, a difficulty which is overcome by the use of the portable clock. However, the use of VLF transmissions provides a practical and accurate method for determining day-to-day time variations. A VLF phase comparator is used to constantly compare the oscillator frequency with one of several available VLF carrier frequencies. In practice, two VLF phase comparators, timed to different frequencies, are employed for checking timing results and to provide a continuous record in the event reception from one station is interrupted. The phase of the VLF carrier waves is highly stable and, in spite of a diurnal variation

of about 40 microseconds, it will, after each 24-hour period, return to the same value within about 2 microseconds.

(3) As outlined in the description of the equipment, the disk shutters used for satellite trail chopping can be synchronized to function within ± 100 microseconds of the reference pulse (jitter) from the time-code generator. These reference pulses are subject to the same time correction as the station clock.

Thus, the uncertanties in the timing are: ±10 microseconds in the initial setting of the station clock, ±40 microseconds of accumulated uncertainties in the day-to-day records, and ±100 microseconds in the jitter of the shutter. Therefore, the total uncertainties are better than ±150 microseconds. Periodic field trips are made with the portable clock to insure that these timing accuracies are maintained.

It should be noted that for star-trail observations, timing requirements are less demanding. For this purpose it is necessary to know shutter times to about ±0.05 second with respect to universal time. This is accomplished with time signals received from Station WWV, Beltsville, Md. In practice, the portable clock is actually synchronized to the oscillator used to generate the time signals. Therefore, the camera stations are, in effect, using the *pretransmitted* time signals of Station WWV as the common time reference. For star trails, times are corrected to appropriate universal time.

To protect the camera, pedestal, and pier from the effects of the wind during the observations, and from the heat of the sun during the day, an astrodome shown in figure 10 was specially designed and manufactured. Anticipated night temperature is maintained during the day by an external air-conditioner unit, thereby reducing the undesirable effects of thermal expansion in the camera and pedestal. In addition, a dehumidified unit protects the camera from the corrosive effects of high humidity.

The astrodome is 6 feet 6 inches in diameter, has a rotatable top, and weighs only 310 pounds. Inside the astrodome, the base of the camera is secured (but not constrained) to a specially designed pedestal which attaches to a concrete pier at ground level. The pier extends into the ground several feet depending upon the type of soil encountered. The astrodome floor provides complete isolation for the camera support.

The pedestal, to be both stable and portable, is made of 0.4-inch thick aluminum tubing, 1 foot in diameter, and is about 2.5 feet in height. The top and bottom plates are attached with a special no-stress weld. When the camera station has been set up, the pedestal is completely filled with water (or with a mixture containing antifreeze) which not only acts to resist temperature

FIG. 10.—Astrodome

changes in the pedestal during the period of the observations, but adds mass to the system to dampen any external shocks and vibrations.

During the observations, the camera is remotely operated by the synchronization system located some distance away in the electronic equipment shelter (shown on the right in fig. 11). To reduce the possibility of disturbance, observers do not remain in the vicinity of the camera during the observational period. Any change in camera orientation during the observations, is detected when the results of the precalibration and postcalibration star patterns are compared during the data reduction.

A highly mobile shelter was designed primarily to house the electronic synchronization system. Space has been also provided for a darkroom, electronic repairs, office, and storage. This unit, 12 feet long, 7 feet wide, and 7 feet high, is capable of being lifted by crane or helicopter; transported by cargo aircraft, ship, railroad car, or flatbed truck; and towed by truck using a special mobility transporter which is attached to the shelter (fig. 12).

Field Operations

Reconnaissance of the tracking site is accomplished in advance of the field work. An ideal site for satellite tracking is an elevated

area, preferably a hilltop, to provide unobstructed visibility around the local horizon (0° elevation angle) and to minimize refraction anomalies. The site should be close to electric power, communication facilities, airport, and local roads; and reasonably near accommodations if local transportation is not readily available. In practice, the selection of the best site is based first on satisfying the visibility constraint with no obstructions above 15° (elevation angle), and then on balancing the remaining factors, weighing the efficiency of station operation with economy of establishing the station and maintaining operations, and still being practical in considering the living conditions of the observing team.

Orbital predictions for the *Echo I* and *II* satellites are furnished weekly by the Goddard Space Flight Center, Greenbelt, Md. These predictions contain look-angle data for each camera station in terms of azimuths from north, elevation angles, slant ranges, and orbital heights at 1 minute intervals during the period the satellite is above the local horizon. The best time for observing all possible simultaneous two- and three-station observations is selected taking into account optimum geometric considerations.

FIG. 12.—Tracking station equipment enroute to new site.

Graphic plots are made of the satellite pass in order to determine the relative angular velocity of the satellite from each camera station. This allows a determination of the length of time the satellite will remain within the field of view of the BC-4 camera in order to program the proper image interval to obtain about 800 satellite images across the entire plate, and the scheduled time of observations.

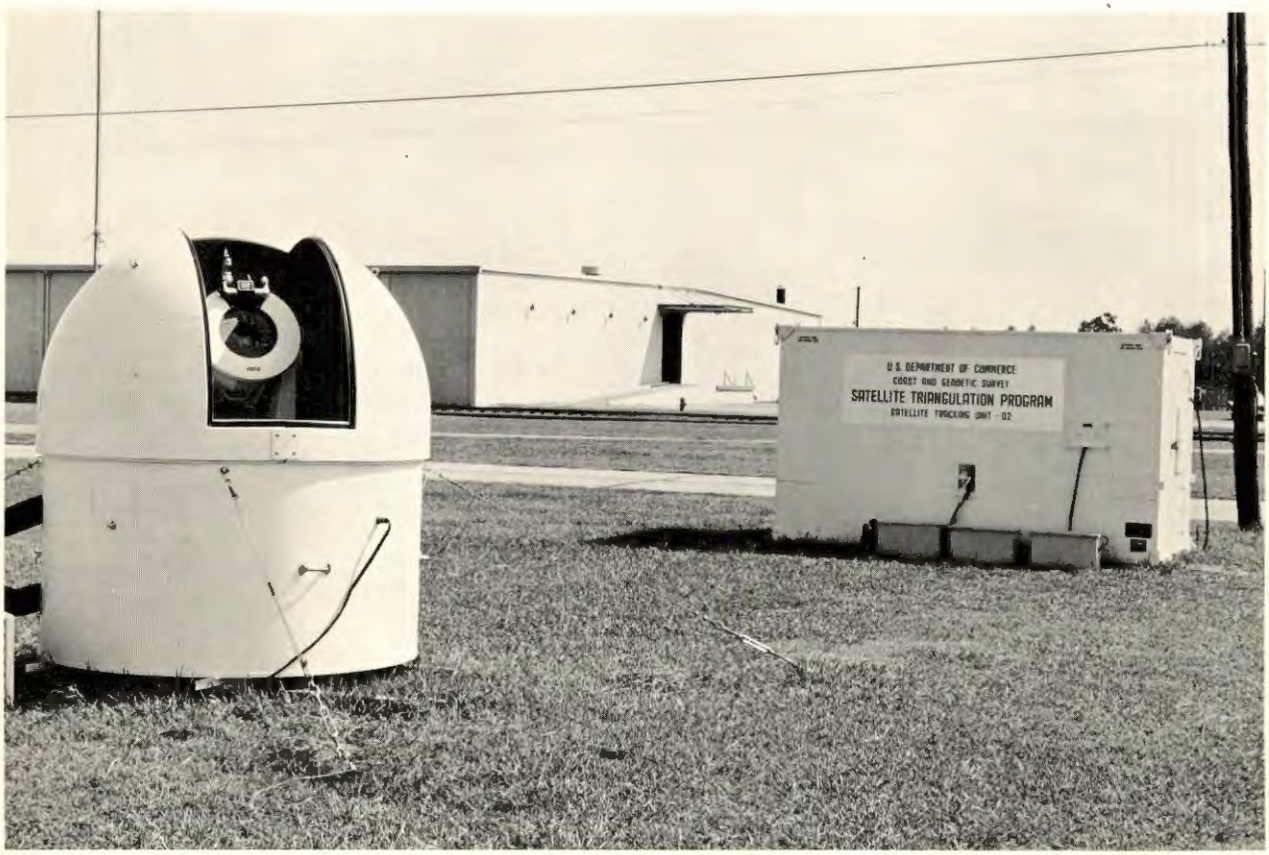

FIG. 11.—Equipment on station.

FIG. 13.—Negative of starplate.

To facilitate the transmission of pertinent observational data to the field, a special 54-digit coded format consisting of 9 six-digit words is used. To detect possible typographical errors during transmission, the sixth digit of each word is a check-digit which provides a check on the validity of the first five digits. In addition, the ninth word provides a cross check on the entire message. Experience during the past year has indicated that approximately half of the observations scheduled are successfully obtained. Adverse weather conditions are responsible for practically all the unsuccessful observations.

The results of the field observations are transmitted by teletype, as soon as possible, to the Bureau Headquarters in order that preliminary plots of successful simultaneous observations can be made.

Quality Control

In contrast to geodetic triangulation, where the quality of the field work can be estimated in the field by investigating triangle closures and side checks, satellite triangulation is dependent upon strict compliance with detailed proven field procedures. Field inspection of photographic plates can judge only the quality of the star and satellite imagery, the quality of the plate development procedure, and check the prescribed shutter format programming (fig. 13). Small bias errors cannot be detected in the field. Periodic

DATA REDUCTION FLOW CHART

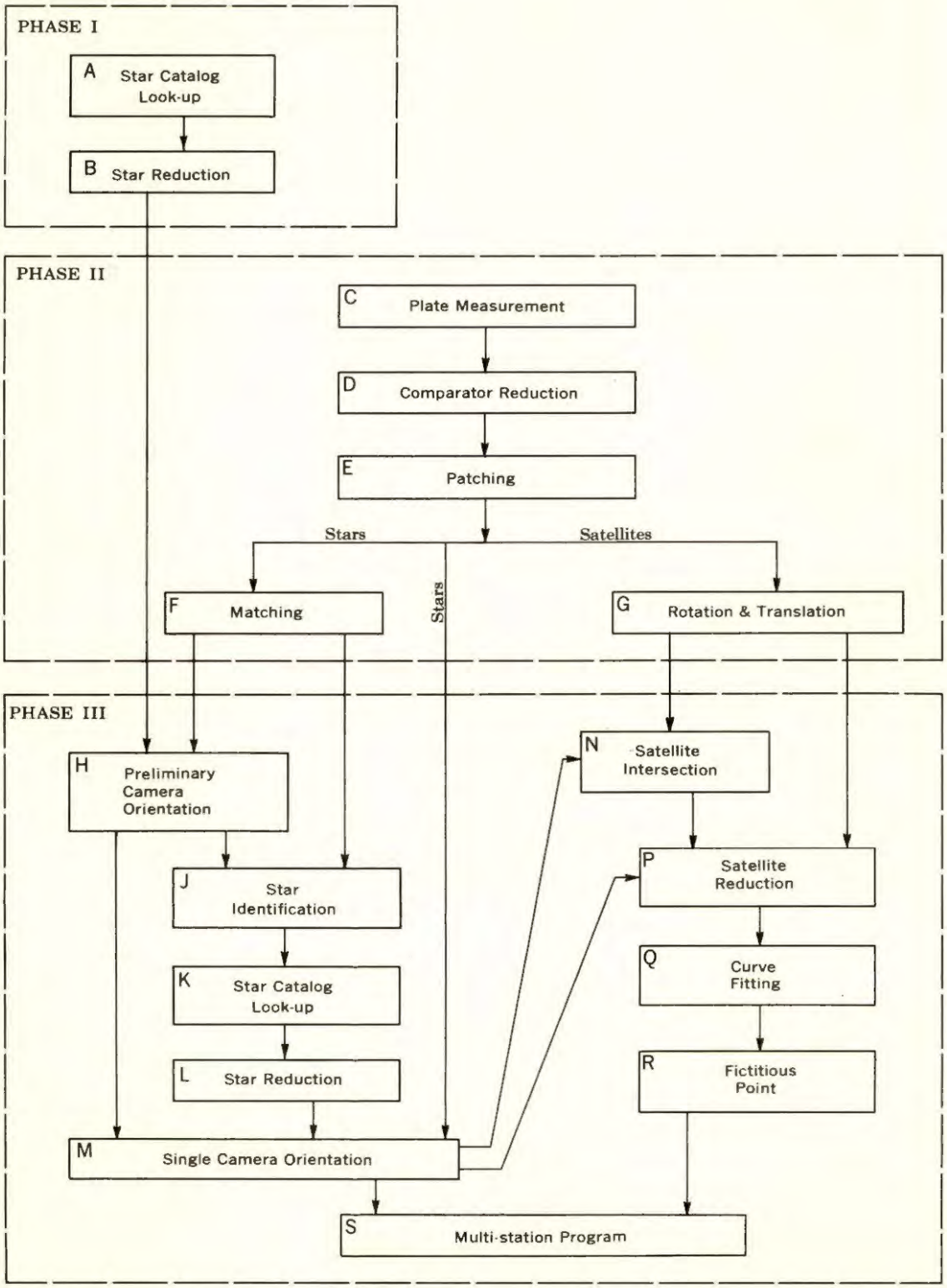

FIGURE 14.

quality control inspections of the field operations by experienced personnel is an important part of the operational plan.

At the Bureau Headquarters, all field records are critically inspected. The plates are carefully checked for good imagery, proper adherence to scheduled formats, and overall quality; and, finally reevaluated on a comparator for actual measuring quality of all images.

REDUCTION OF DATA

Data reduction begins with the photographic plate and shutter timing records as they are received from the field. While the sequence of operations is arranged for maximum efficiency, the solution of the basic triangulation problem consists of three principal tasks:

(1) to determine the internal calibration and the external angular orientation of the camera for each photograph through the measurement of plate image coordinates of numerous stars of known position,

(2) to, in effect, compress many satellite images into the plate coordinates of a single fictitious satellite image, and

(3) to adjust a network of satellite observations involving several fixed camera orientations at each of several camera stations, in such a way that the individual camera station positions are determined by minimizing the sum of the squares of the plate coordinate residuals of the corresponding satellite images.

The reduction of satellite camera data requires a meticulous plate measuring procedure and a number of electronic computer programs. This portion of the work will be discussed in the operational sequence of data reduction which is divided into three principle phases:

1. preliminary evaluation and computations,
2. plate measurement and accuracy evaluation, and
3. geometric reduction of data.

Figure 14 is a diagram showing the phases and alphabetically arranged steps within each phase.

Preliminary Evaluation and Computations

Prior to data reduction, the photographic plates and timing records are ***logged in,*** checked for quality, freedom from cloud coverage, and simultaneity of satellite observation from two or more camera sites. The successful ***events*** (satellite passages simultaneously recorded from at least two camera stations) are plotted on a map diagram along with the camera station locations and the altitude angles between camera baselines and satellites. This graphic worksheet is used to select, from a plethora of events, those which provide the most ideal geometric configuration, ~~as outlined in the introduction.~~ 1 In addition, with the aid of star charts, ~~six or~~ seven prominent stars are identified on each selected plate for later use in determining the approximate orientation of the camera, after their plate image coordinates have been measured. 5

Data reduction begins with a computer program referred to as *Star Catalog Look-up* (Step A) which is used to search the star catalog for the right ascension and declination of the six or seven stars and to prepare punched card output of the catalog data needed for updating the catalog positions of these stars to the time of observation.

A *Star Reduction* program (Step B) is then used to apply the star catalog data to update the catalog values of right ascension and declination and to apply corrections for atmospheric refraction considering the specific zenith distances, diurnal abberation, temperature and atmospheric pressure at the camera station. The card output of this program is then set aside awaiting measurement of plate coordinates of these six or seven stars which are required for the preliminary camera orientation (Step H).

~~The next three paragraphs are devoted to a description of the plate measuring instruments or comparators (figs. 15 and 16), the precision, and some of the problems attending the measurement of satellite camera plates.~~ 2 The comparators used presently by the Coast and Geodetic Survey feature 9- by 9-inch measuring stages which are manufactured with such precision that a measuring accuracy of approximately one micron is attainable with only linear mathematical compensation for differential measuring screw length and coordinate axis perpendicularity.

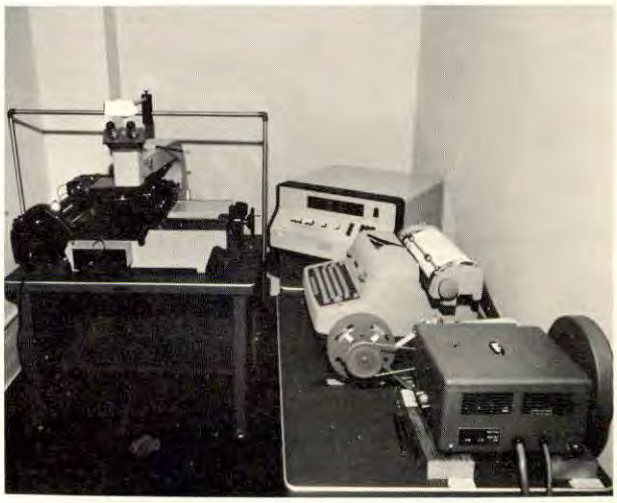

FIG. 15.—Monocular comparator and readout.

FIG. 16.—Stereocomparator and readout.

These comparators are equipped with high quality optical systems for direct binocular viewing with linear magnifications up to 40 times plate scale. ~~A choice of reticles is possible to enable the most precise and bias-free pointings on star and satellite images~~. The comparators are operated in environment-controlled rooms equipped with air filtration, temperature control ($\pm \frac{1}{5}°$ centigrade), and relative humidity control (± 5 percent).

A standard error of coordinate measurement within the range of 0.7 and 1.3 microns is maintained for all comparators through frequent measurement of a precisely calibrated grid plate in each of the four primary rotational orientations by three different operators. These twelve sets of measurements are separately reduced allowing corrections only for linear differential measuring screw length and nonperpendicularity of coordinate axes. The electronic computer program used for this reduction also makes a least squares fit of the corrected plate measurements of the 25 grid intersection points to the true or calibrated grid values and determines the residual standard error of coordinate measurement.

The comparators are equipped with electronic readout systems with typewriter and ~~either punched card or~~ paper tape output~~s~~. The output record consists of a point identification number, which is assigned by the comparator operator, and the rectangular plate coordinates *(x,y)* of each pointing to the nearest micron.

Plate Measurement and Accuracy Evaluation

Returning to the sequence of data reduction, the second phase, plate measurement and accuracy evaluation, will now be described. The measurement of a satellite camera plate (Step C) involves the determination of a coherent set of plate coordinates for five images of each of approximately 75 stars recorded on the plate before satellite passage; for five images of each of approximately 75 stars recorded after satellite passage; for approximately 400 satellite images in the center of the satellite trail; and for three sets of eight drilled holes measured every two hours during the plate measuring process. In addition, a complete repetition of the above measurements is required with the photographic plate rotated approximately 180° from the first position in order to reduce the residual bias between star and satellite image pointings. This amounts to a total of over ~~3,500~~ 2500 measurements (~~7,000~~ 5000 coordinates) that are obtained for each satellite camera plate. The large number of plate measurements is required not only for statistical reasons, but is necessary to obtain the optimum possible assurance with regard to the absence of bias errors.

Approximately 16 man-hours are required to complete the measurement of each plate. A set of eight drilled reference holes are made in the plate emulsion at the four corners and the midpoints of the four sides so that a continuous check can be made on the position and orientation of the photographic plate throughout this ~~18~~ 16-hour period, and in order that the plate can be removed to enable shift work on the comparators. When properly executed, the edge sharpness of this type of mark makes it an excellent target for optical pointing.

The ~~100~~ 75 stars selected from those recorded on the plate before and after the satellite passage need not be the same stars. However, they are carefully chosen for uniform distribution throughout the useful portion of the plate with a higher density in the vicinity of the satellite image trail. Each star trail consists of five separate images which are measured to minimize pointing and photographic emulsion inconsistencies. The approximately 400 measured satellite images are distributed along about 12 cm. of the central portion of the trail.

Sequential Steps D through G as shown in Figure 14 may be considered part of Phase II of data reduction because, through the transformation, analysis and rejection of image measurements, these steps result in the final set of plate image coordinates used in the spatial triangulation.

The comparator measurements are processed with a computer program referred to as the *Comparator Reduction* (Step D). This program transforms the raw comparator coordinates of all points to a coordinate system having its origin near the plate center and one of its coordinate axes passing through two of the four corner drilled holes. The program also applies

corrections to these raw comparator coordinates for linear, systematic comparator errors such as differential measuring screw length and non-perpendicularity of coordinate measuring axes. This program may also he instructed to apply predetermined camera calibration constants for the compensation of lens distortion and a translation of coordinates to a system having the principal point of the plate as its origin.

The next step (Step E), referred to as *Patching*, consists of transformation of each 2-hour set of measurements of the eight drilled holes into a single coherent set. The rejection limit for a 2-hour set of measurements is set at a mean coordinate deviation of 0.6 micron between that individual set and the mean coordinate values derived from all sets of measurements. At the same time all star and satellite measurements are also transformed along with the associated drilled hole measurements. This computer program completes the refinement of image coordinates in the first position and in the 180° rotated position separately.

The next step (Step F), the *Matching* program, combines the refined coordinates of the zero and 180° rotated sets of star image measurements into a single bias-free set by making a "hest fit" and further refining the image coordinate values by computing the mean coordinate for each image after the best fit transformation. The standard deviation of the individual coordinates from the mean is computed as a measure of the precision of the measuring and Patching procedure. If the standard coordinate deviation is greater than 1.5 microns, the entire set of star measurements is rejected.

Rotation and Translation (Step G) is the treatment of the satellite images in the zero and 180° rotated positions with the same transformations given the star images by the Matching program. As before, a single set of mean image coordinates is computed for use in the next phase of data reduction and a standard coordinate deviation is computed to show the magnitude of operator bias between star and satellite image pointings, together with the standard error of a single satellite pointing. This value is used to determine the probable freedom from residual pointing bias and the ahility of the comparator operator to minimize his pointing bias.

Geometric Reduction of Data

The third phase of data reduction, the geometric solution of the triangulation problem, begins with *Preliminary Camera Orientation* (Step H). This program requires as input, the astronomical data for the ~~6 or~~ 7 pre-identified stars and their refined plate coordinates obtained from the Matching program (Step F). Close approximations of the camera orientation parameters, referenced to a local coordinate system, are computed by this program.

The next step (Step J), referred to as *Star Identification*, computes the approximate right ascension and declination of all stars measured on the plate using the approximate camera orientation parameters from Step H and the refined plate coordinates of all stars from Step F.

With the approximate right ascensions and declinations of all measured stars now known, the Star Catalog Look-up is used again in Step K, just as it was in Step A, for the identification of all stars. In step L *Star Reduction* is performed for all measured stars just as it was done for the pre-identified stars in Step B.

The next problem, *Single Camera Orientation* (Step M), is to determine the final orientation of the camera using all measured star image coordinates and their updated, refraction corrected, star catalog values. The solution of this problem is an iterative computational process and involves the rejection of points having excessively large disparities between their measured plate coordinates and those computed from the given catalog coordinate values such as would occur if a star were misidentified or a comparator pointing number was incorrectly designated. After rejection of information effected hy gross errors or related to double stars, the data is processed three more times in a single computer run. The first set of data includes all of the stars, the second only the pre-event stars and the third only the post-event stars. The pre and post results are used to compute criteria which assure that the camera orientation did not change during the observation period. The Single Camera Orientation solution computes not only the external angular orientation of the camera but also the camera principal distance, the coordinates of the principal point and radial lens distortion parameters.

The Single Camera Orientation when fitting approximately 100 star images (~~100~~ 25 pre-event and ~~100~~ 25 post-event) to the catalog positions, presently has a typical standard plate coordinate error of less than 2.5 microns. Relative weights for plate and catalog positions are introduced in the solution. The standard error of the catalog positions is assumed to be about ±0.4 micron at plate scale. A mean plate coordinate error of 2.5 microns for approximately 100 stars causes the direction of an individual ray to be effected with a standard error from a minimum of ±0.3 second of arc at the center of the plate to a maximum of ±0.5 second at a point 6 cm. from the plate center.

The next step (Step N), consists of a coordinate transformation program to convert the approximately known geodetic ellipsoidal coordinates of camera stations to cartesian coordinates in a

chosen reference system. Next, the *Satellite Intersection* program uses the single camera orientations obtained in Step M for two or three cameras simultaneously observing the same event and the approximately 600 associated satellite image coordinates from Step G, to obtain a preliminary position and *slant* ranges for each satellite image.

The slant ranges and satellite positions are used in *Satellite Reduction,* (Step P) of Figure 14, to correct each satellite plate image position for lens distortion, diurnal aberration, atmospheric refraction, difference in light travel time from the satellite to the different camera stations and the displacement of the satellite image because of the phase angle at the satellite between the sun and observing station.

These refined satellite image coordinates are then submitted to a least squares *Curve Fitting* program (Step Q), which successively fits curves of 5th through 7th order polynomials to the image coordinates using a power series with respect to time to smooth random errors of the satellite imagery which originate from the measuring process, emulsion shifts and the atomspheric shimmer effect. The corresponding residuals, both along and across the satellite trail, are separately plotted with respect to time for visual analysis of the curve fit and randomness of the residuals. The residuals are also plotted as a histogram and compared with the corresponding normal distribution curve.

Numerous results from these curve fits have been obtained which show a typical standard deviation of 2.5 to 3.0 microns for a single satellite image. Making allowance for a standard deviation of 1.5 microns for measurements of image coordinates, a contribution of 2.5 microns or about 1.5 seconds of arc results from the shimmer effect. This result is in agreement with independent studies of this phenomenon.

In the next step (Step R), a *Fictitious Point* is computed for the satellite on each plate of an event. This together with curve fitting (Step Q), is a data compression process whereby the coordinate measurements of approximately 600 satellite images are combined into a single fictitious image near the center of each plate. Corrections for the difference in light travel time to the different camera stations and time corrections for lack of synchronization of camera station oscillators are applied to the coordinates of the fictitious point at this time. This completes the refinement of satellite imagery.

The standard deviation of a computed fictitious satellite position is less than ±0.2 micron at the center of the plate which corresponds, with a focal length of 300 mm., to ±0.1 second of arc. When combined with the aforementioned standard deviation of the orientation at the center of the plate, which is about ±0.2" to ±0.3", the accuracy of the final direction to the satellite should be about ±0.3". In practice, one must be aware of the possibility that some insufficiently resolved bias errors may still exist. The most critical hias error is the one which affects the coordinate measurements between star and satellite images. Automation of the image measuring process by electronic image sensing may be helpful.

The next and final step in satellite data reduction is the *Multi-station Program* (Step S) wherein as many camera stations and events as are geometrically coupled are treated with a least squares adjustment in accordance with any assigned relative weighting among the input data. The approximate ellipsoidal coordinates of all camera stations, the final camera orientation parameters from Step M and the fictitious satellite image coordinates for each plate from Step R constitute the primary input data for the adjustment.

The scale of the satellite triangulation must be obtained from external sources. Scale can be applied by enforcing the distance between two stations. It can also be applied by introducing the coordinates of two or more ground stations with appropriate weights. The output information provides among other data: the adjusted coordinates of the ground stations in both the cartesian and ellipsoidal systems and, for previously unknown stations, the standard errors, the residuals of the individual plate measurements; the standard error of the plate measurements and the standard error of unit weight for the problem under consideration.

THE COAST AND GEODETIC SURVEY SATELLITE TRIANGULATION PROGRAM

Results Obtained on First Triangle

The Coast and Geodetic Survey's satellite triangulation program commenced on an operational basis in August 1963, when three field parties began observations at Aberdeen Proving Ground, Md.; Chandler Air Force Station, Minn.; and Greenville Air Force Base, Miss. These stations form a triangle that averages about 1,500 kilometers on a side. In order to enable a critical analysis of the results, each camera station was tied into the Coast and Geodetic Survey's first-order triangulation net.

Observations were made on the *Echo I* satellite, which ranged in altitude from 1,300 to 1,900 kilometers. During the 52-day period from August 13, 1963, to October 3, 1963, 103 simultaneous observations were possible, of which 73 were three-station and 30 were two-station events. No scheduled event was lost because of

450 Camera.

instrument breakdown or human error. Sixty-six, roughly two-thirds of the possible events, could not be observed because of unfavorable weather conditions. Of the remaining 37 missions shown in figure 17, nine were perfect simultaneous observations from all three stations, 17 events were perfect simultaneous observations from two stations, and 11 events were usable but not quite perfect (i. e., baze or clouds obscured a small part of the satellite or star trail on one plate of each event).

Six events were used for a preliminary adjustment of the satellite triangulation. Two of these events (No. 68 and No. 106) are three-station observations, while the other four events are two-station observations. The locations of the six satellite subpoints are shown in figure 18. In order to perform a complete error analysis different adjustments were computed, using various combinations of weights on the independently given geodetic coordinates and distance constraints.

Of the various adjustments performed on the Maryland-Minnesota-Mississippi triangle, two examples of particular interest will be presented here (figs. 19 and 20).

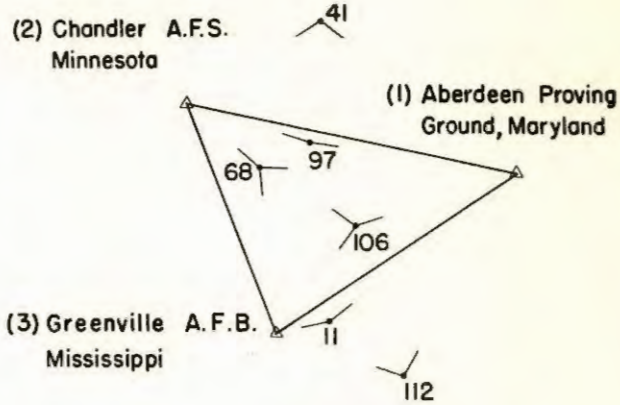

FIG. 18.—Events used in the preliminary adjustments of the Maryland-Minnesota-Mississippi triangle.

In the first problem, the Maryland station coordinates were held fixed by the application of large weights, while the Minnesota and Mississippi station coordinates were assigned zero weights. Scale was determined by applying a distance constraint to the Maryland-Minnesota line. In other words, the distance between these two stations, as derived from the classic triangulation, was held fixed by assigning a sufficiently

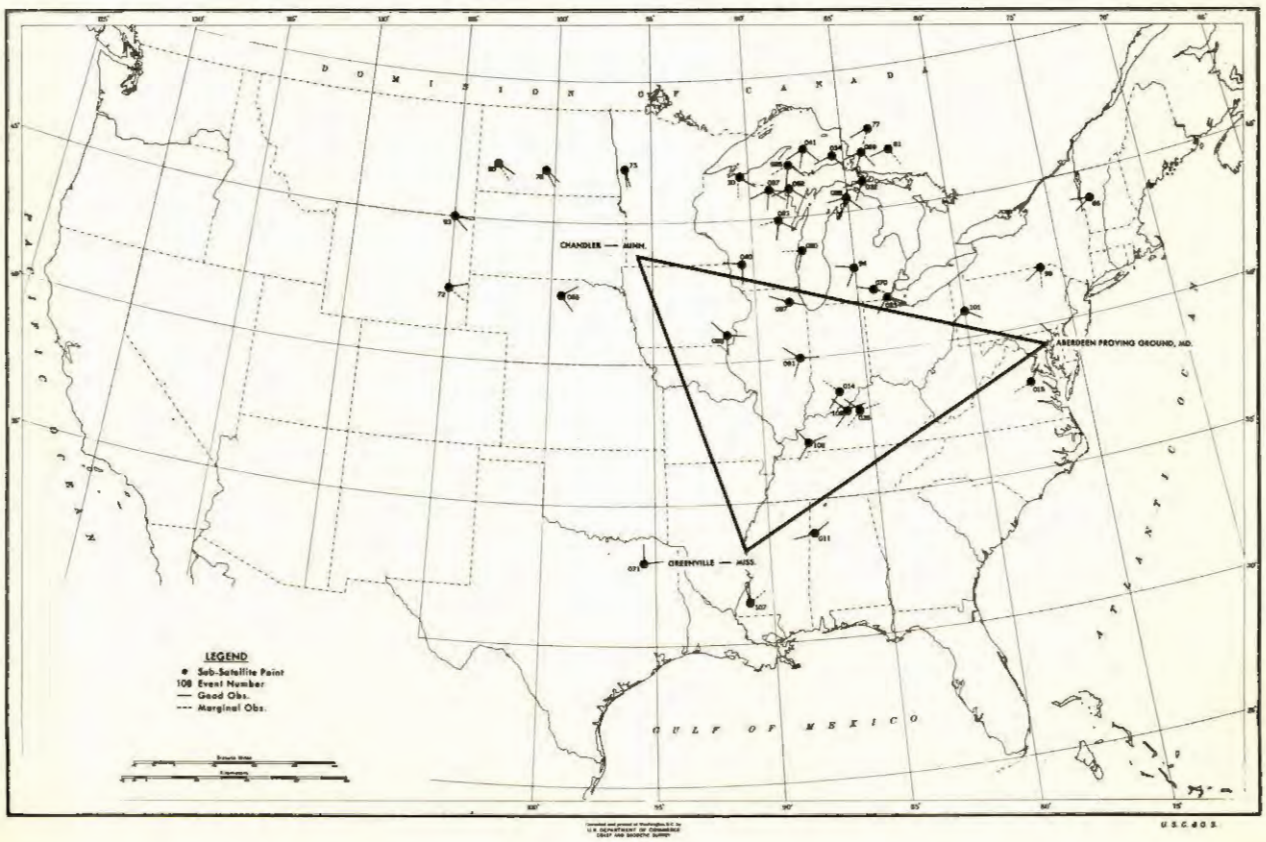

FIG. 17.—Successful observations from 1,500 kilometer test triangle.

large weight. The results of this adjustment are given in a table, figure 19. The distribution of the corresponding plate residuals are shown in a table, figure 20.

The lack of constraints on the geodetic coordinates of the Minnesota and Mississippi stations permitted a free adjustment of the photogrammetric measurements. The standard error of unit weight of the plate measurements after adjustment is ±0.3 micron. This value is a measure of the ***precision***, or internal consistency, of the photogrammetric procedure. It should not, at this point, be interpreted as representing the ***absolute accuracy*** of the photogrammetric system. Undetected systematic errors could bias the results without affecting the internal precision. The results of numerous adjustments indicate, however, that the absolute accuracy of the photographic measurements is better than ±0.6 micron or better than 1 part in 500,000. But whether or not the theoretically obtainable accuracy of ±0.2 to ±0.3 micron has already been obtained remains to be verified with the adjustment of additional missions.

RESIDUAL ERRORS ON THE PLATE MEASUREMENTS AFTER ADJUSTMENT

Satellite #	Station	Problem #1 v_{i_x} (microns)	Problem #1 v_{i_y} (microns)	Problem #2 v_{i_x} (microns)	Problem #2 v_{i_y} (microns)
11	Maryland	-0.11	-0.11	-0.03	-0.03
	Mississippi	-0.08	-0.17	-0.02	-0.04
41	Maryland	-0.04	-0.08	+0.00	+0.02
	Minnesota	-0.10	-0.00	+0.02	+0.00
68	Maryland	+0.03	+0.08	-0.26	-0.70
	Mississippi	+0.08	-0.03	-0.75	+0.23
97	Maryland	+0.13	+0.13	-0.09	-0.09
	Minnesota	+0.15	+0.15	-0.10	-0.10
106	Maryland	-0.11	-0.06	-0.88	-0.62
	Minnesota	+0.05	+0.10	-0.23	+0.68
	Mississippi	+0.00	+0.01	-0.29	+0.59
112	Maryland	+0.09	+0.05	+0.78	+0.44
	Mississippi	+0.02	-0.11	+0.14	-1.02

FIGURE 20.

PROBLEM 1

STATION	WEIGHTS φ	WEIGHTS λ	WEIGHTS H	CORRECTIONS (Meters) Δx	CORRECTIONS (Meters) Δy	CORRECTIONS (Meters) Δz	STANDARD ERRORS (Meters) Δx	STANDARD ERRORS (Meters) Δy	STANDARD ERRORS (Meters) Δz	
1. Maryland	10^{20}	10^{20}	10^{20}	0	0	0	0	0	0	Distance 1-2 constrained with wt.=10^{-7}
2. Minnesota	0	0	0	-8.4	-0.7	-19.7	±1.4	±1.0	±6.3	
3. Mississippi	0	0	0	+0.1	-2.6	+30.7	±1.9	±3.5	±3.9	

Std. error of plate measurements = ± 0.27 μ

Std. error of unit weight for problem = 0.27 μ

PROBLEM 2

STATION	WEIGHTS φ	WEIGHTS λ	WEIGHTS H	CORRECTIONS (Meters) Δx	CORRECTIONS (Meters) Δy	CORRECTIONS (Meters) Δz	STANDARD ERRORS (Meters) Δx	STANDARD ERRORS (Meters) Δy	STANDARD ERRORS (Meters) Δz	
1. Maryland	10^{20}	10^{20}	10^{20}	0	0	0	0	0	0	No distance constraints
2. Minnesota	$.25 \cdot 10^{-10}$	$.25 \cdot 10^{-10}$	$.25 \cdot 10^{-13}$	-4.4	+0.8	-2.4	±3.4	±3.2	±4.6	
3. Mississippi	$.25 \cdot 10^{-10}$	$.25 \cdot 10^{-10}$	$.25 \cdot 10^{-13}$	-0.5	-3.5	+5.9	±3.2	±3.5	±4.4	

Std. error of plate measurements = ± 0.61 μ

Std. error of unit weight for problem = ± 0.79 μ

FIG. 19.—Events used in the preliminary adjustments of the Maryland-Minnesota-Mississippi triangle.

The corrections to the X, Y, and Z coordinates of the Minnesota and Mississippi stations, as well as their respective standard errors are given in figure 19. The X and Y corrections are relatively small; however, unusually large corrections are obtained for the Z coordinates: -19.7 meters at Minnesota and +30.7 meters at Mississippi. (The corrections are roughly in the direction of the ellipsoidal heights of the stations.) The large Z corrections could partially be explained by some uncertainties of the geoid undulations and orientation of the North American 1927 Datum. Based on present experience, any combination of these uncertainties could scarcely account for more than 15 meters. Either some undetected systematic error still exists in the satellite triangulation; or, more likely, this result is caused by the relatively poor geometry, in a vertical sense, in the determination of the Minnesota-Mississippi line, because no events west of this line have been observed. At any rate, a complete reconciliation of the satellite triangulation results and the geodetic information is not possible at this time. With the incorporation of more missions into the adjustment and extension of the satellite triangulation over the entire United States and Canada, valid conclusions on these questions can be expected.

As the X and Y coordinates correspond sufficiently closely to horizontal coordinates, the standard errors of the X and Y corrections, ranging from ± 1 meter to ± 3.5 meters, indicate an accuracy of about 1 part in 750,000 for the determination of the horizontal positions. The Z coordinates are slightly weaker (their standard errors are on the order of ± 4 to ± 6 meters) caused, in this example, by the particular geometry. Furthermore, no events west of the Minnesota-Mississippi line have been incorporated into this adjustment. Observations in this area, as well as additional observations inside, and north of, the triangle will be included in future adjustments, thus strengthening the triangulation.

In the second adjustment (figs. 19 and 20) weights are applied to all ground station positions

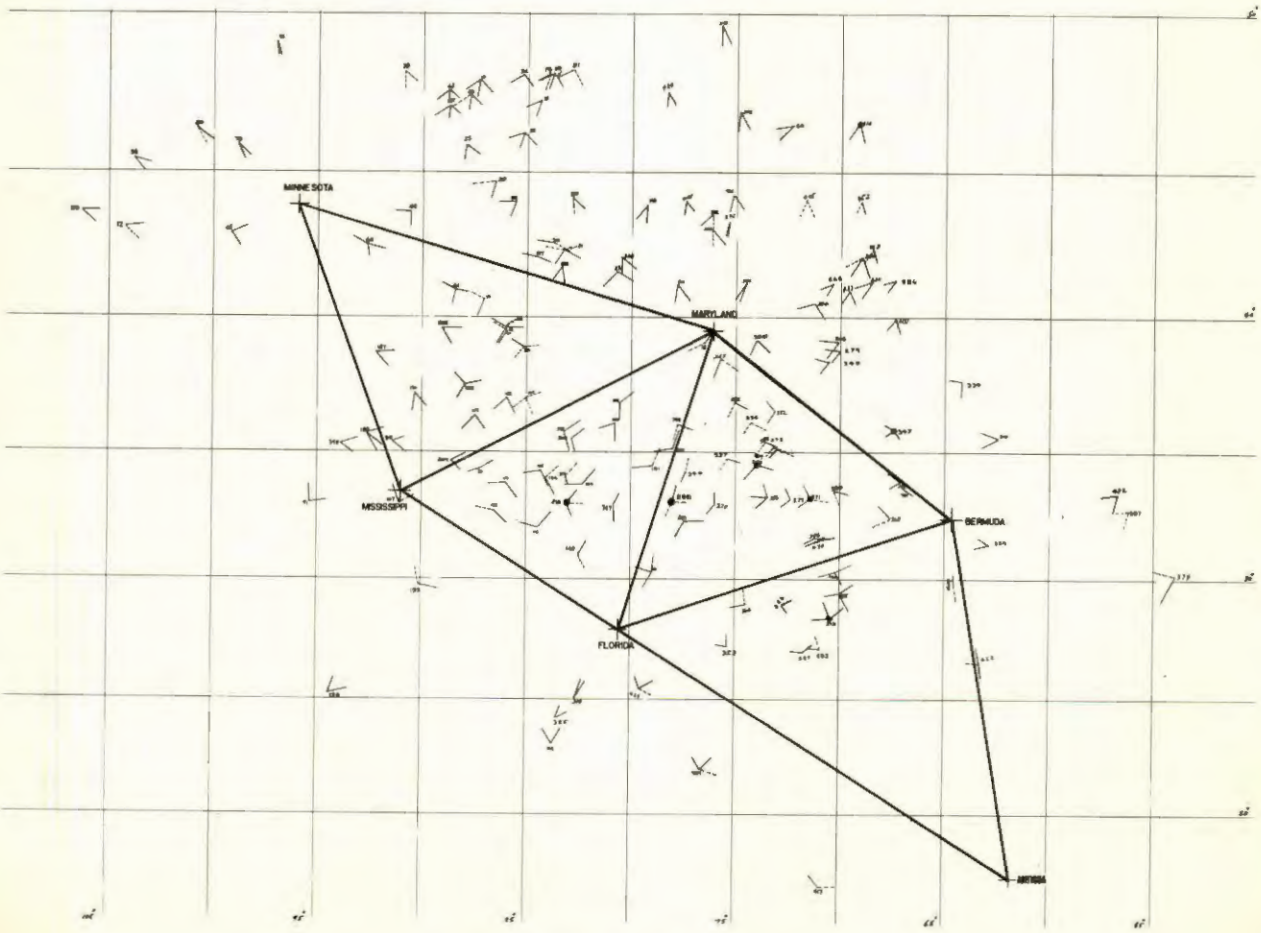

FIG. 21.—Status of scheduled observations.

according to the present estimates of the accuracy of the first-order triangulation in the United States.

The weights introduced correspond to a standard error of ±0.14 second of arc (approximately ±4.5 meters in latitude and ±3.5 meters in longitude), for the horizontal coordinates of the Minnesota and Mississippi stations, while the Maryland station was held fixed. The weights assigned to the vertical coordinates at Minnesota and Mississippi correspond to a standard error of ±4.5 meters, which is a realistic estimate of the accuracy of geoid height differences, as determined by astro-geodetic and gravimetric surveys.

The standard error of unit weight of the plate measurements after adjustment increased to ±0.6 micron (1 part in 500,000). This was expected, since the weights applied to the station coordinates constrained the geometric configuration of the spatial triangulation, forcing the photogrammetric measurements to absorb errors in the geodesy as well as in the photogrammetry.

Preliminary Positioning of Bermuda

A similar reduction has been performed for the triangle Maryland-Florida-Bermuda. This reduction also is of a preliminary nature, because of the relatively small number of missions which have been measured up until the time of writing of this report. An urgent need for an improved position of the Bermuda datum necessitated the action taken.

The triangulation combines one triple mission (No. 219) and 6 double missions (Nos. 218, 223, 288, 316, 347 and 371). The locations of these missions may be identified by the black circles on figure 21.

By again holding the Aberdeen, Md., station fixed and enforcing the Maryland-Florida distance, the result indicates the following shift of the coordinates of the stations Florida and Bermuda with the appropriate standard deviations in meters.

The shifts at the Florida station are within the North American 1927 Datum and the shifts of the Bermuda station are with respect to the Bermuda Astro 1957 Datum (fig. 22).

The fact that the satellite triangulation method consistently provides directions within ±0.5 second of arc or better, is especially significant because such directions have an absolute meaning with respect to the right-ascension declination system, as compared to an accuracy of about ±0.3 second of arc which is obtained today in first-order triangulation for a relative direction.

It can, therefore, be predicted that the photogrammetric satellite triangulation technique will provide the necessary accuracy for increasing the geometric fidelity within individual geodetic datums. Moreover, satellite triangulation, as executed by the Coast and Geodetic Survey, will provide significant information about the basic orientation of the North American 1927 Datum and will prove invaluable for a worldwide triangulation net.

RESIDUAL ERRORS ON THE PLATE MEASUREMENTS AFTER ADJUSTMENT

Satellite #	Station	v_{f_x} (microns)	v_{f_y} (microns)
218	Maryland	+.28	+.44
	Florida	+.63	+.22
219	Maryland	+.19	-.22
	Florida	+.06	-.47
	Bermuda	-.16	+.32
223	Florida	+.15	+.05
	Bermuda	-.05	-.15
316	Maryland	-.09	+.07
	Florida	+.03	+.10
347	Maryland	+.22	+.19
	Bermuda	-.16	-.30
371	Maryland	+.02	+.00
	Bermuda	+.00	+.02
288	Maryland	-.58	-.52
	Florida	-.50	-.58

FIGURE 22.

Since the completion of operations on the Maryland-Minnesota-Mississippi triangle, three additional triangles have been observed (fig. 21). In November 1963, the tracking station in Minnesota moved to Patrick Air Force Base, Fla. Observations continued on the Maryland-Mississippi-Florida triangle until April 1964. At that time, the Mississippi station moved to Bermuda, and operations commenced on the Maryland-Florida-Bermuda triangle. In June of this year, the Maryland station transferred to Antigua Island; field work presently continues on the Bermuda-Florida-Antigua triangle.

Planned Continental and World Networks

The four triangles thus far observed represent the beginning of the Coast and Geodetic Survey's continental satellite triangulation net. Figure 21 shows schematically all observations obtained so far. Figure 23 presents the contemplated continental satellite triangulation net.

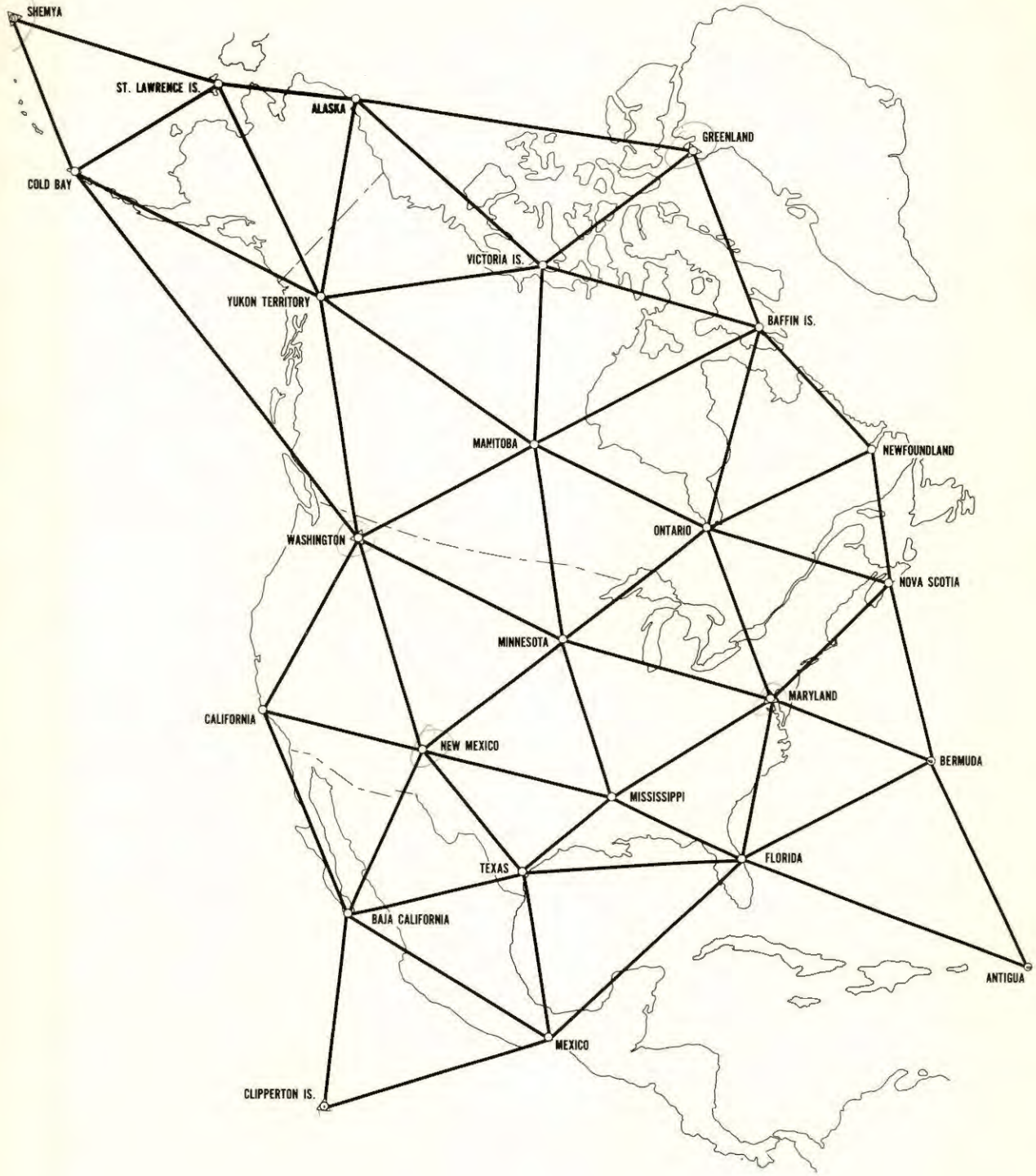

FIG. 23.—Contintental network.

In addition to the coverage of the United States proper, the continental satellite triangulation will progress northward through Canada to Alaska. In order to tie Alaska and the Aleutians to stations in the conterminous United States, three stations in Canada are required. These stations will be located at Lynn Lake, Manitoba; Whitehorse, Yukon Territory; and Cambridge Bay, Northwest

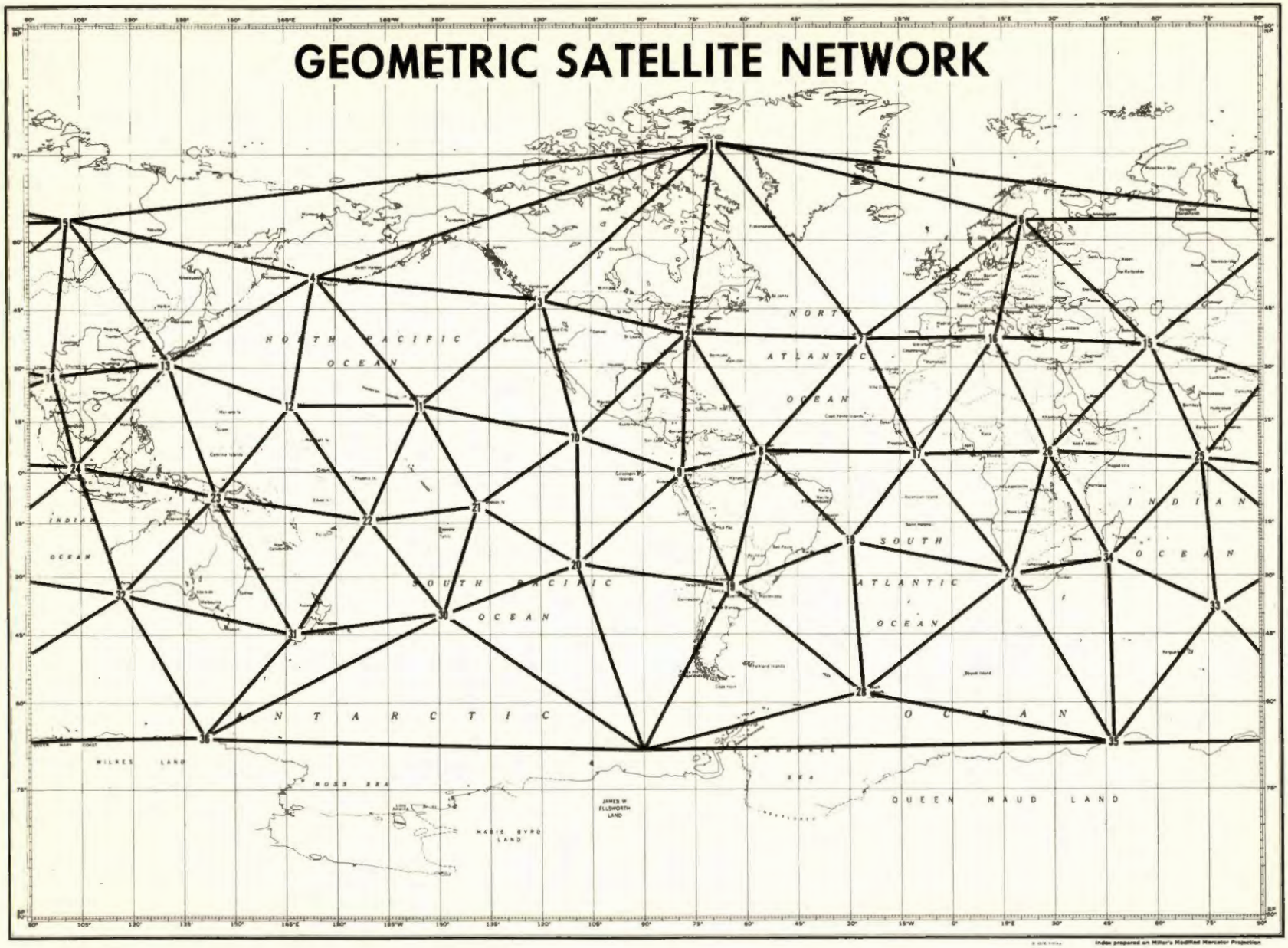
GEOMETRIC SATELLITE NETWORK
NORTH PACIFIC OCEAN
NORTH ATLANTIC OCEAN
SOUTH PACIFIC OCEAN
SOUTH ATLANTIC OCEAN
INDIAN OCEAN
ANTARCTIC OCEAN
WILKES LAND
ROSS SEA
MARIE BYRD LAND
JAMES W. ELLSWORTH LAND
QUEEN MAUD LAND
Index prepared on Miller's Modified Mercator Projection

FIGURE 24.

Territories. The Canadian government is cooperating in the establishment of tracking stations at these sites.

In order to have sufficient darkness for the stellar photography in the far north, the program proceeded with observations at the Canadian stations during the 1964-65 winter.

It is contemplated to complete the Lynn Lake-Minnesota-Washington triangle, as well as the three triangles in the western United States during the spring and summer of 1965. It is hoped that the remainder of the Alaskan triangulation can be completed during the fall of 1965 and winter of 1965-66.

Transcontinental Geodimeter traverses, which are now being undertaken by the Coast and Geodetic Survey in which the standard error is not expected to exceed one part per million, will be used to scale the satellite triangulation. Eventually, with international cooperation, the net can be extended to eastern Canada, Central America, and South America.

The continental satellite triangulation has been specifically designed as a secondary, or fill-in, net within the proposed worldwide scheme (fig. 24). Three stations in the continental net will also be included in the worldwide program. These stations are: Aberdeen Proving Ground, Md.; Larson Air Force Base, Wash.; and Shemya Island, Alaska. The triangle side lengths in the worldwide net average about 4,100 kilometers, as opposed to about 1,600 kilometers in the continental net.

Currently, the Coast and Geodetic Survey, in cooperation with the Department of Defense and the National Aeronautics and Space Administration (NASA), is planning such a worldwide net. These plans are being made in anticipation of NASA's contemplated launching of an *Echo I* type satellite in a polar, nominally circular orbit of about 4,200 kilometers height at the beginning of 1966.

The ultimate selection of a worldwide reference net obviously will be influenced by secondary considerations such as political and physical accessibility of station locations, the need for incorporating already available geodetic information established within the major world datums, the subsequent execution of astrogeodetic and gravimetric surveys in the neighborhood of the selected sites, and the incorporation of stations which are already installed in the worldwide satellite tracking network, as e.g., operated by the Smithsonian Institution Astrophysical Observatory.

Although the geometric significance of satellite triangulation has been stressed, the ultimate benefits to physical geodesy must not be overlooked. The proposed worldwide net will, for the first time, provide an accurate system of tracking stations on a common datum, from which the perturbations of orbiting satellites can be observed. Data collected from these observations are ideally suited for determining the position of the center of mass and the overall shape of the gravitational field of the earth.

The realization of worldwide satellite triangulation is no longer a question of technical feasibility, but it will depend ultimately on convincing the continuously expanding political world that the earth has shrunk technologically to such an extent as to require worldwide cooperation in order to enhance our geophysical knowledge. Geodesy, with its novel possibilities, is ready to contribute its share.

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