field-determined age on these 20 stands. Any photo-determined age that coincided with field age would lie directly on the 1:1 line. The regression line (b) is for the 20 observations. Field and photo ages are obviously correlated, and since the line of relationship does not differ significantly from the 1:1 line, it would appear that the formula could be used with some degree of confidence. The standard deviation of the difference between field and photo ages is ±17 years.

Another way of evaluating these results is to consider how many of these 20 stands could be correctly assigned to their proper age group. The 20-year age groupings suggested for National Forests (Gross, 1950) were used. It was found that only 7 of the 20 stands were placed in their correct age group. These latter results present a weak case for aerial photo age determination.

This study showed that using aerial photos to determine a usable stand age was impractical. However, for the benefit of others who may wish to study this problem further, the findings on the correlations between stand age, stand height, crown closure, and crown diameter are presented.

The formulas developed showed several interesting relationships between photo-measured variables and stand age. Table 1 shows the amount of variation accounted for by the various formulas.

In this test, there was very little loss when one variable, crown diameter (formula 2), was dropped. There was only a slight drop in variation between the nine variables of formula 1 and four variables of formula 3. Most important was the finding that height measurements alone (formula 4) can achieve most of the possible aerial photo age determination.

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*A Report on the Camera Calibration Phase of the C&GS Satellite Geodesy Program**

EUGENE A. TAYLOR,
Lt. Cmdr.,
B. FRANK LAMPTON,
Cartographer,
U. S. Coast & Geodetic Survey

(*Abstract is on next page*)

Introduction

The Coast and Geodetic Survey is developing a satellite geodesy program based on the photogrammetric tracking of passive satellites, such as Echo I, simultaneously from three or more mobile camera stations. In this approach, the satellite becomes a temporary elevated target visible from each tracking camera; thus the three-dimensional configuration will form a geometric model free from orbital uncertainties associated with the dynamic approach. Scale will be provided to the models by measuring precise baselines several hundred miles in length and accurate to 1 part per million. Data reduction techniques are based on those developed by Dr. Hellmut Schmid, formerly with the Ballistic Research Laboratories, Aberdeen Proving Ground, Maryland, and presently with GIMRADA, Fort Belvoir, Virginia.[1]

It is planned to extend a network of satel-

[1] Now scientific advisor to the Coast and Geodetic Survey.

* Presented at the 1963 Annual Meeting of the American Society of Photogrammetry in Washington.

lite triangulation across the country to improve the internal accuracy of the existing triangulation network, and improve the locations of Hawaii, Aleutian Islands, and other off-shore islands. Later, ties can be effected to other geodetic datums, and eventually form a world-wide geometrically conceived reference system.

For the past year, the Coast and Geodetic Survey has had its first satellite tracking system (Figure 1) in operation at Aberdeen, Maryland, primarily to test, calibrate, and evaluate the camera system. New observing techniques were developed during this period. With the delivery of the second and third tracking systems in February 1963, it is planned to complete the calibration phase this summer by making a series of simultaneous observations from test triangles varying in size from 3 meters, 25 meters to 900 miles. The tracking camera locations will, of course, be tied to the first-order triangulation network.

The purpose of this report will be to discuss the tests and calibrations made on the first C&GS tracking system, and to outline some of the considerations peculiar to the overall program.

ABSTRACT: *The Coast and Geodetic Survey is developing a satellite triangulation program to improve the internal accuracy of the geodetic control network across the United States, and later effect ties to other geodetic datums. This program is based on the optical tracking of passive satellites simultaneously from three or more camera tracking stations. For the past year, this Bureau has been evaluating and calibrating its first tracking system which features the Wild BC-4 ballistic camera equipped with the Astrotar lens cone and special synchronized shutters. Over 1,000 points images, 30 microns in diameter, have been obtained on a single photographic plate, each timed to better than 1 millisecond of true time. The presentation includes a description of the satellite triangulation program and instrumentation used, and a discussion of the results obtained during the single camera calibration phase.*

DESCRIPTION OF SYSTEM

First, however, it will be desirable to describe briefly the C&GS tracking system which was developed at the Ballistic Research Laboratory, Aberdeen Proving Ground, Md., after 8 years of development at an estimated cost of some $3 million. The tracking system was designed around the Wild BC-4 ballistic camera (Figure 2) which combines proven components of the highest mechanical and optical quality. Shutter timing, operation, and synchronization are accomplished by an associated electronic synchronization system.

Basically, this system is designed to chop a satellite trail against a background of stars whose identities and positions are accurately known. The apparent path of the

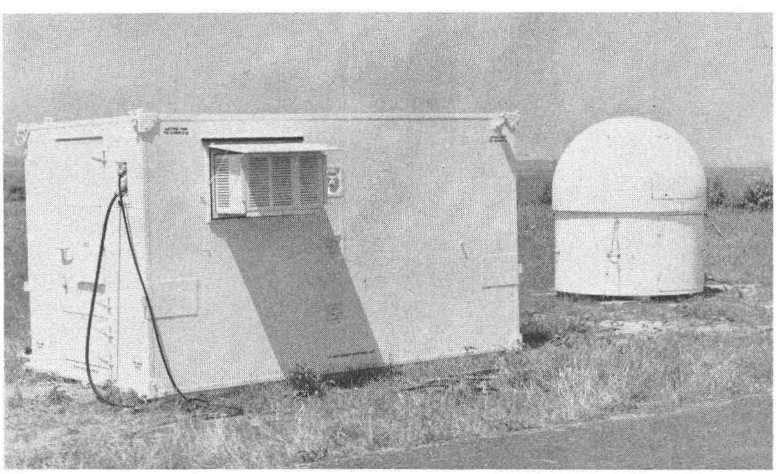

FIG. 1. Tracking station consisting of electronic equipment shelter and astrodome.

satellite from each camera station will be defined on the photographic plate by point images closely spaced across the plate, appropriately coded to facilitate image identification. The end result from each photographic plate will be the apparent right ascension and declination of each satellite image with the corresponding exposure time known to better than ½ millisecond.

The BC-4 features the horizontal and vertical circles of the Wild T-4 astronomical transit which are used for orienting the camera prior to the observations. The Astrotar lens has a focal length of 300 mm., aperture of 117 mm., and an iris diaphragm which can be varied from f/2.6 to f/32. This feature allows the image diameter to be optimized with respect to the measuring mark of the comparator. Exposures are taken on precision glass plates $215\times190\times6$ mm. with an effective exposure size of 180×180 mm. The field of view is about a 33° square.

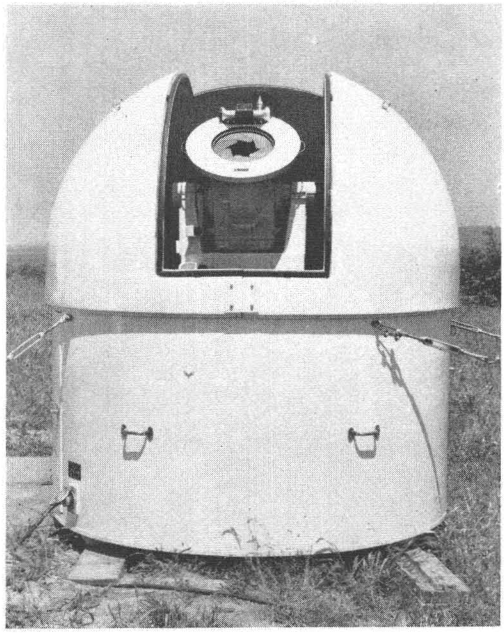

FIG. 2. Tracking camera in portable astrodome.

SHUTTER SYNCHRONIZATION

Between the lens elements are three rotary disk type shutters used for chopping the satellite trails. These disks are driven by a high precision gearing system with constant speed maintained by a 500 cycle synchronous motor. Through reduction gearing and a selection of gear blocks, various exposure rates and exposure durations can be selected for the tracking program. Observations have been made which recorded over 1,500 images on the plate from a single satellite pass.

Further reduction of the exposure rate and coding of the image sequence are accomplished by an auxiliary capping shutter mounted in front of the lens. This shutter is also used for chopping star trails before and after the satellite is tracked, in order to determine the interior and exterior camera orientation. When stars are being tracked, the disk shutters are automatically locked in the mid-open position.

To obtain a geometrical accuracy of ±1 second of arc for a zenith observation of a 1,000 kilometer high satellite, it is necessary that the mid-opening of all satellite chopping shutters be timed to at least 0.7 millisecond with respect to a common time standard. The synchronization accuracy of this system is assured to be at least ±150 microseconds which eliminates, practically speaking, the time error.

Multi-station synchronization of the chopping shutters to less than ±150 microseconds will be accomplished in the following manner:

(a) Each mobile camera station will be equipped with a local time standard consisting of a time code generator and a precise crystal oscillator having a frequency stability of less than $\pm5\times10^{-10}$ (Figure 3). A very low frequency (VLF) phase comparator will be used to monitor one of several VLF frequencies in order to determine the time code generator corrections, and the frequency drift rate of the oscillator. Periodic adjustments to the oscillator frequently are made to minimize the time correction.

(b) The initial setting of the local time standard to the common time reference will be made by transporting between stations a calibrated portable crystal clock (Figure 4) having a rated frequency stability of about 2×10^{-10}. In practice, this clock will be synchronized to a convenient time standard such as the stable oscillators at Station WWV, Beltsville, Maryland, before and after all field stations have been set. It would not be unreasonable to expect that the time code generators at all stations would be synchronized to less than 20 microseconds, and that subsequent time corrections relative to the common time reference would be known to within 50 microseconds over an extended period. All time standards

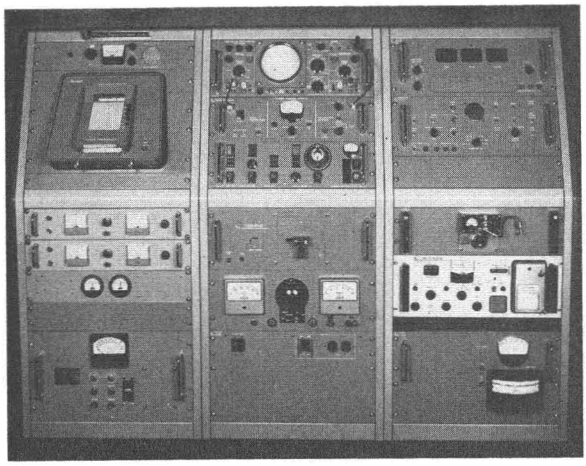

FIG. 3. Camera synchronization console.

will be checked periodically to insure synchronization.

(c) The disk shutters can be synchronized to the local time standard to function within ±100 microseconds of pulses derived from the local time standard. Circuitry is provided in the synchronization system by means of an electronic gate, to detect any exposure that varies more than 100 microseconds from the desired timing pulse, and record that exposure as worthless. These variations in the intervals between exposure pulses from the camera, referred to as jitter, are caused by small electronic and mechanical disturbances in the gearing system. Prolonged testing of the system indicates that the jitter varies between ±20 and 40 microseconds.

Thus, the total accumulation of timing uncertainties is well below the tolerable 0.7 millisecond.

METRICAL PRECISION

In the development of an optimum satellite geodesy program, it is imperative that the metric quality of each individual step in both the data acquisition and data reduction phases be critically evaluated in order to estimate the unavoidable individual errors.

It is hardly necessary to point out that the final results of this program will have to take into account such errors as those attributed to the physical design of the comparator and camera lens, and the anomalistic effects caused by the atmosphere. Furthermore, it will be necessary to consider the phase of the illuminated satellite which can introduce angular errors due to the fact that all cameras will not receive light from the same portion of the satellite. The apparent positional error along the orbit due to the finite time for light to travel from the satellite to the camera must also be accounted for. Other sources of error that have been or will be investigated include atmospheric shimmer, camera vibrations, emulsion shift, instability in the camera mount, comparator operator bias, and timing uncertainties. While most of the individual investigations have been completed, the final results are still being compiled for analysis and evaluation. The conclusions will be published as separate reports at a later date.

In the reduction of the data, the purpose of the plate measurements is to interpolate a specific point of the satellite orbit into the background of stars as given by the specific

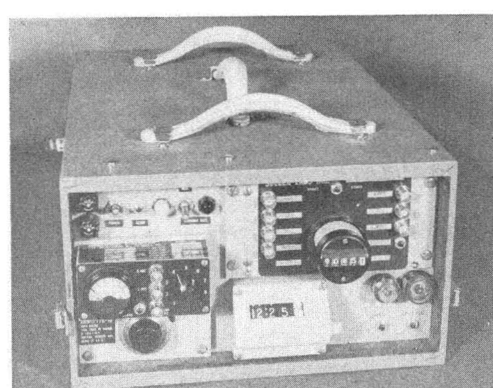

FIG. 4. Precision portable crystal clock.

TABLE 1

ACCURACY IMPROVEMENT WITH INCREASED OBSERVATIONS

9 Unknowns			
n *No. points*	$m(\mu)$	*Center* σ (″)	*Edge* σ (″)
10	5.8	2.40	2.95
25	5.2	1.40	2.25
50	4.8	0.95	1.75
96	4.1	0.60	1.09
195	4.2	0.40	0.89
287	4.2	0.35	0.62

TABLE 2

VARIATION IN STANDARD DEVIATION WITH ORDER OF DIFFERENCES

	X	*Y*
$p=1$	$\sigma_1 = \pm\ 151.50\mu \pm 8.87$	$\sigma_1 = \pm\ 2.28\mu \pm .13$
$p=2$	$\sigma_2 = \pm\ 2.86\mu \pm .19$	$\sigma_2 = \pm\ 2.30\mu \pm .15$
$p=3$	$\sigma_3 = \pm\ 2.74\mu \pm .20$	$\sigma_3 = \pm\ 2.31\mu \pm .17$
$p=4$	$\sigma_4 = \pm\ 2.60\mu \pm .20$	$\sigma_4 = \pm\ 2.32\mu \pm .18$
$p=5$	$\sigma_5 = \pm\ 2.47\mu \pm .21$	$\sigma_5 = \pm\ 2.35\mu \pm .19$

$$n = 100 \qquad \sigma^2 = \frac{\sum_{i=1}^{n-p} (X_{i+1} - X_i)^2}{\binom{2p}{p}(n-p)}$$

right ascension and declination coordinates. This operation can be compared to measuring a direction with a theodolite. On one side we have a pointing error, which in our case is the orientation error of the camera. On the other side we have the aiming error, which in our case is the error in the image. The two errors are independent.

The orientation error depends upon (a) the number of stars carried, and (b) the unknown parameters to be determined in order to simulate the photogrammetric bundle. Experience has shown that 9 unknowns, 6 geometric and 3 physical parameters, must be determined for each plate exposed. The accuracy in terms of orientation is shown in Table 1.

The first column of the table shows the number of points or stars carried in the least squares solution. The second column indicates the mean error of unit weight obtained from the corresponding least squares solution of the star measurements. Columns 3 and 4 show the importance of carrying large numbers of stars in each individual plate reduction. Consequently, in order to reduce the orientation error in the center of the plate to ½ second of arc, it is necessary to carry about 100 stars (Figure 5).

(Please turn the page for Figure 5)

In studying the error of the satellite image sequences, the method used was based on the estimation of dispersion from differences. This method was developed by von Neumann and Morse[2] for determining the standard error of observations which display some kind of trend. Table 2 shows that the standard deviation in the direction of the image sequence X is fictitiously large for the first-order differences, which indicates the presence of a strong trend. Higher-order differences give the standard errors with the trend eliminated. The standard deviation of an individual image was determined to be 2.5 microns or about 1.7 seconds of arc for the BC-4.

Because several hundred images will be measured, it is considered justifiable to assume that the statistical improvement will be by a factor of 3 to 4, or in other words to ±0.5 second of arc.

Adding both ½ second errors obtained with the orientation and image measurements in accordance with the Gaussian law of error propagation, 0.7 second of arc is obtained. Allowing 0.3 second bias error, it is believed that the accuracy of a final direction to the satellite is ±1 second of arc in geometry and ±150 microseconds in time.

When Echo type satellites are launched into near polar orbits around 2,000 miles high, the C&GS tracking system will be particularly adaptable to a world-wide network. As a matter of interest, theoretical studies are now being made to investigate the error propagation in such a network, to determine in which way the 1 second directional uncertainty will propagate into the final station coordinates.

[2] Morse, Anthony P., "The Estimation of Dispersion from Differences," BRL Report No. 557, Ballistic Research Laboratories, Aberdeen, Maryland, July, 1945.

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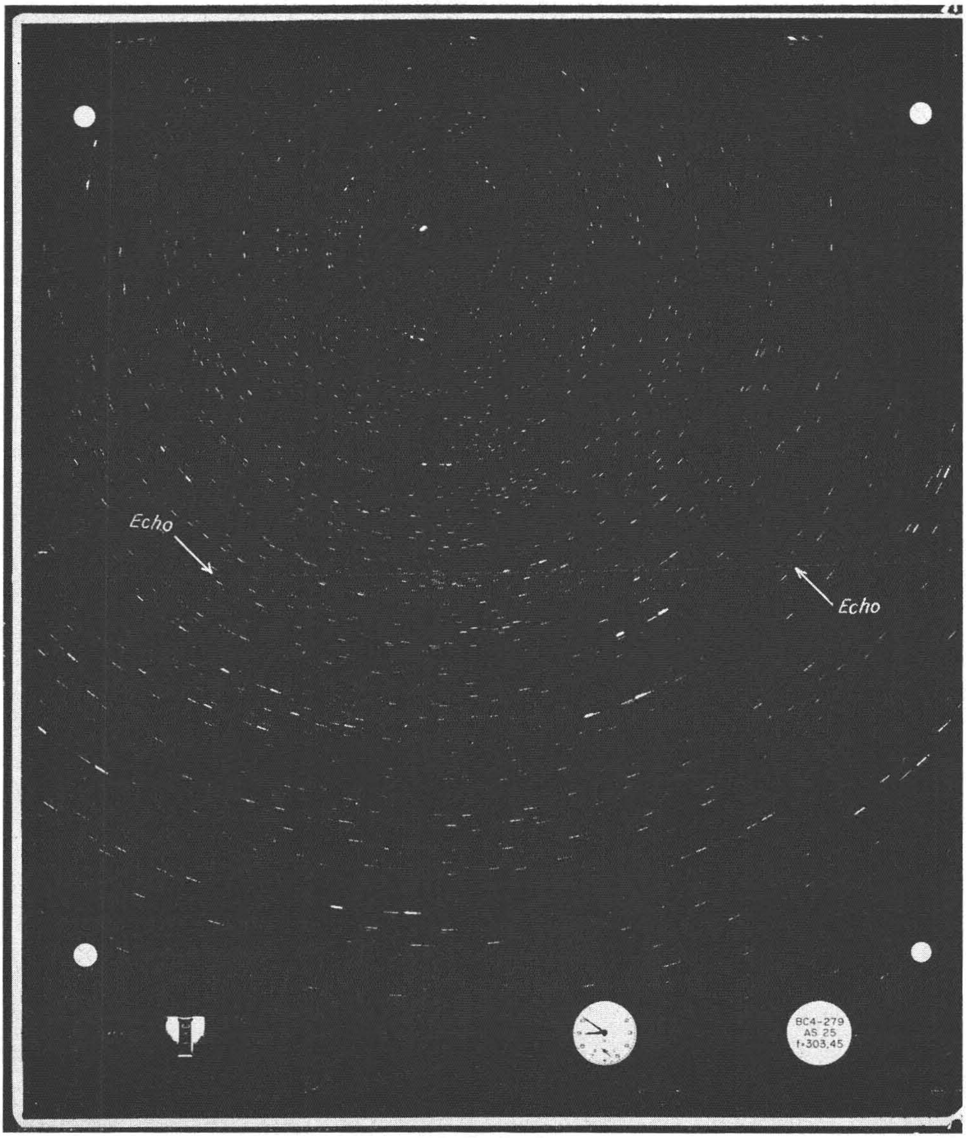

FIG. 5. Photograph of ECHO I orbiting past the constellation Ursa Minor (center of picture) at 0412 EST on 31 March 1962. Exposures at 1/30 sec., f/2.6, image interval 0.4 second.

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