FLARE TRIANGULATION BETWEEN FLORIDA AND THE BAHAMAS

Lt. Comdr. Franklin R. Gossett.

U. S. Coast and Geodetic Survey.

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This project was organized in 1946 as a joint cooperative task between the Hydrographic Office of the Navy, the Army Map Service, and the Coast and Geodetic Survey. The Survey furnished one officer and three observers with instruments ; the Army Map Service furnished a senior engineer and six observers with instruments ; and the Navy furnished all additional personnel and equipment including the three ships U.S.S. *Tonawanda AN-89*, *Marietta AN-82*, and *Simon Newcomb AGS-14*, and two *PB4Y-1* planes with crews. Project headquarters were established at an auxiliary field about 3 miles from the Naval Air Station at Miami.

The general objective of the project was to test and develop methods of flare triangulation, and to determine the degree of accuracy that may be expected from the method. The specific objectives of the project were : (1) to test the method on a test figure using two or more instruments at each of three known stations to allow for complete computations from the station to the flares and back through the eccentric instruments to starting points ; (2) to connect the Florida mainland (N. A. datum of 1927) to Bahama stations ; (3) to connect the Florida Keys to Cuba ; and (4) to form a closed loop to the Cuba connection by four additional legs or figures to cover the Bahamas. Only (1) and (2) were completed.

FLARE METHOD OF TRIANGULATION.

The flare method was developed by Lt. Col. W. E. Browne, of the Royal Engineers, and was originally intended for use in making a connection between the south coast of England and the coast of France, in the vicinity of the Normandy beaches, shortly after D-day. It was found impossible to attempt the connection at that time. After V-E day, the method was tested over the 90-mile gap of the Skagerrak, and the results obtained were sufficient to establish the practicability of the method for extending and connecting major triangulations.

The flare method is essentially a long-line method, applicable where distances between points exceed the sight distance limit of ground structures (maximum lines about 200 miles). The only limitations, with respect to observing, are the height and intensity of the flare and clear weather visibility.

The method is based on simultaneous theodolite pointings, from three known and three unknown stations (or three established on a different datum), on parachute flares dropped by plane at three previously computed approximate air-station positions between the known and unknown stations, and theodolites synchronized by radio from the plane.

In figure 1, an airplane, flying a great circle course between the known and unknown stations and in a parallel direction to them, drops a flare as near as possible to the previously computed approximate positions of each of the air stations A1, A2, A3. Prior to the beginning of operations, watches of all recorders are synchronized (or correction determined) by radio time tick. By radio, the plane warns the observers of the particular air station being approached, the expected time of flare release,the actual release, the ignition of the flare, and a time warning until the first pointing of the theodolites. Successive warnings are usually given at 30 seconds, 20 seconds, 10 seconds, and then single-second warnings from 5 seconds — 5, 4, 3, 2, 1, and "mark". From the time of ignition of the flare all the observers are "tracking" the flare with their theodolites. On "mark", the recorder logs the time, and all the theodolite pointings are perfected and read. The recorders' logged times serve to identify the simultaneous pointings on each flare. The time procedure is repeated consecutively at regular intervals (in the Florida-Bahamas project the interval was 45 seconds) until the flare is extinguished, allowing several simultaneous pointings to be made on each flare.

It is assumed that given a sufficient number of acceptable observations, computation from each side gives the change of origin, the scale change, and azimuth swing between the two systems ; and to that the connection can be established from either side.

OPERATIONAL PROCEDURE.

The following operational procedure proved most successful :

After receiving the 1600 weather forecast, all stations were notified on the 1700 schedule as to the night's operation, that is ; (*a*) if weather was favorable, observations to start at 1900 ; (*b*) if doubtful, all ground stations were to make hourly reports on observing conditions beginning at 1900, and (*c*) if unfavorable (area storm conditions), operations canceled for the night.

The plane was sent up when all three known stations (Pisgah, Weed 2, and Congress) were favorable and one or more of the three unknown stations (Walker Cay Pinder Point, and Gun Cay) were favorable or improving. It usually required an hour and a half after take-off orders for the plane to get into the air and to the first flare station.

Station Congress, at Miami, which was near the airfield, was advised by telephone when the plane took off. This station then notified all other stations by radio. Instruments were then set up at all stations and azimuth lights turned on. As soon

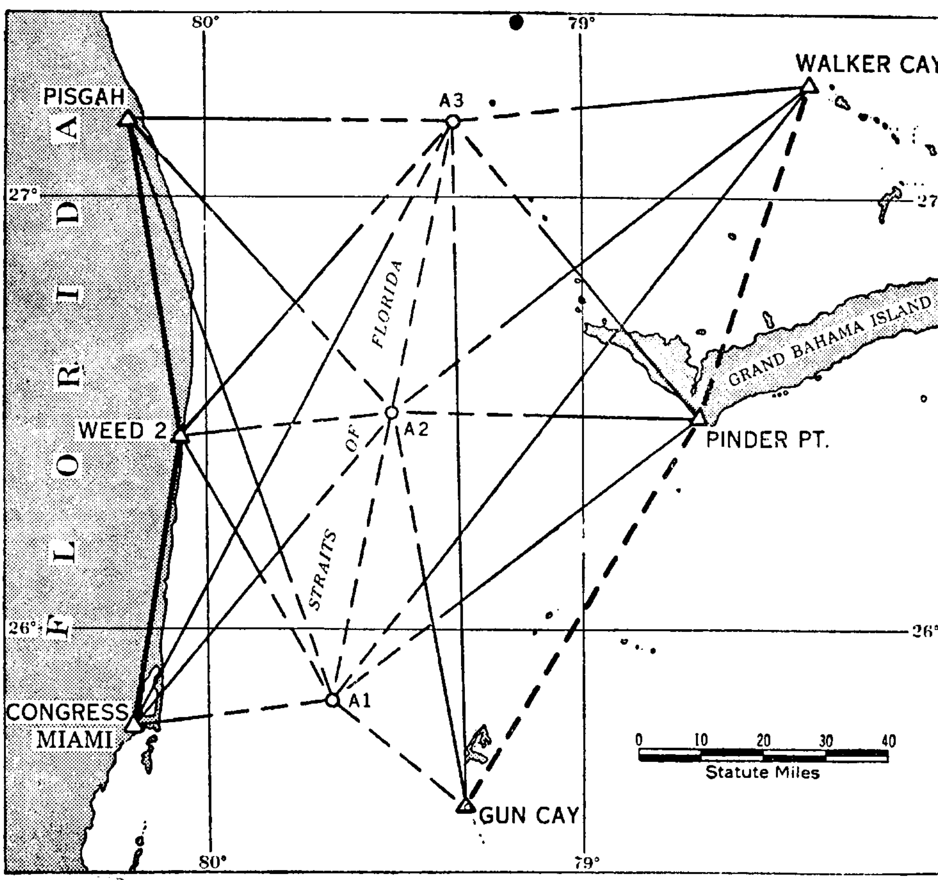

FIG. 1
Flare triangulation connecting the Bahama Islands with Florida.

as possible after the plane was air borne, radio communication between the plane and the stations was established. Since the plane radio was usually unsatisfactory — seldom could all stations hear the plane — the control of observations was transferred to the middle ground station, Weed 2, thus reducing the plane radio communications to identification of the air station being approached, to "flare away", and to "flare ignited." (The flares were released at 20.000 feet). At times this had to be relayed, or when the plane radio failed entirely, the ground lookouts reported when the flare ignited and the control station, Weed 2, took up the count, i. e., 30 seconds, 20 seconds, etc., to "mark".

Before each flare drop, the plate setting, position of telescope (direct or reverse), flare number, and air station number were given by radio from the plane and control station to all stations ; and prior to the beginning of observations, watches of all recorders were synchronized by radio time tick from the control station.

The plane navigation was principally by contact flying and dead reckoning, since LORAN control, although attempted regularly, failed because of interference of the plane radio, the unfavorable location of the LORAN station with respect to fixes in the air station area, and unfavorable atmospheric conditions. This made it necessary to furnish the plane with ground control assistance to insure the flares being dropped reasonably close to the air-station positions.

For this purpose, a small plotting board was used with a tracing of Coast and Geodetic Survey Chart 1112 on which were plotted the ground stations, the air stations and meridian and azimuth lines to flare positions. Each ground station was previously furnished with the angle from its azimuth mark to each air station. Each station reported the flare position in degrees right or left of the air station after each flare had been observed. A quick position was obtainable by plotting cuts from three stations with a celluloid protractor. By this method, when the ordinary plane navigation methods failed, the distance and direction the flare was off position could be furnished the plane about two minutes after the flare was extinguished, thus enabling the plane to determine drift constants and to correct course before arrival at the next station.

Between 8 February and 4 April, 1946, 14 flights were made, 12 at night, and 128 flares were released, of which 18 were duds. On the last flight, which was in daylight, an attempt was made to sight flares of 300,000, 750,000, and 1,000,000 candlepower, in order to establish the feasibility of daylight observing. This was unsuccessful as no station was able to see the flares.

INSTRUMENTAL METHODS.

Each of the Florida stations (Pisgah, Weed 2, and Congress) had a Coast and Geodetic Survey instrument on the station center and a Navy instrument on a nearby eccentric set-up. Each of the Bahama stations (Walker Cay, Pinder Point, and Gun Cay) had a Navy instrument on center and an Army instrument on the nearby eccentric station. (See fig. 1).

To eliminate instrumental errors, as much as possible, eight plate settings were used, four direct and four reverse, providing equal distribution over the circle as follows : 1-O-D, 2-202-R, 3-45-D, 4-247-R, 5-90-D, 6-292-R, 7-135-D, 8-337-R. (The first number is the position number, the second is the plate setting in degrees, and the letter is the telescope position). An acceptable flare observation was required to have a minimum of four simultaneous pointings from all six stations.

The observers wore headphones except where loud-speakers were available. The usual method was to point on the expected position, and perfect the pointing with the finder when the flare ignited. The flare was seldom dropped close enough to the expected position to be in the telescope. Flares normally appeared about like a planet or bright star. The light made a good pointing, showing a steady point between the cross-hairs. On calm nights the flare moved slowly in a straight line, but there was considerable lateral movement when the wind was strong. However, once sighted, the flare did not move out of the telescope between 45-second pointings. Except when visibility was almost perfect, distant flares, on lines about 100 miles or over, were difficult to pick up, requiring almost total dimming of the telescope light. To prevent jamming the tangent screw, flares were followed with the telescope unclamped until the 10-second warning, then with the tangent screw until the "mark" signal was received. "Mark" signals were then received at 45-second intervals, with the intervening 30-second, 10-second, etc., warnings, and usually four to six pointings were obtained before the flare was extinguished. The average burning time of the flares was 4 minutes and 45 seconds.

When the "mark" signal was heard over the loud-speaker, or when the observer with headphones repeated the "mark", the recorder logged the time. Because of the relayed "marks" to the recorders, where the observers had headphones, some slight discrepancies in recorded times were obtained. However, the recorder times were close enough to identify simultaneous pointings which was their purpose, the theodolite pointings being made simultaneously only upon receipt of the radio "mark" signals. The readings on the azimuth mark initial before and after each flare had been sighted on were meaned and subtracted from each flare pointing.

METHOD OF COMPUTATION.

Lists of Directions were prepared on modified Coast and Geodetic Survey Form 24-A with all observations reduced to zero on the azimuth light in the usual manner. Since each pointing represents the instantaneous position of a moving target, no abstract or means of pointings is possible. All record books and lists were computed and checked in the field.

For the computation, 24 flares were selected, 8 at each air station, which were considered the most suitable for computation on the basis of the following criteria : (1) at least four completed pointings from each ground station, the plate position settings and direct and reverse pointings being evenly distributed through the observations ; and (2) proximity to the desired air station — those nearest were chosen.

By using four observations from each station on each flare, it was possible to

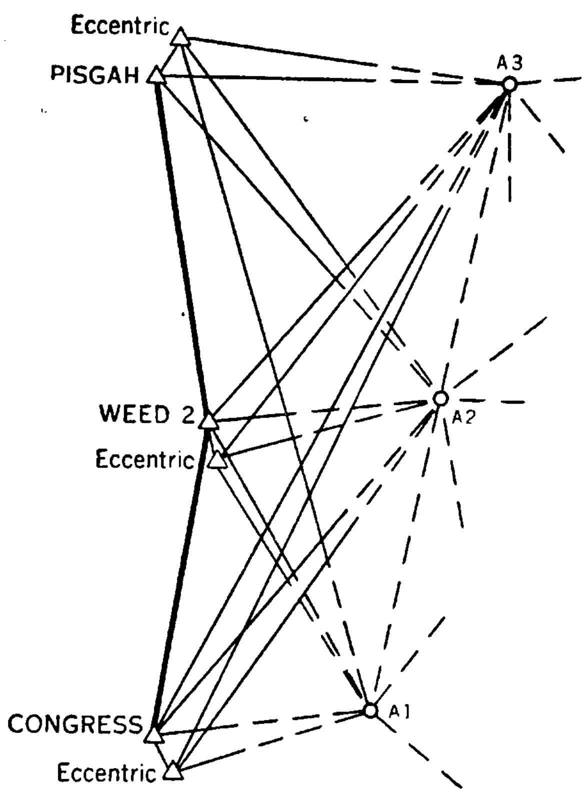

FIG. 2
Test figure for determining accuracy of flare triangulation method.

compute 32 positions of each air station, 32 positions of each eccentric instrument at the Florida stations for the test of method, and using the same 32 air-station positions, obtain 32 independent positions of each of the three Bahama stations. In addition there were available, if desired, the extra positions not utilized on the 24 selected flares and the observations on 46 additional flares, which were acceptable, although not by the adopted criteria.

For the test figure, the final computations were made in the office of the Coast and Geodetic Survey. For the positions of the Bahama stations, the computations were completed by the Hydrographic Office in cooperation with the Army Map Service.

In the test figure, the eccentric instruments at stations Pisgah, Weed 2, and Congress were considered the unknown stations. (See figure 2). In the field, inverses were computed between the three known stations, Pisgah, Weed 2, and Congress. Geographic positions and azimuths to the corresponding initial stations, were then computed for the eccentric stations.

In the office computations the four pointings on each of the 24 selected flares were designated 1, 2, 3, 4. To compute the eccentric stations used in the test phase it was necessary to inverse from A1 to A2 and from A2 to A3. The procedure used was to take the three flares of each circle position and inverse from A1 (pointing No. 1) to A2 (pointing No. 1) ; A2 (pointing No. 1) to A3 (pointing No. 1) ; A1 (pointing No. 2) to A2 (pointing No. 2) ; A2 (pointing No. 2) to A3 (pointing No. 2) ; etc. After the 32 pairs of inverses were computed, angles at each of the eccentric stations were taken out from 32 sets of observations. The problem was then in the form of a three-point fix. However, since an azimuth at the eccentric station was desired, one condition equation was introduced. By using this azimuth condition, angles at the flare positions could be taken out, thereby eliminating the laborious task of computing a three-point fix for each set of observations. With angles at the flare positions taken out, 32 single equation adjustments were made for each of the eccentric stations. This procedure was also used to determine the positions of the new stations on the Bahama Islands.

RESULTS OF TEST.

A comparison is given below of the fixed geographic positions of the eccentric stations at Pisgah, Weed 2, and Congress with those computed through the air stations (Table 1).

TABLE 1. — Comparison of fixed geographic positions of eccentric stations with positions computed through flare stations.

Station (eccentric).	*Fixed position.*	*From flares.*	*Closure (proportional parts).*
PISGAH	N 27°13'03".366	03".448	1/72,000
	W 80°13'06".607	06".596	
WEED 2....................	N 26°25'54".723	54".749	1/150,000
	W 80°03'46".401	46".368	
CONGRESS................	N 25°46'30".299	30".268	1/108,000
	W 80°11'25".201	25".251	

Note that the position closure at Weed 2 (eccentric) is smaller than the closures at the other two stations. There are no small angles in the triangles involving this middle station ; therefore, small errors in observation have less effect on the adjusted results.

The comparison between the astronomic positions and the flare established positions of the Bahama stations is given in Table 2.

TABLE 2. — Comparison of astronomic positions with flare established positions.

Station.	*Flare established position.*	*Astronomic position.*	*Closure (proportional parts).*
WALKER CAY	N 27°15'25".88 W 78°24'16".65	36".01 23'57".81	1/10,000
PINDER PT	N 26°30'20".19 W 78°45'51".03	08".83 46'01".09	1/30,000
GUN CAY	N 25°34'24".57 W 79°17'48".79	29".27 18'00".86	1/25,000

COMMENTS AND RECOMMENDATIONS.

The following comments and recommendations are based on the experience and data gained in the field work and in the office computations and adjustments :

(1) INSTRUMENTS. — An illuminated finder sight is desirable. Heavier cross-hairs are desirable so that the telescope light may be reduced to a minimum for faint flares. A positive, reliable, easily regulated instrument lighting system is necessary. A firm instrument support and separate foot-boards for the observer should be used.

(2) COMMUNICATIONS. — Radio voice is preferable, because more information can be given more quickly and all communications are immediately understandable to all concerned. Loud-speaker receivers are preferable to headphones. Less elaborate battery-operated commercial receivers with built-in speakers are available. The ground radio transmitters and receivers used were satisfactory except for the portable generators. About 50 percent additional units for spares should be provided. A good clear channel night frequency is necessary. When a frequency of 4625 kc. was used, occasional interference from a Texas airways station was noted. Excessive radio day-time schedules should be eliminated.

(3) SYNCHRONIZED TIME. — This is important, since it is the means of identifying the simultaneous pointings from all stations on the flares. A WWV time check of each recorder's watch logged in the angle book before and after each night's work would be satisfactory.

(4) FLARES. — Flares used were odd lots, some old and defective, causing a large percentage of duds and, therefore, a loss of observing time. The 300,000 candle power flares were visible on clear nights to the eye and satisfactory for instrument pointings over all distances used (29 to 110 miles). On nights that were not quite perfect for observing, more pointings would have been obtained if the 750,000 candle power flares had been used. Flight altitudes were increased from 17,000 to 20,000 feet to assist observers on long lines.

(5) PLANES. — The *PB4Y-1* (Liberator) plane was suitable for the high altitude work. Principal defects were unsatisfactory radio and navigational equipment. LORAN was unsatisfactory in the drop areas. Radar equipment should be used as a navigational aid in such projects. Quick ground plot of each flare with radio position to plane is an effective assistance. This could be accomplished more quickly by having two or three additional suitably located instruments cut in each flare on igniting and notify the plane immediately on a separate radio frequency. It might also be possible to have a ship with searchlight pointed upward maintain position under each flare station. Probably one ship under the middle air station would furnish adequate navigation control. Such a ship being centrally located would also make an excellent station for radio control of "marks". If a suitable parachute flare projectile could be obtained for firing from a survey ship, the aviation component on flare triangulation could be eliminated.

(6) OPERATIONS HEADQUARTERS. — A central office is necessary for administrative purposes, supply, mail, radio communications, field records and data,

assembly, and checking. A large well-equipped survey ship would be ideal headquarters and control unit for this type of work.

(7) PERSONNEL. — The quality of the triangulation work depends largely on experienced observers, well-trained recorders, microscope readers, and lightkeepers. Frequent changes in the assisting personnel should be avoided.

(8) AEROLOGICAL CONDITIONS. — Since unlimited visibility is essential, projects should be planned for that season of the year most likely to produce a large number of clear nights. Hence, for future projects, exhaustive preliminary weather investigation should be made in the areas to be surveyed and close aerological coordination obtained during the observations.

(9) OBSERVATIONS. — As a result of the adjustment computations made in the Washington office of the Coast and Geodetic Survey, it is recommended for the field work of future projects of this kind, that observations be made from three eccentric stations in addition to the true station. The four observations may then be reduced to one direction. If observations are taken on four flares in each area, with three pointings on each flare, 12 positions could be computed for each station in the scheme. By using this procedure, the observer would have more time to get accurate pointings, final results would be as good as that obtained in the Florida-Bahamas project, and there would be a considerable decrease in the expense of the project.

CONCLUSION.

The method of flare triangulation is practicable from a field operational standpoint, but almost perfect weather conditions are essential. Because of the large outlay of personnel and equipment involved, a large percentage of adverse weather conditions may make the cost prohibitive.

The accuracy of results obtained seems to depend largely on the ground observational procedure, the more experienced observers obtaining more consistent pointings and a larger number of pointings per flare.