SHORAN—A PRECISION FIVE HUNDRED MILE YARDSTICK

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In 1938 the author was studying the effects of multipath signals on television transmissions, and was intrigued by the simplicity and accuracy of determinations of increased path lengths made possible by measurements of the displacement of the secondary signals on a cathode-ray tube screen. It was apparent that somewhat similar principles could be used in a device in an airplane to measure distances from fixed ground stations for navigational purposes.

The equipment that was then visualized would involve reflected or re-transmitted pulsed radio waves together with a sweeping cathode-ray tube beam as a stop-watch to measure the elapsed round-trip transit time. In that period, before the start of World War II, pulsed radio-wave concepts were not widespread and the term radar had not been coined.

Early analysis of possible circuit configurations indicated the tremendous number of practical aspects that had to be considered. Frequently during the investigations the use of continuous wave signals with measurements in terms of wave lengths of the radiated energy appeared to be simpler and more straightforward than the pulse technique which had been chosen. However, as appealing as that concept seemed in many respects, it has always been resisted on the basis that minute traces of multipath signals, received at either terminal, would cause disproportionately large errors in phase, and thus in distance measurements, without any indication of their presence.

Months of evaluation and test of preliminary equipment designs culminated in a contract award by the Air Force to Radio Corporation of America to construct a blind navigational device utilizing the principles evolved. It was to be used primarily for bombing through the overcast and was named Shoran.

It soon became apparent that the degree of cathode-ray tube deflection linearity which could be realized under all conditions, including variations of orientation in the earth's magnetic field, was obviously insufficient for precision measurement purposes. Therefore, it was necessary to resort to the so-called set-back principle. In this mode of operation the transmitted pulse is radiated prior to display of a zero time marker by an adjustable interval such that it arrives back at the point of origin coincident with the T_0 pulse. Then when the cathode-ray tube indicates pulse coincidence, the dials show the elapsed transit time. Thus, the precision of adjustment of the interval determines the accuracy of Shoran measurements.

The basic adjustable unit as finally developed is a quadrature-phase goniometer. It is supplied with two components of a pure sine wave at a crystal-controlled frequency of 93,109.87 cycles per second. This frequency was chosen because the period of one cycle is nearly equal to the one-mile round-trip transit-time of radiant energy through standard air at sea-level pressure, and because it is also an exact sub-multiple of several frequencies which can be derived from the Bureau of Standards radio transmissions from WWV in Washington, D. C.

The rotor of the goniometer can be turned through any angle in the crossed space and time quadrature fields of the stator to provide a phase delay of the fundamental frequency. One degree is approximately equal to the round-trip transit time equivalent to fifteen feet. The fixed-phase stator voltage is distorted and clipped to form the zero-time marker and the voltage from the rotor is processed to become the transmitter actuating pulse.

Additional goniometers, connected to the basic unit through ten-to-one and one-hundred-to-one step-down gear ratios, are supplied with stator currents at one-tenth and one-one-hundredth of the frequency of the basic unit respectively. These serve to sort out one of each hundred of the 93,000 pulses produced each second. Thus,

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* On April 22, 1960, the Society in Executive Session voted to award the Magellanic Premium to Mr. Seeley for his work on Shoran, which is now recognized as the basic method of navigation for ships and planes. The Magellanic Medal was presented to Mr. Seeley on November 10, 1960.

the fundamental unit can be rotated through 36,000 degrees, or the equivalent of one hundred miles, before the distance readings repeat. It has been assumed that the navigator will know the particular hundred-mile segment of distance which will include his position.

For either a determination of exact position, or of the distance between two ground points, it is necessary to have two simultaneous measurements. Therefore, two goniometer chains are included in each Shoran instrument. In operation the transmitter is commutated between the two about five times per second and simultaneously changed in frequency so that each base station will receive and retransmit only those pulses directed to it. Each goniometer chain can be rotated in either direction by a mechanically coupled computer driver at any precisely adjusted rate corresponding to a distance progression velocity between zero and about mach 1, to maintain pulse coincidence.

In the mechanical alignment of the goniometer zeros the phase of the transmitted pulse is set ahead by a fixed-standard angle which is the equivalent of nearly 1,700 feet of distance. This compensates for the time required for the pulse to traverse two transmitters, two selective receivers, and all plane and ground-station cabling between units and antennas. Adjustable delay devices are included in each ground station equipment to allow for variations in required lengths of base station cabling and other variables. Figure 1 illustrates a typical Shoran ground-station set-up. Two corner reflector antennas are mounted atop the collapsible plywood mast. One of these is for the receiver and the other is for the transmitter. The reference point, from which distances are determined, is the bisector of a line between the monopoles of these two antennas.

Both the plane and base-station transmitters develop peak power of about fifty thousand watts. The duty cycle of the plane transmitter is such that the average radiated power is less than fifty watts. However, the ground transmitters are equipped to retransmit all pulses that are received from several planes that may be using that station at the same time so they are constructed to operate with considerably higher average power output when it is necessary. Most Shoran work over the last twenty years has used carrier frequencies between two hundred and three hundred megacycles, corresponding to wave lengths between one meter and one and one-half meters.

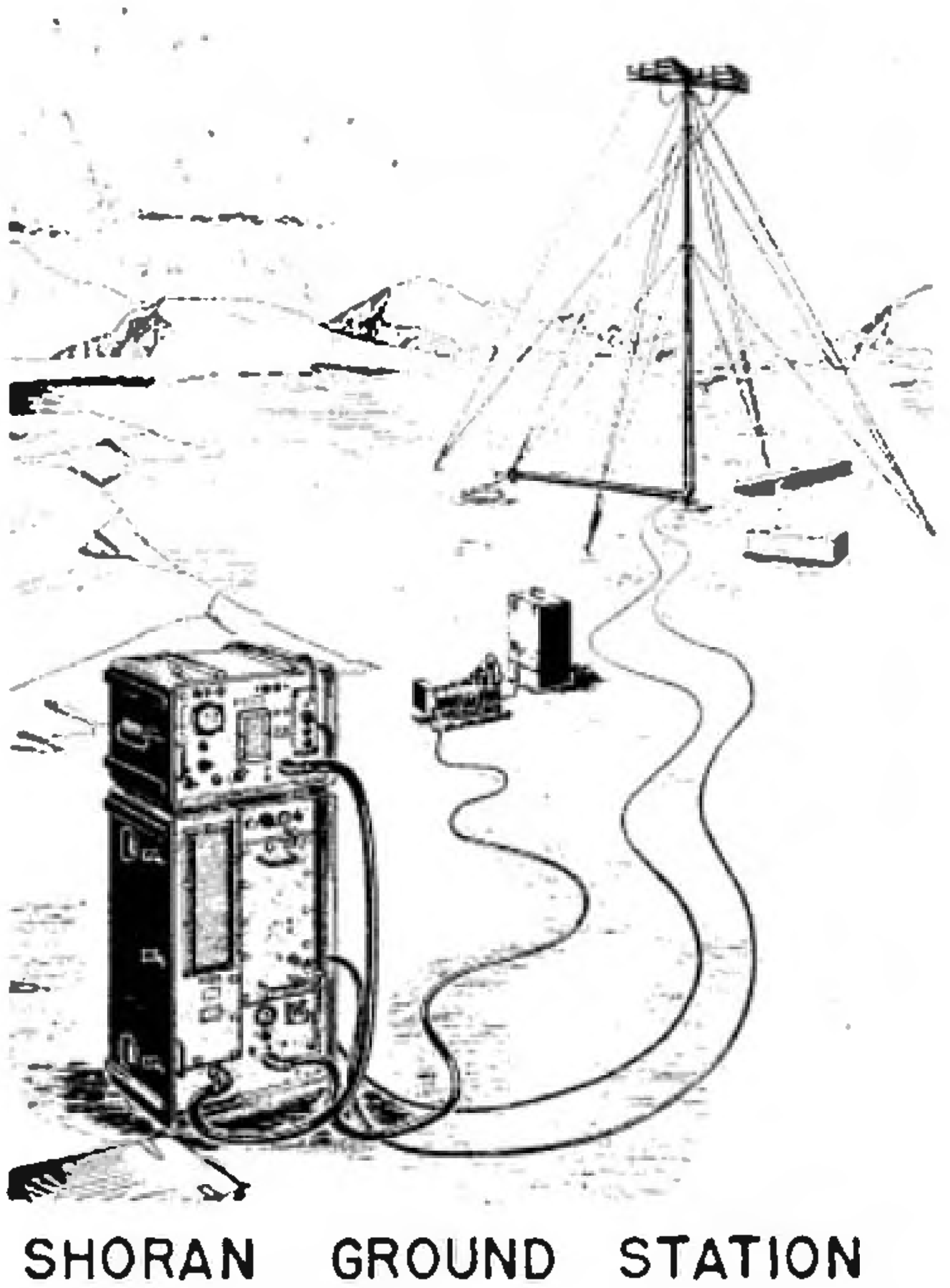

FIG. 1. A Shoran ground station.

When the first version of this equipment was completed, it was installed in a B-17 military plane and ground stations were placed at Montgomery, Alabama, and Tallahassee, Florida. Without previous bombing experience, the author was able to equal the record of trained visual bombadiers in dropping sand-filled practice bombs from 20,000 feet on a target in the bay near Eglin Field, Florida.

The finally devised Shoran timing and indicating unit, which includes the receiver with commutated gain controls, is shown in figure 2 coupled to a bomb-dropping computer. An earth-inductor compass in the tail of the plane and a true air speed indicator also supplied information to the computer. The functions of the computer were to calculate the vector winds, make corrections in the bomb release point and target approach path, then to guide the plane on that path by connections with the auto-pilot and finally to release the bomb at the proper instant. Usually the target-position information and the ballistics of the particular bomb to be released were programmed into the computer before the plane left its home base. Thereafter, unless evasive flight action was necessary, the bombardier had little to do except to adjust the rate and drift goniome-

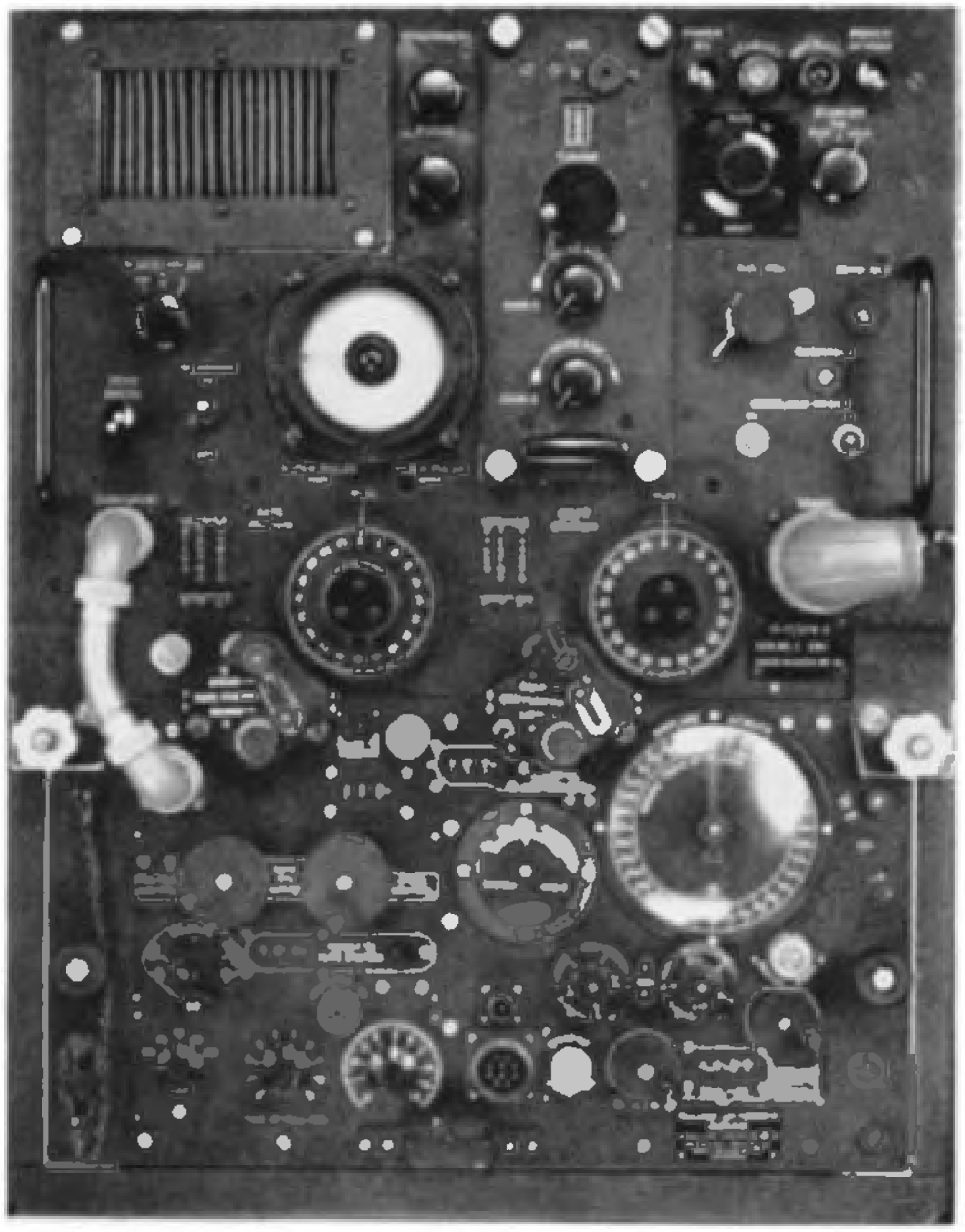

FIG. 2. Shoran plane equipment as used for bombing.

ter drive velocities to maintain pulse coincidence on the cathode-ray tube screen. It is now history that the accuracy of Shoran bombing, as used in the war and in the Korean engagement, exceeded that of any other bombing method regardless of target visibility or identification difficulties.

During early test flights with control stations on the east coast of Florida the author had uncovered an error of several hundred yards in the plotted position of Memory Rock, a small island in the Bahamas out of sight of any other land mass. Subsequent tests with Zenith cameras at fixed ground sites and triggered gas lamps beneath the plane had indicated the probable error of a Shoran navigational fix to be considerably less than the dimensions of the plane.

These results attracted the attention of geodesists who recognized the emergence of a valuable new survey tool. The 7th Geodetic Control Squadron of the Air Force, under the command of Col. Carl I. Aslakson, who was on loan from the U.S. Coast and Geodetic Survey, undertook a project to determine the potential accuracy and best methods of utilization of Shoran for survey purposes. The author worked with this group and devised several equipment modifications which were applied to existing Shoran gear to increase the measurement accuracy several fold over that which had been more than ample for bombing purposes.

In the meantime, the U.S. Coast and Geodetic Survey began using the equipment for hydrographic charting, particularly in the waters surrounding the Aleutian Islands. Perennial fogs in this area had so completely bogged down the operations that had been under way using conventional techniques that the job had appeared interminable. With Shoran it was completed in a few months.

During this same period several large oil companies in the United States had received permission to prospect for oil in some of the huge jungle regions in South America, provided they first established survey control points in these hitherto uncharted and all but impassable areas. This stipulation appeared prohibitive until Shoran survey techniques were evolved and supplied a practical solution to the problem. Some of these companies also used their Shoran gear for position control in their offshore oil prospecting in the Gulf of Mexico.

In August of 1946, as the investigations of the 7th Geodetic Control Squadron began to unfold, the War Department issued a call for a Shoran Geodetic Surveying Conference stating that the results were so amazing in their accuracy and were of such tremendous importance that they would have a direct relationship to many pending Army and Navy projects.

One of those projects was to determine the true position of the islands of the Bahamas, the West Indies, and the Caribbean archipelago with respect to continental North America. It had been realized for many years that relatively extreme gravitational intensity anomalies in those areas indicated probable errors in the vertical at each astronomically determined control point. It was known that in this area a plumb-bob does not point to the center of the earth, the surface of the sea is tilted and the horizon is actually misplaced. But the magnitude and direction of these discrepancies could only be determined by a rigid trilateration survey back to the mainland. Since most of the distances involved were well beyond line of sight, the project had been using large Roman-candle type flares with synchronized sightings by several theodolites at the distant points. This system did not yield particularly satisfying results.

Early in 1945 Colonel Aslakson had undertaken an exhaustive series of Shoran measurements of the grid line joining five accurately located control points in the Denver, Colorado, area. These ten lines were of various lengths between ninety-eight and three hundred and eight miles.

Later on, this operation was moved into the Florida area and worked with a six-station grid between Daytona Beach and Key West as shown in figure 3. The flat terrain here allowed the use of radio-frequency altimeters, a big help in the study of the true effects of temperature, pressure, and humidity of the air through which Shoran radio waves must travel. There are two of these effects. One is on the velocity of propagation and the other is on the length of the radio path as altered by refraction due to variations in effective density along the route. Today every Shoran survey measurement is adjusted in accordance with temperature, pressure, and vapor pressure information secured simultaneously along the line adjoining the two stations. At present these adjustments are so well understood that errors from this source are negligible.

As this program progressed, the group developed the line-crossing techniques and the corresponding flight patterns that would provide the most dependable information. New photographic recording computers were developed which automatically make between fifty and one hundred pictures of the two mileage dials on each line crossing so that a plot of the sum of the two distances can be drawn as shown in figure 4. A curve such as this for each line crossing, smoothed by the system of least squares, adjusted for weather, plane altitude, and crystal frequency, and then averaged with data from other crossings of the same line gives the true ground distance between the two positions.

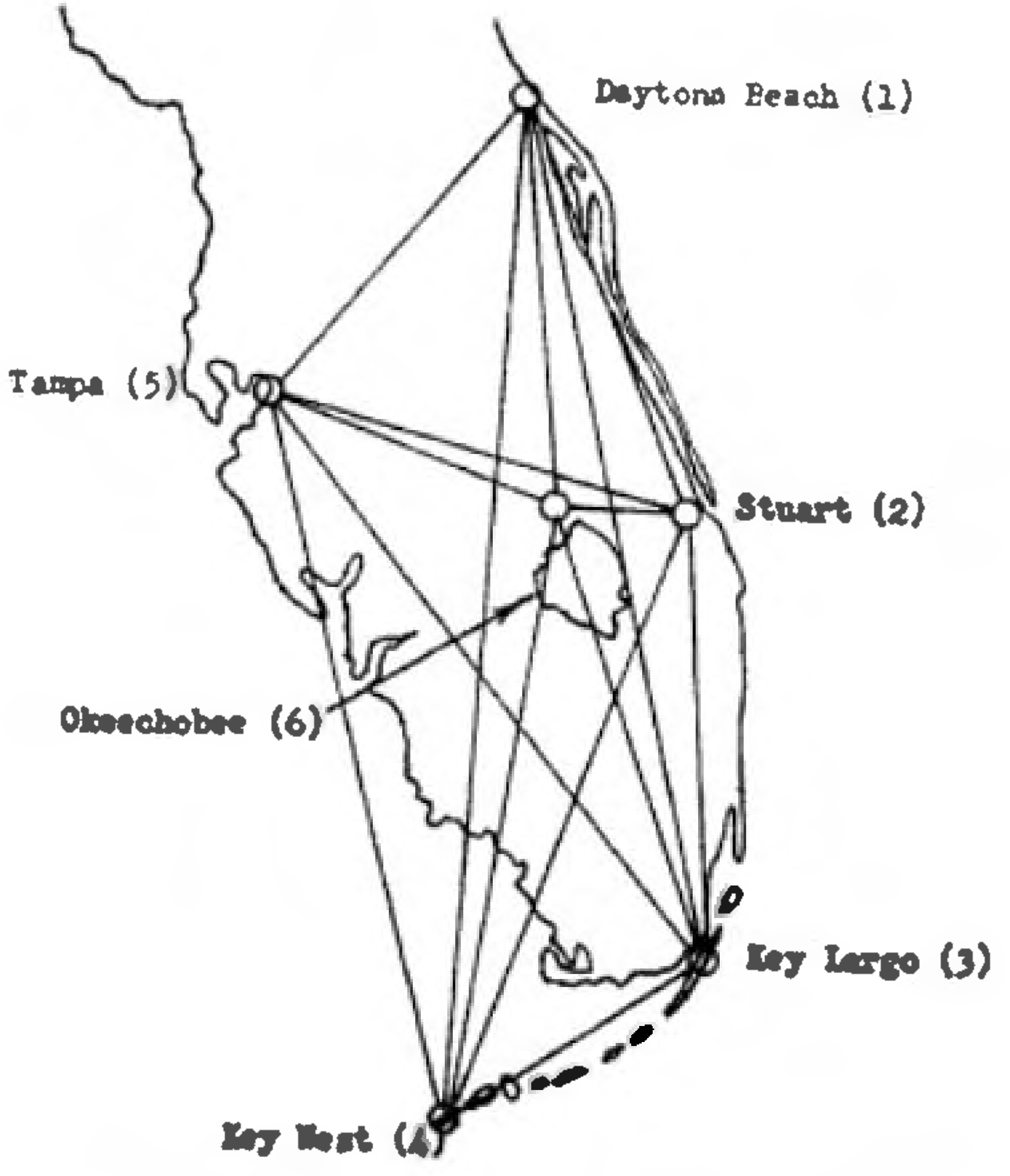

FIG. 3. Distances in Florida surveyed by both land and Shoran means for comparison purposes.

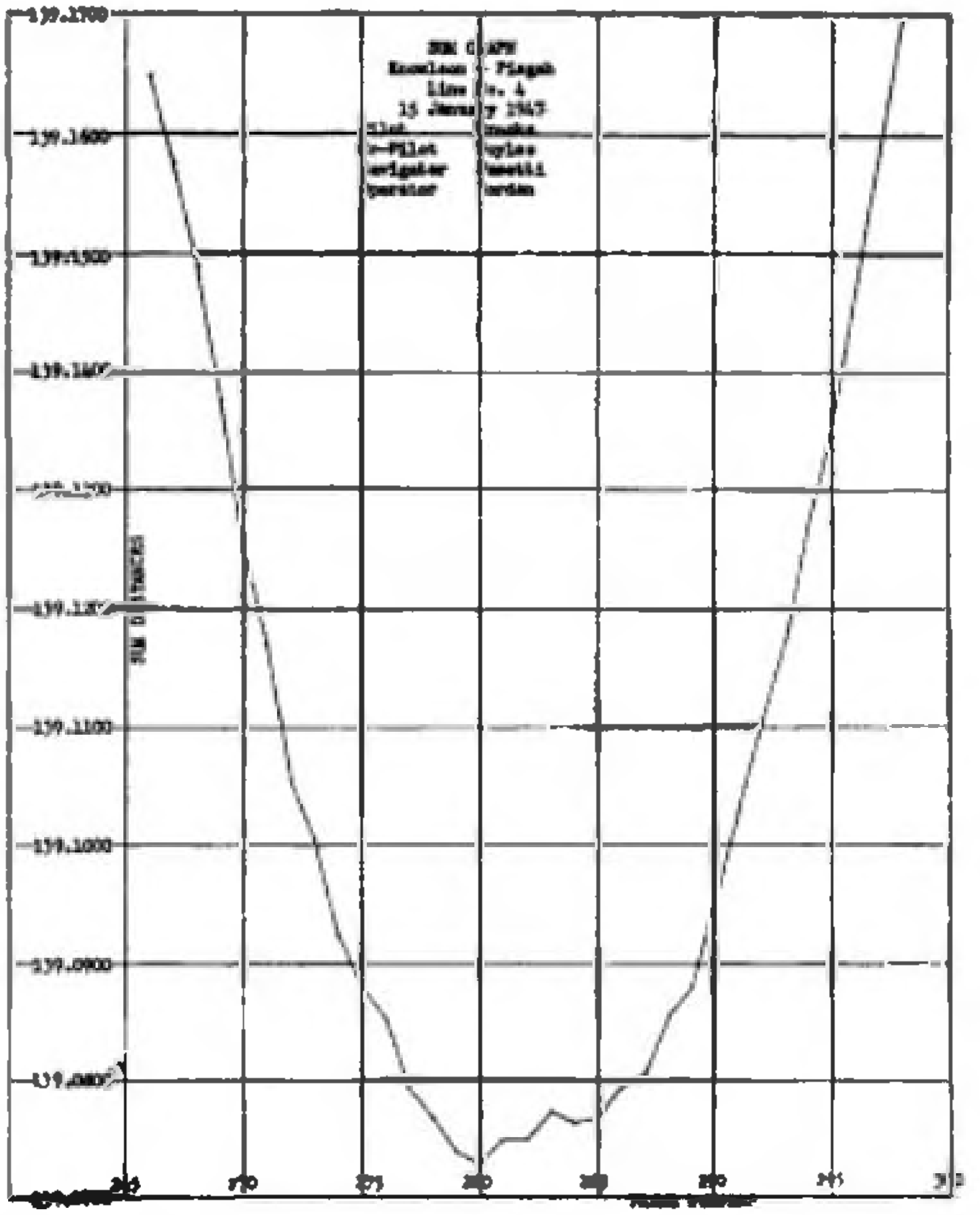

FIG. 4. In Shoran surveying the distances from the plane to each of two ground stations are added as the plane crosses the line adjoining them.

At the beginning of the Shoran development, we used the so-called Anderson value for the constant c, the velocity of radiant energy in vacuo. This was 299,776 kilometers per second. This value had been confirmed by Birge[1] in 1941. However, the refinements in the equipment and in the techniques of use brought to light an error which was proportional to distance. This could only be rationalized by the assumption that the Anderson value was incorrect.

As a result, Aslakson submitted two separate articles to the British publication *Nature* setting forth evidence that the Anderson value was too

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[1] Birge, Raymond T., The general physical constants with details on velocity of light only, *Rep. on Progr. in Phys.* 8, 1941.

low by about sixty parts per million. The first of these articles appeared in Volume 64 in 1949 and the second in Volume 168 in 1951. The final value adopted by Aslakson from all Shoran measurements of known distances was 299,793.1 kilometers per second. This was the same as the value determined by Bergstrand[2] using optical means and published by him in 1950. In 1951 Essen[3] published the results of his work with cavity resonators and proposed a value of 299,792.8 kilometers per second. This is only one part per million less than the Bergstrand and Aslakson value.

After correcting all previously accumulated Shoran data from the Florida complex with the new value of *c*, an incompatibility of 35 feet at an azimuth of 39 degrees remained in the location of station (4) at Key West. See figure 3. As a result, a resurvey was recommended and was made by the U.S. Coast and Geodetic Survey. This confirmed an error of 36 feet at an azimuth of 37 degrees and was ample evidence, if more was needed, that Shoran could provide first-order survey accuracy.

By 1950 the so-called Caribbean Area Project of the 7th Geodetic Control Squadron was in full swing. For the first time the true locations of many of the West Indies and Caribbean Islands with respect to the mainland of the United States were being determined. The vector deflection of the vertical could now be established at those islands. Many of the islands were found to be over a mile distant from the positions repeatedly determined by astronomical survey. A few of the positions were over two miles in error.

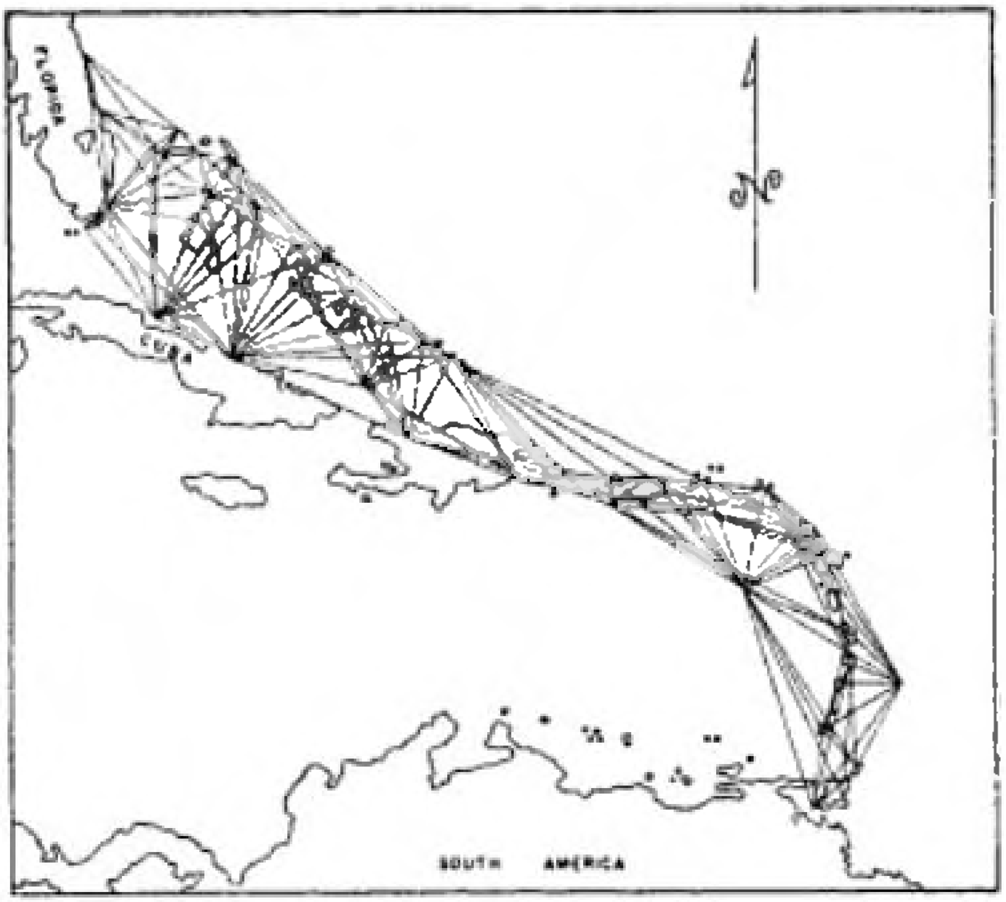

FIG. 5. Shoran survey lines have established the position of islands in the Bahamas and the Caribbean archipelago.

That particular project was completed several years ago. The trilateration construction for this area is strong and the results may be relied upon for first-order survey accuracy. The structure is shown in figure 5.

This work is continuing, not only in the Western Hemisphere, but across oceans and now has linked other continents with ours. Some of the over-water hops have been as long as 885 kilometers. Shoran surveys are daily adding to our knowledge of dimensions and locations on the earth's surface and of the shape of the earth spheroid.

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[2] Bergstrand, Erik, A determination of the velocity of light, *Arkiv för Fysik* 2 (15), 1950.

[3] Essen, L., Proposed new value for velocity of light, *Nature* 167: 258, 1951.