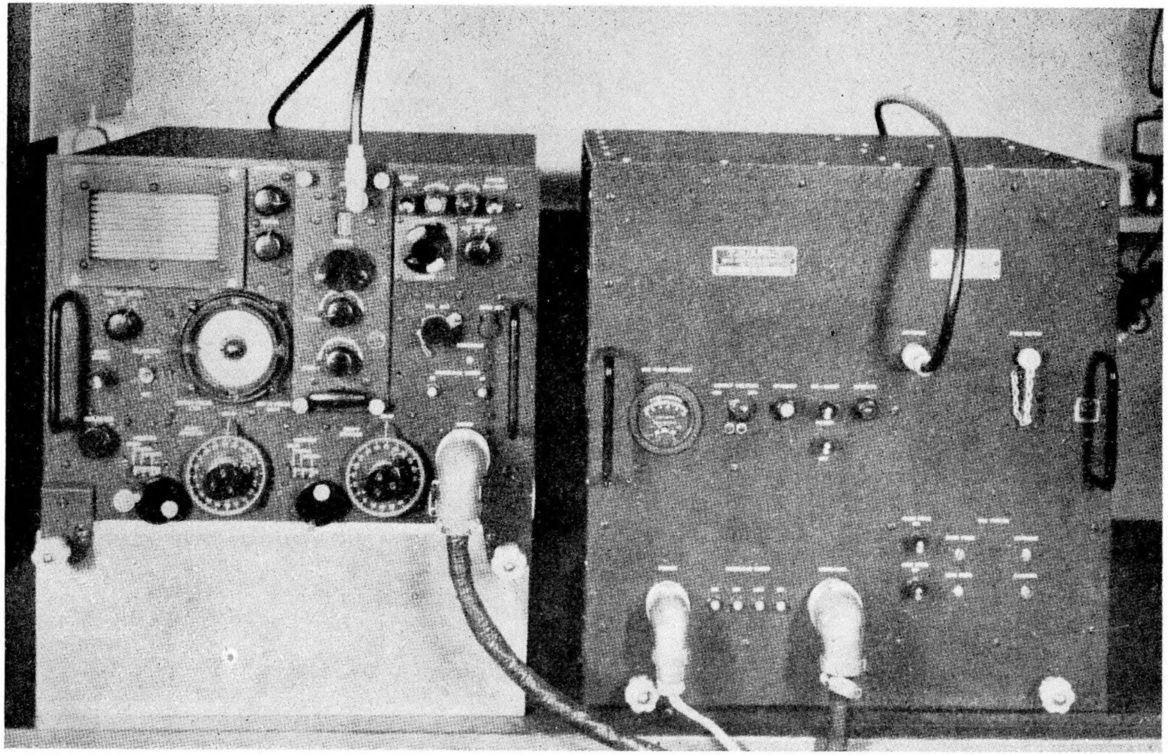

FIG. 1

Indicator and transmitter for ship installation *(Indicator-left ; transmitter-right)*.

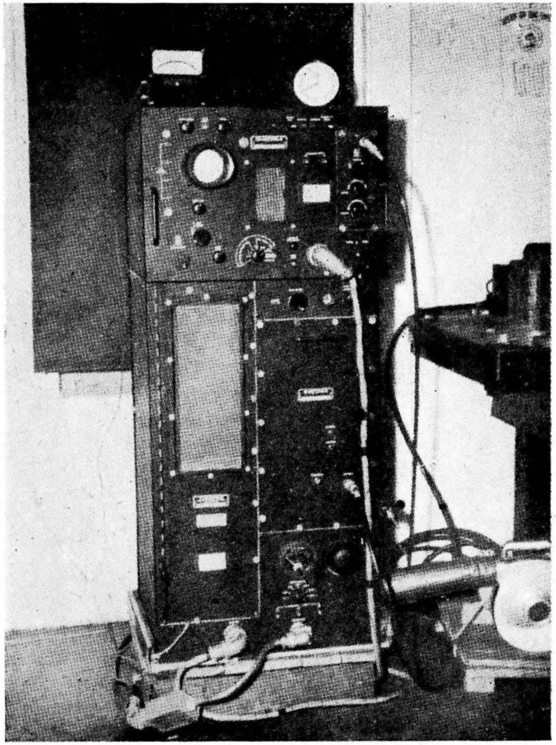

FIG. 2

Monitor and Transmitter
at ground station at Cape Elisabeth, Me.

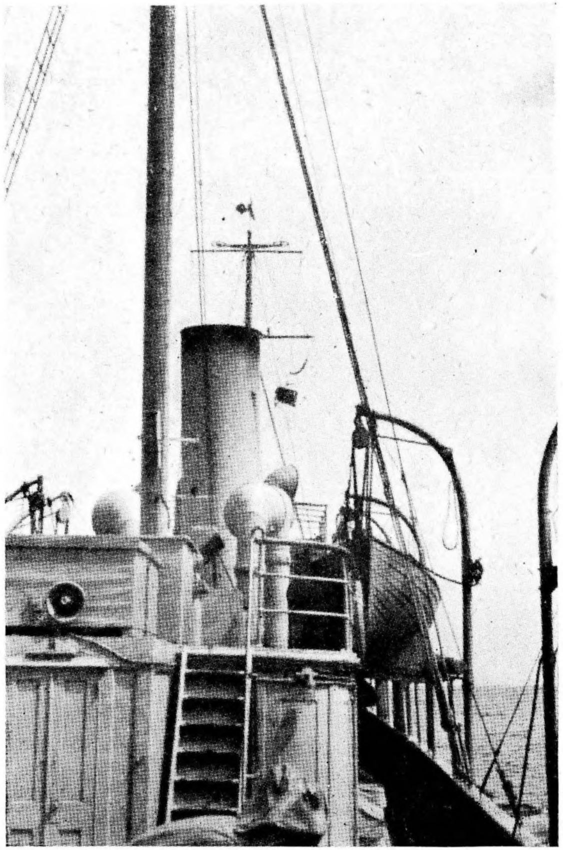

FIG. 7

Shoran antenna array on "Lydonia".

ELECTRONICS IN HYDROGRAPHIC SURVEY

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U. S. Coast and Geodetic Survey.

This paper discusses the development and present status of electronic methods in the Coast and Geodetic Survey insofar as they pertain to position fixing in hydrographic surveying. Part I deals with Shoran and is based on experimental work conducted by the ship *Explorer* in Alaska during 1945, and on subsequent experiences in actual survey work in Alaska by the ships *Explorer*, *Pioneer*, and *Surveyor*, and by the ship *Lydonia* on the Atlantic coast. Part II deals with the Electronic Position Indicator, designed in the Bureau to extend accurate position fixing beyond the limits of Shoran, and is based on laboratory tests in the Washington Office, and on actual field application by the ship *Hydrographer* in the Gulf of Mexico during 1947.

PART I. SHORAN

The *fixing* of the position of a ship engaged in offshore hydrographic surveys has been a problem for many years. Until the invention of Radio Acoustic Ranging (R.A.R.), the only method available was Precise Dead Reckoning, which left very much to be desired in the way of accuracy. Radio Acoustic Ranging became the standard method for offshore control in the Coast and Geodetic Survey in the early twenties, and continued to be the control system until the beginning of World War II. This method was hailed as a great achievement and an enormous area was surveyed under this system. There were, however, several disadvantages inherent in R.A.R., none of which were likely to be completely overcome. Among these were :

(1) There was a paucity of information on the actual path of the sound wave through the water. While experimental data proved the theory of propagation in general, many peculiarities were encountered, such as the wide divergence of successive distance measurements in deep water, which could not be accounted for.

(2) Shore stations were usually difficult to set up, and more difficult to maintain ; but even as these were replaced by automatic sono-radio buoys, there was still a great amount of servicing and difficulty experienced with the "ground" control, and consequent much loss of time to the surveying ship.

(3) An explosive was required to produce the sound signals, which in itself constituted a considerable element of danger, not only to the individual handling it, but to the entire vessel.

World War II brought forth several new navigational systems which changed the picture entirely. One of these was Shoran—short for SHOrt RAnge Navigation.

WHAT SHORAN IS

Shoran is the name given to a special type of Radar system which gives extremely accurate determinations of positions. The equipment was designed and built by the Radio Corporation of America for the particular purpose of controlling the position of an aircraft during a bombing mission. The fact that the equipment was designed to be used in and transported by aircraft is reflected in the general design of all components, including the power sources.

The very great accuracy of the Shoran fix has made it an essential control method for hydrographic surveys. Shoran has been in use by the Coast and Geodetic Survey since 1945, and it has become the standard control system for surveys extending as far as 50 to 100 miles offshore.

The Shoran method is based on the fact that radio waves travel through the atmosphere at a very near constant velocity of 186,218 statute miles per second. Half of this velocity is 93,109 — a value of considerable significance in the operation of Shoran.

Success of the method is due to the accomplishment of electronic engineers in devising means for accurate measurement of the remarkably small time intervals involved in the travel of radio waves to a target and back. In the familiar Radar, dependence is placed upon the reflection of radio waves from natural objects encountered. Shoran strengthens and specializes this principle by use of responding radio stations set up at known points, which return intensified signals from the specific positions of the responding stations.

A Shoran system consists of one ship equipment (Radio Set AN/APN-3) and two ground equipments (Radio Set AN/CPN-2), each with all accessories such as antenna systems, transmission lines, and power sources. The ship set (fig. 1) consists essentially of a transmitter which, keyed by the indicator, sends out signals to the ground stations ; and an indicator which measures the elapsed time between a transmitted pulse and the return signal from the ground station. A ground station (fig. 2) consists mainly of a monitor which receives the ship's signals and, after a short delay, triggers a transmitter which returns the signals to the ship. The loop, or round-trip, time intervals measured in the ship's indicator are converted directly into one-way distances (in statute miles). If the positions of the two ground stations are accurately known, then the position of the ship can be determined from the intersection of the two circular arcs, the centers of which are the respective ground stations, and the radii are the measured distances.

The principle of determining the position of a vessel from Shoran-measured distances is shown in figure 3.

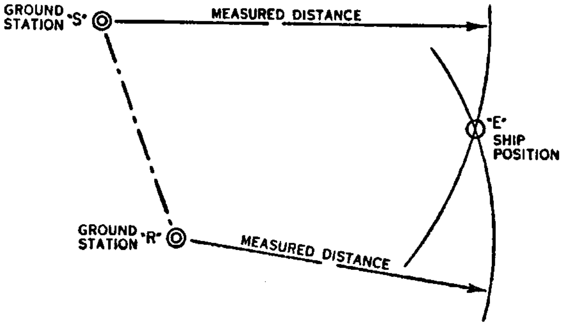


FIG. 3
Position by Shoran distances.

A single pair of distances will not necessarily give the true position of the ship unless other data are known, particularly which distance corresponds to which ground station. Assuming that the correct relationships of the distances are not known, then two or three pairs of distances are required to fix the position of the ship. From the additional fixes and a knowledge of the course and distance run, the correct pair of distances can be selected, because only one set of fixes will agree with these conditions. (See fig. 4). It can be seen from the figure that if the course steered is in a southeasterly direction, only points A, B, and C will plot on this course, therefore a, b, and c are obviously not the true positions.

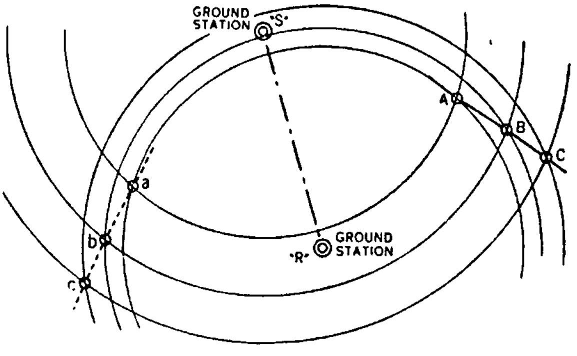


FIG. 4
Position ambiguity resolved.

The Shoran system measures the distances from the ship to the two ground stations by measuring the time required for the radio signals to travel from the ship to the ground stations and back. When the elapsed time is accurately known, the distance is easily computed from the relationship :

$$D = \frac{Vt}{2}, \text{ where}$$

D = the distance in statute miles,
V = the velocity of the radio wave in statute miles,
t = the time required for the round-trip in seconds, and
2 = constant to reduce to one-way distance.

The velocity of the electromagnetic waves through the atmosphere at a standard barometric pressure of 29.92 inches of mercury has been assumed to be 186,218 statute miles per second — a value which is probably accurate within 10 miles of the true value (error not greater than one part in 18,600). While the effects of changes in barometric pressure are calculable, they are negligible so far as hydrographic surveys are concerned ; a change of 1 inch in pressure will change the velocity about 2 miles per second, or cause an error of about 1 part in 100,000, if neglected.

SHIP EQUIPMENT.

Figure 5 shows a block diagram of the entire Shoran system. The ship equipment is the heart of the system. To break it down still further, the ship equipment

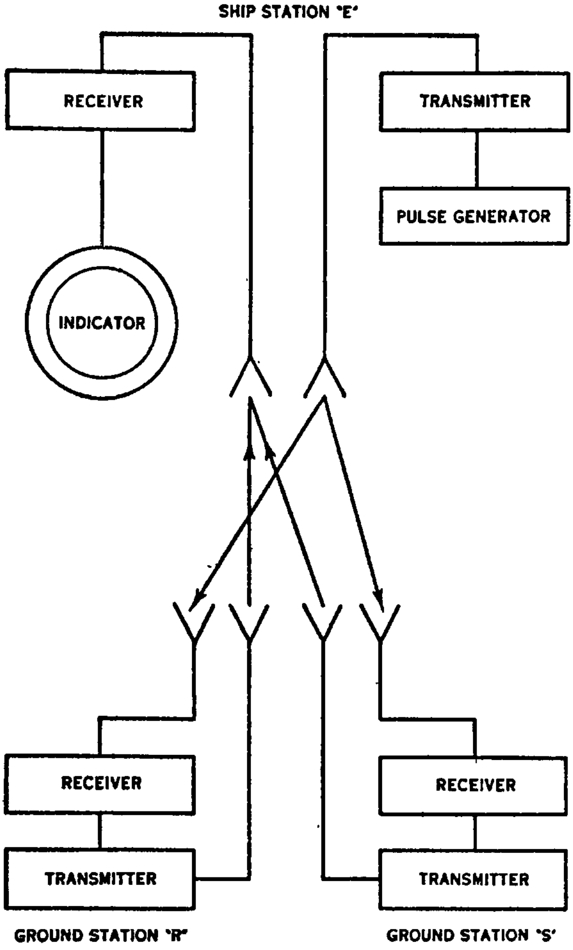


FIG. 5
Block diagram of Shoran system.

consists of a signal source (pulse generator), a transmitter, an antenna system, a receiver, and an indicator. False signals originating in the ship are radiated from the ship's antenna and received at the ground station. There the pulse is sent through the receiver to the input of the transmitter, then retransmitted back to the ship. At the ship, the pulse is passed through the receiver, and then routed to the indicating circuits in which the time lag, or loss, with respect to the original outgoing signal is measured. This lag — or round-trip time — is converted directly into statute miles (tenths, hundredths, and thousandths) by the method of calibration.

THE SIGNAL SOURCE.

Since two simultaneously measured distances are required for a fix, it is necessary to be able to send pulses to each of the two ground stations without mutual interference and then show the returned signals in such a way as to separate them and indicate the respective distances correctly. This is accomplished by transmitting on two frequencies, a separate one for each ground station, so that each station receives the pulse alternately, each on its own frequency. This alternation between ground stations occurs at a rate of about 10 times per second. The ground stations retransmit to the ship on a third frequency. The équipment thus provides continuous simultaneous indications (as far as the eye can detect) of the distances between the ship and the two ground stations.

THE TRANSMITTER.

The transmitter is of the ultra high frequency class, and is capable of transmitting over a range of some 50 megacycles, from about 210 to 260. Figure 6 shows a block diagram of this unit. (See also fig. 1). The keying pulses are received from the indicator, and are correctly shaped and amplified, and then used to "key" or modulate the radio frequency oscillator which sends corresponding bursts of radio energy to the radiating system. The oscillator is a tuned-grid, tuned-cathode, push-pull circuit in which the grid and cathode circuit tanks are resonant transmission lines. The plates are at all times at zero radio frequency volts with respect to ground. Since no d. c. voltage is applied to the oscillator except during the times of transmission, the stage does not oscillate except in very short bursts when the voltage is supplied from the modulator. To produce the high accuracy of the system, a very short, almost rectangular, pulse is required — of the order of 1/4 microsecond. With this width of pulse, the peak power per signal is between 10 and 15 kilowatts.

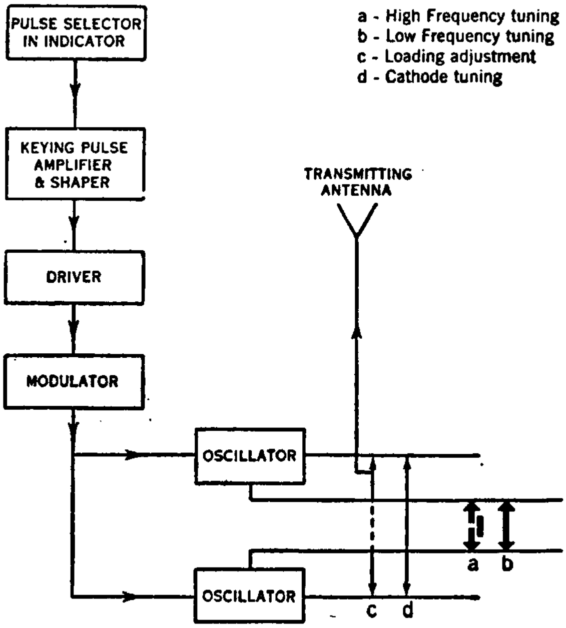


FIG. 6

Block diagram of Transmitter.

To provide for the transmission of pulses on two distinct frequencies, the oscillator tuning is accomplished by two short-circuiting bars placed across the grid transmission line. One of the bars is normally open, but can be made a short circuit by means of a vacuum relay which is closed at suitable intervals by the commutator. When the relay is open, the transmitter sends out low frequency pulses, and when it is closed it transmits high frequency pulses. As with other events, the frequency of alternation between transmitting low and high frequency pulses is about 10 times per second. With this duty cycle of 1/10 second, about 30 bursts of energy are transmitted in each pulse train.

THE ANTENNA SYSTEM.

The receiving and transmitting antennas are special dipoles, and are almost alike except for length. This difference is due to the fact that they are used on different frequency bands. The receiving antenna, which is the shorter one, is designed for optimum results in the frequency band 290-320 megacycles, while the transmitting antenna is designed for use on 210-260 megacycles. Both are extremely broad-banded and accept frequencies within their range with little loss. The dipoles are connected to their respective components by means of low-loss high frequency transmission lines. (See fig. 7).

THE RECEIVER.

An ultra high frequency superheterodyne receiver is used in both the ship and ground station equipments, all units being identical. (See fig. 8). It is a separate unit, designed for easy replacement and servicing. It will tune over a range from about 210 to 320 megacycles, and has an extremely broad-band width of some 4 megacycles obtained by the stagger-tuned intermediate frequency amplifier. This permits the proper amplification of the pulses so that they appear in their correct shape in the cathode ray tube for easy alinement. The receiver will accept signals which are 1 or 2 megacycles off frequency with little loss of signal strength. The tuning of the receiver is accomplished by means of a vernier dial turned by a crank on the front panel.

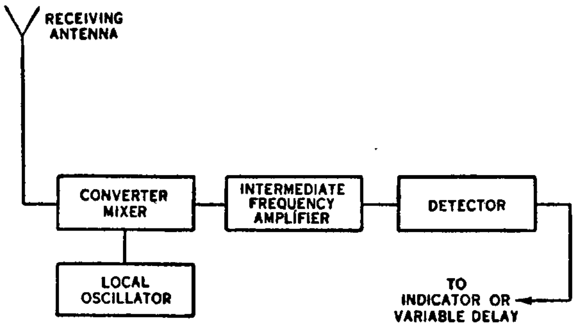


FIG. 8

Block diagram of Receiver.

Since the receiver will, in general, have to accept and amplify signal pulses from two widely separated sources, one of which may be nearby and the other at a considerable distance, it is provided with two gain controls so that the amplitudes of the pulses from each station can be brought to the correct size without the saturation of the one in order to have suitable size for the other. This requirement is met by making use of a commutator which selects the proper control according to which ground station is being pulsed. The commutator also selects the circuits which place the pulses on the indicator tube, with the result that the pulses from one ground station appear as outward radial deflections, and those from the other as inward deflections, thereby always identifying which pulse corresponds to which station. The commutator also selects the transmitting frequency of the pulses to the ground station.

THE INDICATOR.

Figure 9 shows a block diagram of the ship's indicator — the unit which measures the time of a round-trip pulse. (See also fig. 1). This is the fundamental function of Shoran.

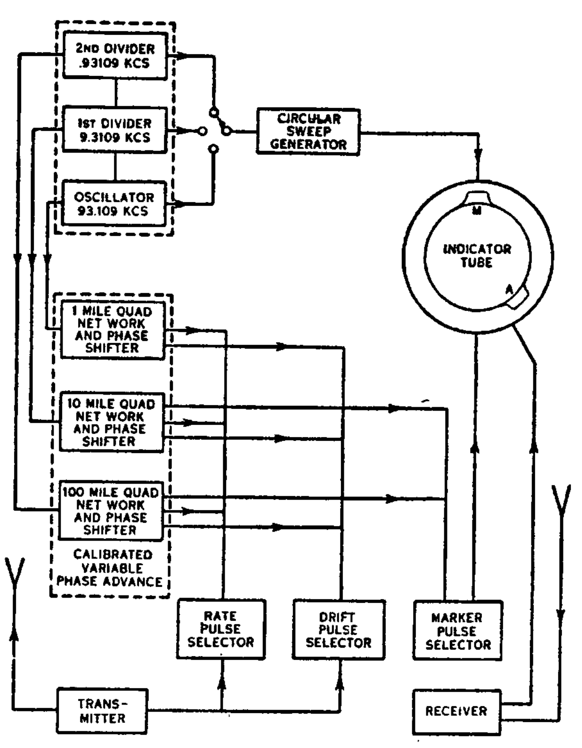


FIG. 9

Simplified block diagram of indicator.

The pulse generators produce trains of short bursts of radio energy and phasing of the standard timing signals applied to them from the oscillator. The oscillator is crystal controlled and of very great frequency stability. The standard timing frequency is 93,109 cycles per second, a cycle corresponding to a 1-mile loop distance. Other frequencies produced by the oscillator are 9310.9 and 931.09 cycles per second, corresponding to loop distances of 10 and 100 miles, respectively.

The indicator tube is a small cathode ray tube which has, in addition to the usual pairs of horizontal (H) and vertical (V) deflection plates, a central electrode for radial deflection. Two alternating voltages (generated in the oscillator) but differing by 90 degrees in phase are applied to the H and V plates with the result that a circular sweep is generated, the velocity of the sweep being very nearly linear and determined by the particular choice of scale setting. This serves as the time base line.

The signal pulses are applied to the radial deflection electrode, and will appear as inward or outward disturbances on the circle depending upon the polarity of the voltages applied. These disturbances very closely approximate the real shape of the pulses applied. One of the pulse generators sends its signals directly to this electrode and they appear at a fixed position on the circle. These are the "marker pulses" and are the reference points "M", or zero, of the sweep. The other pulse generator keys the transmitter. Pulses which have completed a round-trip to a ground station are sent to the deflection electrode and may appear as pulse "A". Since pulse "A" must travel a round-trip through the air to the ground station and back, it will appear at some point further around the sweep than pulse "M" which was transmitted, or rather formed, at the same instant, but had to travel over only a very short wire.

The relative positions of these two pulses can then be made to indicate the distance between the ship and the ground station. A certain fraction of this measured distance is due to the delays inherent in the various circuits of the equipment, both in the ship and at the ground station ; but the greater portion is due to the time required by the pulse to make the loop trip. It is, however, possible to calculate or measure the equipment lags. If then, this delay error can be automatically subtracted from the vernier reading for each measured distance, the resulting values would require no further adjustment. This is accomplished by the simple process of setting the marker pulse sufficiently far ahead so that an "offscale" reading equivalent to the total delay, in both ship and ground equipment, is obtained when the equipment is "zeroed". The delay in the ship equipment is generally very small. The ground station delay is 0.180 statute mile. The off-scale reading of pulse "M" is therefore standardized at 99.820, with further adjustment for the ship equipment delay by the zero adjustment.

Instead of using directly the pulses "M" and "A" on the indicator tube as the measure of the distance between the ship and the ground station, a more accurate method is used. Stated simply, it consists of producing the transmitted pulses sufficiently earlier than the corresponding marker pulses "M" so that the returning pulses "A" retransmitted from the ground station arrive just in time to coincide with their respective marker pulses (as indicated on the cathode ray tube). This phase advancing is accomplished in the circuit labeled "Calibrated Variable Phase Advance". During navigation, the operator adjusts the phase advancing device so that pulse "A" just coincides with pulse "M". He then reads from the scale and vernier, which are mechanically connected to the phase shifter, the distance between the ship and the ground station. As the ship moves away from the ground station, the advance will become greater in order to permit the coincidence of "A" and "M". The pulse repetition rate is 931.09 per second. With this rate a phase advance of 360 degrees will correspond to a distance of 100 miles (round-trip of 200 miles). A 360-degree advance, then, is the same as a zero-degree advance, and the system begins repeating. Thus a distance measured as 25 miles could be 125 or even 225 miles, as far as the indicator could tell. Therefore it is necessary to know the ship's position within 100 miles or so to be able to fix its position with accuracy.

The trace shown on the fluorescent screen of the indicator tube is circular with a reference pip at the top, and the two distance pips showing somewhere else. In making the distance measurements, the two distance pips are alined with the marker pip. When operating on the 1-mile scale, this sweep makes 93,109 "revolutions" per second, corresponding exactly to 1 statute mile per revolution. The sweep length, with a diameter of about 2 inches, is approximately 6 inches. It is a simple matter of using the verniers attached to the calibrated phase advance circuits to divide this 6-inch sweep into hundredths or even thousandths of a mile.

GROUND STATION EQUIPMENT.

The ground station equipment was designed so that it could take care of the "challenges" from several ships (up to 20) at the same time. As a consequence, this equipment is somewhat larger than the ship equipment. The monitor is the central control unit, and the complete functioning of the ground equipment can be checked in this unit. The block diagram in fig. 10, although somewhat generalized, shows how each circuit serves its purpose in the equipment. (See also fig. 2). The oscillator is crystal controlled and is the master-timing frequency generator for the entire system—both ground and ship equipment. The crystals at both ground stations are always used so that there is a continuous mutual check on operations. The crystal is of very great stability, and, for this precision, requires that it be housed in a thermally controlled oven. Its frequency, like that in the ship equipment, is 93,109 cycles per second, a cycle corresponding to 1-mile loop time. Frequencies corresponding to 1, 10 and 100 miles are also derived from this crystal.

THE MONITOR.

One of the main functions of the monitor is to send timing pulses to the ship. While the ship station equipment depends upon an oscillator of great stability and accuracy for correct distance measurements, the crystal is subject to a small frequency drift due to temperature changes during the operating period. Therefore, provision has been made at the ground station to generate and transmit trains of pulses with an accurately fixed repetition rate, which the ship operator may receive and use as a standard frequency in adjusting the ship station oscillator. This is accomplished by setting the function switch to "operate-monitor". On this setting, certain signals, at a pulse radio frequency of 9310.9, are sent to trigger the transmitter. These pulses appear in the indicator in the ship as stationary or slowly traveling pulses. If the pulses are stationary, the ship equipment is in adjustment ; if they are moving, the small adjustment for calibration synchronisation (cal sync) to stop them requires but a few seconds. The regular challenge pulses from the ship are being returned during the time these timing pulses are transmitted. Errors of from 10 to 15 cycles in the ship's crystal can be taken care of without difficulty. In the "operate" position only the signals from the ship are retransmitted ; in this position the signals from the ship are displayed in the monitor's indicator tube.

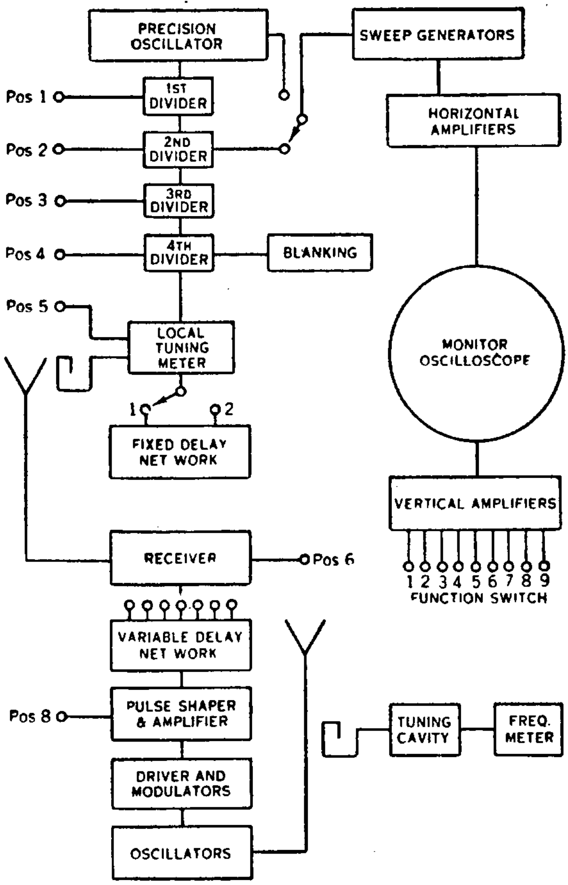


FIG. 10

Simplified block diagram of ground station equipment.

The "operate monitor position" is also used to check the zero adjustment (zero adj) of the ground equipment. But in either this position or "operate", the following signal path is set up. Pulses originating at the ship station are received on the antenna and amplified and detected in the receiver. The selectivity of the receiver is such that it will not accept signals which are intended for another ground station. The output pulses of the receiver go to a "Variable Delay Network" which is an artificial transmission line consisting of many sections made up of capacitors and inductors. These pulse signals, in passing through this chain of circuit sections, are delayed by a fixed amount of time in each section, and pulses delayed by the accumulated amount due to any number of sections can be picked off at will by connecting the output terminal to the proper section. The delay-per-section is approximately 0.05 microsecond. The purpose of this delay network is to enable the ground station operator to standardize to a predetermined value the over-all delay in his equipment. This delay must be standardized, for any uncontrolled variation from a fixed known value will cause a variation in the total round-trip which the signal pulse is supposed to measure.

At the same time that the ship equipment is being checked for accurate synchronization with the ground station, the ground station operator is making his "zero adj", or checking his station delay. These operations are accomplished by generating two pulses in the radio frequency generator. One pulse is picked up by the receiver and passes through the same path that the retransmitted signal follows ; that is, through the receiver and the variable delay network, leaving the station via the transmitter and antenna. The other is a demodulated oscillator grid pulse envelop which passes through a "Fixed Delay Network".

This fixed delay network is the standard of time used in the station delay measurement. When the transmission time through the retransmission circuit consisting of the receiver, the variable delay network, the transmitter, and all associated components is made equal to the retransmission time through the fixed delay network, the station delay has been standardized at 0.180 statute mile. The delay takes into consideration all of the delays occasioned in the transmission lines to the antenna system.

Thus, there are two pulses starting out at the same time. One travels through the fixed delay network which introduced the standard delay into its transmission ; the other travels through the ground station receiver, the variable delay network, the transmitter, and all external and intervening components experiencing a delay called the "Circuit Delay". Both finally show on the screen of the indicator tube, where, if the leading edges of the two pulses are in coincidence, the "zero adj" has been properly made. If the leading edges are not in coincidence, then an adjustment to the variable delay network is made to cause the desired coincidence.

The delay at the ground station has been standardized at 0.180 statute mile. In making the proper setting for zero at the ship equipment, the delays there must be considered, and they are in addition to this standard delay. Actually circuit delay in the ship equipment is relatively small as compared to the 0.180 statute mile. It is generally either computed or measured by laboratory methods.

THE TRANSMITTER.

The transmitter at the ground station is similar to, but somewhat larger than, the corresponding unit in the ship. The main differences are : the ground transmitter needs to transmit on but one frequency (290-320 megacycles per second), and must be capable of "answering" to the pulses from as many as 20 ships. The transmitted pulses are as nearly identical as possible with those from the ship, but the peak power per pulse is somewhat in excess of 15 kilowatts.

THE ANTENNA SYSTEM.

The antenna system consists of two dipoles identical with those of the ship, but interchanged in use : the long one has become the receiving, and the short one the transmitting. These dipoles are mounted on a special antenna base and reflector system, and elevated on a 50-foot telescoping plymold mast. There is considerable advantage to be gained from the use of the reflector system, as the signals are "beamed" with a gain ratio of close to 5 to 1. The system has been used successfully for distances up to 40 or 50 miles without the reflectors, when two ships were operating in widely separated sectors ; but the reflectors are quite necessary for distances greater than 40 to 50 and up to 100 miles. (See fig. 11).

OTHER GROUND EQUIPMENT.

In addition to the components just described, there are the necessary power plants to furnish the electrical power to the ground equipment. The power requirement is 1.500 watts of 400- to 2600-cycle 115-volt a. c. and 400 watts of 27-volt d. c., and is furnished by a gasoline driven generator set. There are usually two such power plants at each ground station to provide against the failure of a single plant.

ERRORS IN THE SYSTEM.

Two types of errors are inherent in the Shoran-system — systematic and random.

SYSTEMATIC ERRORS.

The systematic errors are those which can be determined precisely. They include errors resulting from the difference between the Shoran and the map distance, from the assumed velocity of the radio wave, and from the changes in barometer pressure.

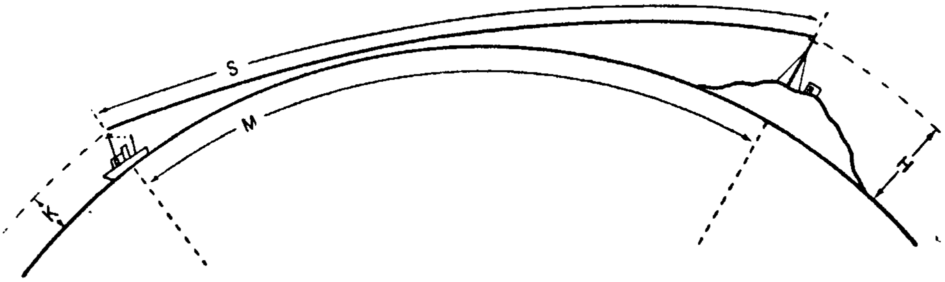


FIG. 12

Path of electromagnetic wave between ship and ground station.

M = Map distance in Statute Miles.
S = Shoran distance in Statute Miles.
K = Height of ship antenna in feet.
H = Elevation of ground station antenna in feet.

Figure 12 illustrates the first of these errors. Because of atmospheric refraction and the elevation of the ground and ship antennas, the Shoran path is neither a straight line nor a great circle as it would be measured on the earth. It closely approximates, however, a circular arc with a radius of about 15.000 statute miles (or more closely as 3.91 times the radius of the earth). The elevation of the antennas above sea level is the dominating factor. The usually low elevations of antenna systems, and the relatively short distances which usually obtain in hydrographic work, make this error negligible.

RANDOM ERRORS

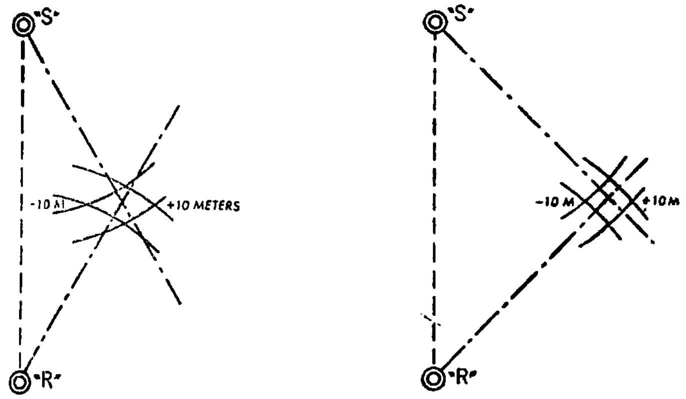
The random errors are of a more serious nature and, while they cannot be eliminated, should, at least, be noted. The probable values of these errors in statute miles are as follows :

(1)	Setting and reading the mileage verniers.............	± 0.002
(2)	Nonlinearity of calibrated phase shift network........	± 0.005
(3)	Zero adjustment in ground station..................	± 0.002
(4)	Nonalinement due to insufficient gain at long distances .	— 0.050

It is not probable that all the errors will be accumulative at the same time. Nos. (1) to (3) are of variable value and sign, and affect distance measurements within the line-of-sight distances from the ground stations. But all four affect the results when greater than line-of-sight distances are measured. This is due to the fact that the full pulse is no longer presented in the indicator-tube, and only the top portion of the received pulses are matched with the marker pulses. Errors considerably in excess of 0.050 statute mile have been noted in lines as long as 100 miles. (See table 1). It is to be noted that pulses undergo a reduction in size and shape at the larger distances, and it must be assumed that the error in these longer lines will be dominated by number (4), thus making the measured lines too long.

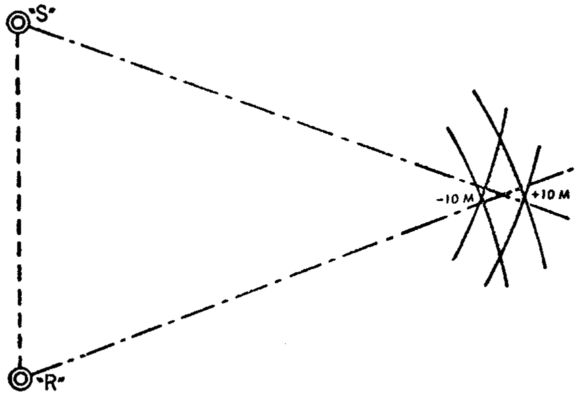
POSITION UNCERTAINTY.

The effects of the random errors in Shoran (the systematic errors being either neglected or applied) are such as to give an uncertainty of position corresponding to the magnitude of the errors and the angle at which the distance arcs intersect. This is illustrated in figure 13, which explains the problem. It will be noted that the smallest figure of uncertainty obtain when the arcs intersect at 90 degrees. and becomes elongated either parallel to or normal to the base line depending upon wheter the intersection angle approaches zero or 180 degrees. It has been determined by long experience that this area of uncertainty is within reason when the angles of intersection are not smaller than 30 degrees nor larger than 150 degrees. If often happens that these limits have to be exceeded, and this frequently occurs in surveys which extend along both sides of the base line (and its extension), and in great distances offshore.



INTERSECTION ANGLE 120°

INTERSECTION ANGLE 90°



INTERSECTION ANGLE 40°

FIG. 13

Position uncertainty due to random errors.

THEORETICAL RANGE OF SYSTEM.

The theoretical line-of-sight distance between two elevated objects is given quite accurately by the formula

$$D = 1.32 \ (\sqrt{H} + \sqrt{h}), \text{ where}$$

D = the distance in statute miles,
H = elevation of ground station antenna in feet. and
h = elevation of ship antenna in feet.

Certain effects of refraction due to atmospheric conditions permit the increase of the constant from the value 1.32 to 1.42 as being the practical upper value. However, it is possible to receive usable pulses at much greater distances than those computed by this formula, using the larger constant. For all practical purposes, the constant can be assumed to be between 1.8 and 2.0 where distances measured are not more than 100 miles, and the station elevations do not exceed 2.000 feet. This was borne out by actual tests in Alaska. (See table 2).

FIRST EXPERIMENTAL WORK.

The first experimental work by the Coast and Geodetic Survey using Shoran for hydrographic surveying was conducted by the ship *Explorer* in the western Aleutians in the summer of 1945. Two ground stations were established ; one on Attu Island (RAN) at an antenna height of 155 feet, and the other on the eastermost of the Semichi Islands (SHOR) at an antenna height of 270 feet. (See fig. 14). With the ship's antenna at a height of 80 feet, theoretical considerations indicated that the ranges to be expected from these two stations might be 31 to 36 statute miles, respectively. The tests, however, showed the actual ranges to be 46.953 and 47.355.

Considerable work was done to determine how well the Shoran fixes compared with the standard three-point fix by sextant angles. The agreement, while neither exact nor very consistent, indicated that the error assumed for the lags in the various equipments was a little too large as originally computed. After adjustment to a more nearly correct value, better agreement was possible between the two classes of fixes. It must be remembered, however, that the nature of the three-point fix is such that the error inherent in it may vary from about 4 yards at a distance of 10 miles from the signals, and with angles of about 30 degrees, to more than 25 yards at a distance of 20 miles, and the same size of angles. Differences as great as 50 yards were found between the Shoran and three-point fixes.

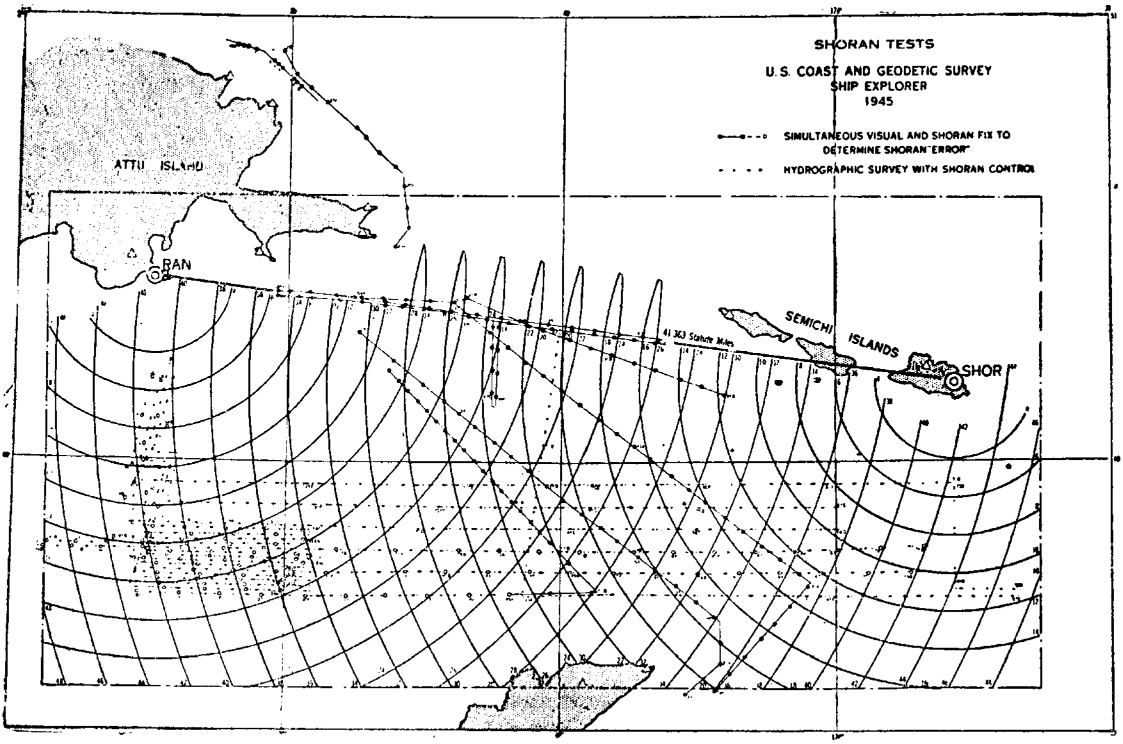


FIG. 14

First experimental Shoran work in Alaska.

A more satisfactory method of determining the combined errors in the Shoran system as used in hydrographic surveying was found by running a three-point fix controlled line along the base line between the two stations. In this case, the three-point fixes are used only to control the position of the ship — that is, to keep the ship as near the course and track as possible. The two Shoran distances were read simultaneously at frequent regular intervals. The sums should always equal the length of the base line. The difference between the mean Shoran length and the computed distance would then be the total Shoran error for both ground stations. Since sum distances were measured at very regular time intervals, it may be assumed that the differences between successive measurements of the distances to one station would be nearly constant and, if plotted against time, would generate a curve which would indicate the non-linearity of the calibrated variable phase advance networks — or what might be termed the "repeating error" of the equipment. The computed length of the base line was 41.382 statute miles (unadjusted) and the Shoran length was 41.364 statute miles. This difference was so small that it was divided equally between the two ground stations, since the actual distribution was unknown. Combined with other data, this indicated that the over-all lag for station RAN was 0.178 and for SHOR 0.192 statute miles, thus making the zero setting (zero set) 99.822 and 99.808, respectively, for the two stations. Since it is not possible to insert two different corrections at the same time for the "zero set", the value 99.808 was used, making it neccessary to ADD 0.014 to all the distances from station RAN.

Other information indicated that the exact position of the "zero set" did not remain fixed, but drifted aimlessly with time. It was, therefore, necessary to check it at least once per hour to determine the correction. The variations were assumed to be linear between successive checks. As the corrections were very small, the mean variation for a definite period, say a work day, was used in making the corrections based on the recorded hourly checks.

With the original installation of the ship's antenna, it was found that there were blanketing effects from the mast and radar equipment when they came between either dipole and a ground station. A new system was designed where the dipoles were mounted on out-riggers which could be swung horizontally through an arc of about 135 degrees, so that both antennas could be kept in the clear at all times. This proved quite satisfactory except that it required the antenna to be properly trained at all times. A newer installation has been devised in which one dipole is mounted over the other on a short mast extending above the radar dome.

FURTHER EXPERIMENTAL WORK.

Further tests of the equipment were made in Puget Sound, Wash. Each ship equipment was calibrated against each ground station so that it was possible to know the "zero set" for each combination of equipments. The ship equipment was installed in a lighthouse, and the ground equipment near another lighthouse. The experiments covered a period of about 2 months and proceeded during all kinds of weather. The results were extremely consistent, but showed marked differences in the various combinations. It was soon seen, however, that if the average "zero set" for all the combinations were used, too serious an error would not be introduced. It was further discovered that the actual effects of using different lengths of interconnecting cable was so small as to be negligible. Therefore the mean value of the various combinations of cable was used in determining the value of the "zero set" for a particular combination of ship and ground equipment. In all these tests the transmission lines at the ship equipment were standardized at 80 feet, a value which closely approximated actual installations.

The mean values of the "zero set" resulting from the calibration of each ship equipment against each ground station equipment ranged from 99.818 to 99.849.

The computed equivalent length of each section of the variable delay lines in the ground equipment, used to set the predetermined over-all delay of 0.180 statute mile, is 0.005 statute mile. This value was determined during the calibration work and found to average 0.0044 mile per section, the deviation from the mean being very small. This value-per-section may be used to correct for maladjustment of the ground equipment if such case arises. If the "zero adj" must be corrected, it is only necessary to add to all distance measurements affected 0.0044 statute mile for each section added in the clockwise direction, or subtract this amount for each section added in the counterclockwise direction. The sections of the delay line are indicated on the dial plate by numbers from 1 to 21 in a clockwise direction. The usual setting is on positions from 11 to 16.

SHORAN IN HYDROGRAPHIC SURVEYING.

The results obtained from the field tests were sufficiently conclusive to warrant the use of Shoran in hydrographic surveying. Projects specifying its use were undertaken during 1946 and 1947 in the Aleutians by the survey ships *Explorer*, *Pioneer*, and *Surveyor*, and on the Atlantic coast by the ship *Lydonia*. Several new developments were made in the Shoran technique to adapt it to special circumstances.

Aleutian Islands.

It was necessary to extend surveys to the westward of Attu Island for a distance of at least 65 miles in order to develop a shoal, with a reported depth of 25 fathoms, which was known to exist in this area. (See fig. 15). As this shoal lay almost on the rhumb line which runs from Unimak Island to Attu Island and could form a very convenient submarine landmark in ocean navigation, it was important that the development be accurately controlled. It was possible to establish a ground station on Cape Wrangell, but a single distance with no other data to assist would not control the survey too well. The reported depth of 25 fathoms furnished the possibility of using the shoal itself as part of the control. Accordingly, a ground equipment was also installed in the ship *Surveyor*, using the same antenna system as was installed for the ship equipment but interchanging the transmission lines to the dipoles.

To make sure of distances in excess of 25 miles, it was necessary to have the station on Cape Wrangell at an elevation of at least 1.000 feet. All the equipment, material, and supplies including a large quantity of gasoline for the power units and cooking stoves, had to be back-packed to the station. (See fig. 16). To complete the installation of this station required about 250 man-days. The antenna system was installed on a low wartime beacon tower at a computed elevation of 1.790 feet. The station was named DAR. A second station (CHICO) was installed at an elevation of 252 feet on the north coast of Attu Island.

Upon the completion of these two stations, intensive use was made of them by both ships in surveying the area to the nortward and northwestward of the island. This project was completed before weather had settled sufficiently to station a ship on the 25-fathom shoal to the westward. A reconnaissance cruise made by the *Surveyor* had located the shoal somewhat further to the westward than originally assumed. The position of the shoal was provisionally determined by Shoran distance from DAR, and courses run. A large mooring buoy was planted on the shoal to serve as the reference point for the ship *Surveyor* (called SAM) when at anchor and acting as a ground station. The buoy was located by a very fortunate combination of Shoran distances measured between the *Surveyor*, at the buoy, and ground stations DAR and CHICO, and the ship *Explorer* which was then some 40 miles northwestward of DAR. The accuracy of the determination of this position was quite good ; the east-west error was probably not greater than 100 feet and the north-south error not greater than 200 feet. The possibility of so large an error was due to the fact that the buoy was not fixed in position, but drifted about over a circle of indeterminate radius.

The survey was completed in less than 150 hours, during which time, 2.053 miles of sounding lines were run and an area of 5.300 square miles covered.

The control was carried out to a maximum Shoran distance of 114 miles. The control was excellent over 85 percent of the area ; single Shoran distances combined with dead reckoning controlled about 10 percent ; and dead reckoning the balance at the extreme western limits. The area near the base line (and its extension), where Shoran fixes are considered indeterminate, offered little difficulty, for all lines were run nearly normal to the base line, and excellent control obtained on all lines except within 2 or 3 miles of the base line. The adjustment of these 4- to 5-milelong sections was very simply made by appropriate spacing of fixes according to time. The swinging at anchor of the station ship SAM required that continual adjustment be made to distances from that station to reduce them to the reference buoy. A graphical method was usually employed :

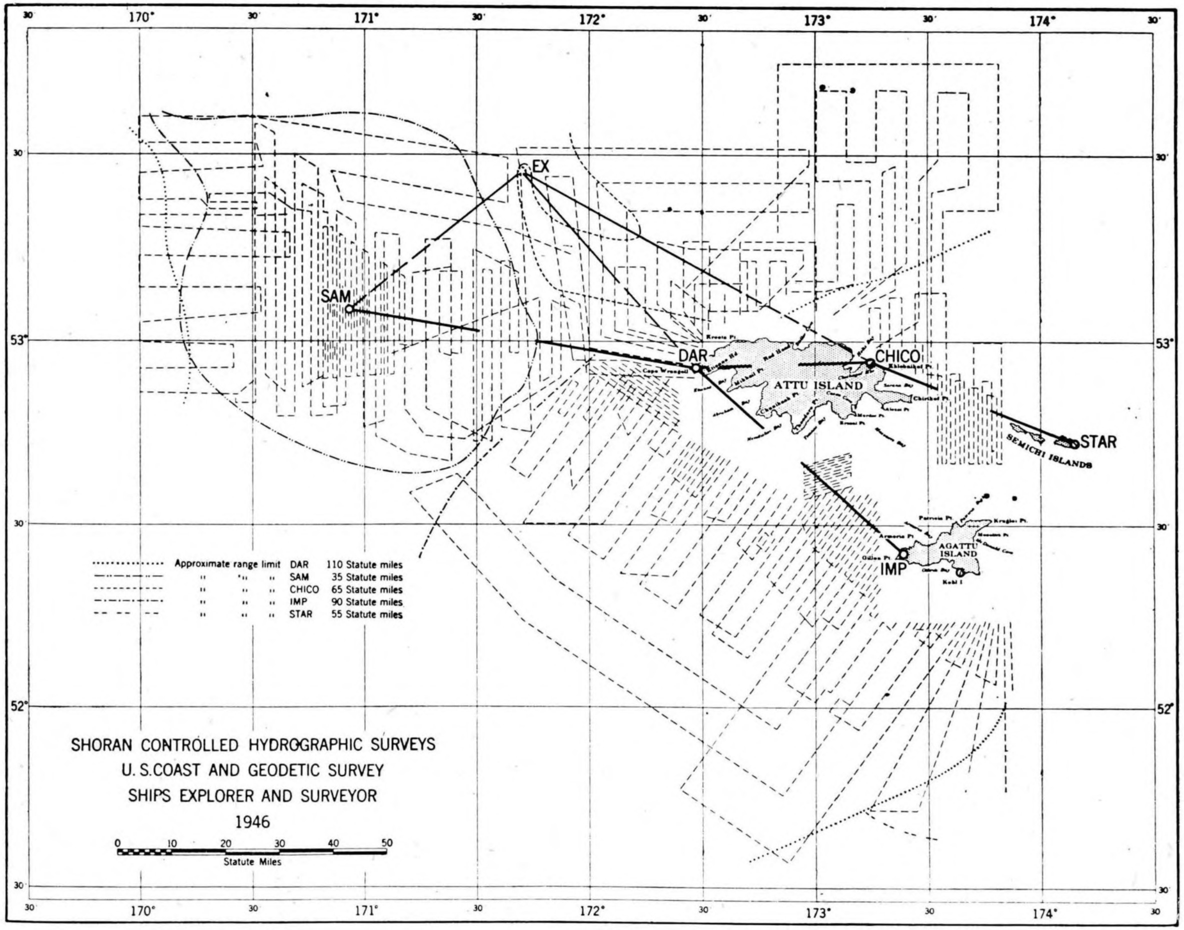


FIG. 15

Shoran hydrographic surveys in the Aleutians.

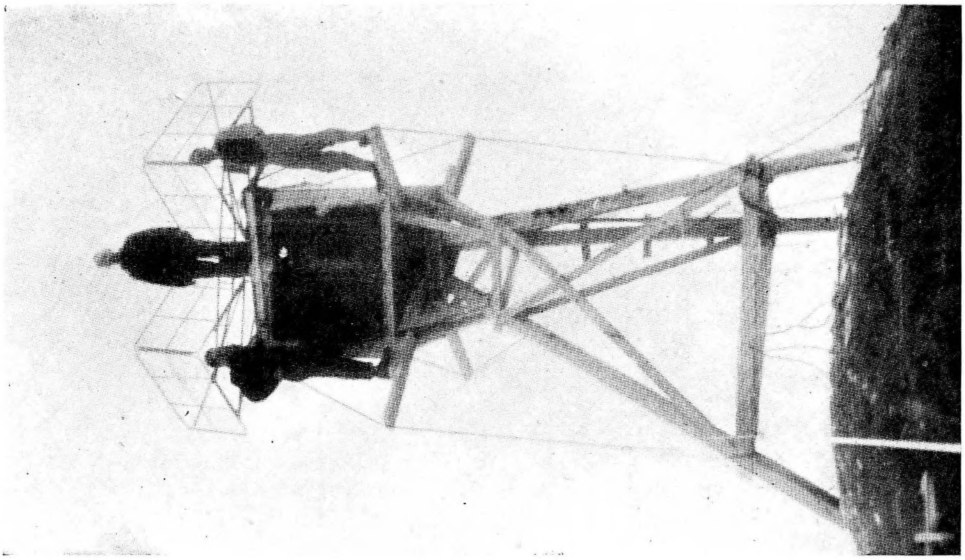


FIG. 11

Antenna on old beacon at Cape Wrangell, Alaska.

FIG. 16

Hauling transmitter to station DAR on Cape Wrangell, Antenna elevation - 1,790 feet.

The intensive development of the shoal was made by launch. A least depth of about 18 fathoms was found. Control of the launch survey was by vertical angle or depression angle and bearings by gyro. Exact correlation was possible after the completion of the survey.

Other ground stations were established for surveying in the area. Surveys were carried out to the limit of Shoran control, and to depths nowhere less than 2.000 fathoms to the northward, and to depths greater than 4.000 fathoms to the southwestward. An area of some 20.000 square miles was surveyed.

In the 1947 work in the Aleutians, Shoran fixes were used to locate buoys, which in turn were used to control the sounding lines. Launches were later used as either survey vessel or station ship, and were of considerable value in the survey of some of the reefs in the area. A record day's work was done by the ship *Pioneer* when 464 miles of sounding lines were run in a 24-hour period.

Atlantic Coast.

Concurrent with the Alaska work, the ship *Lydonia* was using Shoran along the coast of Maine. Somewhat different conditions prevailed here than in Alaska. The coast is relatively low, and it was difficult to obtain any great elevation near the beach. Therefore, it was not expected that distances much in excess of 35 miles could be obtained. Two ground stations were established, one at Cape Elizabeth (LIZ) at a total height of 119 feet ; and the other on Mt. Agamenticus (MEN) at a total elevation of 700 feet. Shoran fixes were obtained as far offshore as 50 miles. In all this area all arc intersections were greater than 30 degrees and smaller than 150 degrees, which gave very strong position determinations in all cases.

Much time was spent in making very careful checks of the operation of the equipment and in obtaining data for future investigation, all obtained during the course of routine operations. The equipment performed very well with almost a negligible amount of time lost on equipment difficulties. It was found necessary to make adjustments to the control crystal at one of the ground stations (MEN) at the beginning of the season. This was accomplished by the use of a harmonic generator and signals from Central Radio Propagation Laboratory's station WWV which indicated that the crystal at station LIZ was correct, but that at MEN was off frequency. The crystal at MEN was adjusted by the simple expedient of placing both ground stations in the "operate-monitor" function, adjusting the ship equipment for the timing signals from LIZ, then adjusting the crystal circuit at MEN until both stations' signals were stationary in the ship's indicator. Operations of the adjustment were controlled from the ship, and were facilitated by the use of radio telephone communication.

Additional hydrographic work, using Shoran control, was later done in this area by the *Lydonia* and along the South Carolina coast. The ground installations were, with two exceptions, at relatively low elevations, ranging between 100 and 154 feet. The relative maximum average distances obtainable from these stations compared favorably with those from stations established at considerable elevations, and indicate that a conservative computation of the range is approximately the same as that observed in the original field tests in Alaska.

TABLE I. — Comparison of Shoran and triangulation measurements. (In statute miles).

Base line	*By Triangulation*	*By* Shoran	*Difference*	*Parts per million*
ALEX-STAR	32.196	32.205	0.009	280
AGAT-ALEX	10.255	10.237	0.018	1800
ALEX-BULL	94.682	94.779	0.097	1000
AGAT-BULL	90.978	91.040	0.062	680
AGAT-SILO	164.704	164.810	0.106	600
RAN-SHOR	41.382	41.414	0.032	770
SILO-VEGA	16.218	16.246	0.028	1800

TABLE 2. — Effective distances from Shoran ground stations.
(In statute miles).

Station.	*Elevation in feet.*	*C = 1.42*	*C = 2.00*	*Average maximum.*	*Maximum definite.*
SHOR .... (1945)	270	36.0	51.0	47.3 (1.85)	47.3 (1.85)
RAN .... (1945)	155	30.6	43.5	47.0 (2.18)	47.0 (2.18)
CHICO .... (1946)	252	35.2	49.6	52.0 (2.10)	72.0 (2.91)
DAR .... (1946)	1.780	72.7	103.0	80.0 (1.58)	114.0 (2.14)
IMP .... (1946)	1.000	57.2	80.8	80.0 (1.99)	94.0 (2.35)
SAM .... (1946)	65	24.1	33.9	35.0 (2.06)	48.0 (2.83)
ALEX .... (1947)	450	42.8	62.3	51.0 (1.71)	68.2 (2.29)
AGAT .... (1947)	984	55.5	77.7	71.0 (1.82)	96.9 (2.49)
BULL .... (1947)	700	50.3	71.3	60.0 (1.79)	70.6 (2.12)
SILO .... (1947)	1,050	58.7	82.7	73.0 (1.78)	97.3 (2.39)
STAR .... (1947)	300	37.3	52.5	46.0 (1.75)	51.5 (1.95)
VEGA .... (1947)	780	51.7	73.0	68.0 (1.88)	93.6 (2.59)
LAUNCH .... (1947)	12	18.0	25.2	19.0 ——	—— ——
				Mean (1.87)	Mean (2.35)

EFFECT OF PULSE SIZE.

The effects of pulse size in the measurement of distances were more observable during the past season's work in Alaska, than previously, as there were more opportunities to cross base lines of known length. In all cases, the Shoran length was too long by an appreciable amount, generally less than 0.100 mile. Of course this difference can be laid, in part at least, to the fact that the signal pulses were not of sufficient strength to give full sized pips in the indicator tube, and hence, it was not possible to aline them correctly with the marker pulses, as already mentioned. It is possible that some suggestion of the relative size of this error may be obtained from a careful study of many such measurements ; however, in the majority of cases, where long distances are involved, it does not have any very serious effect. This is shown in table 1.

PRACTICAL RANGE OF SHORAN.

In the original field tests of Shoran it was the belief that the practical range of the equipment was considerably greater than the computed range obtained from the formula

$$D = C\ (\sqrt{H} + \sqrt{h}),$$

where C = 1.42. This inference was substantiated by actual operating conditions. The data in table 2 are based on the experiences in Alaska and show that the distances expectable in Shoran may be obtained by using a value of C = 1.87.

In the table, the column marked "average maximum" represents the average of the maximum distances obtained from two-distance fixes. The column marked "maximum definite" is the maximum distance obtained with certainty from any one station. The figures in parentheses in these columns denote the values of C corresponding to the distances.

It is to be noted that the greatest distances measured are considerably larger than the "average maximum" and that under favorable conditions it might be possible to obtain distances corresponding to a value of C = 2.35.

In the area between the "average maximum" distances and the "maximum definite" distances, two-distance Shoran fixes were obtained about 50 percent of the time. During the rest of the time, control was either by a single Shoran distance and dead reckoning to adjust the line, or by dead reckoning alone. Skip areas several miles in extent were often observed during the 3 years' work-areas in which no signals could be received from a particular station but beyond which excellent signals could be received. There has been insufficient study to determine the exact nature and extent of these areas with the view of correlating them to wave length and distance, though they are supposed to be interference areas. Weather conditions often limited the range to values much shorter than the "maximum definite" values for a given station. Therefore, it should not be inferred that the value of $C = 2.35$ will always hold for all conditions of weather, locations of stations, and so on. Rather, it is useful information in laying out work on a project in that it does indicate that control can be carried far beyond the usual concept that the system is limited to but little greater than optical ranges.

PREPARING AND PLOTTING FIELD SHEETS.

Of considerable importance in Shoran surveys is the selection of the scale on which to plot the work as it progresses. The accuracy of Shoran permits close development on a scale as large as 1 : 20,000 ; at the same time, the limited area available on such a scale makes it desirable to use smaller scales wherever possible. Therefore, scales ranging from 1 : 20,000 to 1 : 200,000 are in constant use. The advantage of the smaller scales is that both control points can be plotted on the sheet (usual maximum size 42 by 72 inches) and all the distance arcs can be easily drawn.

In preparing the boat sheet, the usual practice is to construct the projection, plot the control, and draw the distance circles. Occasionally all the control data are not known, as was the case with the survey of the shoal west of Attu Island. In such cases, since the distance between the ground stations can be measured, it is only necessary to lay off to scale the positions of the two control stations on a blank sheet, placed so that the work can be accomplished without too many "dog-ears" ; the distance circles are then drawn in. In the particular case of the shoal west of Attu, the position of one ground station (DAR) only was known, but the distance DAR-SAM had been measured, and the azimuth was known approximately. DAR was then plotted on the centerline of the sheet near the right-hand edge, and SAM at the measured distance westward (also on the centerline). The distance circles were then drawn in. This permitted the survey of an area some 25 miles north and south of the centerline, and as far westward as control would allow.

The spacing of the distance circles depends somewhat on the scale of the sheet, and is indicated in table 3. In some rare cases, as where the scale does not permit the control point to be plotted, it may be necessary to plot the distance circles from several points computed on each circle. This requires a great deal of time and labor. A practical way of overcoming this is to make a sheet on a scale on which all the necessary data can be plotted. The distance circles are then drawn and the section of the sheet for the large-scale survey is reproduced on the desired scale. To simplify the identification of the circles, each series of circles, corresponding to each ground station, is drawn in a distinctive color.

Plotting the Shoran fix is accomplished with an Odessey protractor (fig. 17). This is a small device, made of transparent plastic, on which a series of concentric circles

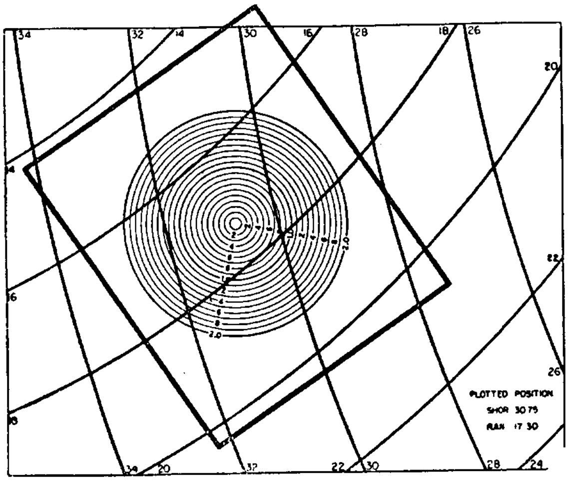


FIG. 17

Odessey protractor for plotting Shoran fixes.

are scribed (or etched), with the radius of the largest circle equal to the interval between successive distance circles on the boat sheet, and the interval between the inner circles any convenient fraction of a mile, generally 0.10 or 0.20 according to the scale used. After the circles are drawn they are approximately numbered from the center outward, usually on three or four equally spaced radii for easy identification. A small hole is drilled through the center to accommodate a needle point for plotting the positions.

To plot a position with the Odessey protractor, the bounding distance circles are first identified on the boat sheet. The protractor is then maneuvered in such a position that the scribed circles representing the increments of distance from the bounding circles are tangent to the approximate distance circles on the sheet. If necessary, distances smaller than the divisions on the protractor may be estimated. With a small amount of practice it is possible to plot a Shoran fix in less than 20 seconds.

TABLE 3. — Scales and distance circle intervals.

Scale of sheet.	*Interval between distance circles.*
1 : 20,000	1 statute mile.
1 : 40,000	2 statute miles.
1 : 80,000	5 statute miles.
1 : 160,000	10 statute miles.

RECORDING SHORAN DATA.

As in any survey, sufficient data must be recorded in the field so that the final office plotting may be accomplished without difficulty. To simplify the recording of a great deal of data a "rubber stamp" method is very adequate, in that it saves a large amount of repetitious writing. The data which are necessary to record are :

1. The value of the "zero set" for each ground station used with the particular ship equipment.
2. The values of the "zero set" as determined by the hourly "zero checks".
3. The distances as read on the two verniers at each position.

The first information to be recorded at the beginning of each day's work is the "zero set" for each equipment. A rubber stamp (No. 101) is provided for this information ; it is placed on the right-hand page of the record book with the other information relative to the survey :

No. 101.		
ZERO SET	—	—
STATION NAME		
ZERO SET	99.8___	99.8___

Prior to the beginning of the day's work, the second of the series of stamps (No. 102) is used. In this, the actual readings at the "zero check" are inserted. If it is practical at this time to make a check of the station synchronism with the ground stations, that information is also written in :

No. 102.		
ZERO CHECK	—	—
STATION NAME		
ZERO CHECK	99.8___	99.8___
CORRECTION	.0___	.0___
CAL SYNC		

The "correction" is the difference between the "zero set" value and that read at a "zero check". The proper sign must be affixed, as the "zero check" value may be either greater or smaller than the "zero set". This information should be recorded at intervals not greater than once an hour. The mean of the series for the day, or for a shorter period, may be used from which to obtain the correction ; obviously, this correction cannot be determined until after the work has been done. This correction is generally so small as to be insignificant for boat-sheet plotting.

In recording the data for a Shoran position, stamp No. 103 is used :

No. 103.		
SHORAN POSITION No.		
STATION NAME		
DISTANCE STA. MI.		
CORRECTION ZERO CHECK		
FINAL DISTANCE		

The only data originally recorded in this space are the two station names and the distances as read from the two verniers at the instant of the position. The position number identifies the position in the record with that plotted on the boat sheet. The "correction" is inserted when it has been computed, and the final distances are those used in the office plotting of the survey.

Data for the positions are usually observed at regular time intervals. It is thus possible to check each position with those previously plotted and to make immediate corrections to misread values. The Shoran observer does not change his vernier settings until the position has been plotted to the satisfaction of the navigator. The time interval between positions will vary with the scale of the survey and the detail of the development. In general, a 3-minute interval is satisfactory for large scales (1: 20,000 and 1: 40,000) ; 5- or 6-minute intervals for smaller scales (1: 60,000 and 1: 80,000) ; and 10- or 15-minute intervals for small-scale surveys (1: 80,000 to 1: 200,000). These intervals correspond roughly to ½, 1, and 2 to 3 miles, respectively (with a vessel operating at 12 knots). Fixes should be observed at each change in course greater than about 10 degrees, and especially at the ends and beginnings of lines at reverse course changes.

A simple routine has been established in obtaining the data for a Shoran fix. At approximately half a minute before the time of the next fix, the recorder calls the attention of the Shoran operator by saying "on the next", meaning that on the next buzz from the interval timer, a fix is to be recorded. The operator adjusts the verniers until the pips are approximately in alinement. About 10 seconds before the fix, the recorder say "ten seconds", meaning there are 10 seconds in which to make final alinement. At the buzz from the timer, the operator releases the vernier cranks, and reads the verniers, first the left-hand one, then the right-hand one : "Forty-one, two ninety six ; twenty-three, four seventeen" both of which the recorder repeats after him. Calling the decimal point is not necessary, since it is obvious that the last three figures form this part of the distance.

Since the ground stations are required to set the monitor on "operate-monitor" for a period of at least 5 minutes before the hour to 5 minutes after, the "zero check" is usually made at this time, for the "cal sync" can be observed then. It is not necessary for these two events to occur at the same approximate time, but it is an expedient to be sure both data are observed.

CASUALTIES TO EQUIPMENT.

There were very few interruptions in the work due to failures in any of the components of the Shoran system, either in the ship or ground equipments. The majority of casualties were in the nature of tube failures. In nearly every case, the failure was in a rectifier circuit, and usually easy to find and remedy. In several cases the failure of the high-voltage rectifiers caused burn-outs of the associated transformers. The possibility of future damage was eliminated by the installation of a fuse in the transformer primary circuit. In a smuch as all of this type of failure occurred in the ground equipment, it is believed that the rough handling occasioned in landing the equipment on the beach and transporting it to the stations caused the damage. (See fig. 18). The fact that this particular part of the circuit was inoperative did not mean that the station was out of commission. The function of receiving and retransmitting signals was not impaired. but the station could not send out timing pulses nor check its operation in any way,

Probably more serious damage, not easily repaired in the field, was to the receiver units. Several receivers were damaged by short circuits developing in an intermediate frequency transformer. This usually developed across the by-pass-to-ground capacity in the transformer, which permitted high enough currents to flow to burn out this capacity and all the filter resistors in the high-voltage side between the transformer and the connecting jack. Damaged receivers have been repaired by replacement of the burned-out transformer and resistors ; but a complete realinement of the intermediate frequency amplifier and even the radio frequency amplifier is advisable in such event before the unit is used in actual work.

The more usual type of failure was in the power units furnishing power to the ground equipments. The high-speed gasoline driven generators apparently did not stand up well under 24-hour operation, day after day. This type of generator is neccessary, however, to furnish the power, especially where shore power is not available to drive a suitable motor-generator. While there were always at least two power plants at each station, it often required the efforts of the entire station personnel to coax them into continuous running.

Another type of failure of the equipment was stoppage of the blower motors in the ground transmitters, due to wearing out of the motor brushes. After several cases of this, the condition was apparently remedied by the use of a different type of brush. Once, at least, the oscillator tubes were damaged by the failure of this blower motor.

CONCLUSION.

Many aspects of Shoran must still be studied in order to understand and use the equipment to the best advantage. These will include a field analysis, along with laboratory investigations of such matters as the various errors which enter into the measurement of each distance within the maximum average range, and those between this range and the maximum possible range ; the so-called repeating errors in the variable calibrated phase advance circuits ; the effect of signal size on the measured distances ; and so on. While some of these errors are considered insignificant as far as the control of a hydrographic survey is concerned, they are appreciable when extending triangulation over a large area.

The work of the last 3 years has furnished an exhaustive test of Shoran as a system of control for hydrographic surveys. A large area has been accurately surveyed, much of which would have been impossible by any other method. The daily proof of the accuracy of the system, the complete ease of operation, and the reliability of the equipment have made this an outstanding control system for surveys extending 40 to 50 miles from shore. It proved satisfactory when used by relatively large ships. The short period of operation when the equipments were installed in a 30-foot motor launch to act either as a control station or as a survey unit has definitely proved that the equipment is usable by small craft and that great dependence can be placed on the small craft in the surveys of restricted waters.

With suitable calibration and adjustment, the system is applicable to the control of wire-drag surveys carried on at great distances from the shore where it might be impossible to use the ordinary three-point fix method. In these surveys it is necessary that each of the wire-drag vessels be fitted with the ship equipment, so that its position is known.

PART II. — ELECTRONIC POSITION INDICATOR

World War II brought forth, besides Shoran, another electronic device for use in navigation. This was a LOng RAnge Navigation system, known as Loran. This system had a large service area because it utilized low frequency radio pulses for transmission. Such pulses are not limited by the line-of-sight range, as is the case with the high frequency pulses of Shoran, but rather follow the earth's curvature. The inherent accuracy of Loran, however, is not within the limits desirable for the control of surveys. Shoran, while very accurate in its determination of a position, had a relatively small service area, if the equipments were installed at low elevations. Some system which would combine the advantages of both Loran and Shoran would be ideal for offshore control, and could replace in its entirety the use of Radio Acoustic Ranging (R. A. R.).

FIG. 18

Landing Shoran equipment at Cape Wrangell, Alaska.

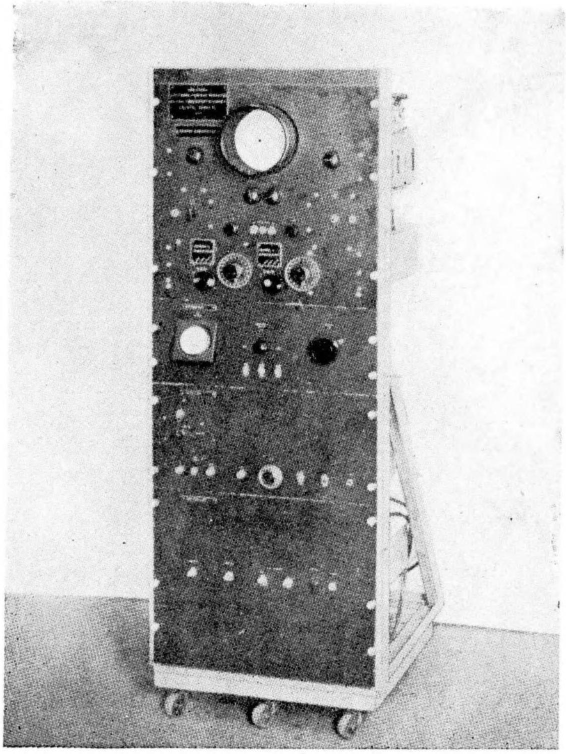


FIG. 19

Ship indicator equipment.
The master controller.

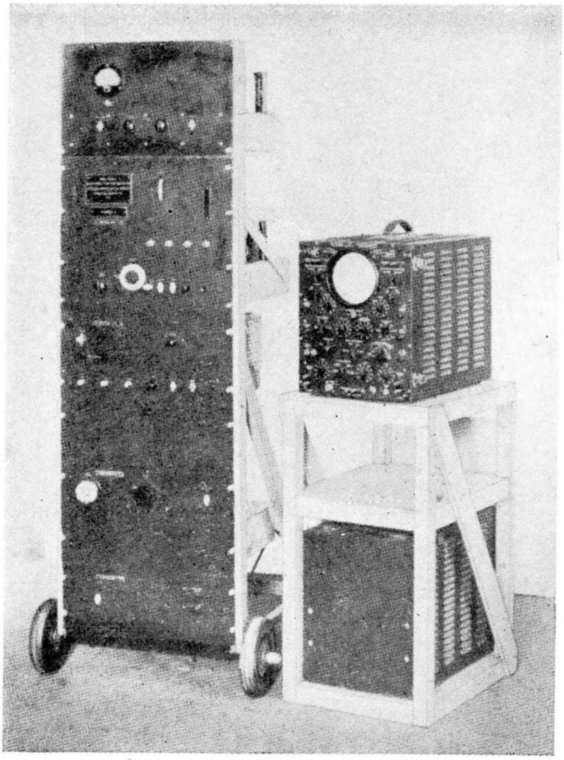


FIG. 20

Ground equipment.
Controller and oscilloscope.

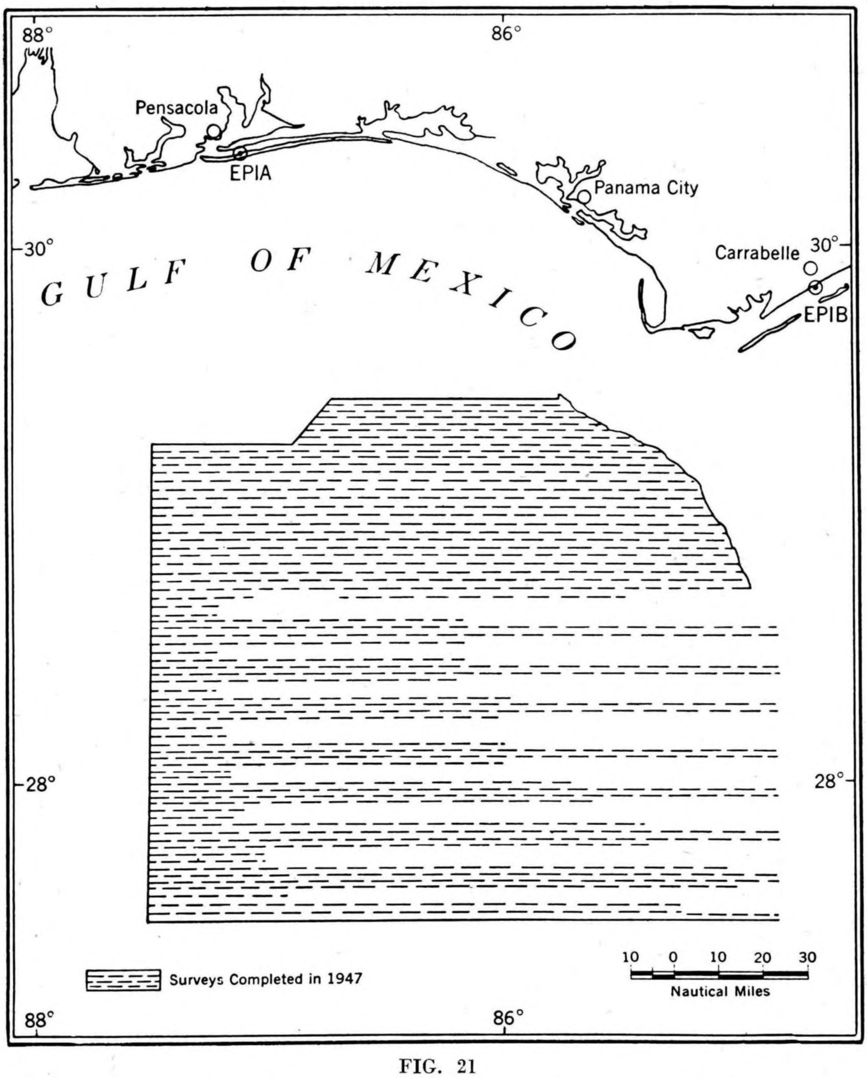


FIG. 21

First hydrographic surveys with the Electronic Position Indicator.

CRITERIA TO BE MET.

To replace R.A.R. completely, it was necessay for the new system to possess certain qualities, among which were the following :

(1) The range of the system must at least equal R.A.R. — that is, the useful range must be not less than 200 to 250 nautical miles from the coast.

(2) The equipment, though not necessarily portable, must be transportable without difficulty, and must be capable of installation at low elevations where erection would be easiest.

(3) The error of a single distance measurement must be less than 100 feet and must be independent of distance.

(4) The equipment must be capable of measuring two distances simultaneously so that a "fix" is determined by a single operation.

(5) The system must be of the two-arc type ; that is, lines of position must be circles whose centers are the individual ground stations.

It was not difficult to see that a "very much glorified" type of Radar equipment had to be designed to meet all these requirements in a single system. Requirements (1) and (2) were easily met by the selection of a suitable frequency and the type of modulation. The Loran system had given excellent results using a low frequency and pulse modulation, but the method of measuring distances did not give the required accuracy. Shoran used a very high frequency with pulse modulation, and required a considerable elevation of stations to obtain the desired distances ; but the method of measuring the distances gave great accuracy. A combination of the frequency and modulation of Loran with the distance measuring features of Shoran would meet all five requirements. The Electronic Position Indicator (E.P.I.) was the result. Since only the frequency band and pulse modulation are common to Loran, the E.P.I. is more like Shoran.

DEVELOPMENT OF E. P. I.

The Electronic Position Indicator was designed and built in the radiosonic laboratory of the Coast and Geodetic Survey. It had its inception in the latter part of 1944, when the original equipment, then called the Radio Ranger, was built. This consisted of one ship and one ground equipment, and was used primarily to determine whether the various assumptions entering into its design were practical, and if the accuracy obtained would meet the requirements laid down. Field tests made during the summer of 1945 were sufficiently gratifying to warrant further research and development in the system. The following 18 months were spent in further design and engineering, and the final equipment, called the Electronic Position Indicator, Model II, Mark 1, was completed. Field tests on this equipment were made during the summer of 1947.

This paper describes the system in a general way, and tells something of the field tests and work accomplished.

PRINCIPLE OF E. P. I.

The principle of position fixing with the E.P.I. is essentially the same as with Shoran. Radio pulses are sent from the ship to two ground stations where they are received and retransmitted back to the ship. The elapsed times are measured at the ship and give the radial distances in microseconds from the ground station. In Shoran distance circles are used.)

Distances are measured by making use of inductive type of phase shifters, there being three phase shifters and three quadrature networks for each distance measuring circuit. These are designed so that they accept most readily frequencies corresponding to 10,100, and 1,000 microseconds of time (100, 10, and 1 kc., respectively). These circuits are so arranged and connected to a "vernier" counter system that they will indicate elapsed time by the angular displacement of the inductors. The main dial reads up to 1,000 microseconds, with the vernier reading directly the hundreds, tens, and units ; tenths microsecond can be estimated. The system repeats itself through about 32,000 microseconds (31.25 pulses per sec.). About one-tenth of a cycle is useful for measuring distances, as the balance is required for other functions of the equipment. As 32,000 microseconds represent a distance nearly equal to 2,600 nautical miles, there is no interference within that radius from each ground station. Since only one-tenth of a cycle is useful, distances of about 260 nautical miles can be measured without blanking out.

Since two distances are to be measured, there must be two distance measuring devices in order to accomplish the measurements "simultaneously". The radio frequency selected is between 1800 and 2000 kc. par second, with a pulse of about 40 microseconds' duration. The pulse repetition frequency is 31.25 per second. These values compare favorably with Loran, but are markedly different from Shoran where the radio frequencies are between 200 and 320 megacycles, and the pulse width is much less than one-fourth microsecond, with a pulse radio frequency of over 930 per second A single radio frequency is used in the E.P.I. system. Signal pulses are sent to both of the ground stations continuously. The ground stations receive them, amplify them, and at fixed time delays (the delay being different for each ground station) retransmit them back to the ship. Here, they are amplified and presented on a cathode ray tube in the indicator. A marker pulse is also shown, it being the point-of-reference from which the distances are measured. The presentation is standard "M"-scan, that is, on both sides of a vertical trace. The marker pulse shows on both sides of the trace, and the returned pulses from the ground stations are shown on the correct side of the vertical trace as the selector circuits determine. The time length of the trace is continuously variable from a maximum corresponding to about 400 miles to a minimum corresponding to about 2 miles. The pulses are adjustable in height from zero to saturation, or about 1-1/2 inches. A special 5-inch cathode ray tube is used.

SHIP EQUIPMENT.

The ship equipment (fig. 19) may be called the master controller of the system. Its function is to initiate a continuous train of short bursts or radio energy to the ground stations and to measure the loop time for the radio wave to travel from the ship to the ground station and return to the ship. The components of a ship equipment include a master controller indicator (distance measuring circuits), a controller (crystal circuits), a receiver, power supply and distribution circuits, and a transmitter.

The functioning of the ship equipment is crystal controlled, a precision 100,000-cycle crystal being used. This frequency necessarily requires that distance measurements be actually "time" measurements, but since distance is directly proportional to time, the particular "yardstick" employed makes no difference. The crystal circuit is designed to obtain a frequency accuracy of at least 1 part in 1,000,000. This is obtained by calibration against Central Radio Propagation Laboratory signals from WWV, using a harmonic generator, and by "pulling" the crystal a few cycles as necessary.

GROUND STATION EQUIPMENT.

The ground stations are not exactly alike in all details, and are known as Channel "A" and Channel "B". The real difference between "A" and "B" is the delay inserted between the received pulse from the ship and the retransmitted pulse to the ship. The ground station equipment consists of a receiver, a transmitter, a controller, a synchronizer, the usual power supplies, and a rather elaborate antenna and ground wire system. (See figs. 20 and 22.)

It is a well-known fact that pulses of energy on low radio frequencies cannot be very short ; that is, the pulse width of 40 microseconds is very long as compared with the pulse width in Shoran, for example (150 to 1). Low frequency pulses cannot be used successfully to "trigger" a transmitter due to the more gradual rise of the leading edge, as compared to that of the high frequency pulse. Therefore, certain devices had to be resorted to in order to make certain of a fixed delay between the arrival of the pulse at the ground station and the time the signal was transmitted back to the ship. Actually, in this equipment, the received signal does not trigger the transmitter at all. The controller and synchronizer determine the time when the pulse is sent back to the ship with respect to the time of the arrival of the ship's pulse. The transmitter may be said to be operating independently of the ship's equipment, sending signals out at a pulse radio frequency of 31.25 per second.

The operation of the ground station is shown on a cathode ray tube in the indicating system. The presentation is standard "A"-scan, on a 5-inch tube. The received signal is shown as one pip, the transmitted signal as a second. When these two are superimposed, the transmitted over the received, then the station delay between the former and the latter is the predetermined station delay. The synchronizer automatically takes care of the alinement of these two pulses, but in case of failure of the synchronizer an alarm is sounded to notify the operator. The error of synchronism is of the order of 0.1 microsecond under static-free conditions. The error is somewhat adjustable so that conditions of extreme static will not cause the alarm to be sounded continuously.

The controller is crystal controlled by means of a 100,000-cycle crystal smililar to that in the ship equipment. It can be exactly synchronized with the ship's crystal by small adjustments in the circuit. Therefore all three units of the system are in synchronism at all times.

The pulsing of the transmitter is then controlled by the effects of the synchronizer. These transmitters are all identical. The combination of identical transmitters and receivers makes it possible to form pulses of very great similarity and, therefore, ease of alinement. The fact that the received pulse comes from a great distance as compared with the individual station's transmitted pulse does not offer any particular difficulty. The transmitted signal passes through a suitable attenuating network so that both received and transmitted pulses may be made exactly the same size at will by observing the effects of adjustments in the indicator tube. The indicator unit at the ground station is a separate oscillograph. The unit was not built into the equipment due to certain complications entering into the construction. This arrangement permits examination into the operation of all circuits, as well as acting as the indicator of the station when in normal operation.

FIELD TESTS.

Final arrangement of the equipment was not completed until a considerable amount of revision and redesign in the laboratory had been made. The laboratory tests could indicate only what the reading errors might be, but could not tell what the overall error on the measurement of a single distance might be. It was quite conclusively proved, however, that the random errors due to misalinement of pulses, either in the ship station or in the ground exquipment, singly or combined, did not exceed the requirement that it should be less than 100 feet. Performance could not be predicted, for actual installations resembling true ground station conditions could not be determined ahead of field tests. It was, however, possible to determine the "zero set" for both stations and the ship equipment.

The Coast and Geodetic Survey ship *Hydrographer* was selected as the operating vessel for the field tests, and the area of the Gulf of Mexico directly south of the line connecting Pensacola and Carrabelle, Florida, as the area in which the tests were to be made. (See fig. 21). The two sites selected for the ground stations were approximately 130 nautical miles apart, and the ground elevation at both places was less than 10 feet above sea level. The requirements were not too rigid : A clear space approximately 300 feet by 450 feet was desirable for the ground wire system, with the longer axis approximately on an east-west line, though this was not too important ; sufficient 115-120 volt a. c. (60-cycle, 1-phase) ; and a suitable building in which to install the equipment and to house the station personnel. These requirements were met at both places.

The station at Carrabelle Beach, Channel "B" (EPIB), was established first. Two telescoping plymold masts were erected, one 50 feet high for the transmitting antenna, and the other 95 feet high for the receiving antenna. The ground wire system was then laid, the wires radiating out from the lead-in insulator anchor of each antenna. The radials for the transmitting system were approximately 150 feet long, those for the receiving about 75 feet long. These are illustrated in figure 22. The installation of the ground system required more time than all the rest of the installation, but it was considered necessary, as dry sand is a very poor conductor. Whether or not the system was too elaborate can be told only by trial with fewer radials.

The installation of the master controller in the ship *Hydrographer* and the ground equipment Channel "A" (EPIA) in the station near Pensacola followed the work of installation of Channel "B". Due to limitations of space in the ship *Hydrographer*, the master controller equipment was installed in the plotting room (directly below the bridge) with provisions made for ready and continuous communications with the bridge. The transmitting equipment was installed in the radio room. The installation of the antenna system required much thought as it was certain that the masts and rigging (all being nearly vertical) would have some directional effect on the receiving system, and possibly on the transmitting system. The simplest installation was finally made, using a nearly vertical antenna for the receiver, and the ship's flat-top for the transmitter. A short whip antenna extending well above the masthead was installed for experimental uses.

One of the tests made of the E.P.I. system was the determination of the actual error in distance measurements, and whether the error was constant with respect to time and distance. When it is considered that the coast-line of Florida is very low, it can be appreciated that difficulties would be experienced in finding areas where rigid fixes on shore objects would be available for controlling the position of the ship, and where E.P.I. distances (as much in the clear of land as possible) could be measured simultaneously for comparison of distances. While not meeting the requirements fully, the area southward from Panama City was the scene of most of the testing work. The tall stacks and tanks in this vicinity afforded excellent three-point fixes from which the ship's position could be accurately determined. The radio path between the ship and EPIA was almost entirely over water, while that to EPIB was nearly equally over land and water.

Considerable time was spent in determining the individual station error, that is, whether the delay set into the equipment was that actually presented. It was necessary to know this before any controlled survey work could be undertaken. The equipment errors at station EPIA were probably quite accurately determined, principally due to the fact that the radio wave always passed over water throughout the full distance. It was observed, however, that the data from EPIB were somewhat more consistent as a rule, not only in tests, but in general operation.

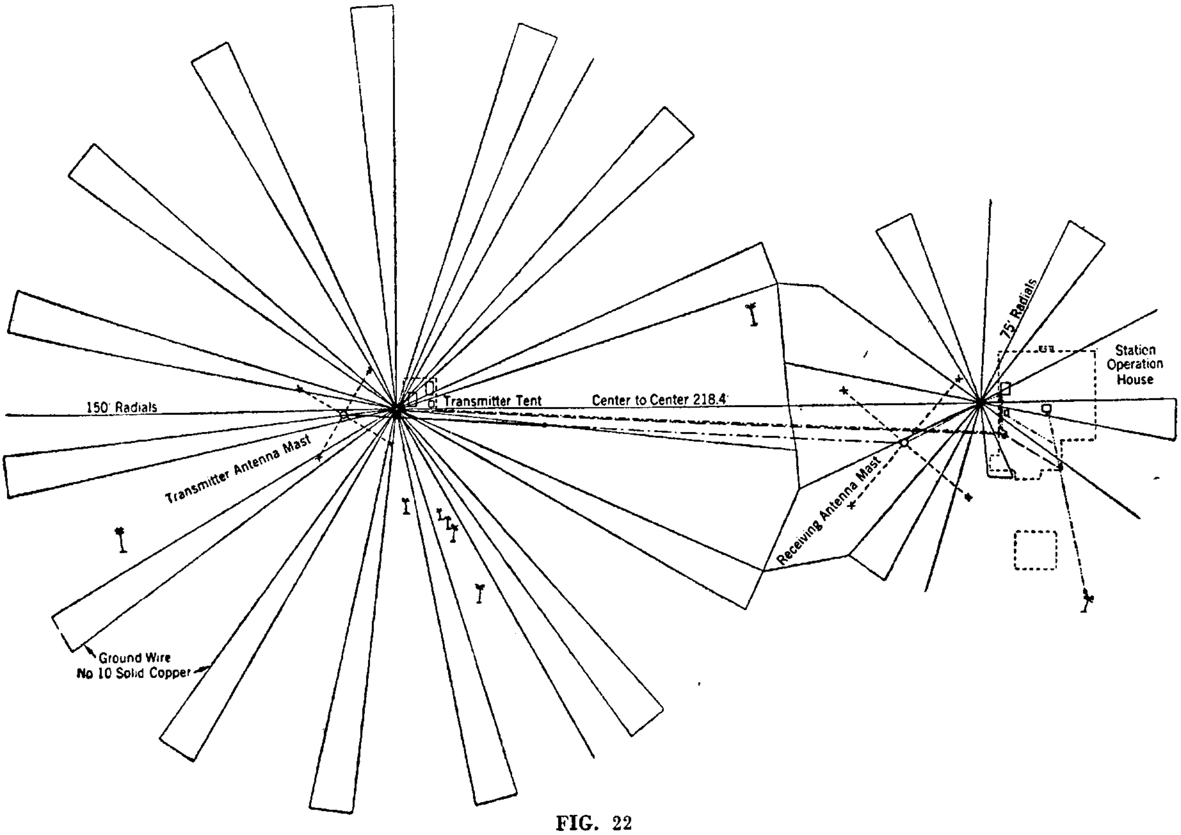


FIG. 22

Plan of ground wire layout at station EPIB, Carrabelle Beach, Florida.

PREPARATION OF FIELD SHEETS.

The area to be surveyed was very large. The base line was 132 miles long, and it was desired to survey out as far as 250 miles from shore — or to the limit of the range of the equipment. It was necessary to make the original projection on a scale small enough to permit drawing all the distance circles to the limit of the work. It will be appreciated that the scale selected should permit this, as it is very difficult to draw circles if the center falls off the sheet. A scale of 1: 400,000 was selected, the projection drawn in, and the two ground stations plotted. The distance circles were then drawn, those from "A" as solid lines, and those from "B" as dotted lines. The interval between circles was made 100 microseconds. The sheet was then reproduced photographically in two sheets, each at a scale of 1: 200,000, and on maximum size (42 by 72 inches). The smooth sheets — those used for office plotting of the field work — were made at the same time. The results of this procedure were excellent, and no appreciable distortion or scale error was observed.

HYDROGRAPHIC WORK.

After the preliminary tests were made, actual field work was undertaken as the real proof of the system. (See fig. 21). There were many interruptions due to inoperative equipment, but the actual delays due to equipment break-down were relatively small compared to those due to weather and other causes. Various experimental work was conducted as opportunity presented itself, not only to determine and check the station errors, but to determine the effects, if any, of the heading of the ship with respect to the base-line — that is, if there were any errors introduced into the system caused by a change in the ship's heading or the relative angle of the ship's antenna system made with those at the ground stations. Several types of antenna were tried in the ship installation to observe the effects of individual antenna for receiver and transmitter, and a common antenna for both. The actual results of these tests will be made the subject of a future paper ; suffice it to say at this time that there did appear to be some small differences. Many cross lines were run. The agreement in the soundings at the crossings was excellent which indicates that the system was performing satisfactorily.

There were a few instances of considerable error in the measurement of distances, one in particular being worthy of note. Sky-wave effects were well known to the laboratory technicians, but as there had been no observance of them at any time during the day, they had not been spoken of. This time the sky waves were quite prominent. As they were the first pips noticed when starting up that morning, they were taken as the usual ground waves. Several hours of very erratic operation passed before the actual facts were known. Of course, as there was no way in which to reduce sky-wave distances to ground-wave distances, this work had to be rejected.

CONCLUSION.

Valuable information was obtained from these field trials and from the actual field work. They can be summed up in the following statement : The equipment performed well and fulfilled all expectations. While the actual error in the measurement of a single distance had not been conclusively determined, it was quite certain that it could not be very much in excess of 100 feet. The range of the equipment was such that it was very easy to carry control to the limit of the sheets, about 2,800 microseconds (equivalent to 225 nautical miles). The indications are that much greater distances are possible. Certain refinements in the equipment are desirable ; some of these can be made in the field, others will have to be made in the laboratory.

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