ELECTRONIC CONTROL SYSTEMS USED ON HYDROGRAPHIC SURVEYS

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During the years 1957 and 1958 I had command of the U. S. Coast and Geodetic Survey Ship *Hydrographer* while the ship was engaged on a survey of Georges Bank, which lies about 100 miles east of Cape Cod on the Massachusetts coast (figure 1). This was a very interesting survey in that three electronic control systems were used to measure distance and furnish position control for the sounding lines. The principal system used was Raydist, and all of the sounding lines run by the ship on the Bank were controlled by this system. In some of the deeper water around the edges of the Bank the Electronic Position Indicator was used to control the sounding lines. And in the shoal areas on the Bank, where the depths were too shallow for the ship, Shoran was used to control the position of the sounding launch.

Electronic methods of position control were first used by the Coast and Geodetic Survey in 1946, at the end of World War II. In that year the Bureau obtained a Shoran system from the U. S. Air Force and used it to control a hydrographic survey in the Aleutian Islands, Alaska. Shoran was designed for use in aircraft, but we found it very adaptable for use aboard ship, and much better for our purpose than the radio acoustic ranging method used prior to the War. In the latter method the travel time of a bomb explosion is used to measure distance. Following 1946 the Bureau obtained more sets of Shoran equipment and increased its use until it was the principal method used to control hydrographic surveys in areas where it was difficult to obtain visual control and which were not too far from shore.

To provide control in the offshore areas beyond the range of Shoran the Coast and Geodetic Survey developed a system that we call the Electronic Position Indicator. Shoran uses high-frequency radio transmitters and the radio waves tend to shoot off into space rather than bend over the horizon. This limits the range to a distance only slightly greater than the line-of-sight distance between the antenna on the ship and the antenna

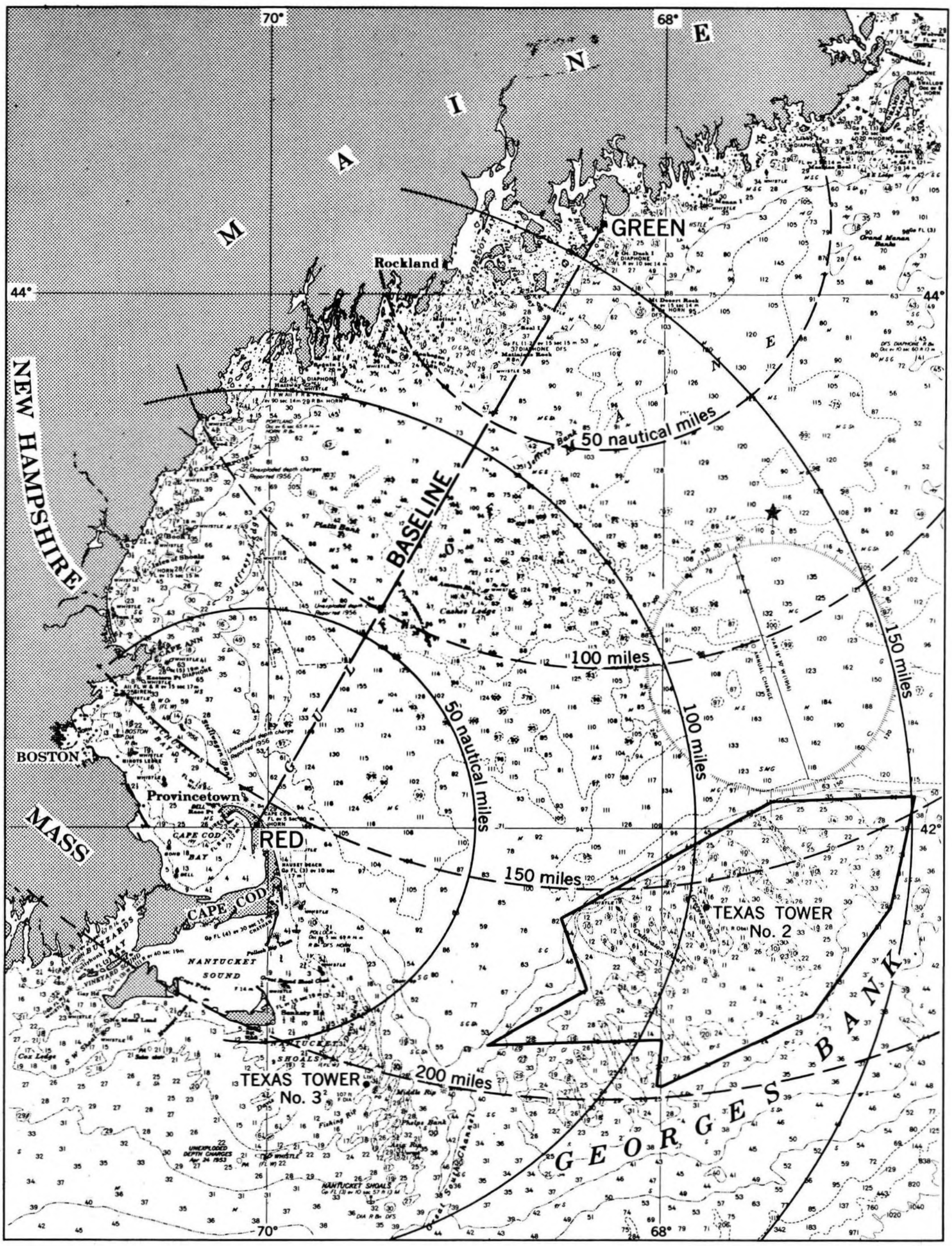

FIG. 1. — Project area of 1957 and 1958 Raydist-controlled survey of Georges Bank.

on the shore station. The Electronic Position Indicator uses radio waves of a lower frequency and longer wave length and these waves will bend over the horizon. This permits the EPI to measure distance when the ship is as much as 450 miles from the shore station.

The Shoran will measure distance with sufficient accuracy so that it can be used to control surveys at scales as large as 1/10 000 if sufficient precautions are taken with the calibration measurements. The EPI, though, due to the use of radio waves with a longer wave length and to the fact that the personal factor in reading the distance is larger than with Shoran is not suitable for use as control on large-scale surveys and its use is best confined to surveys at scales of 1/100 000 and smaller.

In planning for the survey on Georges Bank it was decided that the principal scale to be used to develop the area would be 1:40 000, and with larger scales in some of the shoaler areas. Neither Shoran nor the EPI were quite suitable as control methods, the first because of the distance from land, even though one fixed station might be placed on the Texas Tower located on the shoal, and the second because it did not have the necessary accuracy. In 1954 the Coast and Geodetic Survey had successfully used a Raydist system on a trial basis to make an inshore survey on the West Coast of Florida. It was decided that Raydist would work equally as well on Georges Bank if a set could be obtained that had sufficient power to permit strong radio signals to be received on the Bank. An arrangement was therefore made with the Hastings-Raydist Company of Hampton, Virginia, for the trial of a Raydist system, and with an agreement to purchase the set if it proved satisfactory and funds were available. The Raydist system worked in a very satisfactory manner and was purchased. During the 1957 and 1958 survey seasons about 17 000 miles of hydrography were accomplished using Raydist for control.

PRINCIPLES OF OPERATION

In order to appreciate the capabilities of the three systems mentioned above it is well to know something about the manner in which they measure distance. The following is a brief description of how the Shoran and the EPI operate, and a somewhat more lengthy description of the Raydist since it was the principal system used.

Shoran is a pulsing type system wherein periodic signals are sent out by a transmitter aboard ship, and when received at the shore station they trigger a transmitter there that sends a return signal to the ship. Aboard ship both emitted and received signals appear as pips in an oscilloscope, and distance is measured by using goniometers to move the signal pips into positions where the incoming pip coincides with the outgoing pip. The dials on the goniometers are graduated in statute miles to hundredths of a mile.

The EPI operates in a manner similar to the Shoran except that the receipt of the ship signal at the shore station does not automatically trigger the shore station transmitter. In place of automatic triggering a system is used wherein both ship and shore station send out periodic signals with the same rate of occurrence, and the shore station operator while observing the signals in an oscilloscope moves the signal from his station so that the transmission occurs coincidental with the receipt of the ship signal. Delays of known size are incorporated in the circuits to prevent confusing one ground station signal with the other. Aboard ship the signal pips as viewed in an oscilloscope are matched by moving one image with goniometers, but the pips are not as sharp and clear cut as in the Shoran. This is due to the longer length of the radio waves used in the system. The goniometer dials are graduated in units which correspond to microseconds of time. One unit on the dial equals about 150 metres, or 492 feet.

The Raydist set purchased by the Coast and Geodetic Survey is a DM Model with 100 watts of power. It is a Distance-Elliptical system where the distance to each of two shore stations appears on the phase meter dials. In some of the prior models the distance to the second shore station was not read direct but had to be obtained by a short computation using the dial reading and the baseline distance between the two shore stations.

Raydist is a phase-measuring instrument and the determination of distance is based on the measurement of a phase difference in two radio signals, one emanating from a transmitter aboard ship and the other from a transmitter at one of the fixed, or shore, stations. In order to measure the distance of the ship from each of two shore stations it is necessary to measure the phase difference at three places, aboard ship and at each shore station. The change in the phase relationship as the ship changes distance from a shore station causes the dials to turn, and there is no necessity to match pips as in a pulsing-type system.

Four radio transmitters and frequencies are required to operate the system, the two distance-measuring frequencies mentioned above and two additional frequencies for a transmitter at each shore station to transmit the information concerning the phase relationship at the fixed station back to the ship. In referring to the shore stations the station with the distance measuring transmitter is called the R_1, or *Red,* station and the other is called the R_2, or Green station. The frequencies used on the *Hydrographer* were 3 280 kc aboard ship for the distance-measuring transmitter, 1 639.8 kc at the Red station for the transmitter whose frequency is compared with the 3 280-kc transmitter, and 2 492 and 2 496 kc for the carrier frequencies. The frequency of the 1 639.8-kc signal is doubled to 3 279.6 kc before comparing it with the 3 280-kc signal so that it will be 400 cycles less than the latter frequency.

Because it is difficult to measure phase directly at the radio frequencies a technique known as heterodyning is used. This is a technique wherein if two radio signals are fed into a detector the issuing signal will have a frequency that is equal to the difference between the frequencies of the entering signals, and will portray the phase changes that take place between the entering signals. In the Raydist the entering signals are separated by 400 cycles and after detection this frequency is fed into a phase meter and used to turn the dials. It is easier to handle the phase measurement at 400 cycles than at the higher radio frequencies.

The distance from the ship to the Red station is measured by comparing the phase of the transmitter on the ship to the transmitter at the Red station. Distance is measured by knowing how many half wave lengths of transmitter frequency there are between the shore station and the ship. Once this number is known and the phase meter dial set to this value at a point where the distance to the shore station is known the Raydist system keeps count of the number of half wave lengths as the ship moves. These half wave lengths are know as lanes and for the radio frequencies used in the Raydist aboard the *Hydrographer* they are about 45 metres, or 150 feet, wide.

The ship and the Red station transmitters are crystal-controlled but there is a small change in phase with respect to each other since they are not phase locked. To overcome this the phase of the two transmitters is compared at the Red station and the phase information in the 400-cycle difference frequency is relayed back to the ship on one of the carrier frequencies. At the same instant the two transmitter frequencies are compared on the ship and the phase information appears in this 400-cycle difference in their frequencies. These two 400-cycle signals represent the difference in phase at each end of the R_1 line being measured. The arbitrary differences between the two transmitters, which may be the result of small fluctuations in frequency, are equal at each end of the line and hence cancel. The phase differences which do appear, and are used to turn the phase meter dials, are the result of changes in phase caused by a change in the R_1 distance between the ship and the shore station.

In the Distance-Elliptical Raydist system the R_2 distance is not measured direct but is derived from knowledge of the R_1 distance and the sum of the R_1 and R_2 distances. This is done to simplify the system and to prevent having to use additional radio frequencies. The phase of the ship and the Red station transmitters is compared at the Green station and the information is relayed back to the ship on the carrier frequency at that station. At the same instant the ship and the Red station transmitters are compared on the ship. The two 400-cycle signals are put into an elliptical phase resolver. The shaft position of this resolver is related to the sum distances R_1 and R_2. By combining the distance information from the Red station phase meter with the elliptical resolver and by a proper gearing arrangement the Green phase meter dial reads only the value R_2, or a direct distance to the Green station.

COMPARISON OF SYSTEMS

In a pulsing-type system, such as Shoran and the EPI, each matching of the signal pips as viewed in the oscilloscope gives an independent measure of the distance from the ship to the shore station. This means that the equipment can be placed in operation in any part of the survey area and it will immediately furnish control. With the Raydist it is necessary to set the dials at a point where the distance to the shore station is known. Should the dials lose the calibration during the course of the survey it is necessary to return to a known point to reset the dials to correct values before the survey can be continued. This is not as much a handicap as it might at first seem for with reliable power sources aboard ship and at the shore stations the phase meter seldom loses the lane count due to equipment failures. It does have a tendency to lose the lane count due to atmospheric conditions and this will be discussed later.

To furnish additional information concerning the correctness of the lane count as shown on the phase meter dials a Brush Recorder makes a record of the change in lane count on a special tape. This tape is monitored and the hydrographer has available information which will enable him to stop the hydrography when the lane count is incorrect.

With the Shoran it is necessary to calibrate the equipment to determine the index error in the reading dials, and then additional calibration is necessary to determine the increase in error with increase in distance from the fixed, or shore, station. Calibrations are also necessary to determine if there has been any change in the system characteristics. On large-scale surveys it is well to make almost daily calibrations and to duplicate the conditions under which the Shoran will be used as much as possible.

It is also necessary to calibrate the EPI to determine the index error in the reading dials. Where possible these calibrations are made at about the same distances as will be obtained during the survey. The index error has a tendency to drift during a period of operation so a survey buoy is usually planted in a convenient location and frequent readings are taken at this buoy. This permits the index correction to be changed to compensate for the drift.

As mentioned previously it is necessary to set the Raydist phase meter dials at a known point, but no additional calibration is necessary. With a pulsing-type system the rapidity with which the leading edge of the pulse builds up is a function of the signal strength and varies with the distance of the ship from the shore station. Raydist being a phase-measuring system is not subject to this type of error. Also small changes in the characteristics of the electronic circuits do not affect the distance as much as they do in a pulsing system. All types of systems, though, are subject to errors when the velocity of propagation of the radio wave, which is considered to proceed over water, is changed by intervening land between the ship and the shore station. For the Georges Bank project the velocity of propagation was taken as 983 167 315 feet per second.

The range of Shoran is a function of the heights of the masts at the shore stations and aboard ship. With this system it is well to raise the antennas at the shore stations by using hill tops and other high points. There is a maximum of about 125 feet of cable between the equipment and the antenna so the height of tower that can be used is limited to about 100 feet unless the equipment is housed in the tower. A rough rule for the range of Shoran is 1 ¾ times the sum of the square roots of the heights of the two antennas at the ends of the line to be measured, as compared to a multiplying factor of 1.3 for line-of-sight distance. This range may be increased under conditions favorable for the propagation of radio waves, and on some days it may be less.

At the EPI shore stations 100-foot tower antennas with ground planes are used. It is not necessary to place the antennas on high land in order to increase the distance at which signals can be received as long as the path to the ship is free of high obstructions in the vicinity of the station. As mentioned previously the EPI has been used at distances as great as 450 miles from the shore stations.

At the shore stations for the Raydist the same conditions apply as for the EPI. At the Red station three antennas are required, one receiving and two transmitting. In 1957 all three were 100-foot towers with ground planes. In 1958 a 35-foot whip antenna was used for the receiving antenna and it was duplexed by placing it on top of the 100-foot tower antenna used to transmit the 1 639.8-kc signal. This reduced the requirement for 100-foot tower antennas at the Red station to two. At the Green station two 100-foot tower antennas with ground planes are required.

On Georges Bank the distance to the Red station on Cape Cod was about 100 miles and the distance to the Green station at Southwest Harbor, Maine, was about 150 miles. At the end of the 1958 field season the latter distance had increased to 175 miles. During the daylight hours strong signals were received and the phase meter dials were ordinarily quite steady and well locked into the correct lane count. With the coming of darkness the sky waves would begin to be received and they would affect the stability of the phase meter dial indicating distance from the station in Maine. On an ordinary day the lane count would be lost several hours after darkness began.

In the summer of 1958 the ship worked on a special project southeast of Georges Bank. The Raydist was not used for control but it was turned on and a strong signal was received from the station in Maine when the ship was 225 miles from the station. At the same time the signal from the station on Cape Cod was weak even though the distance to this station was only 175 miles. This was due to the duplexed antenna used at this station in 1958, as mentioned previously. If the duplexed antenna is not used the signal from this station should have as much or more range than that from the other station. No attempt was made to determine the maximum range of the Raydist but it is believed that it may be as great as 250 miles under good conditions. During the use of the Raydist it was noticed that distance from the shore station seemed to have an adverse effect if the radio propagation conditions were poor.

RADIO INTERFERENCE

The high radio frequencies used in the Shoran system are not adversely affected by static conditions, and there is little difference between the daytime and nighttime range. In using Shoran it has been noted, though, that the effective maximum range varies from day to day depending on weather conditions.

The EPI signals are affected by static conditions, and with continuous static present it is almost impossible to match the signal pips with any degree of accuracy if the ship is a considerable distance from the shore station. On Georges Bank we were using the EPI during the night at a distance of about 175 miles from the station at Southwest Harbor, Maine. On many of the nights the sky-wave signal would be visible in the oscilloscope and would cause interference with the ground-wave signal. Usually it was possible to obtain readings with sufficient accuracy to continue hydrography, but the crooks in the sounding lines indicated the poor quality of the control. The sky-wave effect would not be as noticeable on the signal from the station on Cape Cod, which was only about 125 miles distant.

With Raydist it is necessary that the signals emitted by the four radio transmitters be received continuously, and interference on any of these frequencies will affect the operation of the lane counters in the phase meter. On Georges Bank we experienced some interference from other users of the 2 492 and 2 496 kilocycles we were using as carrier frequencies. The Raydist has a monitor that can be used to listen to the tone of the 400-cycle difference frequency signals as originated aboard ship or at either of the shore stations and the radio interference would be easily recognizable in this signal. The Boston Marine Operator broadcasts on a frequency of 2 505 kc and often it would almost be possible to make out the words in the message. Interference of this kind did not appear to adversely affect the operation of the Raydist if the signals were coming in strong, but at night when the sky-wave effect was present this type of interference was often the deciding factor as to whether the phase meter dials would continue to operate with the correct lane count.

Static conditions will affect the operation of the phase meter dials, and its effect is worse at night when the sky waves are present. The worst kind of static conditions was the presence of precipitation static. With static present and if rain began to fall on the ship it was almost certain that the lane count would be lost. A steady fall of rain did not have any adverse effect. Static or thunder shower conditions along any of the paths followed by the radio signals, or near either the ship or the shore stations, may cause trouble. Some time was lost on Georges Bank due to this condition, but on even the worst days it was possible to accomplish some hydrography.

As mentioned previously Raydist is a phase-measuring system and the thing that determined the length of the ordinary work day on Georges Bank was the presence of sky waves in the signal received from the Green station during the hours of darkness. During the daylight hours the phase meter dials would be firmly locked to the lane count, but shortly after sunset it was normal to begin to receive the sky waves. With the sky waves arriving out of phase with the ground waves the phase meter dials begin to oscillate through an arc that increases in size as the strength of the sky wave increases relative to that of the ground wave. Sometimes the Green station dial would oscillate through an arc that might approach a complete revolution and still return to the correct lane count. At times extra lanes would be put in and then a few minutes later be taken out again. If it was possible to keep track of the lane count so that the error did not exceed one lane hydrography would continue if being run at a scale of 1/40 000. When there was a probability that the error might exceed this amount hydrography was terminated.

Often after a period of sky-wave reception shortly after sunset the Raydist dials would settle down and be as steady as during the daylight hours. This condition usually would not last more than several hours and it was rare that lane count would remain accurate later than midnight. There were four nights in each year when the Raydist worked all night, and on only three of the eight nights was there no gain or loss of lanes. An interesting point in this connection is that one of the nights when no loss of lanes occurred was a night when the Northern Lights were very prominent and ordinary radio reception was poor. Operations in the morning usually began at sunrise. On some mornings the sky waves would affect the Green station dial right up to the time the sun was visible, and there might be an especially bad burst of activity a few minutes before sunrise. With the appearance of the sun the Raydist dials would usually settle down and remain stable all day.

USE OF RAYDIST

Due to the fact that it is necessary to set the Raydist dials at a known point it is necessary to have some kind of a reference point in the survey area. On Georges Bank we were fortunate in that the U. S. Air Force has built a Texas Tower and we used one leg of this tower for a permanent

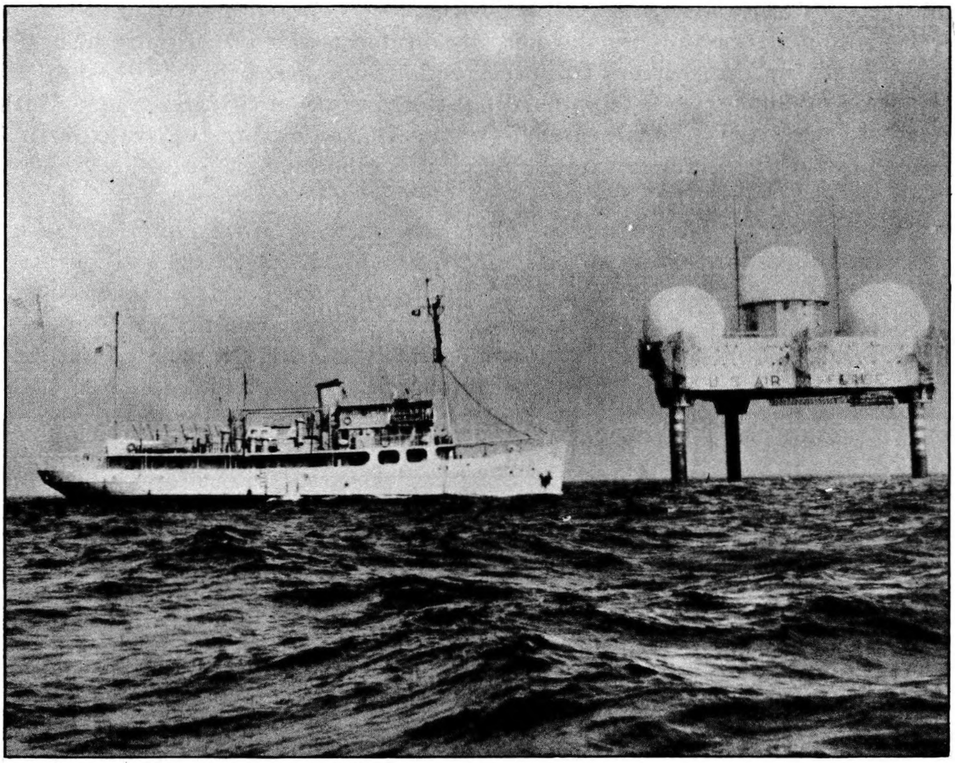

FIG. 2. — Texas Tower No. 2 on Georges Bank and Ship *Hydrographer*.

reference point. A picture of the tower and the survey ship *Hydrographer* is shown in figure 2. The position of the tower was determined by setting the Raydist dials at Cape Cod and then making the run to Georges Bank. The agreement between the runs was good. One run was made between the Texas Tower on Georges Bank and the Texas Tower which is on Nantucket Shoals and about 70 miles southeast of the Red station on Cape Cod. The position of the tower on Georges Bank as determined by this run was in good agreement with the values obtained by reference to Cape Cod and indicates good distance measuring qualities for the Raydist.

When working in areas removed from the vicinity of the tower on Georges Bank it was necessary to have a reference point for setting the dials in the vicinity of the work. Buoys were used for these points, and by planting the buoys in the more shallow water with a short scope of anchor line, and by considering the scope of the anchor line, it was possible to set the dials accurately as referred to the position of the tower. One problem with the buoys was finding them in the fog that is so prevalent on Georges Bank during the summer months. To assist in the search a 2 × 2-inch pole was placed on top of the buoy and 1-pound coffee cans were nailed to the four sides of the top of the pole, with the bottoms of the cans against the pole. This made a good radar target and in a calm sea the ship's radar would pick them up at a distance of several miles.

In using electronic methods to measure distance on hydrographic surveys it is necessary that the distances be measured from the point aboard ship where the transceivers for the echo depth recorders are located. For the Shoran the antennas are on the foremast which is usually near the position of the transceivers so no corrections are necessary. With the EPI the scale of the survey is so small that no corrections are necessary. With Raydist corrections are necessary. On the *Hydrographer* the transmitting antennas for the 3 280-kc signal was on the mainmast and the two re-

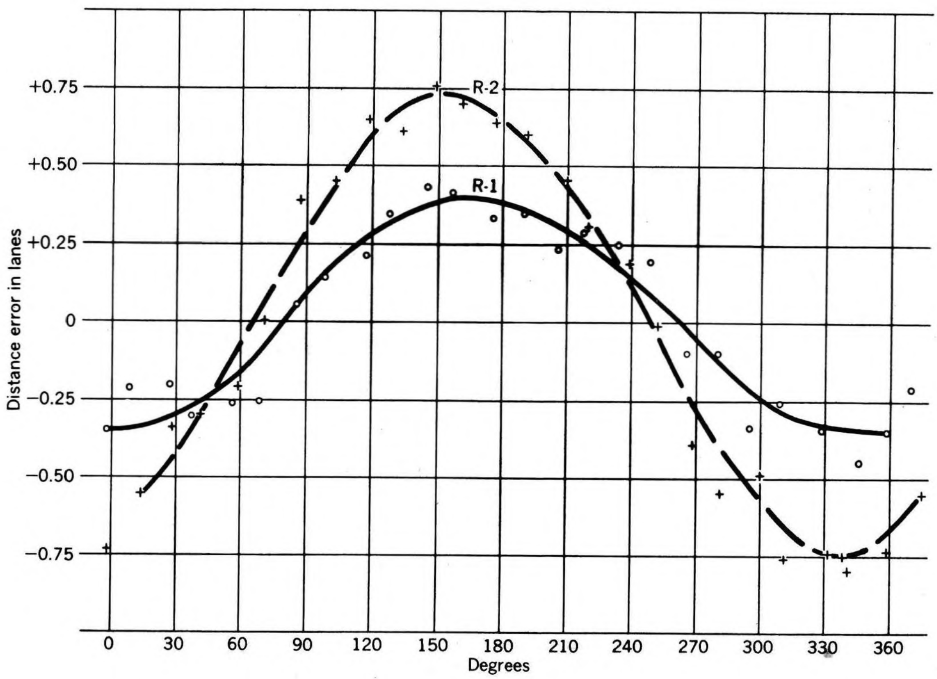

FIG. 3. — Distance corrections as related to ship's heading.
Tests made at Provincetown Harbor, June 1958.

ceiving antennas were on the foremast. To correct the R_1 distance to the Red station to the foremast required the use of the correction formula : R_1 correction (in lanes) = — 0.35 cosine (SH — A_r), where SH is the heading of the ship by gyro compass and A_r is the azimuth from the ship to the Red station. The distance is measured from a point midway between the two masts, which are about 100 feet, or 0.7 Raydist lanes, apart. To correct the R_2 distance to the Green station to the foremast required the use of the correction formula : R_2 correction (in lanes) = 0.35 cosine (SH — A_r) — 0.7 cosine (SH — A_g), where the symbols have the same meaning as given above and A_g is the azimuth from the ship to the Green station. The R_2 distance is measured by an elliptical formula wherein the sum distance R_1 plus R_2 is measured and then the R_1 distance is subtracted in the phase meter. The R_1 distance in the sum distance is measured from the foremast while the R_1 distance subtracted in the phase meter is measured from a point midway between the masts. The R_2 distance in the sum distance is measured from the mainmast.

To check the accuracy of the correction formulas the ship was anchored in Provincetown Harbor at the end of Cape Cod and simultaneous sextant fixes and Raydist readings were taken on each 15-degree change in heading as the ship was swung about the anchor. With the anglemen remaining in one position near the foremast the corrections determined should be in accordance with the above formulas. Figure 3 shows the correction curves, where the abscissa is the relative heading of the ship as compared to the Red and the Green shore stations, and the ordinate is the

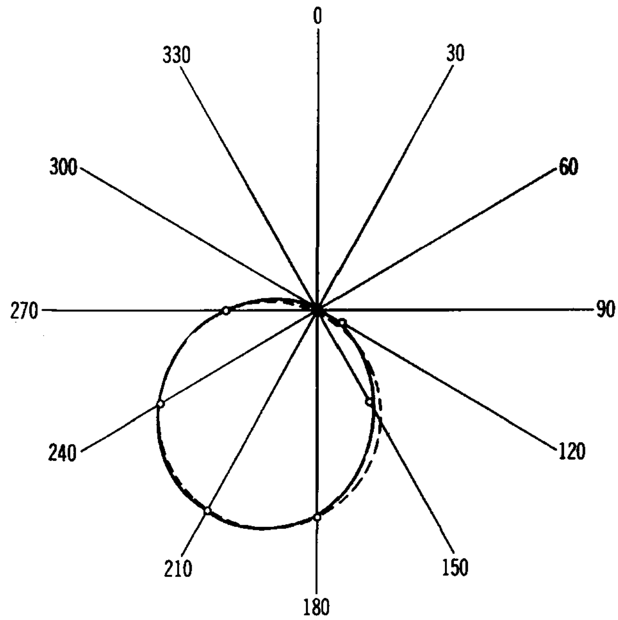

Fig. 4. — R_2 corrections where R_1 station is 90° to right of azimuth to R_2 station. Plotted azimuths to R_2 station minus ship's heading or 360° minus azimuths in fig. 3.

correction in Raydist lanes. Both curves agree with the correction formulas.

A more interesting interpretation is obtained if the R_2 curve is plotted in polar coordinate form as shown in figure 4, where the radial lines are the supplemental angles of those used in figure 3 and the distance from the center is the correction. A circle with a radius of 0.35 lane will coincide almost perfectly with the points denoting the corrections, indicating good agreement in the values. This point is especially significant when it is considered that the ship was over 150 miles from the Green station. At the point where the test was made the Red station was almost exactly 90 degrees to the right of the Green station. Under other conditions the figure would not be a circle and the relative position of the figure would change.

A correction to the R_2 distance to the Green station may also be necessary depending on the antenna arrangement at the Red station. In 1957 three 100-foot tower antennas were used, with the 2 496-kc transmitter antenna over the station center and with the 1639.8-kc transmitter antenna 250 feet distant on one side and with the 1 639.8- and 3 280-kc receiving antenna 250 feet distant on the other side, the three antennas in line.

With this antenna arrangement there is a correction to the R_2 distance because the 1 639.8-kc transmitting antenna is eccentric from the station center. The formula for the correction is : R_2 correction (in lanes) = d cosine (A_s — A_t), where d is the distance, in Raydist lanes, of the 1 639.8-kc transmitting antenna from the station center (1.7 lanes in 1957), A_s is the azimuth from the Red station to the ship, and A_t is the azimuth of the 1 639.8-kc antenna from the station center.

In 1958 the antennas were rearranged at the Red station. A 35-foot whip antenna to receive the 1 639.8-and the 3 280-kc signals was placed on top of the 100-foot tower antenna used to transmit the 1 639.8-kc signal and the duplexed antenna was placed over the station center. The 2 496-kc antenna was placed 250 feet off the center of the station, but the position of this antenna does not appreciably affect the distance. With the duplex antenna no correction is necessary to the R_2 distance as the azimuth of the ship from the Red station changes. There is one objection to the duplexed antenna and that is that the strength of the 2 496-kc signal has to be decreased to prevent interference with the duplexed antenna system. This limits the range at which useable signals can be received to about 125 to 150 miles.

In the DM Raydist as used on the *Hydrographer* the frequency of the transmitter on the ship determines the width of an R_1 lane, or half wave length.

For a frequency of 3 280.000 kc the lane width is 149.87307 feet. The basic R_2 lane width is the same as for the R_1, 149.87307 feet, but it is necessary to apply a correction as the ship moves away from the point where the dials were set to known values. The size of the correction is given by the formula :

$$R_2 \text{ correction (in lanes)} = + .00012\ [(\Psi''_R - \Psi'_R) - (\Psi''_G - \Psi'_G)]$$

where Ψ indicates the phase meter dial reading and the subscripts R and G refer to the R_1 and the R_2 dials, respectively, and $''$ and $'$ indicate the calibration point and the point for which the correction is desired, respectively. This correction is due to the elliptical method used to measure the R_2 distance and the fact that the frequencies are not exactly 3 280 kc.

SUMMARY AND CONCLUSION

At the present time the Coast and Geodetic Survey is using three different electronic systems to furnish control for hydrographic surveys. Two of them, Shoran and the Electronic Position Indicator, are pulsing systems and the third, Raydist, is a phase-measuring system.

Shoran is the most widely used system. The Coast and Geodetic Survey began using this system shortly after the end of World War II and it is now used to control most of the surveys that are not too far distant from the shoreline. For surveys beyond the range of Shoran and where a high degree of position accuracy is not required the EPI is used. For surveys a considerable distance offshore and where good position accuracy is desired the Raydist has been found very suitable.

The three systems, Shoran, EPI and Raydist, complement each other and each has characteristics that make it useful for certain conditions.