ELECTRONIC POSITION INDICATOR

by Commander C. A. BURMISTER
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Hydrographic surveys which will furnish adequate information for the compilation of the nautical charts of the coastal waters of the United States and its possessions must necessarily extend many miles offshore and must be controlled by some method so that the positions of the soundings are accurately fixed. There are, generally speaking, three zones in which such hydrographic surveys are made: (1) The area close inshore where visual fixing is relatively easy, using sextants to measure angles between signals ashore and plotting them by means of the three-arm protractor; (2) the area which is within the optical range of elevated shore positions and where an electronic system (Shoran) can be used to fix the positions of the soundings; and (3) the area which is beyond the optical range of any shore signal and which extends beyond the continental shelf, where an electronic system — the Electronic Position Indicator — can be used. Actually, there will be zones of overlap between the three systems of control; shoran and visual fix may easily have an overlapping area several miles wide, while the Electronic Position Indicator might easily take in some area controlled by visual fix and shoran. For a low-lying coast, the visual fixing zone may be limited to a very few miles — certainly not in excess of ten (10); the width of this zone is increased as the shore elevations are increased, but only proportionally to the square root of the elevations. Much of the time visual fixing is prevented by haze, fog, rain, darkness and other sources of interference to sight. Here, then, even for work very close to the shore, shoran is extremely useful, for the equipment can be easily installed in small hydrographic launches. With shoran accuracy equal to, if not better than, that of the visual fix, this system operates equally well under most conditions which would prevent visual fixing. Shoran's useful range is limited by the fact that it employs ultra-high radio frequencies. In this case the electromagnetic waves tend to travel in paths which are almost straight lines. The slight downward curvature of these paths, together with diffraction and other atmospheric effects, increases the range somewhat beyond the theoretical maximum. Nevertheless, the range is not much in excess of 30 miles for the low coast where antennas cannot be elevated more than 100 feet; but the range may be as great as 70 or 80 miles where high elevations for the shore installations are available. Under very favorable conditions, the range may exceed the theoretical limit by a factor as great as two (2). Since the continental shelf along the Atlantic Seaboard, in the Gulf of Mexico, in the Bering Sea, and other places, is as much as 100 miles offshore, shoran will not give the control required for hydrographic surveys in these critical areas. Hence, the Electronic Position Indicator was designed and perfected by the U.S. Coast and Geodetic Survey as the system complementary to shoran, one which would be able to carry adequate control beyond the limits of shoran and out several hundred miles.

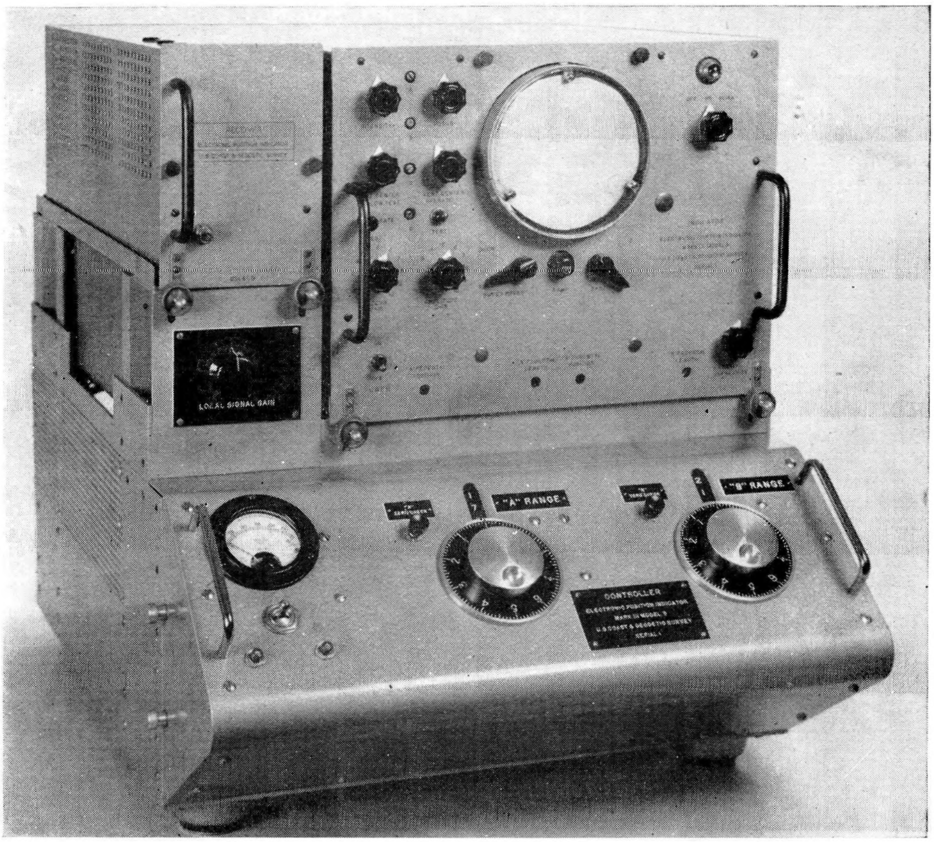
Briefly, the Electronic Position Indicator, abbreviated to EPI, is a pulse-type arcuate (rho-rho) system which requires ship (mobile) equipment capable of transmitting pulses of electro-magnetic energy and of measuring very small increments of time (distance); and two ground stations (fixed) which are capable of transmitting similar pulses accurately synchronized with those from the ship. The ship instrument measures the time for the pulses to travel from it (the ship) to the ground stations and return. The time intervals between the ship and each of the two ground stations are measured simultaneously at a rate of more than 20 times per second. With the positions of the two ground stations accurately known and plotted on a boat sheet, the ship's position can easily be determined graphically, either by using the round-trip times directly or by converting them into actual ground distances. For this system, the velocity of propagation of electromagnetic waves through the atmosphere has been assumed to be 299,690 kilometers (186,224 statute miles) per second. Although it is possible to fix the ship's position at any time, it has been found preferable to establish a schedule of definite time intervals between fixes in advance of starting the work in order to facilitate the operation of the equipment.

The measurement of long lines is made possible with the EPI system because of the low frequency of radio wave employed. For frequencies lower than about 5 megacycles, the ground wave is propagated for considerable distances. For higher frequencies, the ground waves are attenuated because of imperfect conduction and other electromagnetic characteristics of the soil or water over which these waves must travel. Frequencies lower than one megacycle are not used because of certain accuracy considerations, although there has been a vast amount of experimental work done in that region of the radio spectrum. The EPI uses a frequency of 1,850 kilocycles, which gives the most desirable range characteristics.

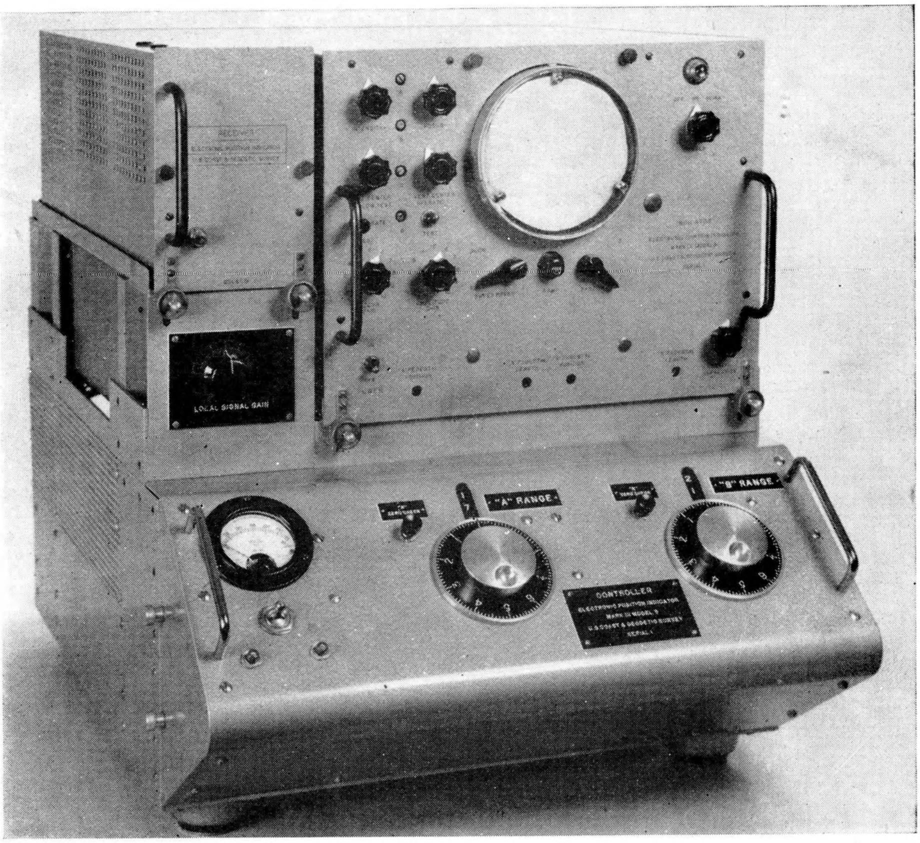
The ground waves not only follow the curvature of the earth but extend to a great distance above it. These waves induce fields in the earth for a short depth. The earth-induced waves, in turn, re-induce a field above the earth. These waves supplement each other as they travel outward from the transmitting station.

At the low frequency used in EPI, it is difficult to start electronic circuits rapidly because of their « inertia ». Also, the amount of space occupied in the radio (frequency) spectrum must be limited to prevent interference with other radio signals. Since the rapidity at which the pulse starts determines to a very large extent the accuracy of the system, the two above-mentioned factors place rather stringent restrictions on this type of radio-location system. At the higher radio frequencies, where the pulse wave-front rises very steeply, the pulse at the receiver output can be made to trigger the transmitter (through a modulator) with almost negligible loss of accuracy. This method is not employed in the EPI system, since the pulse at the receiver output takes some eight to twelve microseconds to rise; therefore, large errors would result when the pulse was noise-modulated or the receiver gain changed. Instead, a synchronizing method is used at the EPI ground stations which precisely sets the time at which the ground station signal will be transmitted with respect to the time when the ship station signal was received.

The rate at which any signal is transmitted, either at the ship- or ground-station, is determined by a quartz crystal oscillator. The crystal in the ship-station oscillator is a high precision, very stable crystal, thermally-controlled to maintain accurate frequency over long periods of time. Those at the ground stations are less accurate, and are not thermally-controlled. But their oscillation frequency is held identical with that of the ship crystal through synchronization with the



Electronic Position Indicator
Controller-Indicator : Ship Equipment
Mark III, Model 3



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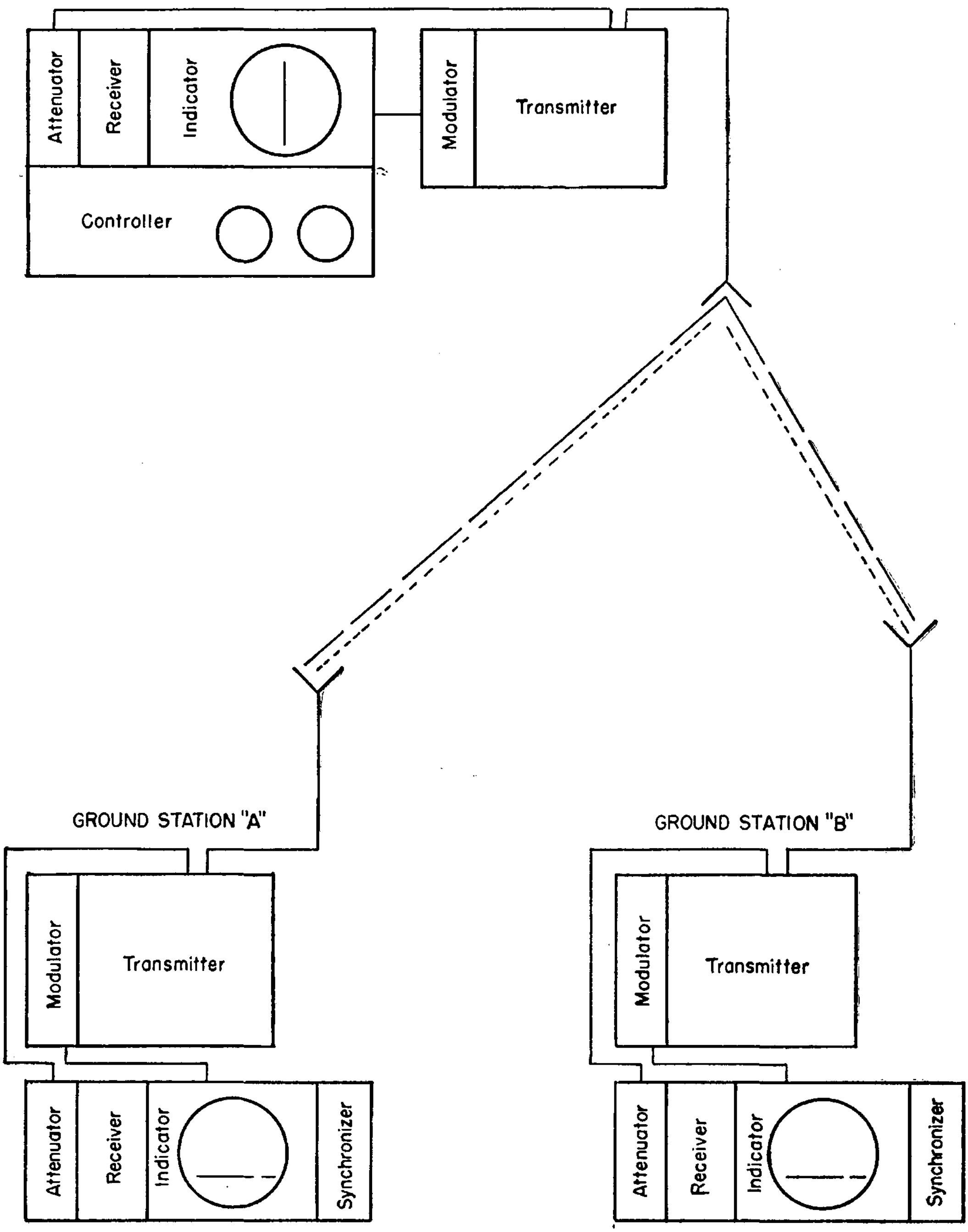


BLOCK DIAGRAM OF E P.I SYSTEM

Fig. 1.

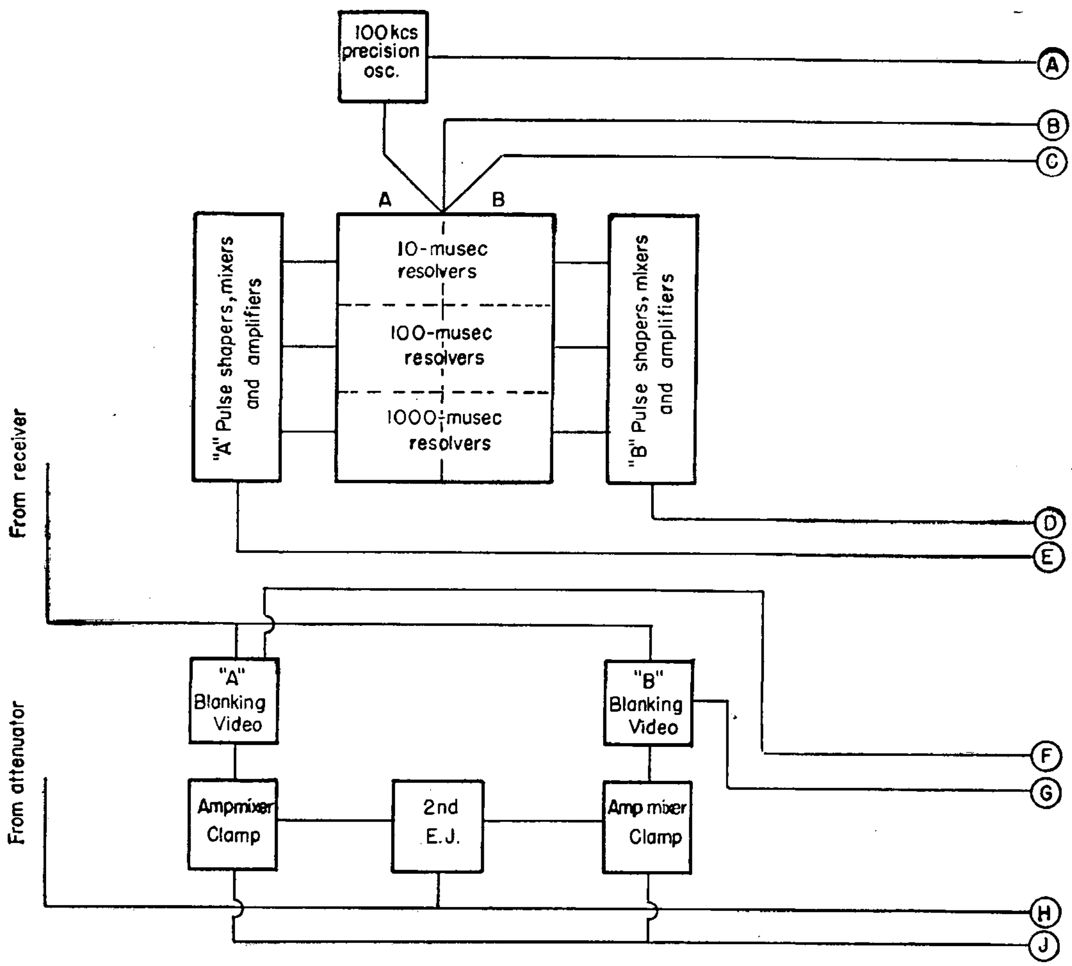
pulse from the ship. The ship's signal, along with the ground station's own transmitted pulse, will appear on the ground station's indicator (cathode ray) tube. The ship's signal may appear to be moving along the sweep relative to the ground station's signal. This pulse is made stationary by adjusting the crystal frequency, then the pulse fronts are equalized and the leading edges matched (superimposed). This results in an exact synchronization between the ship- and ground-station, which means that the pulse rates and phase-relationships are correct and that the ground station is transmitting its pulses at the correct time *after* the reception of the ship's signal. Once this synchronization has been perfected manually, the adjustment is maintained automatically over long periods of time with but occasional fine manual adjustments.

The system has been calibrated for a velocity of propagation of electromagnetic waves in the atmosphere of 299,690 kilometers (299,792 kilometers per second in vacuo). So far a velocity correction has not been indicated. The pulse repetition rate is 41-2/3 pulses per second, with a pulse length of about 50 microseconds with a peak pulse power of about 10 kilowatts (average power about 25 watts). The receiver bandwidth is about 85 kilocycles. The minimum practical range is about 14 miles; however, distances as short as about seven miles have been accurately measured. Under low static conditions, dependable measurements as long as 500 miles can be made, but when static conditions are bad, the range may be shortened to less than 200 miles. Since static conditions are usually worse at night, it is customary to work the more remote areas during the day time, and those nearer the ground-stations at night subject, of course, to the speed limitations of the surveying vessel.

The normal installation of the EPI equipment requires one ship (mobile) equipment and at least two ground (fixed) stations. The positions of the antennas (radiators) at the ground-stations must be accurately determined by triangulation or other satisfactory methods which will give the accuracy required in the work. The survey is no better than the accuracy with which the positions of these stations are determined. A simplified block diagram of the system is shown in figure 1. It gives a picture, in very simplified form, of the components required to make up the system, and should be referred to during the study of the discussion which follows:

THE SHIP EQUIPMENT

There are three principal functions of the ship equipment: (1) To transmit pulses of electromagnetic energy to the ground stations; (2) to receive similar pulses from the ground stations, along with the much attenuated pulse transmitted by the ship equipment; (3) to present all three pulses in such a way on the indicator (cathode ray) tube that, when the leading edges of the ground station pulses are properly matched with their respective ship pulses, the distance (or time) intervals between the ship and each ground station may be read off on suitable range dials and verniers. To accomplish this, four pieces of equipment are required for the ship installation and three for each ground station, plus, of course, certain accessories. These are, for the ship: the Controller, the Indicator, the Receiver, and the Transmitter. For the ground stations, the equipment is: the Indicator-Controller, the Receiver, and the Transmitter. These pieces of equipment will be described briefly in the following paragraphs. It will be convenient to refer to the block diagrams of each component as it is described. (Refer to Figs 2 and 3.)



BLOCK DIAGRAM OF SHIP CONTROLLER

Fig. 2.

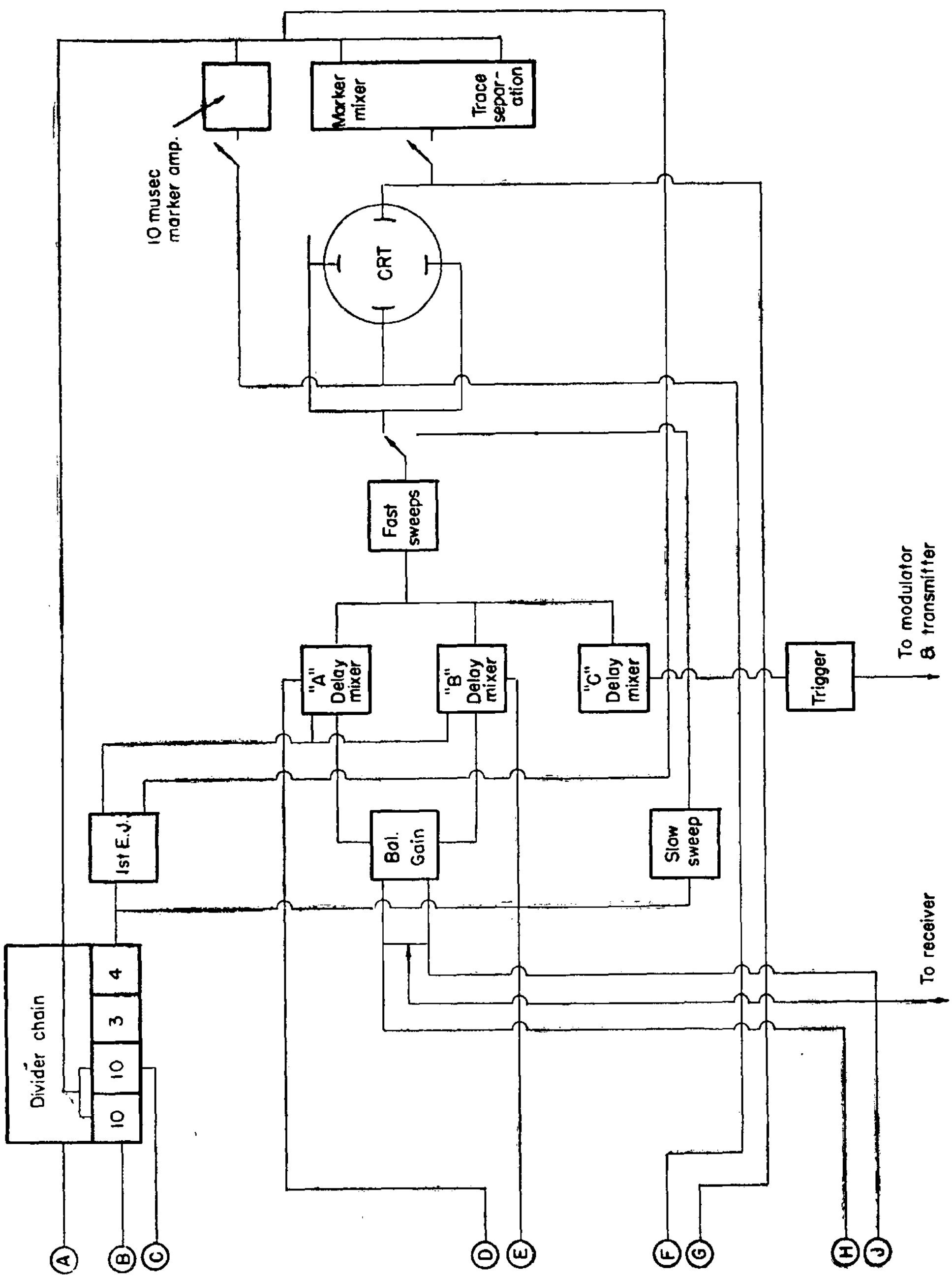
The timing of the entire system is controlled by a precision, highly stable, thermally-controlled 100-kilocycle crystal oscillator in the ship controller. Signals from this oscillator pass through a chain of step-charger divider circuits located in the Indicator. The dividers are 10, 10, 3, and 4 (in that order). The outputs from the various dividers are used to produce signals for various purposes, such as the distance measuring circuits, gating circuits required in delays, and trigger pulses to start the transmitter.

The 100-kilocycle voltage from the oscillator goes to both the step divider chain and to the 10-microsecond synchro-resolver circuits in the Range units. The output of the first divider (by 10) continues to the second divider and to the 100-microsecond synchro-resolver circuits. The output from the second divider (also by 10) goes to the third divider and to the 1,000-microsecond resolver circuits. The output of the third (by 3) goes to the fourth by (4), then to the first Eccles-Jordan multivibrator which gives a division by (2). This last division results in a final repetition rate of 41-2/3 per second, or periods 24,000 microseconds long.

The signals from the 10-, 100-, 1,000-microsecond resolvers of each set pass through mixer circuits and are used to measure the distances between the ship and each of the ground stations. The resolver system on the left side of the controller is called the « Alpha » Ranger, while that on the right side is called the « Beta » Ranger. The units of each group are mechanically connected together so that their rotational speeds are always maintained at the correct ratios and phases. Each group is operable independently of the other through any number of turns of the main dial (vernier). The maximum reading, without repetition, is 9,999.9 microseconds, which is greater than the maximum range of the system, which may generally be considered as about 6,000 microseconds (roughly 550 statute, or 480 nautical miles). The counting is done by means of a large calibrated (vernier) dial counting to 10 microseconds, with direct subdivision to tenth microsecond. This dial is direct-connected to a counter which reads the tens, hundreds and thousands of microseconds. The pulses from the Rangers go to the Indicator where they are combined in a mixer circuit with a delayed gate which was started by the output from the chain of dividers. A selected group of pulses from this mixer circuit starts the sweep circuit, which will be used to display the ground station pulses on the cathode ray tube. It can be seen that the time-position of the sweeps is moved by means of the Rangers until the sweep can occur simultaneously with the reception of the ground station signal. Thus, the ground station signal can be shown on the indicator tube, regardless of its time relation to the ship's transmitted pulse. The trigger which starts the transmitter also starts a sweep so that the transmitted signal may be shown on a fixed stationary sweep. When the movable (ground station) sweep has been adjusted by its Ranger until the ground station signal is in coincidence with the ship pulse, the distance between the ship and that ground station may be read off on the vernier dial and counter. This distance is actually read in loop-microseconds.

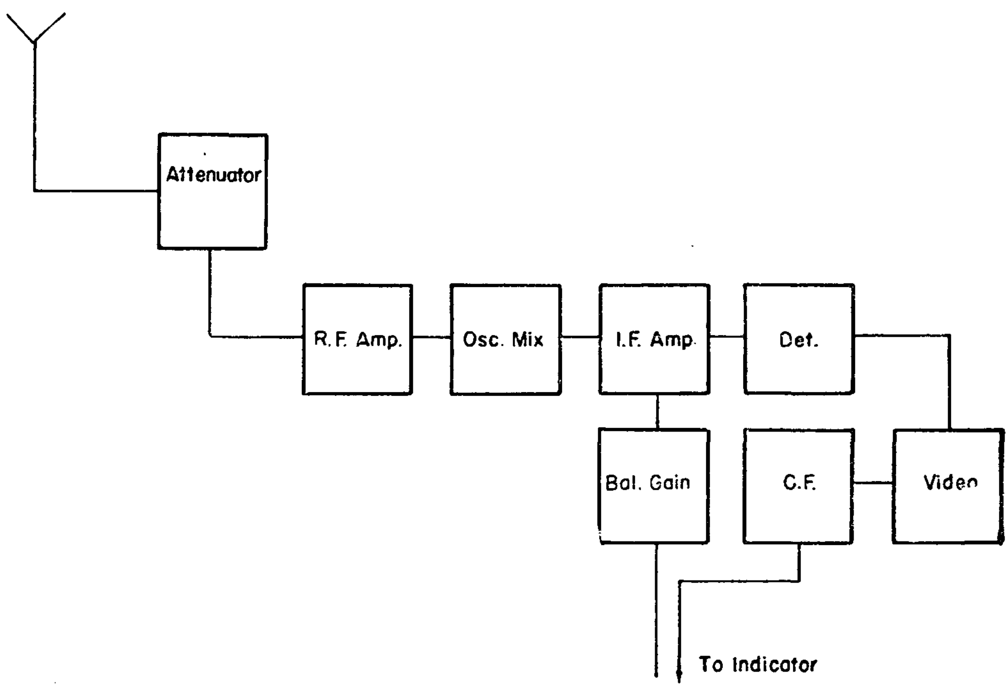
There are two blanking video amplifiers and an Eccles-Jordan multivibrator (the latter called the 2nd E.-J.) included in the Controller. The functions of the blanking circuits are : (1) To separate the video signals from the receiver so that the « A » signal will appear on the left of the vertical sweep line and the « B » signal will appear on the right of it; (2) to blank out undesired signals while the desired one is being presented. That is, they form an electronic commutating device between the « A » and « B » signals and the ship signal.

The Eccles-Jordan (2nd E.-J.) multivibrator is a square-wave generator whose only purpose is to furnish proper blanking to the video blanking circuits and thus



BLOCK DIAGRAM OF SHIP INDICATOR

Fig. 3.



BLOCK DIAGRAM OF RECEIVER

Fig. 4.

commutate the ship's video signal from one side to the other of the sweep on the cathode ray tube. This circuit is operated every 12,000 microseconds by a signal generated in the 1st Eccles-Jordan circuit which is in the Indicator.

The circuits in the Indicator include, besides the step-charger dividers and the first Eccles-Jordan (1st E.-J.), already mentioned, the « A », « B », and « C » delays, various mixers, shapers, and amplifiers and the sweep-generating circuits for the cathode ray tube and the cathode ray tube itself, on which are presented the data for measuring the ship-to-ground-station distances. The 1st E.-J. circuit is operated directly from the last of the step-divider circuits. Its purpose is to divide the operating period in to two exactly equal halves so as to separate, in timing, the events which occur during each cycle.

Three delays are used, as follows: « A » delays the sweep signals for the « Able » ground-station sweeps; « B » delays the sign signals for the « Baker » ground-station sweeps; and « C » delays the local — or ship — transmitted signal sweep. « C »-delay starts at « Zero » time, while the « A » and « B » delays are started 12,000 microseconds later. The delays are set as follows: « A » at 2,000; « B » at 7,000, and « C » at 1,000 microseconds. The mixers associated with each delay are used to generate pedestals of definite length on which a specific number of pulses will stand.

The pulse selectors select the pulses which stand on the pedestals, but exclude both the pedestal and all other pulses. The signals from the pulse selectors operate the Fast sweeps on the cathode ray tube. All distance measurements are made on the Fast Sweep.

The Slow sweep is started by a signal from the last divider circuit. The slow sweep, therefore, is started every 12,000 microseconds, lasts nearly that long, the brief shortening being required for the fly-back time. This sweep is used primarily to « find » the ground station pulses and for certain tests. The « C »-selector also generates the trigger which is applied to the modulator which keys the transmitted pulse.

The Receiver is a broad-banded double-detection (superheterodyne) type of unit with one radio-frequency stage, a mixer, three intermediate-frequency amplifiers, a detector, and a video amplifier. (See Fig. 4). There is a conventional gain control, and a special commutated gain control. Signals from the antenna pass through an Electronic Attenuator before entering the Receiver. These signals are transformer-coupled to the grid of the radio-frequency amplifier. The secondaries of this transformer are tuned to 1,850 kilocycles by means of adjustable powdered iron cores. The plate circuit is R-C coupled to the mixer grid which is tuned to the signal freqeuncy. There are three sets of filters designed to reject any intermediate frequency of 1,050 kilocycles. The gain of this stage is connected to a Balanced Gain control which adjusts the gain between the times the « Able » and « Baker » signals are received. The oscillator operates at a frequency of 2,900 kilocycles which will give the intermediate frequency of 1,050 kcs. Most of the broad-banding is accomplished by stagger-tuning the three I.F. transformers; but additional broad-banding is gained by loading the secondaries of these transformers with relatively low value resistors. The gain of this receiver is such that a 5-microvolt signal at the input will produce a signal of about 200 volts at the output of the video amplifier. When carefully adjusted, the receiver has a bandwidth of close to 85 kilocycles, down about 6 db. from the center frequency.

BLOCK DIAGRAM OF TRANSMITTER

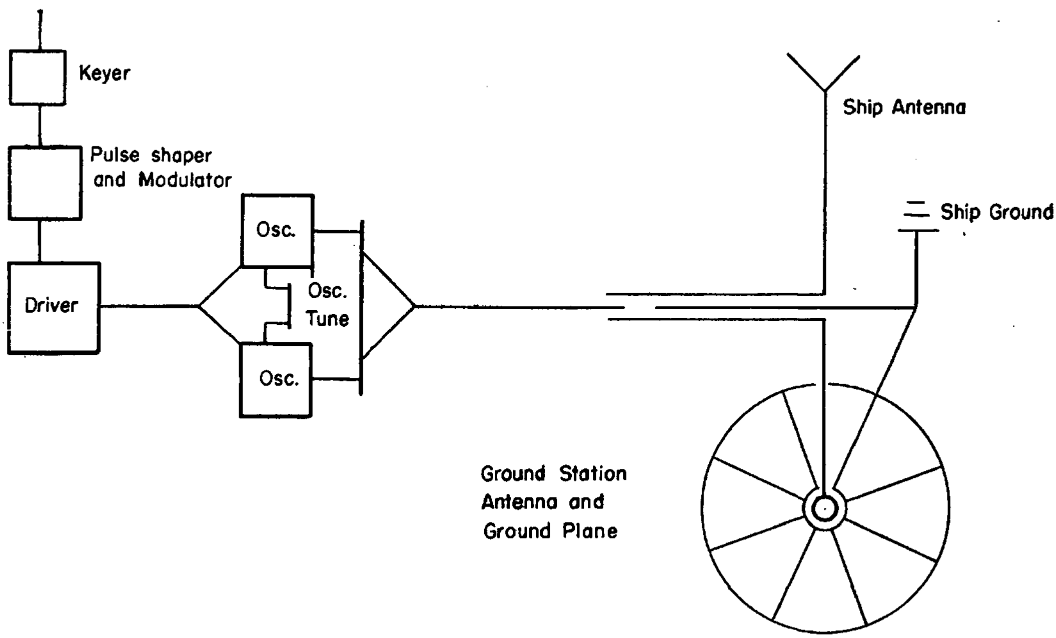


Fig. 5.

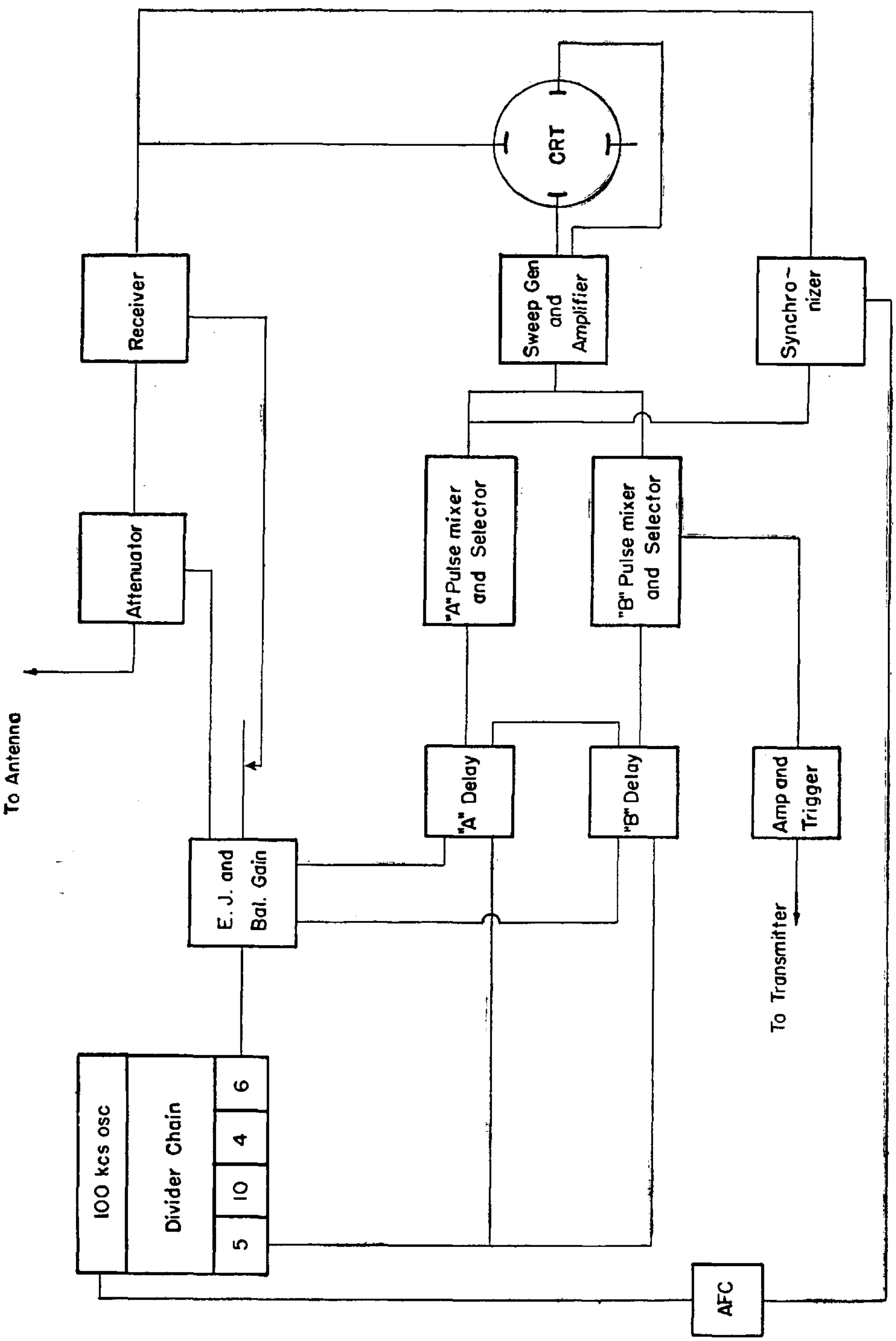
The Electronic Attenuator serves three principal functions; (1) it amplifies weak ground station signals; (2) it offers a high attenuation to strong local signals; (3) it permits the local signal to pass through an adjustable resistance network so that the local signal may be made equal to the ground station signal at the input to the receiver. To produce these effects it is necessary for the amplifier portion to function normally during the time of reception of the ground station signals and to be turned off during the time of transmission (reception) of the local signal. This is accomplished by the process of blanking.

In the well-designed attenuator, the attenuation between the input and output terminals should be very high, in the order of 120 db., so that the only signal at the output terminal will be that passing through the resistance network. Input and output terminals are isolated and shielded from each other; all closed circuits are made as small as possible to reduce magnetic coupling; a ground bar runs through the center of the unit. The adjustment on the attenuator is called the Local Signal Gain; its range must be such that the local signal may be made nearly equal to the remote (ground-station) signal. The Balanced Gain Control in the Indicator will take care of signal differences where they are more than 40 db., but less than 80 db.

The Electronic Attenuator is coupled to the Antenna through the Receiver-Coupler. The purpose of this coupler is to transfer as efficiently as possible signals to the Receiver without absorbing appreciable energy from the antenna during periods of transmission This is, of necessity, a compromise circuit, the coupling being accomplished by means of a small high-voltage vacuum capacitor (15 pfd.), connected to the same point as the transmitter coupler. This small capacitor is used for the reason that the ship antenna is usually very short (much less than a quarter wave length) and therefore very reactive.

The transmitting section consists of the Transmitter, Modulator and the Transmitter-Coupler. (See Fig. 5.) The Modulator, which is built into the Transmitter, is triggered by the signal from the Controller, which is a short positive pulse. This pulse is amplified and shaped in the Modulator, which produces a sufficiently large, positive pulse to operate the key tube in the Transmitter. The Transmitter consists of the key tube and a push-pull oscillator which is conventional in most respects except in the method of keying. By using a high cathode resistor, the oscillator will not operate between signals. Between signals the key tube is biased beyond cut-off, but when a large positive phase from the Modulator arrives, this key tube conducts strongly. This reduces the bias on the oscillator tubes and they start to oscillate and continue do so as long as the key tube conducts. The pulse generated in the transmitter has a rise time of about 2.5 microseconds between the 0.1 and 0.9 points, with a duration of about 60 microseconds, and a peak pulse power of about 10 kilowatts under normal settings. This power can be raised to nearly 18 kilowatts when full voltages are applied. The ten-kilowatt pulse is sufficiently strong to serve satisfactorily over distances of more than 500 miles.

The transmitter is connected to the Antenna through the Transmitter-Coupler. This is, in part, the same unit as the Receiver-Coupler. Two 52-ohm coaxial lines (in parallel) connect the output of the Transmitter to the Coupler input. The primary function of the Coupler is to match the output (50-ohm) of the Transmitter to the 30-ohm antenna. An L-type coupler is used, having capacitive shunt reactance and inductive series reactance, with the inductance on



BLOCK DIAGRAM OF GROUND STATION CONTROLLER INDICATOR

Fig. 6.

the load side of the capacitance. An r.f. ammeter is installed in the Coupler to assist in making the adjustments for match.

A single Antenna serves for both reception and transmission of signals. This antenna must, of necessity, be a compromise installation. It should be a quarter-wave length, be broad-banded, and entirely in the clear from all external metal objects which would disturb the field pattern. This would require a vertical antenna more than 100 feet high, which is quite impossible on most surveying vessels. The compromise antenna is usually a T-type, with the vertical portion as long as possible, installed as much in the clear of the stack, rigging and other antennas as practicable. The flat-top horizontal portion is used for top-loading, which helps to make the current distribution in the vertical portion more nearly uniform. The lead-in insulators must be of the high-voltage type. Because the antenna is very short, its base impedance is high, and high voltages will exist near the base. The base should be protected by some sort of conventional guard.

The average ship antenna will be only 60 or 70 feet long, which will make its natural period about 2,200 kilocycles. When properly loaded, this antenna will present a load of about 15 ohms resistive, and -j115 reactive at 1,850 kilocycles.

Each component, with the exception of the Electronic Attenuator, has its own power supply which furnishes the necessary voltages for its proper functioning. These are all conventional in design. The Electronic Attenuator is supplied from the Receiver.

THE GROUND STATION EQUIPMENT

There are two principal functions of the ground station instrument: (1) to receive radio frequency pulses from the ship; and (2) to transmit a signal back to the ship after a definite time delay following the ship signal. To accomplish these functions, three pieces of equipment are needed: (1) the Controller-Indicator; (2) the Receiver; and (3) the Transmitter, together with various associated components.

Several of the components in the ground station equipment are identical with those in the ship installation: namely, the Receiver, the Electronic Attenuator and the Transmitter. These units, then, will receive no further discussion here.

The timing of the ground station equipment (See Fig. 6) is controlled by a 100-kilocycle crystal oscillator located in the Controller-Indicator. While this crystal is of high accuracy, it is less precise than that in the ship equipment, and is not thermally-controlled. Signals from the crystal oscillator pass through a chain of step-charger divider circuits. The output of this chain produces pulses which are used to start various gating circuits needed to give the proper delays and to produce the transmitter trigger, sweep triggers and synchronizer trigger.

Since the correct functioning of the system depends upon an exact correlation of the oscillating frequency of the ground station crystal with that of the ship crystal, there is an automatic frequency control circuit with an additional fine frequency control for manual setting. The AFC circuit is conventional: the AFC error voltage will always be such that its direction tends to correct the oscillating frequency of the ground station crystal to that of the ship crystal.

The step charger circuits are very similar to those in the ship Indicator, except that the divisions are: 5, 10, 4, and 6. The ultimate result is the same as in the ship unit, but the different sub-frequencies are required. These circuits are conventional. The divider chain is followed by an Eccles-Jordan circuit (a square wave generator) which divides the last interval into two exactly equal parts 12,000 microseconds long in the same manner as the first E-J circuit in the ship Indicator. The output of this E-J circuit starts the ground station « A » and « B » delays. As these two delays require very sharp tripping pulses, the square waves are differentiated.

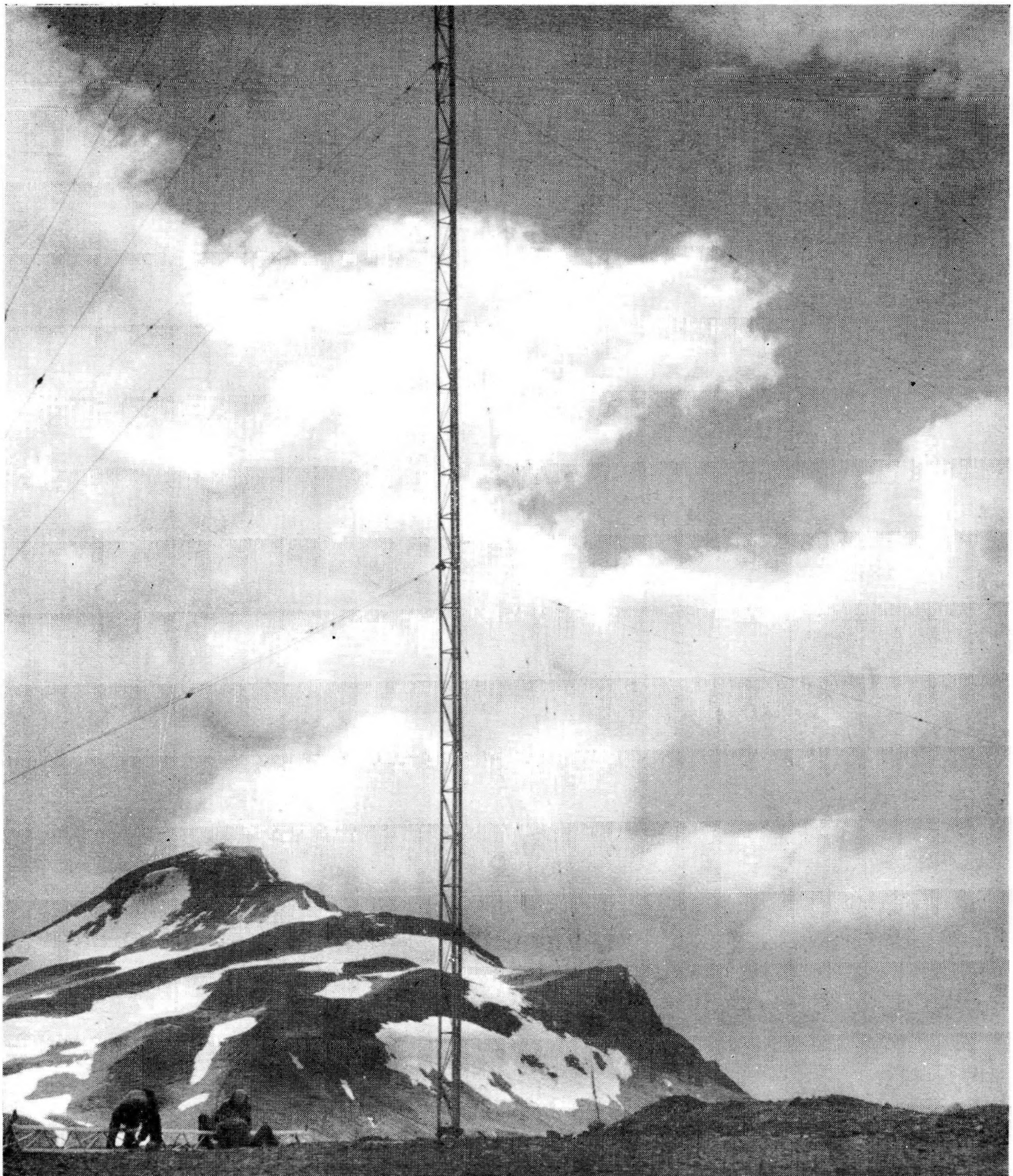
The « A » and « B » delay circuits are essentially the same, except that the « A » is set for 1,000 microseconds at both ground stations, while the « B » delay is set for 2,000 microseconds at the « Able » station and 7,000 microseconds at the « Baker » station. These circuits are monostable multivibrators and are turned On by a positive differentiated pulse from the E-J circuit. The two halves of the square wave generator are 180° out of phase with each other. Since the two delay multivibrators are turned On by opposite sides of the square wave generator, they are half the square wave cycle apart, or 12,000 microseconds in time. Negative pulses 500 microseconds apart (from the second divider) are fed into the same circuits: these turn the multivibrators Off, always at the precise 500-microsecond interval, as may be selected by the operator. The « A »-delay is sometimes called the « remote signal delay » and the « B »-delay the « local signal delay ».

The « A » and « B » delay circuits are followed by mixer and pulse selector circuits. Those following the « A » delay generate special voltages for the fast sweeps on which will be seen the ship (or remote) signal. Those following the « B » delay generate the trigger which starts the transmitter.

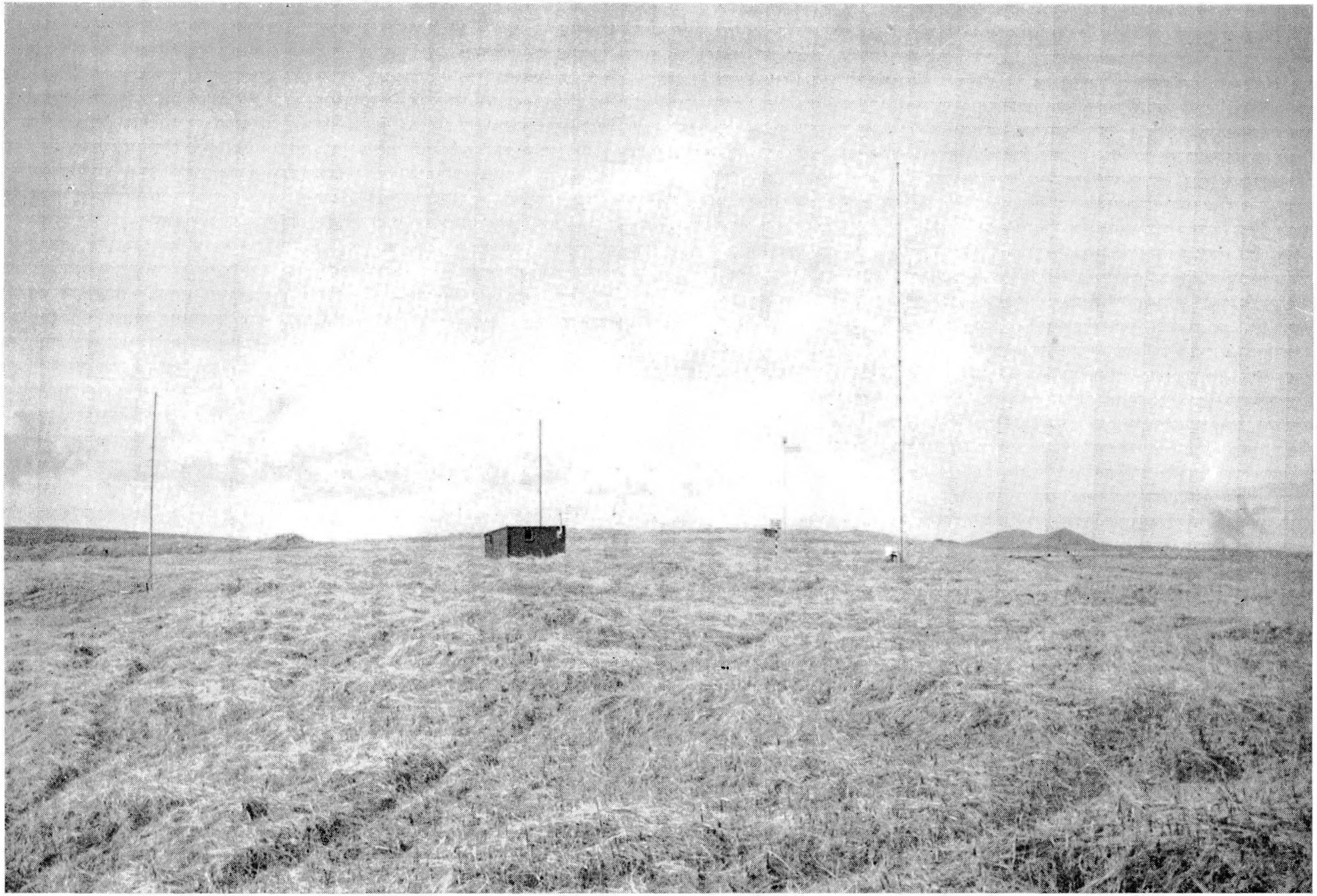
The pulse selector circuits are followed by a pedestal generator, which is another monostable multivibrator. It produces a square-topped wave for each « A » and « B » pulse. They are impressed on the vertical deflecting plates of the cathode ray tube and are seen as two pedestals, one on each of the slow sweeps. Three pedestal lengths are available, at the wish of the operator, through the fast-sweep switch. The fast-sweep generator is controlled by the output of the pedestal generator. The output of this generator is applied to the horizontal deflecting plates of the indicator tube through a paraphase amplifier which is a phase-splitting device used to convert the saw-toothed waves from the fast and slow sweeps into symmetrical push-pull voltages.

The cathode ray tube is a type 5CP1, which has a 5-inch green fluorescent screen of moderate persistence. The sweeps are horizontal, and are controlled by the usual centering, focusing and brilliance adjustments.

The ground-station functioning is maintained in the correct time-relationship with the ship by means of a synchronizer. The purpose of this component is to keep the ground-station crystal oscillator operating at exactly the same frequency as the ship oscillator. This is accomplished by mixing a gate pulse controlled by the ground-station oscillator with the leading edge of the wave front of the ship pulse (at the output of the receiver). The output of the mixer is rectified, and the resulting DC voltage stored in a capacitor. This voltage is the control-error voltage used in the AFC mentioned previously. Should a frequency (or phase) change occur between the ground station and ship crystals, the gate will move with respect to the ship pulse, with the result the mixing occurs at a different point on the wave-front. This produces a change in the mixer output, which means that there is a different error voltage. The direction of this error voltage



Close-up of 100-foot Radio Mast
at EPI Ground Station in Alaska



EPI Ground Station completed
100-Foot mast on right ; 50-Foot shoran mast next left (almost behind target)
Equipment Hut, with communications antenna mast directly behind and to the left

change will always be such as to correct the ground-station oscillator frequency. The AFC will correct for relatively large deviations from the correct frequency and will maintain almost perfect synchronization over long periods of time, unless interrupted by continuous and long bursts of static. Synchronization is performed manually when first starting up the equipment. When nearly perfected, the synchronizer will « take over », and will maintain correct adjustment within limits of about one tenth (0.1) microsecond under normal conditions. The state of synchronization is indicated visually both on the cathode ray tube and on a dual needle meter. Exact synchronization is accomplished when the leading edges of the two pulses shown are exactly superimposed and when both needles of the meter are zero-centered. Excursions of 20 to 30 microseconds can be adequately handled by the synchronization circuits.

The Indicator-Controller has its own power supply which provides all the necessary voltages for the correct operation of the unit.

The other components used at the ground station, namely, the Receiver, Electronic Attenuator, the Transmitter (and Modulator), and the Antenna-Coupler are identical with corresponding components in the ship equipment and will receive no additional treatment here. Their functions and operation are as previously described.

The Antenna at the ground station does not present the problem which that on the ship does. Essentially, the radiating system at the ground station consists of a nearly quarter-wave-length vertical radiator and its ground plane. The most satisfactory radiating assembly is a fabricated mast about 100 feet high. This structure is made of aluminium angles and plates, and has a triangular cross-section of about 12 inches on a side. The mast is made up of ten ten-foot prefabricated sections carefully bolted together for electrical continuity. Each section weighs about 18 pounds. The mast rests on an insulated base, and is held erect by means of five sets of insulated guys. This mast is of the so-called « boom-type »; that is, the mast is assembled on the ground and hoisted to a vertical position by means of a boom (usually consisting of three sections similar to those used in the mast proper). The base is provided with pivoted sections for this purpose. The mast must be erected over a triangulation station or on a site readily accessible to triangulation for accurate location.

Since most soil is an indifferent conductor of electrical energy, a ground plane must be laid out. The ground system causes a spreading out of the large currents flowing in the earth near the mast base; it also keeps the radiation at a low angle, which is desirable, as this system uses only the ground waves. The ground system will, generally, consist of 32 radials of not smaller than A.W.G. (1). No. 16 copper wire, each radial being about 100 feet long. All radials are carefully and thoroughly bonded together at both the center of the radial pattern and at the extremities by bonding wires. The inner ends of the radials are often attached to the mast base itself through brass bolts. Thirty-two radials seem to be a practical maximum; doubling the number will add only a few per cent improvement in field strength; and doubling the length will add even less. Such an installation will present an ohmic resistance of about 31, with a reactance of 0 at 1,850 kilocycles, with very little change in either resistance or reactance with frequency

(1) American Wire Gauge.

changes of 50 kilocycles. The voltage at the base of the antenna is relatively low even when a 10-kilowatt signal is being radiated.

Primary power at the ground station must often be supplied by the user. If such is the case, at least one, preferably two, gasoline or diesel-engine-driven generators must be furnished. These should have a capacity of about 5 kilowatts of 115-volt, 60-cycle, single phase alternating current. While 5 kilowatts is considerably in excess of the equipment requirements, the additional power can be used for station operation, and generally provides a steadier source of power.

Extensive studies have been made, both in the laboratory and in the field, to determine the system's accuracy and consistency. During the laboratory tests, all factors that could contribute to instrumental error were studied. Field conditions were simulated as well as possible, but closed circuits were used, which made the tests nearly noise-free. Field tests were made as test buoys anchored in known positions from which the distances to the ground stations could be precisely computed. The paths between the buoys and the ground stations were approximately 45, 90, 110 and 275 nautical miles. The tests extended over several months, with a total of 267 sets of observations. The data in the table below are presented as a percentage of observations that come within the fraction of a microsecond indicated. The data are as read: there has been no modification or weighting of the results.

Microseconds plus or minus	Field tests 267 observations	Laboratory tests 21 sets of observations
0.1 (15 meters)	35 %	26 %
0.2 (30 meters)	53 %	53 %
0.3 (45 meters)	72 %	71 %
0.4 (60 meters)	83 %	82 %

Other field test show that there is little change in correction due to signal strength or distance between the ship and the ground stations. The system remains stable over long periods of time. Static can produce a considerable error in any one reading, but check (repeat) fixes may be taken to verify unreasonable readings, if necessary, and a creditable survey will result.

As in any system of distance measurement, two types of errors can occur, namely, systematic and random. The systematic errors are those which can be determined accurately, and, once determined, their magnitude can, at any time, be predicted fairly readily. Such corrections can always be applied to measurements to make them more nearly correct. Systematic errors include such factors as:

(1) Incorrect velocity of propagation of electromagnetic waves;

(2) Non-linearity in distance-measuring (Range) circuits;

(3) Initial (Zero) correction.

The calibration of the system is based on an assumed velocity of propagation of electromagnetic waves of 299,690 kilometers per second at a standard sea-level barometric pressure of 760 mm. of mercury (29.92 inches) or 299,792 km/s in vacuo. It is most probable that the error caused by this assumption is not greater than 5 parts in 200,000. The velocity is subject to changes in barometric pressure, humidity and so on. Since this correction is generally quite small, due to the relatively small range in the changes, such corrections are often neglected in hydrographic survey control, but may be applied when measuring lines in trilateration.

The non-linearity of the range measuring circuits can be determined in the laboratory, and the corrections can be applied if necessary. They do not exceed, generally, a value greater than 0.1 microsecond. This correction can also be neglected in hydrographic survey work, especially if the scale is smaller than 1:100,000.

The third error is in Zero-ing the range dials and verniers. There will generally always be a small initial correction to apply to all distance measurements since it is quite difficult to make the vernier read exactly Zero to correspond to Zero time (distance). This error can readily be determined at the will of the operator; it is quite stable; it should be applied to all distance measurements. The laboratory setting of the vernier is such as to make this as small as possible, though it has run as high as 2 or 3 microseconds in some instruments.

The random errors are of a more serious nature; they are often of considerable size and there is no definite way for the prediction of their magnitude. These random errors may be classified as those inherent in the ship equipment and those in the ground station equipment.

At the ship they are:

(1) Misalignment of local and distance pulses;

(2) Careless reading of the distance vernier and dials;

(3) Poor alignment of pulses due to insufficient or incorrect gain settings at various distances (Balanced gain).

Those at the Ground Station are:

(1) Poor synchronization at the time of fix;

(2) Incorrect setting of the Balanced Gain.

The effects of these errors in the EPI system (whether the systematic errors are applied or not) are such as to cause an uncertainty in position which is related directly to the magnitude of the error (summation) and the angle at which the distance arcs intersect. The figure of uncertainty is smallest and approaches a rectangle in shape in the regions of the service area where the lines of position intersect at 90°. This figure becomes elongated normal to the base line as the angle approaches 0°, or as the lines of position become externally tangent on the base line. The figure is elongated parallel to the base line in the regions most remote from the base, where the lines of position tend to become internally tangent. The figure is also elongated normal to the base line extended where the lines of position are also internally tangent. These areas of relatively great indetermination should be avoided as much as possible.

Experience has shown, and it can be demonstrated geometrically, that the figure of uncertainty may be kept reasonably small if the angle of intersection is kept within the limits 30°-150°. In the occasional cases where it is not feasible to move one of the ground stations to a site which would give better control, the limits may be extended to 20°-160° maximum. The greater limits would be particularly applicable in areas far remote from the ground stations where especially close development is not required (that is, in deep water, or very flat bottom).

In the case where the ground stations are separated by a large expanse of water which must be included in the survey, as when one station is on the mainland and the other is on an island, there will result a relatively large lens-shaped area, symmetrical about the base-line, where the uncertainty becomes so great that it is impossible to plot the EPI position. The area cannot be adequately surveyed without moving one of the ground stations to a more favorable site. Assuming the base-line to be about 200 miles long and the limiting angle of intersection to be 30°, this area will be about 50 miles wide midway between the two ground stations and will have an area of approximately 5,000 square miles. A similar condition will obtain in the region(s) which include the baseline extension(s).

Where it is not practical (or possible) to move one of the ground stations to a more favorable location, it is possible to make an acceptable survey by using a combination of « precise-dead-reckoning » and EPI fixes. It is essential that the dead-reckoning be accurately kept while on line between the areas of good EPI fiixing, and that EPI fixes be taken at uniform intervals of time to facilitate the final adjustments. The lines of sounding should be run normal to the base lines. The plot of an EPI fix, however indeterminate it may be, will always show the approximate position and trend of the sounding line with respect to the control stations, but it will not show the ship's position with respect to (distance from) the base line. Several strong EPI fixes should be observed as soon as possible after emergence from this area to check each other, then the dead-reckoning can be plotted using the EPI fix data to assist in the adjustment. It will be apparent that once the track line has been plotted it is not difficult to plot the EPI fixes in their correct relation to the base line. The EPI fixes are taken at uniform intervals to simplify the adjustments of these lines.

It occasionally occurs that one of the ground stations may go off the air, due to equipment failure or other difficulties. If the station operator informs the navigator that the period will be relatively brief -say an hour or two, it is not necessary for the ship to cease operations temporarily. The survey can be continued using the single distance data with dead-reckoning information to control the ship's position. When the station resumes operation, two fixes will generally suffice to establish the ship's true position, and the partially-controlled line(s) can be adjusted by the usual methods. It is only required that sufficient dead-reckoning data be kept to make the adjustment; it is not essential that the ship retain a particular course, and course changes as great as 180° (reverse courses) can be made and successfully adjusted.

The EPI system has a low order of ambiguity. It is possible to plot two positions from each set of fix data. That is, the two arcuate lines of position will intersect in two points, one on each side of the base line. Actually, this ambiguity is of little concern to the navigator, for these two points are widely separated, and the navigator should know on which side of the base line he is operating. This ambiguity is easily resolved. A series of fixes will plot in a straight line in either place, but the plotted direction of the line will agree with the true direction only in the correct area except in the case where the « test » line may be run parallel to the base line. The speediest way to resolve the ambiguity is to set the course to cross the base line. The plot of several fixes will immediately solve the problem.

Should it happen that both ground stations or the ship equipment cease operation for any length of time, it is only necessary to observe two or more fixes when the work is resumed to definitely position the vessel. It is never necessary to run to a known position to re-establish control.

Fixed floating check points (usually large navigation buoys anchored at a short scope of chain in relatively shoal water) are often a great convenience in checking the operation of the system. Such control points are most practically located somewhere near the base of operations so that the ship can pass them without too much detouring. The position of the check point may be determined either by visual fix (sextant angles on shore signals); by triangulation from shore; or by the EPI fix data, should the buoy be out of sight of land. Any discrepancy in the system functioning will be immediately apparent and remedial steps can be taken at once; or, if an error was known to exist, it can then be corrected. If such a check point is established, there should be adequate room all around it for maneuvering the ship to any position.

Calibrations (checks) at such points may be made in two ways. The simplest is to maneuver the vessel alongside the buoy, as close by as possible, and take fixes at appropriate instances. Such fixes may be taken with the ship on several headings to make certain that there has been no error due to heading. The other method is that of circling. The ship circles the buoy at a relatively slow speed, keeping distances from it by means of a range finder (or depression angles). EPI fixes are taken at uniform time intervals until the circling is completed. Each EPI fix is an eccentric position relative to the buoy. Each may be reduced to center individually and the final results meaned; but much less labor is involved if all the distances to each station are meaned at once; the two results are almost identical. It is only necessary to reduce each position if the distance from the buoy varies greatly with each fix.

Actual system calibration may be accomplished in one of two ways. EPI fixes are taken simultaneously with visual (sextant) fixes and the two plotted as accurately as possible on a distortion-free plotting sheet. Such computations as are necessary to determine the differences between the EPI distances and the true distances, as determined by the visual fixes, are made. The mean of all such observations will generally suffice as the EPI correction. This method usually affords a calibration over a short distance compared to the range possible with the system and may often be very close to one ground station and at a very great distance from the other. The better method of calibration is to use both Shoran and EPI simultaneously. It is necessary to have a shoran ground station established at or near each of the EPI ground stations. Calibrations may then be made by comparisons of distances measured by the two systems, the distances being reduced to a common denominator. Such calibrations may be made over a distance of many miles (20 or 30, as practical). If the calibration is made near each ground station, then a check is made on both long and short distances from each ground station. An analysis of the results will show if there is a change of correction with distance, or if there is a repeating non-linearity in the system. Generally the spread has been relatively small, and the mean of all the differences has been used as the correction. The siting of the shoran antenna with respect to the EPI antenna is important to simplify computations. The antenna should be so located that the calibration course may be either with the two antennas in range or on the perpendicular bisector of the line joining them. In the first case, the distance between the two antennas becomes a constant factor and can be eliminated; in the latter case, the Shoran and EPI distances are corrected for their known errors before the final comparisons are made.