MASSACHUSETTS INSTITUTE OF TECHNOLOGY
RADIATION LABORATORY SERIES

LOUIS N. RIDENOUR, *Editor-in-Chief*

LORAN

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

RADIATION LABORATORY SERIES

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28. INDEX—*Henney*

LORAN

Long Range Navigation

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LORAN

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Foreword

THE tremendous research and development effort that went into the development of radar and related techniques during World War II resulted not only in hundreds of radar sets for military (and some for possible peacetime) use but also in a great body of information and new techniques in the electronics and high-frequency fields. Because this basic material may be of great value to science and engineering, it seemed most important to publish it as soon as security permitted.

The Radiation Laboratory of MIT, which operated under the supervision of the National Defense Research Committee, undertook the great task of preparing these volumes. The work described herein, however, is the collective result of work done at many laboratories, Army, Navy, university, and industrial, both in this country and in England, Canada, and other Dominions.

The Radiation Laboratory, once its proposals were approved and finances provided by the Office of Scientific Research and Development, chose Louis N. Ridenour as Editor-in-Chief to lead and direct the entire project. An editorial staff was then selected of those best qualified for this type of task. Finally the authors for the various volumes or chapters or sections were chosen from among those experts who were intimately familiar with the various fields, and who were able and willing to write the summaries of them. This entire staff agreed to remain at work at MIT for six months or more after the work of the Radiation Laboratory was complete. These volumes stand as a monument to this group.

These volumes serve as a memorial to the unnamed hundreds and thousands of other scientists, engineers, and others who actually carried on the research, development, and engineering work the results of which are herein described. There were so many involved in this work and they worked so closely together even though often in widely separated laboratories that it is impossible to name or even to know those who contributed to a particular idea or development. Only certain ones who wrote reports or articles have even been mentioned. But to all those who contributed in any way to this great cooperative development enterprise, both in this country and in England, these volumes are dedicated.

L. A. DuBridge.

Preface

THE preceding volumes of the Radiation Laboratory Series are surveys of radar system engineering, radar systems of navigation, and radar beacons. Like radar, the long-range system of navigation described in this volume depends upon the transmission and reception of pulsed radio signals, but it makes use of much lower radio frequencies and does not involve reflection from a target.

The Loran system was developed at the Radiation Laboratory during World War II to meet the needs of the Navy in convoy operations and to provide all-weather navigation for aircraft by day and night. At the close of the war, some 70 Loran transmitting stations were in operation, providing nighttime service over 60 million square miles, or three-tenths of the surface of the earth. About 75,000 shipborne and airborne navigation receiver-indicators had been delivered by various manufacturers, while the Hydrographic Office had prepared and shipped $2\frac{1}{4}$ million charts to the operating agencies.

The purposes of the present volume are to describe the Loran system, its principles and its equipment, as they existed at the end of the war and to offer suggestions for their adaptation and improvement for civilian service in time of peace. Since electronic time measurements are fully discussed in other volumes of this series, these techniques have not been treated in detail here. Similarly, relatively little space has been devoted to material found in the instruction books for various items of Loran equipment.

Wherever possible, the individual chapters have been written by those members of the group who have been most closely associated with the material concerned. However, many former members of the group who contributed greatly to the development of Loran concepts and equipment have been unable to describe their work in this volume. To Mr. Melville Eastham belongs the credit for the organization and administration of the Loran Group during the difficult early days. His leadership made the whole development possible and procured the needed support from the Services before the merit of the system had been fully demonstrated. Mr. Donald G. Fink and Professor J. C. Street made many contributions and successively assumed the administrative burdens after the retirement of Mr. Eastham and before being called to more responsible duties elsewhere. Throughout the program Mr. Walter L. Tierney, who managed all field activities, was a source of strength to the entire group. Professor J. A. Stratton made valuable preliminary studies of propagation at Loran frequencies, but his knowledge and talents were soon demanded for other purposes. After the Loran system had been successfully demonstrated, Mr. Robert J. Dippy, the originator of the Gee system, brought the experience of the British laboratory, TRE, to bear upon Loran problems and helped the group especially in improving the designs of the receiver-indicator and the transmitter timer.

The U.S. Coast Guard, Bureau of Ships, General Electric Company, Sperry Gyroscope Company, Fada Radio and Electric Company, Radio Engineering Laboratories, and the Bartol Research Foundation have kindly supplied photographs and granted permission for their use as illustrations of Loran ground stations and equipment. The Hydrographic Office has granted permission for the reproduction, as Appendix A, of a summary report on its Loran program. Thanks are also due to Miss Constance Henderson for her aid in preparing the drawings and to Miss Corinne Susman for her capable service as editorial assistant.

The publishers have agreed that ten years after the date on which each volume of this series is issued, the copyright thereon shall be relinquished, and the work shall become part of the public domain.

THE AUTHORS.

CAMBRIDGE, MASS.,
October, 1946.

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PART I
THE LORAN SYSTEM

CHAPTER 1

INTRODUCTION

By B. W. Sitterly and D. Davidson

The Loran system is a radio aid to navigation. It provides means, independent of all other aids (including even the compass and the log or air-speed meter), for locating a moving vehicle at a given moment and for directing it to a predetermined point or along a predetermined path. There are many other radio aids by which ships or aircraft may be located or guided; these operate in accordance with various principles, and as a background to the discussion of Loran it is profitable to consider some of these principles and to describe and compare some of these aids briefly.

NAVIGATION BY FIXING OF POSITION

In general, a navigator locates himself at the intersection of two lines of position on the surface of the earth. Each line is the locus of the points at which some observable quantity has a specific value. For example, the visual compass bearing of a recognized landmark places the navigator upon a line that is the locus of all points from which the landmark has the given bearing. This line is practically identical with a rhumb line (line crossing successive meridians at a constant angle) on the earth, laid off from the mark along the reverse bearing. A sextant altitude of the sun places the navigator upon a line from all points of which the sun will be seen at that altitude. This line is a circle on the earth, centered at the subsolar point, of spherical radius equal to the complement of the altitude. It will be convenient to classify navigation aids according to the forms of the lines of position that they give.

1·1. Position from Measurement of Two Bearings (Lines Are Radii). *Direction-finding.*—This is the familiar method used in visual piloting of a ship, in which the navigator takes bearings of two known marks and plots on the chart the reverse bearings from the marks; the intersection of the lines is his location. Conventional radio direction—finding is the same geometrically; each mark is a transmitter sending out radio signals. In the simplest form of system the operator, instead of sighting over a pelorus, hears the signals through a receiver connected to a loop antenna that he rotates around a vertical axis until an aural null is obtained. The normal to the plane of the loop then lies in the direction from which the signals come. If the distance between the receiver and the transmitter is considerable, the line of position will not be quite straight on a chart, nor will its direction at the transmitter be quite the same as at the receiver, but a simple correction can be applied to the readings to allow for these differences. There are many more elaborate forms of radio direction-finder, employing more complex antennas, automatic null-seeking or scanning and visual instead of aural presentation, but all operating in accordance with the same principles.

As a refinement to facilitate the operation of the direction-finder, the loop can be rotated automatically by a motor, with the indication electrically coupled so that it follows the rotation of the loop. Compensation for quadrantal error can be made automatically, and all bearings can be presented as true bearings.

An increase in precision may be gained by transferring the direction-finding function to receivers at fixed ground stations. The navigator uses no equipment but his communications transmitter, with which he asks the stations for bearings. Their receiving antennas determine the directions of his signals, and they communicate the bearings to him for plotting.

Orfordness Beacon.—The British "Orfordness" beacon exemplifies an ingenious technique by which the navigator obtains his bearing from a ground station by a time measurement, using only his communications receiver and transmitting no signals himself. The ground station or beacon transmits a steady tone from a loop antenna that is rotating once a minute about a vertical axis. The radiation pattern has two opposite null lines that sweep around the beacon at the rate of 6° per sec., and as one of these passes the north direction, the signal is given a coded interruption. The azimuth of a navigator from the station is therefore six times the interval in seconds from the time when he hears the interruption to the time when the null passes over him (or this amount plus 180°).

Sonne.—The German "Sonne" beacon (termed "Consol" by the British) combines the principles of the Orfordness beacon and the common radio range described in Sec. 1·5 but is much more elaborate and accurate than either. The ground station has three fixed vertical antennas in line, so spaced, keyed, and phased that interference between their signals produces a radiation pattern of about a dozen sectors in which successions of dots are heard that alternate with sectors in which dashes are heard. Since the dots and dashes are interlocked, along the radial lines bounding the sectors they merge into a steady tone (equisignal). The dots and dashes are emitted, one a second, for a minute, during which time the radiation pattern is slowly rotated by shifting the phases of the two outside antennas, and hence at the end of the minute each dot sector has moved into the place of the adjacent dash sector, and vice versa. During the next minute a steady omnidirectional tone is emitted by the central antenna. Then the dots and dashes are repeated, starting at the initial configuration and going through the same rotation again, and so on. A navigator determines his radial line of position within his sector by measuring the time that elapses from the beginning of any dot-and-dash period to the instant at which the advancing equisignal boundary of the sector sweeps over him. He does this by simply counting the dots and dashes for these beat seconds, and one changes to the other as the boundary passes. Which sector he is in must be determined by conventional direction finding on the signal during the steady-tone period or by dead reckoning. The transmissions are received on an ordinary radio receiver in the 250- to 500-kc/sec region, and fixes are plotted on a special chart giving the various zones and a key for each zone for interpretation of the received dot-and-dash cycle.

Omnidirectional Radio Range.—The so-called "omnidirectional radio range" operates still differently. It may be regarded as a development of the radio range of commercial air traffic (see Sec. 1·5) to which the Sonne beacon is also akin. Four antennas mounted at the corners of a square at a ground station send out a continuous signal, the different antennas being phased so that a figure-eight radiation pattern results, and the phases are steadily and uniformly shifted so that the pattern rotates around the station. At a distance, the received and rectified signal has an audio modulation whose phase at any instant depends on the azimuth of the receiver from the station. In order to obtain a bearing from the phase of the audio modulation some reference direction must be established. This is done by exciting a center antenna in the square at the carrier frequency, amplitude-modulating the signal at 10 kc/sec and frequency-modulating the 10-kc/sec modulation at the frequency (60 cps) of rotation of the radiation pattern. This reference frequency modulation is made to reach its maximum when the maximum of the directivity pattern passes through North. At any receiving point, the difference in phase between the reference signal and the rotating signal is examined, and this phase difference in degrees is exactly equal to the bearing to the beacon in degrees. A 180° ambiguity occurs, but this is resolvable in the receiving apparatus.

The receiving equipment contains a receiver whose output is fed to two separate channels. In one, a low-pass filter sorts out the 60-cps modulation of the carrier (the rotating phase signal), whereas in the other a high-pass filter presents the 10-kc/sec subcarrier to a discriminator that, in turn, removes the subcarrier and yields the 60-cps reference signal. By suitable comparing and indicating circuits, the phase of the reference voltage is compared with that of the rotating phase voltage, and the bearing is shown on a meter.

For the long-range version of the system, the 10-kc/sec subcarrier would be replaced by a 1-kc/sec subcarrier, and large towers would be used instead of high-frequency arrays.

1·2. Position from Measurement of One Bearing and One Distance (Polar Coordinates).—A compass bearing on a visible object plus a sextant measurement of its apparent size or a radio bearing on a beacon plus a measurement of the interval between the receptions of synchronized radio and sound signals coming from it will provide a navigator with his polar coordinates with respect to the object or beacon. (The bearing as observed must be reversed, of course, since it places the origin at the observer.) The celestial altitude and observed azimuth of a heavenly body will theoretically give similar information, but it is not useful practically because the linear equivalent of the uncertainty of the compass reading may be a hundred miles as a consequence of the great distance to the substellar point that is the origin of the coordinates.

Radar (Range and Bearing).—Most radar systems give distance and direction (range and bearing). A highly directional transmitting antenna sends out a narrow beam of energy and rotates or fans over a sector, in order to scan its field. The returning echoes are made to intensify the beam of a cathode-ray tube. The range is commonly presented by deflecting the electron stream of this cathode-ray tube away from a normal equilibrium track down the axis of the tube (where it produces a light spot at the center of the circular screen) toward the edge of the screen, the range being approximately proportional to the deflection. By synchronizing the direction of the deflection with the scanning mechanism of the antenna, bearing on the earth's surface is presented as bearing on the screen. This displaying mechanism is the well-known plan position indicator, PPI. It gives the observer, in effect, a map of the region scanned, centered at his location. Because the distance measured by the travel time of the signal is the airline distance (slant range) and not the projection of this on the ground, the map is somewhat distorted. The measured ranges are accurate, being taken with reference to accurate calibration markers provided by a precise high-frequency oscillator, but a correction that is a function of the range and the difference of elevation between the observer and the target must be applied to reduce the observed slant range to range from the point on the ground beneath the observing aircraft.

The terrain in the vicinity of the aircraft is scanned by a narrow beam of energy produced by a suitable antenna and reflector. It is fanned vertically so as to irradiate all objects on the ground at different ranges but at the given bearing. This fan beam is rotated or oscillated back and forth so as to cover either the full 360° of azimuth or a selected sector of it, as desired. Because of the differing reflectivity of the various features of the terrain, and because of the distinctive echoes returned by some geographically prominent ones such as cities and large bridges, a plot of the scanned terrain is presented on the radar oscilloscope or PPI. Although such systems are seldom used for navigation by actually plotting positions of the aircraft on a chart, they have been widely used for what can be thought of as extended visual piloting. In cloudy weather the radar information takes the place of visual information, and even in fair weather the radar data supplement visual observation in a useful way.

The properties of such radar systems and various applications of them are discussed at length in Vol. 2 of the Radiation Laboratory series entitled *Radar Aids to Navigation.*

Radar Beacons.—It sometimes happens that important places on the ground are not unambiguously marked by characteristic radar patterns on the PPI. This can be remedied by the use of radar beacons. The beacon acts to some extent as an amplifier of radar echoes. It has a receiver that detects the pulses sent out by a radar set and causes them to trigger the beacon's transmitter to emit single reply pulses or groups of pulses. Since the time required for the circuits of a beacon to act can be made to be negligibly small, the reply is much like a radar echo. It differs in that it can have any desired frequency and can be a pulse or group of pulses differing in duration from the original interrogating pulse. The replies can thus be coded for identifying the beacons. Since the frequency of the reply is different from that of the interrogating radar pulse, the reply pulses can be received and displayed separately from the radar echoes, provided that the radar set has a receiver tuned for these beacon signals. Such radar-beacon systems are discussed further in Vol. 2 mentioned above and more thoroughly in Vol. 3 entitled *Radar Beacons.*

Rebecca-Eureka.—One radar-beacon system that found considerable use in the war is called the Rebecca-Eureka. In this system an aircraft carries an interrogator (the Rebecca), which may transmit on any one of a group of frequencies around 200 Mc/sec. Directional receiving antennas (dipole and director) are mounted on each side of the fuselage near the nose, and by lobe switching these are made to receive replies from a fixed ground beacon (the Eureka) alternately. Transmissions of the Rebecca are made from a stub mounted under the fuselage. The indication provides two vertical deflection-modulated traces back to back in the center of the oscilloscope; range is measured upward from the base. Thus the vertical displacement of the signal gives the range, and the horizontal deflection of the signal gives a left-right indication; a beacon to the left gives a greater deflection in the left half of the oscilloscope than in the right. Since the screen has a grid superimposed on it, bearings can be estimated roughly. Homing to a Eureka beacon is accomplished by flying a course such that the oscilloscope deflections to the right and left remain equal. The range of the system is about 25 to 50 miles, depending upon the Eureka beacon and the altitude of the aircraft. Some of the Eureka beacons weigh only about 20 lb complete and hence are readily portable.

Control of Aircraft by Ground Radar.—Use has also been made of ground radar stations for determining the azimuth and distance of aircraft, the location to be communicated to the navigator. This has been employed particularly in the surveillance and tactical control of military aircraft. Ships or aircraft may be detected at the station merely by the radar signals that are reflected from them, or they may carry radar beacons, which will also identify them to the station. If separate receivers are provided, the same transmitter may be used to handle at the same time craft with radar beacons and those without. When a single craft or group of craft is to be located or directed, increased accuracy in bearing may be obtained by using special transmitting antennas which project two-lobed or alternating-lobed patterns nearly in the same direction. The equisignal zone between the lobes is narrow, so that discrimination in angle is considerably improved. These systems and methods are also discussed in Vol. 2 of this series.

It is to be noted that in general the bearing is much less accurately determined than is the range, so that for the most precise determination of position two ranges should be used rather than one range and one bearing.

1·3. Position from Measurement of Two Distances (Lines Are Circles).—This form of position finding has many varieties. Three commonly used methods that do not use radar technique may be mentioned. The distance of a visible mark of known linear dimension may be calculated if the apparent angular magnitude of this dimension is measured with a sextant; this distance is the radius of a circular line of position whose center is the mark. Distance from a point is also the quantity obtained in celestial navigation, as was mentioned above. A navigational beacon that emits simultaneously a radio signal and a sound signal in air or under water gives the navigator a measure of his distance from the beacon, for this is proportional to the time interval between the radio signal and the sound signal as they are received by him. Two observations of any of the above sorts establish two circular lines of position; their intersection gives the fix.

Radar and Radar-beacon Methods.—Since a radar set can readily measure range to an accuracy of a few hundred feet or better, a precision much higher than it gives for measurements of bearing, it is peculiarly suitable for getting fixes by measuring the distances to two objects at known positions. In principle this can be done by using two natural radar echoes. In practice this procedure is not so accurate as it might appear to be at first glance, since the connection between the observed range of an echo and the exact distance to some particular point of the extended object that produces the echo is not always well enough known. If the full potentialities of the method are to be realized, radar beacons at accurately known locations must be used. Systems of this type in which apparatus in an aircraft measures the distances from it to two beacons on the ground are known as H-systems.

In this type of system, in which ranges only are measured, there is no need for using directional antennas in the interrogating aircraft. The particular radio frequency used is of no consequence, provided that it is high enough to allow the use of the short pulses required for accurate measurement of distance. The principal H-systems used during the war and their frequencies are the following:

1. *Gee-H.* Gee-H operates at 80 to 100 Mc/sec for interrogation, 20 to 40 Mc/sec for reply. The transmitters of the Gee system were modified so that they could operate as beacons in addition to emitting their regular pulses (see Sec. 1·4), and special interrogating equipment was added to the aircraft.
2. *Rebecca-H.* The Rebecca-H operating in the 200-Mc/sec region made use of the airborne Rebecca equipment previously mentioned with special high-powered Eureka beacons.
3. *Micro-H.* Micro-H operates in the 10,000-Mc/sec region. The airborne AN/APS-15 bombing and navigational radar sets interrogate AN/CPN-6 ground beacons.
4. *Shoran.* This system operates in the 300-Mc/sec region. It was specially designed for this purpose.

All of these H-systems except Shoran involved a somewhat makeshift adaptation of existing equipment. Shoran was developed for this type of navigation alone, with careful attention to appropriate instrumentation. It has remarkable over-all accuracy, errors of fix of less than 75 ft being readily obtainable. It was just coming into widespread use in bombing of high precision as the war ended. It seems likely that it will be of great usefulness for accurate mapping by aerial photography.

Although the H-system is simple enough in principle, the computation of the location from the two observed ranges or the advance computation of the two ranges to a desired location is laborious. During the war much effort had to be spent on computations of this sort.

One advantage of the H-system is that numerous aircraft flying independently can get fixes by interrogating the same beacons. The number that can use the beacons at the same time varies in the different forms of the system because of differences in the design of the beacons and in the effects on the airborne equipment of the beacons' replies to the other aircraft.

Oboe.—The Oboe system, much used during the war for accurate blind bombing of the Ruhr valley, is the converse of the H-system. Two ground stations measure the distance to a beacon-carrying airplane and give it signals so that it can fly on a circle of predetermined radius about one station and release a bomb when it arrives at the proper distance from the other station. In this system the careful measuring can be done in ground stations that are spacious compared with the cabins of aircraft. The traffic capacity is low, however, and a high degree of coordination between the ground stations and the airplane is required.

In both the H-system and the Oboe system the distance from the ground stations is limited to the radar-horizon range given roughly by the formula

$$r_{(\text{miles})} = \sqrt{2h_{(\text{feet})}}.$$

These systems are discussed in greater detail in Vol. 3 of the present series entitled *Radar Beacons.*

1·4. Position from Measurement of Two Differences of Distance (Lines Are Hyperbolas).—During World War I a method was developed for locating enemy guns by measuring the differences between the times at which their reports were heard at three different listening posts. The posts were electrically connected so that the three detonations received from a shot from a given gun could be recorded on one chronograph. The time interval, from the arrival of the report at one post to its arrival at another post, is a measure of the amount by which the gun's distance from the latter post exceeds its distance from the former. This difference is precisely the constant that defines a hyperbola with respect to the two posts as foci. The time interval between the reception of the gun's report at the middle listening post and its reception at one end post locates the gun upon a hyperbolic line of position that passes between the two posts and is concave toward the nearer one. The interval between the received reports at the middle post and at the other end post locates the gun upon another hyperbolic line of position. The two hyperbolas intersect at the gun.

This particular system has never been used in navigation. Employing sound signals, it possesses no advantages over other short-range locating systems but is more complex. Systems similar in principle, however, using radio signals and radar time-measuring techniques, with reversal of the direction of travel of the signals (so that they are sent out by ground stations and received by the navigator), have been developed in Great Britain and the United States within the past five years and have proved extremely valuable. The most widely used of these systems are Gee (British) and Loran (American).

In Gee and Loran the fundamentals of operation are the same. Two ground transmitting stations define a family of lines of position by emitting pulses in such a manner that the pulses from one are distinguishable from those of the other. The interval from the emission of a pulse by station A to the emission of the next pulse by station B has a fixed, known value. The interval between these pulses as they are received by the navigator depends upon his location. It will be equal to the fixed value if the navigator is equally distant from the stations. It will be greater than the fixed value if he is nearer to A (for then the pulse from B, traveling farther than that from A, falls farther behind it in time) and less if he is nearer to B (for then the pulse from B gains by its shorter journey). Every distinguishable interval characterizes a different hyperbola of position, which is a fixed line on the earth's surface and may be precomputed and drawn on a chart. Two pairs of stations (which may be three stations in all) define two intersecting families of lines of positon, forming a Gee lattice or Loran grid; two observed time intervals, one from each family, define an intersection or point on this coordinate system.

The navigator is provided with a receiver having a cathode-ray tube, the face of which displays the successive incoming pulses as pips upon a calibrated time base, in the manner of radar. The time intervals are accurately read by means of the calibrations (the latest Loran indicator shows them directly on numbered dials). The navigator enters the chart with the numbers as read and finds by inspection the corresponding point among the grid lines.

Gee.—In the Gee system the baselines are approximately 75 miles long and are disposed with the master station in the center and two or three slaves dispersed around it. Each of these groups of stations (chains) operates on a different radio frequency, and there are half a dozen frequencies available in each of four bands. This frequency flexibility is necessary, since as many as six chains have been operated in one region; it was also convenient during World War II to have different frequencies available in order to make the enemy's problem of jamming the system a more formidable one. The frequencies commonly employed are between 20 and 85 Mc/sec; hence the range is slightly more than optical, the best results being observed at high altitudes.

The navigator's indicator presents visually a family of four or five pulses, two being transmitted from the master station and one from each slave. A double slow-trace pattern having a total length of 4000 μsec is employed. By the use of delay circuits, four fast traces can be initiated at such times that the master-station pulses appear on two fast traces and the inverted pulses from any two slave stations appear on the other two fast traces. Each of the slave pulses can be laterally adjusted to lie with its base coincident with the base of one of the master pulses. When this adjustment is completed, the two time differences (between each of the master pulses and its corresponding slave pulse) are read from the relation between families of markers which can be switched onto the oscilloscope traces. The most closely spaced family of markers has a unit separation of $6\frac{2}{3}$ μsec and interpolation to tenths permits a reading to $\frac{2}{3}$ μsec. The received pulses are about 6 μsec in length.

Gee is a free-running system (as is Loran). The recurrence rate of the stations (250 pps) is based on the recurrence rate of the master station. The master may drift, and the slaves will follow this drift in rate without affecting their time difference. To a navigator this drift is immaterial, for his equipment is also freely running. As soon as he has received the signals from the ground stations, he adjusts his equipment for minimum drift during the time of measurement. Once he has made the lateral adjustment of the pulses (in Loran it would be the match of the pulses), he no longer requires the signals and can make the actual reading at his leisure. In the meantime, the signals may have drifted with respect to his equipment, but this will, of course, have no effect on his reading or any subsequent readings.

Standard Loran.—Loran is a pulsed medium-frequency long-range system of hyperbolic navigation. Shore stations, synchronized in pairs by means of ground waves, provide lines of constant time difference of arrival of the pulses from each pair. The navigator may select any two pairs to obtain a fix, reading the time difference of one pair at a time. In the daytime, only ground waves are available, and they are used over water out to 700 nautical miles or more. At night, ground waves are received only to 500 nautical miles because of the higher noise level; but because of the stability of the lower ionospheric layer, fixes are available out to 1400 nautical miles by using single reflections from this layer. As many as eight station pairs can be operated on a single radio frequency, and four radio frequencies have been assigned. The pairs at a common radio frequency are identified by means of the different recurrence rates at which they operate.

A pair of received signals is displayed on a double-trace oscilloscope pattern whose total length is about 40,000 μsec. By the use of delay circuits two fast cathode-ray traces are initiated at such times that one trace exhibits the master signal and the other exhibits the slave. The leading edges of the pulses are superimposed, and the amplitudes are made equal. When this final adjustment is complete, the time difference is read by removing the signals and reading the relation between families of markers that are switched onto the traces. This time difference establishes one line of position, and it is necessary to repeat the procedure with pulses from a second pair of stations to secure a second time difference and line of position. The total time required to take and plot a fix under average conditions is about three minutes.

SS Loran.—Sky-wave Synchronized Loran is a nighttime version of Loran wherein a pair of ground stations are synchronized by the reflection from the lower ionospheric layer. Baselines are from 1000 to 1400 nautical miles in length. Stations are usually disposed in a quadrilateral formed by two pairs. The navigator follows the same procedure as in Standard Loran except that sky waves only are used for reading. Coverage over both land and sea is good, and signals are equally well received at all altitudes. Over most of the coverage area crossing angles are greater than 70°, and the position lines of a pair are almost parallel. The system can be used for general navigation and has been used for area bombing by the RAF.

Decca.—The British Decca system is similar in geometrical principle to Gee and Loran but very different in detail. The transmitting stations send out c-w signals; their interference generates hyperbolic coordinates that are continuously and automatically presented by phase meters that form part of the navigator's receiver. Operation of these meters is wholly differential; the coordinates of the point of departure must be set into the instrument manually at the beginning of every continuous run.

As in other hyperbolic systems, at least three stations (two pairs) are necessary to establish a fix. The master station transmits at the basic frequency of the system, and the slave in one pair radiates at a different frequency related to that of the master by some simple ratio such as 3/2 or 4/3. The other slave in a triplet operates at still another simply related frequency. Each slave monitors the master's transmissions and maintains its own emissions at its assigned frequency but with phase rigidly related to that of the master. The family of hyperbolic lines that result are thus lines of constant phase difference.

The navigator's equipment consists of a receiver channel for each station (three in all for fixing), suitable multiplying and phase-comparing circuits, and two phase-indicating meters (similar to watt-hour meters). Maintenance of a constant-phase reading indicates that a hyperbolic line is being followed, and changes in phase may be summed up when cutting across these "lanes." The wavelengths used are of the order of a mile, and the reading precision has been variously quoted to be $\frac{1}{1000}$ to $\frac{1}{50}$ of a wavelength.

Since interfering continuous waves can distort the readings in Decca almost without limit and without the navigator's being immediately aware of it, the use of baselines more than 100 miles long is not satisfactory, because of the distorting effects of sky waves at greater distances, and the geometrical accuracy is therefore low. The useful service radius is similarly limited to as little as 200 miles.

POPI.—The post office position indicator, POPI, embodies a different application of hyperbolic navigation. It was advanced by the British Post Office as a general navigational system that when fully exploited in its principles might even provide blind-approach and glide-path facilities. It has not been introduced to service or commercial usage, having been carried through the trial stage only.

Two signals originate from two vertical antennas located a short distance apart, the operating frequency being alternately transmitted from each antenna at the rate of five times per second. Since the antennas are separated, the phase difference registered everywhere describes a family of confocal hyperbolas, with foci at the antennas. In POPI, the antennas are erected so closely together compared with the distances to the receiver that the family of hyperbolas effectively degenerates into a system of straight lines issuing from a point midway between the radiators. Thus, although POPI is technically a hyperbolic system, for all practical purposes it must be considered a radial system.

The system of lines is mirrored with respect to the line joining the radiators. To avoid ambiguity, signals are also radiated from a third antenna located at the third corner of an equilateral triangle. Usually the spacing is a half wavelength. The keying sequence is then "*A*, *B*, *C*, space, *A*, *B*, *C*, space," etc., and the receiver compares the phases of any two. The bearing is determined by selecting the signals from the two antennas that are most nearly equidistant, and the remaining signal is used to establish the sector. Six sectors are defined, and the purpose of selecting the signals from the two antennas most nearly equidistant is to obtain greater discrimination (near the perpendicular bisector there are more lines per mile and therefore the geometrical accuracy is greater). This choice of signals from the two more nearly equidistant antennas is also advantageous from a propagational standpoint. For signals traveling equal distances errors arising from ionospheric reflections are smaller than for signals traveling unequal distances. A navigator requires at least two POPI stations to obtain a fix with his indicator.

The chief feature that distinguishes POPI from other systems is the method of presenting the coordinate information in the navigator's equipment. In what has been described above, the phase differences that occur over the radiation pattern are obviously those of radio frequencies, a typical frequency being 800 kc/sec for the system. In order to facilitate detection and measurement it is desirable to examine the phase difference at audio frequency. This audio frequency is supplied by radiating a frequency that differs from the operating frequency by a small amount of about 80 cps, from a fourth antenna placed at the center of the triangle. Since this is mixed in the receiver with the transmissions from the other antennas, an audio signal results. The original phase difference between the r-f signals received from two antennas is equal to the phase difference between the audio signals that result from the beating of these two r-f signals with the signal from the central antenna. The receiver delivers an audio signal into a "ringing" circuit which continues to oscillate with a definite phase relationship to the incoming signal even after the signal is no longer received. The output of this circuit is compared in phase with the output of a similar circuit actuated by the second signal (in the *A*, *B*, *C* sequence), and the difference is recorded on a meter. An interval follows, and the comparison is made a second time, the whole cycle recurring five times per second. Actually, there are three signals in the sequence, and the navigator can select any two of these for the phase comparison.

NAVIGATION BY TRACKING AND HOMING

1·5. Tracking.—A vehicle may be directed along a given path by any of the methods mentioned above, except by celestial observations. Celestial navigation is unique in that the lines of position which it furnishes move over the surface of the earth at a speed much greater (in low and middle latitudes) than the cruising speed of any aircraft that is now practicable. All the other forms of visual and radio navigation may be used to guide a navigator along a track that may be a straight line, a circle, a hyperbola, or some other curve (a "true course" by compass, for instance, is a spherical equiangular spiral, or rhumb line). In the following discussion, only radio and radar methods of tracking will be considered.

Radio Range.—The most widely used method of defining a path for traffic is the radio range. In the commonest form of this, a ground station has two crossed loop or Adcock antennas. The code letter *A* (dot-dash) is transmitted from one of the antennas, while the other sends out the letter *N* (dash-dot), interlocked with the *A*. Since each antenna pattern has two lobes separated by nulls and these patterns are crossed, the result is a combined pattern of four sectors, two where *A* predominates and two where *N* predominates. Since the successions of *A*'s and *N*'s are interlocked, a continuous tone is heard along the equisignal boundary between adjacent sectors. This tone, heard in the communications receiver of the navigator, guides him along the boundary. If he departs from it, the tone breaks into *A*'s or *N*'s, and the letter tells him the side to which he has wandered. The four tracks defined by this system may be directed as desired by suitably choosing the forms of the antennas, the angle between them, and the relative power of the *A*'s and *N*'s. The tracks are straight, extending out from the station.

Circular Tracks by Radar.—If a navigator directs his craft so that the radar signal returned from an identified mark on the earth maintains a constant delay, indicating a constant distance, the track followed is a circle around the mark with radius equal to the distance. The distance may be chosen so that the circle passes through a desired destination. The navigator may use his indicated distance from a second mark as a measure of his approach to the destination; when this distance coincides with the known separation between mark and destination, he has arrived. The marks are generally radar beacons. As described, the method is simply a particular use of the H-system of position finding that has been discussed in Sec. 1·3.

Hyperbolic Tracks.—A constant reading, maintained on the Gee, Loran, or Decca indicator carried by a vehicle, guides the vehicle along one member of the family of hyperbolas generated by the pair of transmitters whose signals are compared. Location along this track is shown by the changing reading on another pair of transmitters as the aircraft cuts across its associated hyperbolic family. A hyperbolic track will also be followed if a radar navigator maintains a constant difference between his distances from two marks or radar beacons, so that these increase or decrease at the same rate. The constant difference may be automatically added to the nearer reading by introducing a corresponding time delay either into the response of the radar beacon on the ground or into the action of the receiver in the aircraft. This difference is then maintained between the actual distances, and the apparent distances remain equal. The radar indicator displays this equality clearly, and the navigator can easily hold to it. The Micro-H bombing system used circular or hyperbolic tracks at will; along the latter, the bomb was released when both apparent distances together reached the precomputed value.

1·6. Homing.—A track defined in one of the ways just described may be chosen so as to pass through any desired destination within range, but it will be a unique track, except in the special case that the destination is the center from which a family of radial tracks proceed (as in direction finding). In that case only is a navigator in any arbitrary location able to travel directly to the destination along one line of position. In every other case he must follow the line of one family that passes through his location until it intersects the line of another family that passes through the destination, or else he must cut across both families.

The obvious and most commonly used method of homing is to steer so that a radio signal emitted at the destination is always received from dead ahead, according to the navigator's direction-finder, or so that the image of the destination on the PPI screen of his radar set always appears dead ahead. This is the special case just mentioned. It is to be noted that if this procedure is followed when there is any cross wind or current, the aircraft or vessel will not travel in the direction in which it is headed but in a curve concave toward the direction from which the deflecting force acts and increasing in curvature as the goal is approached. The navigator may maintain a straight approach by heading to windward of the direction of the destination, but this requires accurate knowledge of the drift.

Homing may be accomplished in the general case, cutting across the two coordinate families, by steering so that the two instrument readings, which indicate the present position of the craft, approach their destination values at rates approximately proportional to the amounts by which they respectively differ from those values. (For example, if the present Gee coordinates of an aircraft are 6.4 and 38.5 and the destination is at 16.6, 35.1, the craft should be steered so that the first coordinate increases about three times as fast as the second diminishes.) In a system like Gee, where both the destination readings can be set into the indicator beforehand, an almost direct homing track may be held by eye estimation of the motion of the pips on the screen. Strict proportionality of change of coordinates could be maintained by the use of rather simple auxiliary equipment, which would direct the craft along a definite track to the destination. Such equipment has not been developed as yet, but suggestions regarding its form and use in the Loran system are given in Chap. 4. The technique might be adapted to any system in which position is referred to a coordinate grid based upon instrument readings.

1·7. General Comparison of Basic Techniques.—Some comparison of the basic techniques can be made without entering into details of instrumentation or operation.

1. The direction-finding and hyperbolic systems, which do not use the echo or bounce-back principle of radar, have a great advantage in range or coverage, both because they are not subject to the twofold dispersal of a signal traveling over a return path and because they can operate with long waves, for which attenuation is much less than it is for short waves and for which range may be extended by ionospheric reflection. Radar systems must use ultrahigh or microwave frequencies in order to get definition in the optical sense.
2. Systems that measure distance by timing of signals give greater line-of-position accuracy than direct angle-measuring systems. With radar systems, accuracy of the circular lines of position is independent of distance or direction. With angle systems, accuracy is inversely proportional to distance. With hyperbolic systems (and the Sonne direction-finding beacon) accuracy depends on both distance and direction. At long distances the hyperbolic systems effectively determine angle by distance-measuring technique, with a considerable advantage in precision. Both angle and hyperbolic systems are affected at long ranges by errors due to variations in the ionosphere, but these affect the direction of

transmission more seriously than the time of transmission, again favoring the hyperbolic systems.

3. Continuous-wave systems require much narrower transmission bandwidths than pulsed systems, per transmission station. But this advantage is balanced by the fact that many pulse-emitting stations may operate in the same band, being distinguished by different pulse recurrence frequencies or different forms of coding, whereas each c-w station requires a band to itself.
4. Pulsed systems can generally work through higher atmospheric noise than can c-w systems and at long ranges are less seriously affected by vagaries of the ionosphere.

CHAPTER 2

HISTORY OF LORAN

BY J. H. HALFORD, D. DAVIDSON, AND J. A. WALDSCHMITT

2·1. Origin of Pulsed Hyperbolic Navigation in the United States. *The UHF Proposal.*—The pulsed, hyperbolic, radio grid-laying system for long-range navigation which finally evolved into the Loran system was first proposed to the Microwave Committee in October 1940, by its chairman, Alfred L. Loomis. This proposal involved the use of synchronized pairs of high-power high-frequency pulse-transmitting stations separated by distances of the order of several hundred miles. The families of confocal hyperbolic lines of constant time difference generated by these pairs of transmitting stations could then be interpreted as lines of position by observers equipped with electronic receiver-indicators capable of measuring the elapsed time between the arrival of corresponding pulses from the two members of each pair of stations. Ranges from 300 to 500 miles for high-flying aircraft were anticipated.

The Army Signal Corps Technical Committee had set up the following requirements for a "Precision Navigational Equipment for Guiding Airplanes" at its meeting on Oct. 1, 1940:

a. General: it is desired to have precision navigational equipment for guiding airplanes to a predetermined point in space over or in an overcast by radio beams, detection apparatus, or direction-finders.
b. Distance: maximum possible. Five hundred miles desired.
c. Altitude: the ceiling of present heavy bombers; about 35,000 ft.
d. Accuracy: the greatest accuracy obtainable. One thousand feet at 200 miles is desired.

The Loomis navigation system proposal was quickly accepted by the Microwave Committee and established as Project 3. A coordination subcommittee whose first recorded minutes are dated Dec. 20, 1940, was formed to arrange for the procurement, installation, and field testing of one pair of transmitting stations and suitable navigation equipment as outlined in the original proposal. This committee was made up of representatives from several of the large electronic manufacturing companies.

Although the precise method of synchronizing the transmitters had not been determined, and no agreement had been reached concerning the most practical method of constructing a suitable navigator's receiver-indicator, the committee initiated the following orders for about $400,000 worth of equipment during December 1940:

a. 2 receiver-indicators—RCA.
b. 2 receiver-indicators (independent design)—Sperry.
c. 2 crystal-controlled timers—Bell Laboratories.
d. 1 1.5-megawatt transmitter—Westinghouse.
e. 1 1.5-megawatt transmitter—General Electric.
f. 6 high-frequency pulse triode transmitting tubes—RCA.

When the orders for equipment were placed, it was estimated that most of the items would be available for test during the summer of 1941.

In addition to much discussion concerning the most practical methods of synchronizing the stations and providing the navigator with time-difference readings, there was considerable indecision concerning the best places to locate the experimental stations. Several mountain peaks were considered before it was finally decided to request permission to use two abandoned Coast Guard lifeboat stations located at Montauk Point, Long Island, and Fenwick Island, Del. This provided a 209-nautical mile baseline entirely over water and at the same time kept the stations within a reasonable distance of the Bell Telephone Laboratories in New York, from which Project 3 was coordinated.

Meetings of the Project 3 Committee and several subcommittees set up to coordinate transmitter, transmitting tube, and receiver-indicator development were held regularly throughout the winter and spring of 1941. The minutes of these various meetings contain numerous discussions of possible methods of synchronization of the stations and of measuring the time difference between the received pulses in the field.

Several distinguished British visitors attended many of these meetings. E. G. Bowen of the British Mission was present at the Project 3 Committee meeting on Dec. 20, 1940. Later, Squadron Leader G. Hignett of the British Embassy also participated. Although these British scientists were aware that a somewhat similar navigational system of hyperbolic grid-laying was under development in England, they were not completely familiar with it and were, therefore, able to give only general advice to the Project 3 Committee.

That the project, new in concept and untried experimentally, was foredoomed to failure under control of a loose administrative committee became apparent. This weakness was recognized particularly by Melville Eastham, who advised turning the central authority over to a full-time group at Massachusetts Institute of Technology that could make trials, suggest changes, and guide the whole development as experiment indicated.

Experiments at Lower Frequencies.—As soon as a few personnel had been hired, Eastham suggested to the Project 3 Committee that some of these people might be assigned the job of assisting RCA and Sperry in the development of a suitable indicator for the system. In the early spring of 1941, a small navigation group (four or five men) was formed, therefore, at Radiation Laboratory under the direction of Eastham and was gradually augmented, until in 1943 there were about 30 staff members. This group was under the technical direction of J. C. Street, on leave from Harvard University.

In addition to the receiver-indicator assignment, this group became interested in the basic concepts of the entire system. By early summer of 1941, the Radiation Laboratory Navigation Group, which had taken over the project from the microwave subcommittee, had come to the conclusion that far greater ranges might be attained from a medium-frequency system wherein sky-wave reflections could be utilized as in communications.

Accordingly, two portable pulse transmitters capable of tuning from 8.5 down to 2.9 Mc/sec and generating pulses of about 5-kw peak power were hastily constructed during the early summer of 1941 for the investigation. These transmitters were set up at the Montauk Point and Fenwick Island stations and pulsed at $33\frac{1}{3}$ pps by impulses from the Bell Laboratories timers that had been installed for use with the still unfinished Project 3 high-frequency transmitters. No attempt was made at synchronization during these tests. When this system was first proposed to Eastham and Bowen, they got the mistaken idea that it was for long-range direction-finding only, not grid-laying, as precision time measurements via the ionosphere were at that time unheard of. This misconception was not clarified until after the successful completion of the tests.

A set of receiving equipment was installed in a station wagon that roved as far west as Springfield, Mo. As expected by the Radiation Laboratory group, the sky-wave signals from the E-layer of the ionosphere were fairly strong and relatively stable. The stability of the first reflection was particularly encouraging. The lower frequencies produced the most stable signals at night, with the higher frequencies giving more stable sky-wave reflections by day.

These tests tended to show that the medium frequencies might be used for a truly long-range navigation system although the potential accuracy could be only estimated. It also became obvious during the tests that the circular sweep form of indicator could not be used satisfactorily for making time-difference measurements to the order of 1 μsec and, furthermore, that some form of two-trace indicator providing for a direct comparison of pulses by superposition of displaced sweeps would be necessary.

While these medium-frequency tests were underway, the first concrete information about the British Gee system was supplied to the Radiation

Laboratory during the late summer of 1941 by A. G. Touch of BAC. The visit of Touch was timely, since it came when all of the early Project 3 ideas on indication had been found awkward, if not impractical. Touch described the Gee system in cursory fashion but left two very important ideas in the minds of the navigation group:

1. Accurate measurements (to better than 1 μsec) could be made with portable equipment.
2. A multiple-trace indicator providing a means of matching pulses in time on delayed sweeps was a practical means of accomplishing this.

Similar conclusions had been reached by the field party that was away making observations at the time of Touch's visit. It is a striking coincidence that this party returned with a strong recommendation for a two-trace indicator at the same time that the Laboratory group had reached the same conclusion from consideration of Touch's report.

The evaluation of the circuits for a workable two-trace indicator followed during the fall of 1941, although many essential refinements came later.

During tests of the first two-trace indicator at Montauk, it was found that the 5-kw signals from Fenwick would be ample for direct synchronization, especially on the lower frequencies. On the basis of this information the Radiation Laboratory group decided that the long-range features of the medium-frequency system were of such great value that this system should receive the full attention of the MIT group, since no great advantage in duplicating the efforts of the British on the high-frequency system could be seen. The work on the original Project 3 was abandoned.

In spite of many technical shortcomings, the medium-frequency stations were synchronized during 1941, by means of the first experimental two-trace indicator located at an intermediate monitoring station at Manahawkin, N.J. (where the two signals had nearly equal amplitudes and could be more easily compared). Shortly thereafter, observers departed for Bermuda with slightly more carefully constructed equipment incorporating the two-trace indicator technique. Because the original low-power variable-frequency transmitters were still being used, the ground-wave signals were not expected to and did not reach Bermuda. Excellent sky-wave results were obtained, however, and the time-difference measurements made during January 1942 indicated an average error in the line of position of only about 2½ miles. Various frequencies (3.0, 4.8, and 7.7 Mc/sec) were used for these tests in order to determine which would give the best sky waves by night and which by day. Many excellent quantitative data were obtained from these tests.

While the observers were in Bermuda, a scheme was devised for changing the recurrence rate of the timing chain by small amounts, thereby providing a simple and effective means for causing the distant signal to appear to drift to a chosen position on the traces of the indicator. Further investigation of this method revealed the possibility of readily providing seven discrete increments in the recurrence rate in steps of 1 part in 400. These various rates could be used to permit the operation and identification of several pairs of stations at the same radio frequency. This improvement applied equally well both to the ground-station timers and those incorporated in the observers' portable indicators.

A few months before the official termination of Project 3, the entire field organization, including its manager, W. L. Tierney of the Bell Laboratories, was transferred to the Radiation Laboratory Navigation Group at Massachusetts Institute of Technology. As this field organization had worked out its own purchasing, receiving, and shipping programs, authority was granted by the Division of Industrial Cooperation of Massachusetts Institute of Technology to continue with these activities independent of the rest of the Radiation Laboratory. This arrangement continued throughout the life of the Loran group (later designated Division 11) and facilitated the carrying out of numerous critical field programs as well as the hasty procurement of much equipment for the Services.

Work that had been initiated during the latter part of 1941 on 100-kw pulse transmitters with plug-in tank circuits for operation on several frequencies was expedited during the spring of 1942 in order to provide a full-scale demonstration of the new medium-frequency system. With this power and frequency of 1.95 Mc/sec it was estimated that ground waves could readily be used for direct synchronization and that ground-wave ranges of roughly 600 to 700 nautical miles over sea water and sky-wave ranges out to 1300 to 1400 nautical miles by night could be achieved. Daytime sky-wave service over similar ranges was to be provided by transmitters operating simultaneously on about 7.5 Mc/sec. These secondary transmitters were actually never installed, partly because of doubt about the real utility of the additional service, but primarily because new transmitters were always required as fast as they could be produced for 2-Mc/sec service in new areas.

One of the most serious shortcomings of the Loran receiver-indicators used for the Bermuda tests was the difficulty of accurately measuring the time difference between two signals of different amplitudes. A relatively simple method of differential gain control was developed, thereby completing the basic evolution of the Loran receiver-indicator as reproduced by the tens of thousands for use during the war.

The First Loran Trials.—By June 1942, the first two high-power (100-kw peak power) transmitters had been installed and tested in the old Project 3 stations at Montauk Point, Long Island, and Fenwick

Island, Del. The first Radiation Laboratory timer (Model A) had been installed at Fenwick, the slave station, and direct synchronism established. One of the Bell timers was used in the master station at Montauk. During the spring of 1942 the basic recurrence rate for the system was reduced from $33\frac{1}{3}$ to 25 pps in order to provide a larger recurrence interval for the accommodation of signals (with sky-wave reflections) from such long baseline installations as were already being planned for linking Labrador and Greenland.

In the same month the first Naval Liaison Officer for Loran was appointed. He was Lieut. Comdr. (now Captain) L. M. Harding, USCG. He and his successors in that office were invaluable in making arrangements for Naval cooperation in trials and in surveying the sites for new stations.

On June 13, 1942, an improved model of the receiver-indicator, incorporating multiple recurrence rates and differential gain control, was taken aloft in a Navy blimp from Lakehurst, N.J., for a full-scale demonstration of the Loran system. Later that month arrangements were completed to send another receiver-indicator and observers out on an extended long-range observation trip on the USS *Manasquan*, a Coast Guard weather ship. The frequencies used for these tests were 1.95 and 7.5 Mc/sec, of which the former gave the better reception. Although only one set of lines of position was available for both of these tests, the results were so encouraging that immediate high-level Army and Navy action was instituted to underwrite the procurement and installation of a number of stations and shipborne receiver-indicators for an operational service test in the Northwest Atlantic, extending from Fenwick Island to Cape Farewell, Greenland, with sky-wave signals extending as far east as the Azores.

NDRC Procurement.—Several joint Army-Navy-NDRC meetings were held during the early summer of 1942 to discuss the progress of the system and to formulate plans for the most expeditious introduction of Loran to service use. As a result of these meetings, representatives of the Radiation Laboratory agreed to have four stations and three lines of position available for a full-scale service test on Oct. 1, 1942. For future installations in the North Atlantic and Aleutian areas, for operational trials, the Navy requested that the following equipment be procured by NDRC:

a. 250 model LRN-1 and model LRN-1A shipborne receiver-indicators.
b. 62 100-kw transmitters.
c. 50 navigator trainer units.
d. 80 transmitter timers.
e. 50 special receivers for transmitter timers.

The total cost of these items amounted to about $1,250,000 for which the

Navy agreed to reimburse NDRC. The question of airborne receivers, although the Radiation Laboratory had initiated development work under NDRC contract at General Electric Company in Bridgeport, Conn., was turned over to the Aircraft Radio Laboratory of the Signal Corps at Wright Field. The Army then requested the Radiation Laboratory to cancel all work being done by General Electric Company, even though they had already finished one excellent model, and gave the job to Philco. This decision set the development and production of the AN/APN-4 airborne receiver-indicator back about a year, although it may have ensured earlier large-scale production.

In anticipation of high-level service backing, negotiations had been opened with the Royal Canadian Navy during the spring of 1942, and two suitable sites had been selected by Radiation Laboratory field engineers at Baccaro Point and Deming Island, Nova Scotia. The RCN arranged for the use of the sites chosen and assisted in the erection of the stations during the summer of 1942. While these stations were being erected, three additional sites were chosen by a joint USN, RCN, Radiation Laboratory flying survey.

During the summer of 1942 the closest possible coordination of the Loran effort with British work in the pulsed-hyperbolic-navigation field was achieved. R. J. Dippy, the originator of the British Gee system, was sent to this country by the Telecommunications Research Establishment at the request of the Ministry of Aircraft Production. During his 8-month stay at the Radiation Laboratory he succeeded in standardizing the physical size of the airborne Loran equipment with its British counterpart so that the sets could be readily interchanged. Eighty-volt taps on the power transformers were also specified for the Loran sets in order that they could be used in British planes that had 80-volt variable-frequency generators. By great perseverance Dippy managed to force these requirements through, with the result that Loran receiver-indicators were readily interchangeable with Gee sets. After getting the airborne program standardized, Dippy assisted in the design and development of new Loran ground-station timing equipment in which the British experience was joined to that of the Radiation Laboratory. Although Dippy was called back to England before this timer could be completed, he contributed significantly to its design.

The summer and early fall of 1942 were spent producing equipment for the two stations in Nova Scotia and for the three northern stations in Bonavista, Newfoundland; Battle Harbour, Labrador; and Narsak, Greenland. The final production design of the shipborne receiver-indicators was subcontracted to the RCA License Laboratory in New York. The RCA engineers also assisted in getting this equipment into production at the Fada Radio and Electric Company. Incidentally, the entire job of production engineering and design of the equipment by RCA, procurement of parts by Fada, and delivery of the first sets to the Radiation Laboratory in September 1942 took less than five months. This was made possible by the unusually good design work of the RCA License Laboratory and by the willingness of the Radiation Laboratory to accept good broadcast-receiver-type parts and construction.

At that time, it was assumed that the Navy would have their own standard type of receiver-indicators in production within a few months, at which time the Radiation Laboratory sets could be discarded. Actually, many of these sets are still in service, and the Navy eventually reordered several thousand substantial copies of the original Fada equipment. It should be pointed out that one of the principal reasons for the excellent results achieved with the Fada equipment was due to the radical method of shock-mounting it. Early in the installation program, it became obvious that the sets would never survive under the extreme conditions of vibration and shock encountered on a fighting ship, and a project was instituted to find a better type of shock-mount. The new mounts had a period of about 2 cps and were so soft that they appeared sloppy. However, they soon proved their ability to absorb the most violent shocks, and gratifying reports began to filter back to the Radiation Laboratory both from the USN and RCN concerning the remarkable ability of the Loran receiver-indicator to stand up under battle conditions.

2·2. North Atlantic Standard Loran Chain. *Establishment of Ground Stations.*—By Oct. 1, 1942, the two Canadian stations had been essentially completed, although no standby equipment was available, and a sufficient number of Royal Canadian Navy personnel had been trained by the Radiation Laboratory to inaugurate regular service by the four-station (three-pair) chain for 16 hr daily. The remaining 8-hr period each day was required for maintenance work and installation of various accessories.

Late in September, the first shipborne receiver-indicators began to arrive at the Radiation Laboratory for final inspection and alignment before being turned over to the Atlantic fleet, whose Commander-in-Chief had stationed a number of noncommissioned personnel at the Laboratory to receive and install these sets on certain carefully chosen ships. The first such installation was on the old battleship *New York*, on Oct. 18, 1942. Other installations followed during the fall until about 45 sets had been put in service by the end of 1942. About 5 of these early sets were turned over to the RCN for use in navigator and maintenance training programs that were set up in Halifax. These Canadian sets soon found their way onto certain key escort craft doing convoy duty along this coast.

In spite of every possible effort by the Radiation Laboratory, the usual procurement and shipping difficulties made it impossible to complete the three northern stations in Newfoundland, Labrador, and Greenland during 1942. Labrador managed to get on the air in November 1942, but food, permanent housekeeping equipment, and personnel were lacking. Newfoundland was ready for synchronization trials in January 1943. Actual synchronization of this pair, however, was delayed due to an unannounced change in recurrence rates and lack of communication between stations and other Naval organizations. The Greenland station was delayed by several unfortunate difficulties, including a storm that destroyed the station buildings—fortunately, however, before the equipment had been installed. With the help of the local service people, the Radiation Laboratory engineers erected spare buildings which the Navy had sent with the expedition. During February the station managed to get on the air, but synchronism was not established immediately owing to the very great distance to the Labrador station. After installing a directional receiving antenna and rebuilding the receivers for greater sensitivity, the pair finally established synchronism in the spring of 1943.

On Jan. 1, 1943, the U.S. Coast Guard formally took over the full responsibility for the original two stations at Fenwick and Montauk Point. At about the same time, the RCN took over the responsibility for the two stations in Nova Scotia. During the winter and spring of 1943, the full effort of the Laboratory was devoted to the design and production of improved timing and transmitting equipment as well as more reliable test equipment and other accessories for the ground stations. The Labrador, Newfoundland, and Greenland stations were turned over to the USCG, which had manned them from the start, during June 1943, and thereafter full 24-hr daily operation was maintained throughout this original seven-station system.

Thus by October 1942, four Standard Loran stations had been established by Radiation Laboratory personnel and later had been operated on a 16-hr-a-day schedule by the RCN and USN. The chain comprised the two test stations, Montauk and Fenwick, as well as the permanent installations at Baccaro and Deming, Nova Scotia. The Fenwick station was later moved to Bodie Island, North Carolina, and the Montauk Point station was moved to Siasconset on Nantucket Island.

The Loran system became fully operational in the spring of 1943 when charts for the four-station North Atlantic chain were made available, and about 40 ships of the United States Atlantic fleet and a number of Canadian corvettes had been equipped with Loran receiver-indicators. In the early summer of the same year, the North Atlantic chain was extended northward and eastward to Newfoundland, Labrador, and Greenland. These stations were established under the supervision of Radiation Laboratory personnel and were operated by the USN. Later the chain was extended to Iceland, the Faeroes, and the Hebrides to give day and night navigational service over the North Atlantic shipping lanes. These stations were operated by the British Admiralty. At the request of Royal Air Force Coastal Command for Loran service along the coast of Norway, a station was installed in the Shetland Islands and was operated by the RAF. Another station was added to the North Atlantic chain at Port-aux-Basques in Newfoundland, in 1945, to serve the Gulf of St. Lawrence.

The Hatteras-Florida chain, consisting of Bodie Island, N.C., Folly Island, S.C. and Hobe Sound, Fla., was established in 1945 to extend Loran service to the Caribbean. The Gulf of Mexico chain, consisting of Matagorda Island, Tex., Cameron, La., and Port Isabel, Tex., is used chiefly for training.

Development of Loran Navigation at Sea.—The operational use of Loran by the USN expanded rapidly after its introduction in the spring of 1943. Installation, maintenance, and navigator-training facilities were set up in many ports on the mainland and in several extraterritorial bases. By the end of the war practically every surface vessel of destroyer-escort size or larger in the United States fleet was equipped with Loran.

Installation of Loran receiver-indicators in surface vessels of the RCN was initiated in the summer of 1943. A maintenance depot and a navigation school were established at Dartmouth, Nova Scotia. At the close of the war approximately 120 corvettes, 40 frigates, 15 destroyers, and 2 cruisers were equipped with Loran receiver-indicators. The Loran system was used extensively in convoy escort and submarine patrol.

Practically all ships of corvette size or larger in the Royal Navy were equipped with Loran receiver-indicators, not only for operation in the North Atlantic, but also in the Indian and Pacific Oceans.

The Loran system was found to be useful not only for normal navigation but for rendezvous between convoys and escorting aircraft and surface vessels and for the accurate location of enemy shipping and U-boats. Few merchant ships were equipped with Loran, but the large fast troopships, which traveled without escort, relied on Loran for navigation.

As reliable airborne receiver-indicators were not available until the summer of 1944, little use was made of Loran by the American Air Forces in antisubmarine operations along the Atlantic Coast. Many valuable Loran trial flights were carried out, however, and the system was used extensively for the training of aerial navigation.

Development of Loran Navigation in the Air.—By the fall of 1944 enemy submarine packs were driven from American coastal waters and, consequently, antisubmarine operations were extended far out to sea. The Royal Canadian Air Force took an active part in these submarine patrol activities. Two very long range, VLR, squadrons of Liberators were organized at Gander, Newfoundland. Because of the difficulty of navigating in bad weather, the pilots had to reserve at least an hour of flying time for searching for the airdrome. When these squadrons were equipped with Loran, it was found that this search time could be almost eliminated, and the patrol range was correspondingly increased.

As mentioned in preceding sections the North Atlantic chain was extended eastward to Iceland, the Faeroes, and the Hebrides in the fall of 1943. These stations were established and operated by the British Admiralty. With the western stations they constitute a conventional Loran chain.

When the French coast was liberated in the summer of 1944, submarine activity and the requirements for convoy protection shifted northward to the Murmansk route. To protect this route and also to facilitate attacks on enemy shipping and installations along the coast of Norway, it became evident that Loran coverage should be extended to this coast. Because all eight of the specific recurrence rates were already assigned to existing or projected stations of the North Atlantic chain, it was decided that a station should be constructed in the Shetlands to transmit on the same radio frequency and at the same recurrence rate as those in the Faeroes and the Hebrides. However, it was to be so phased that its signal would always appear on the lower trace of the navigator's receiver-indicator and to the right of the signal from the Hebrides. It was further to be identified by a distinctive blink. The station was constructed and put into service by the RAF in November 1944. Used extensively by surface vessels escorting convoys to Murmansk it also aided the RAF Coastal Command on such missions over the coast of Norway as the attack on the *Tirpitz*.

RAF Coastal Command took an active and continued interest in Loran from the time of its introduction in the European Theater. A training school for Loran navigators and maintenance men was established by Coastal Command at Mullaghmore in northern Iceland in the fall of 1944. The installation and training programs were carried out smoothly and efficiently. Coastal Command made use of Gee for short-range missions and Loran for long-range missions. The installations were so arranged that an aircraft could carry either Gee or Loran, the choice depending on the type of navigation provided over the proposed route. Navigation by Loran was confined primarily to the area covered by the North Atlantic chain, although later, as described below, SS Loran coverage was used for anti-U-boat patrol over the Bay of Biscay. At the end of the war in Europe, Coastal Command was operating nine squadrons of Liberators, seven squadrons of Wellingtons, seven squadrons of Sunderlands, three squadrons of Catalinas, and four squadrons of Halifaxes, or a total of approximately 450 aircraft. These were engaged in meteorological, antishipping, anti-U-boat, convoy-escort, and reconnaissance operation. Loran and Gee sets were available for all these aircraft, and either Loran or Gee equipment was carried on almost every sortie. There were also four USN squadrons of Liberators engaged in anti-U-boat activities operating with Coastal Command. They were also equipped with the alternative Loran or Gee installation.

2·3. European Sky-wave Synchronized Loran. *The Proposal.*—On returning from loan to the Bureau of Ships where he assisted in getting some official Naval activity started on the production of Navy-approved shipborne receiver-indicators, as well as preparing the complete operating and maintenance instructions for the original NDRC receiver-indicators, J. A. Pierce assumed the leadership of the Loran Operational Research Group. The principal interest of this group was in the analysis of sky-wave propagation of Loran signals in order to establish reliable sky-wave correction curves. As Pierce had suspected from the earliest days of the medium-frequency project, the probable errors of sky-wave observations over distances greater than a few hundred miles were strikingly low, and transmission was remarkably stable over the longer distances. This led to the informal experimental test of a very important new concept on the night of Apr. 10, 1943. The Fenwick Island station was requested to attempt to maintain synchronism by means of the sky-wave signal received from Bonavista, Newfoundland, 1100 nautical miles away, during one of the regular off-schedule periods. The results of this experiment were observed at the Radiation Laboratory and revealed a line-of-position probable error of only 0.5 mile. And thus Sky-wave Synchronized Loran (usually referred to as SS Loran) was born.

Although SS Loran could be used only at night, it made possible 1200- to 1300-nautical mile baselines, and it could be used nearly as well over land as water. Here then was a method of providing fairly accurate navigational coverage over most of central Europe, far deeper into enemy territory than any other existing system. The first proposal was to have one pair of stations in Scotland and near Leningrad and another between Scotland and North Africa. It soon appeared, however, that it would not be easy or expedient to try to arrange for a station in the U.S.S.R. at that time, and hence a plan was prepared that called for one station in Scotland and three in North Africa.

As these plans were being made and being introduced in England by D. G. Fink, who had become head of the Loran Division upon the retirement of Eastham, arrangements were made for extensive tests of the SS Loran concept in the United States. Equipment was assembled and modified to provide four transmitting stations. The new Radiation Laboratory experimental station at East Brewster, Mass., and a new station at Gooseberry Falls, Minn., were synchronized to provide an

East-West baseline, and stations at Key West, Fla., and Montauk Point, Long Island, gave a North-South baseline. This test system was ready for full operation in the early fall of 1943. Night after night, Army, Navy, and Royal Air Force observation planes flew throughout the East-central United States navigating entirely by SS Loran—the observers including high-ranking officers of all three services. At the conclusion of the tests late in October 1943, a complete report covering ground-station performance, as well as the detailed results of the navigational tests, was prepared by the RAF delegation in Washington. The average error of hundreds of navigational fixes proved to be between 1 and 2 miles over the entire service area.

At the conclusion of the SS Loran tests, a joint committee consisting of a representative of Chief of Naval Operations, one from Air Ministry, and one from the Army Air Forces decided that the system was of such operational value as to justify the diversion of much needed U.S. Navy ground-station equipment to the European Theater for RAF use. The test system was immediately dismantled, and the equipment returned to Radiation Laboratory for reconditioning. Seven Radiation Laboratory engineers and a computer went to the European Theater to aid in putting the system in service.

Establishment of Ground Stations.—With the reluctant approval of the British Admiralty, after an extended study of possible interference with established communications, the 1900-kc/sec channel was chosen for the European SS Loran system. Installation and testing of the four ground stations shown in Fig. 2·1 were completed in the spring of 1944.

Tactical use of the system was delayed by a scarcity of reliable air-borne equipment and by a lack of satisfactory charts. The early air-borne sets, AN/APN-4 Modifications I and II, were unsatisfactory for high-altitude service because of a tendency of the high-voltage trans-former to form corona. This weakness was corrected in the AN/APN-4 Modification III, but sets of this type did not reach the European Theater in sufficient numbers until late in the summer of 1944.

The early charts were inconvenient to use because the sky-wave corrections were tabulated on a separate sheet and inaccurate because of insufficient knowledge of E-layer reflections in the European area. The sky-wave corrections were based on relatively few measurements of the ground-to-sky-wave interval made in the British Isles under conditions that were not entirely equivalent to those encountered in Loran oper-ations. These measurements indicated that the E-layer at the relatively far northern latitude was several kilometers higher than it had been observed in Loran tests in the United States. Subsequent observations showed that a sky-wave correction curve based on Loran measurements accumulated in the United States from Loran transmitting and monitor stations during the SS Loran tests gave more accurate results. In the revised charts, the sky-wave corrections were derived from the more extensive and reliable American observations and were incorporated in the time-difference values shown on the charts. The revised charts were made available early in the fall of 1944.

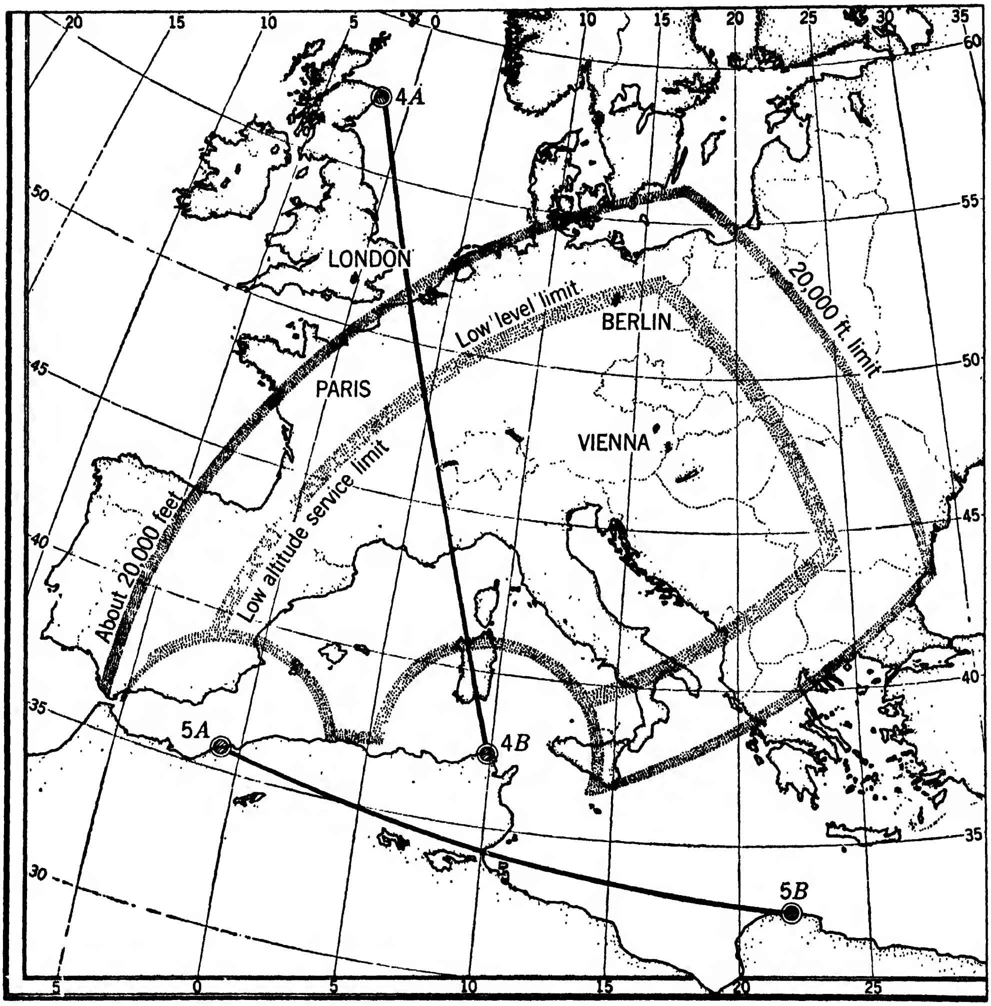


FIG. 2·1.—Area over which SS Loran was available for air navigation during the winter of 1944–1945 at low level and at 20,000 ft.

The transmissions from Port Errol in Scotland were synchronized by means of the first sky-wave reflection from the E-layer (first-hop E) with the transmissions from Bizerte in Tunisia. The transmissions from Oran in Algeria (on a different recurrence rate) were similarly synchronized with the transmissions from Apollonia in Libya. Transmission was maintained from about an hour before dusk until about an hour after dawn.

Development of SS Loran Navigation.—The navigators were instructed to use only the first-hop E-reflections in making their time-difference measurements. The range of the first-hop E-reflection is limited by the curvature of the earth and the height of the reflecting layer. It is found to be approximately 1400 statute miles for low-flying aircraft and approximately 1600 statute miles for planes flying above 20,000 ft. The coverage area shown in Fig. 2·1 extends over a large portion of continental Europe. Over the Channel coast the signal from Apollonia was rather weak. To improve the signal in this area and to extend the coverage over the Channel and southern England, a station was eventually established at Brindisi on the heel of Italy to replace the one at Apollonia. However, it was never used tactically in operations against the enemy because the war ended before the charts for the new system were available.

Trials made with the experimental SS Loran system in the United States and reports from the European SS ground transmitting and monitoring stations indicated that the probable error in timing (the sum of errors due to variation of sky-wave transmission and equipment and personal errors in timing) amounted to about 8 μsec, which corresponds to a probable positional error of 1 statute mile near the baseline and 1.6 statute miles near the limit of the coverage area. Because of the time required to obtain a fix and the high speed of the planes, this accuracy was not realized in the air.

It was originally intended that a homing chain, consisting of three Standard Loran stations should provide navigational information for aircraft returning to their home airfields and that Loran should be the only navigational system required. Unfortunately, the sites were chosen to give coverage over southeastern England at relatively high altitudes. The stations were too far apart to provide satisfactory signals at the altitudes at which the planes were returning to their home fields (a few thousand feet). Consequently, the homing chain was abandoned, and aircraft were equipped with both Gee and Loran. Gee was used for homing and for short missions over the continent wherever Gee cover was provided. Loran was used for night operations deep in enemy territory beyond the range of the Gee stations.

The European SS Loran system was first used operationally by the RAF Bomber Command in October 1944. Because most of the operations of this command were carried out at night and at rather long range, the SS Loran system was well suited to its needs. Ultimately all bombers in the command engaged in deep missions over enemy territory were equipped with both Gee and Loran.

The largest group in Bomber Command was 5-Group, composed of about 350 Lancasters and 20 Mosquitoes. It was almost self-sufficient, as it had its own bomber force, flare force, pathfinders, and windfinders.

It had developed a method of vector bombing at night by the use of target-indicating flares. The main bomber force was preceded by a number of windfinding planes, a flare force, a "controller," and one or more of his deputies. The windfinding planes informed the rest of the force of the direction and velocity of the winds along the route to aid them in their navigation and bombing. The controller directed the dropping of the target-indicating flares and, later on, the bombing of the target. Flying low and fast, usually in a Mosquito, he observed the location of the flares in relation to the target, selected one conveniently to windward of the target (so that smoke of subsequent bombing would not obliterate the flares), and directed the flare force to reinforce it. Then as the main bomber force came in, he directed it to bomb the target-indicating flares, using a false wind vector such that the bombs would strike the target rather than the target-indicating flares. He corrected any tendency of the bombing to drift away from the target by modifying the false-wind vector. On nights of poor visibility, parachute flares were placed above the clouds and over the target by means of Gee, H2S, or Loran.

The Pathfinder Force, 8-Group, was composed of roughly 170 Lancasters and 200 Mosquitoes. Its function was to lead the heavy bombers of other groups to the target and to mark the target by means of flares. The Mosquitoes also engaged in intruder operations and nuisance bombing. All planes of this group were equipped with Loran and Gee. Serious objection was raised to the use of a trailing antenna, especially with the fast Mosquitoes, because it reduced the speed and maneuverability and had a tendency to break off. A fixed antenna with coupling unit was finally developed that gave satisfactory results.

Early in February 1945, the Mosquitoes of 8-Group bombed Berlin. This nuisance bombing of Berlin continued almost every night until the end of the war. Loran was used for navigation and for bomb release. To obtain sufficient accuracy for bombing it was necessary to reduce the time required to take a reading. The indicator was modified by the addition of a second pair of time-difference controls in order to provide separate controls for each of two recurrence rates. The pilot followed a Loran line passing over the target and released the bombs on crossing the proper Loran line on the other recurrence rate. Although no great accuracy was claimed for the system, its users considered it highly effective and a relatively simple, safe method of bombing.

2·4. Loran in the China-Burma-India Theater. *Establishment of the Hump Triplets.*—In the fall of 1943, a Loran system was proposed to provide navigation over the Army Air Transport Command route from India to China. The route at that time was a nonstop flight for an airline distance of less than 500 nautical miles over mountainous country with peaks up to 17,000 ft. The greater part of this distance was over enemy territory. In addition, the route was plagued by seasons of very high winds, monsoons with heavy rain, continual low overcast, numerous thunderstorms, and heavy precipitation static.

This system, as originally conceived, consisted of a single pair of stations at each end of the route, providing overlapping lines of position nearly parallel to the line of flight. These were to guide the large number of aircraft engaged in this operation without danger of collisions.

Lightweight, Air Transportable equipment was designed and constructed by Radiation Laboratory for four such stations. A prototype installation was made in a mountainous section of California, flight-tested, and reported on by Headquarters, Army Air Forces, Office of the Air Communications Officer.

However, theater operations did not permit straight-line routes but rather required a system providing navigational fixes. The plans were, therefore, amended to include a triplet on each side of the Hump.

Owing to the overland synchronism paths, the baseline lengths are limited to roughly 50 to 75 nautical miles depending on the soil conductivity and the noise level.

Owing to poor coordination by the various AAF organizations in the United States the ground-station equipment did not reach the theater until August 1944.

Geographical coordinates for one station, Paya, as determined by astro-observations were found to be in error by about 0.8 nautical mile due to the deflection from the vertical resulting from the near-by Himalaya Mountains. The coordinates that proved to be correct were obtained from the Survey of India charts. The need for highly accurate coordinates is especially great for short baseline systems. The ground-station installations and operation were handled by the Fourth Army Airways Communication System Wing, AAF.

The Assam Hump (India) triplet was tested and finally placed in operation in October 1944.

Flight tests and subsequent reports indicated a ground-wave range eastward over the Hump of 280 to 300 statute miles during the daytime and 200 to 250 miles at night. The daytime westward range over the flat lowland country is somewhat greater, with ranges of more than 400 statute miles having been obtained. In this case the range was limited only by the receiver sensitivity and noise.

The system orientation fortunately provided coverage not only for the northern direct Hump route in use when the system was conceived but also for the tactical areas of Myitkyina, Bhamo, etc., and the final Hump route via Myitkyina.

Approval of the required air-hump tonnage (60 tons) for the triplet east of the Hump was withheld by the China Theater Commander until after the successful testing of the Assam triplet.

The China triplet was placed on a 24-hr operating schedule on Mar. 15, 1945.

Sky-wave Synchronized Pairs.—In addition to these two triplets comprising the Hump system, the China and India-Burma Theaters' Loran program quickly expanded to include the SS Inland China pair, the East India Coast Standard triplet, the SS Burma pair, and the Chengtu triplet. A Radiation Laboratory representative was assigned as a technical observer to the Headquarters Fourth AACS Wing, AAF, India-Burma Theater for the period June 1944 to March 1945, to assist in all phases of the Loran program.

An SS Loran pair was requested by the Twentieth Bomber Command, AAF, to provide line-of-position navigation over enemy-occupied China to the edge of the Japanese home island. Used in conjunction with the APQ-15 high-altitude radar equipment, night navigation over this large area was to be furnished.

As originally conceived, a station was to be located near Luchow, Kweichow, China, and the other near Paoning, Szechwan, China. This orientation placed the center line (perpendicular bisector of the baseline) directly through the southwestern Japanese home islands and gave a baseline length of about 480 nautical miles. It did not provide coverage over the home bases of the Twentieth Bomber Command near Chengtu, Szechwan, China, owing to the nearness of the northern station to this area. However, the loss of Luchow and all of the surrounding area to the Japanese forced a relocation of the system.

The slave station was combined with the southern slave station of the Kunming Hump triplet chiefly to alleviate the Hump supply problem. The master station at Manchung, Szechwan, China, was sufficiently removed from the Chengtu area to provide homing coverage from the pair over this important area. This relocation of the pair provided a useful increase in the baseline length to about 605 nautical miles and placed the center line toward Formosa, retracting the coverage toward Japan. Operation on this pair began Mar. 15, 1945, on a 24-hr-a-day basis.

East India Coast System.—This system was requested by the RAF to provide long-range navigation over the Bay of Bengal, the Andaman Islands, and Rangoon and by night to Bangkok and toward Singapore. The equipment was allotted by the Joint Chiefs of Staff to the AAF from the U.S. Navy. The siting, installation, and initial operation were the responsibility of the Fourth AACS Wing, AAF. Operation was initiated on Apr. 15, 1945.

This system was turned over to the Royal Air Force on July 1, 1945.

RAF flight reports indicate excellent signals at 700 to 800 statute miles. Errors were reported to be less than 1 mile for the favorable coverage areas and up to 2 to 3 miles in the unfavorable regions (off the baseline extensions).

Loran Navigation in the Air.—Initial requests for airborne sets were made by the ATC and the Twentieth Bomber Command in March 1944. By the time the China triplet was placed in operation, which completed the Hump system ($1\frac{1}{2}$ years after its inception), the tactical situation in Burma had been cleared up, the Hump route moved south over more favorable terrain, and a large number of radio beacons had been installed across the route. The Hump tonnage had been increased to about 30,000 tons per month. The ATC aircraft, numbering more than 300 type C-46, were 90 per cent equipped with AN/APN-4's. The radio compass was the common navigational instrument in use, with Loran being employed more frequently as personnel familiarity with it improved.

The eastward coverage toward the China coast, Kweilin, Luchow, etc., of the Kunming Hump triplet was still of great value both for tactical and expanding ATC and combat cargo operation. Small initial shipments (ATC) were received in October 1944. A severe shortage of airborne equipment continued to exist through 1944 and until late spring of 1945. Installation of equipment for ATC—India-China Division received top priority. Combat cargo and troop carrier units of the Tenth Air Force and Combat Cargo Task Force (RAF and AAF) were next on the priority list under a plan to provide a minimum of two installations per squadron for training and pathfinding purposes at the earliest possible moment. This plan was then extended to include heavy bombardment (China Theater and India-Burma Theater), photomapping, night fighters, and air-sea-rescue in roughly this order. This plan was completed in the early part of 1945.

The presence of airborne installations in replacement and additional aircraft helped alleviate the very poor airborne set supply situation so that all of the units had a high percentage of installations by the summer of 1945.

2·5. Operations in the Pacific.—Loran chains in the Pacific were planned to cover as much of the advance to Japan as was possible geographically. Support of naval and air operations in the forward areas was envisaged, but due consideration was also given to coverage of the supply routes from Hawaii and the United States. Loran planning was carried out at a high level as early as 1943 with the purpose of coordinating the establishment of Loran service with military and naval advances in the island war.

North Pacific Chain.—By the time the North Atlantic chain became familiar to the Atlantic fleet, a directive was issued, in January 1943, for Loran coverage in the Aleutians. Two rates began 10-hr operation in October 1943, extending service to 22-hr operation in January 1944. With the addition of one more pair in July 1944, 24-hr transmissions followed. This chain employs the same recurrence rates and radio frequency as the North Atlantic chain, yet no records of any interference between the two areas have been reported. In the sweeps to Paramushiru in the Kurils and in the naval campaign off the Aleutians both before and after the last Japanese were eradicated from the westernmost part of these islands, the Loran chains on our Alaskan steppingstones played a very important role. Since Aleutian weather is inclement, celestial observations were entirely out of the question. Conditions there are so bad that it was only with extreme difficulty that astrometrical observations at the stations were obtained during the siting process.

Central and Southwest Pacific Chains.—The Hawaiian triplet came into service in October 1944. A month later a second triplet in the Phoenix Islands became operational. The capture of the important Japanese bases in the Marshalls (Kwajalein, Majuro, etc.) enabled establishment of a triplet there, with service beginning in December 1944. As soon as Guam and Saipan were in Allied hands, the Marianas chain (Guam, Saipan, Ulithi) was sited, becoming available to navigators in December 1944. This preceded the peak days of the B-29 raids, and therefore Loran service in the area from the Marianas westward paved the way for the heavy bombers to do more effective work by justifying a reduction in fuel reserve and an increase in bomb load. The Coast Guard continued its installation program in 1945 with the triplet Ulithi-Suluan (East Philippines)-Mapia in April. These pairs were ground-wave synchronized by day and sky-wave synchronized by night. The coverage of these somewhat overlapped that of the Morotai-Pulo Anna-Palau triplet, which was placed in service in January 1945; and when the war was near its end, the Ulithi-Suluan-Mapia triplet was withdrawn. When position lines were needed over Japan to cross with those from the Marianas, the link between Okinawa and Iwo Jima was formed in May and June 1945. At first, this pair was ground-wave synchronized by day (baseline 727 nautical miles) and sky-wave synchronized by night, but soon afterward, by the use of suitable antennas and by auxiliary monitors, the pair employed ground-wave synchronization entirely. To bolster activities in the South China Sea, a triplet on the western Philippines (Luzon-Talampulon-Palawan) became serviceable in July 1945.

The Army Air Forces undertook coverage of the lower East Indies with a chain in northwestern Australia. This was known as the Banda Sea chain and commenced service in September 1944, guiding sweeps on the Celebes, Java, and Halmahera.

With the end of the war, the requirement for a navigational system for the occupation air and sea forces in Japan has resulted in the current

TABLE 2·1.—LORAN OPERATIONS BY TWENTY-FIRST BOMBER COMMAND

No. of missions	No. of aircraft	No. of fixes	Max. fix range, miles
26	109	Not reported	1000
29	112	Not reported	750
34	117	Not reported	800
37	145	Not reported	850
38	229	Not reported	Not reported
39	191	Not reported	1000
40	313	Not reported	Not reported
41	310	4350	1200
42	295	Not reported	1070
43	331	Not reported	1500
44	298	Not reported	1200
45	251	Not reported	1200
46	161	Not reported	Not reported
47	102	Not reported	Not reported
48	135	160	1200
49	94	Not reported	Not reported
50	149	Not reported	1200
55	230	2225	1500
59	194	1312	750
60	53	364	1000
63	221	1400	1000
64	167	Not reported	1000
67	348	2362	1250
68	337	2992	1425
70–95	627	Not reported	1000
96	131	1050	1300
97–125	640	Not reported	Not reported
126	106	790	900
139	195	1998	1150
146	170	1428	712
163	343	2935	885
167–171	218	Not reported	Not reported
172	102	681	895
174	524	4318	693
176	516	4968	1083
178	309	2148	842
181	514	2386	1200
183	452	Not reported	1091
186	510	Not reported	911
187	509	Not reported	893
188	523	Not reported	911
189	449	1767	848
191	116	1044	900
	14,249		

installation of a Loran pair between a site near Tokyo Bay and one of the islands adjacent to Okinawa. This pair and the Okinawa-Iwo Jima pair provide excellent cover from the Bonins to Japan.

West Coast Chain.—Priority dictated that the first chains in the Pacific should be in the forward areas, and, consequently, the gap between the west coast of the United States and Hawaii has been sorely felt all along, particularly by the air transports and by the fleet moving in and out of San Francisco. In June 1945, the first step in filling the West Coast gap began with the AT triplet Point Arguello-Point Sur-Point Grenoble covering the approach to San Francisco. These AAF stations will be replaced later by a West Coast chain of six pairs, extending from Vancouver Island, British Columbia, to Guadalupe Island, Mexico. When this has been accomplished, great-circle flying from Japan to the United States will have fairly complete Loran coverage, since the Aleutian chain already provides much of this. Throughout the war, the principal radio-navigational systems between California and Hawaii were certain radio ranges at either end and radio beacons installed aboard lightships several hundred miles to the east of Hawaii. The first of the final six Loran pairs has been operating since July 1945, between Point Grenville and Cape Blanco, and the link between Vancouver and Point Grenville became operational in October 1945.

Airborne Operations.—The files of the War and Navy Departments contain a large number of reports summarizing the use of the Pacific chains by various services. Rather than include here any individual testimonials, we present a table of the results of a large number of B-29 missions to Japan (Table 2·1). The number of fixes per sortie (where reported) averages about eight. The variations in performance are attributed by the War Department to the advent of new B-29 wings to those already in the Marianas and to the departure of those who had completed their tours.

2·6. Charting and Training. *Charting.*—During the last part of 1944 and in 1945 a large portion of the Pacific Ocean was covered by Coast Guard Loran installations made under Navy auspices at the direction of the Joint Chiefs of Staff. The only exceptions were the China-Burma-India installations and a Standard Loran triplet installed by the Army Airways Communication System for the Army Air Forces along the northwest coast of Australia. In both of these programs Radiation Laboratory engineers participated. Figures 2·2 to 2·4 show views of various Loran ground stations.

One of the most critical aspects of the rapid expansion of Loran coverage to include a large fraction of the navigable world was the tedious computation, drafting, and reproduction of the necessary navigators' charts and tables. Although this was initially handled by the

Radiation Laboratory group, the Hydrographic Office of the Navy prepared to assume this responsibility during the latter part of 1942. To ensure minimum delay in this undertaking, F. G. Watson, who was responsible for the original work, resigned from the Radiation Laboratory, accepted a Navy commission, and departed for Washington to assist in setting up a suitable Loran section. Since its inception, that department has produced a total of $2\frac{1}{2}$ million copies of well over a

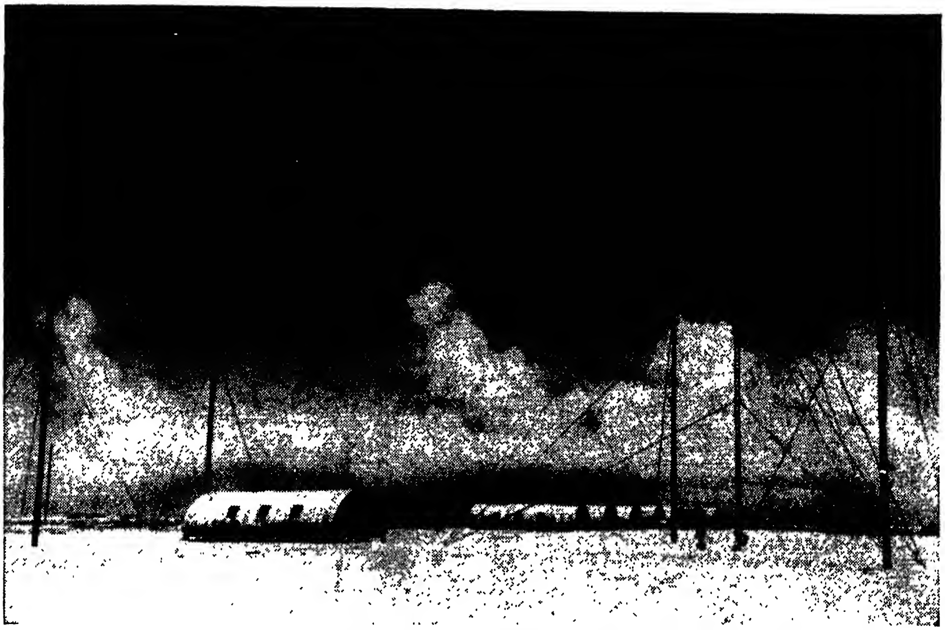


FIG. 2·2.—A typical ground station. Building to the left contains equipment; those in the background are quarters. The Wincharger tower is at the right. (*Courtesy of U.S. Coast Guard.*)

hundred different charts covering over 60 million square miles of the earth's surface. During April 1945 alone, 230,482 Loran charts were distributed to all services. These charts have been produced both in this country and at certain forward bases where suitable facilities were installed. The detailed history of the Hydrographic Office charting activity is given in Appendix A. The Royal Air Force and the AAF also produced a number of Loran charts for inland areas in which the Navy had little interest.

Training of Ground-station Operators.—During late September and early October 1942, after the experience gained from putting the Canadian stations in operation, a series of talks was given at the Radiation Laboratory, summarizing for the technical staff of the Loran Division all the information then known and of value to the system. Up to this point only a few Royal Canadian Navy personnel had received a sketchy training at the Montauk and Fenwick field stations and in the Laboratory

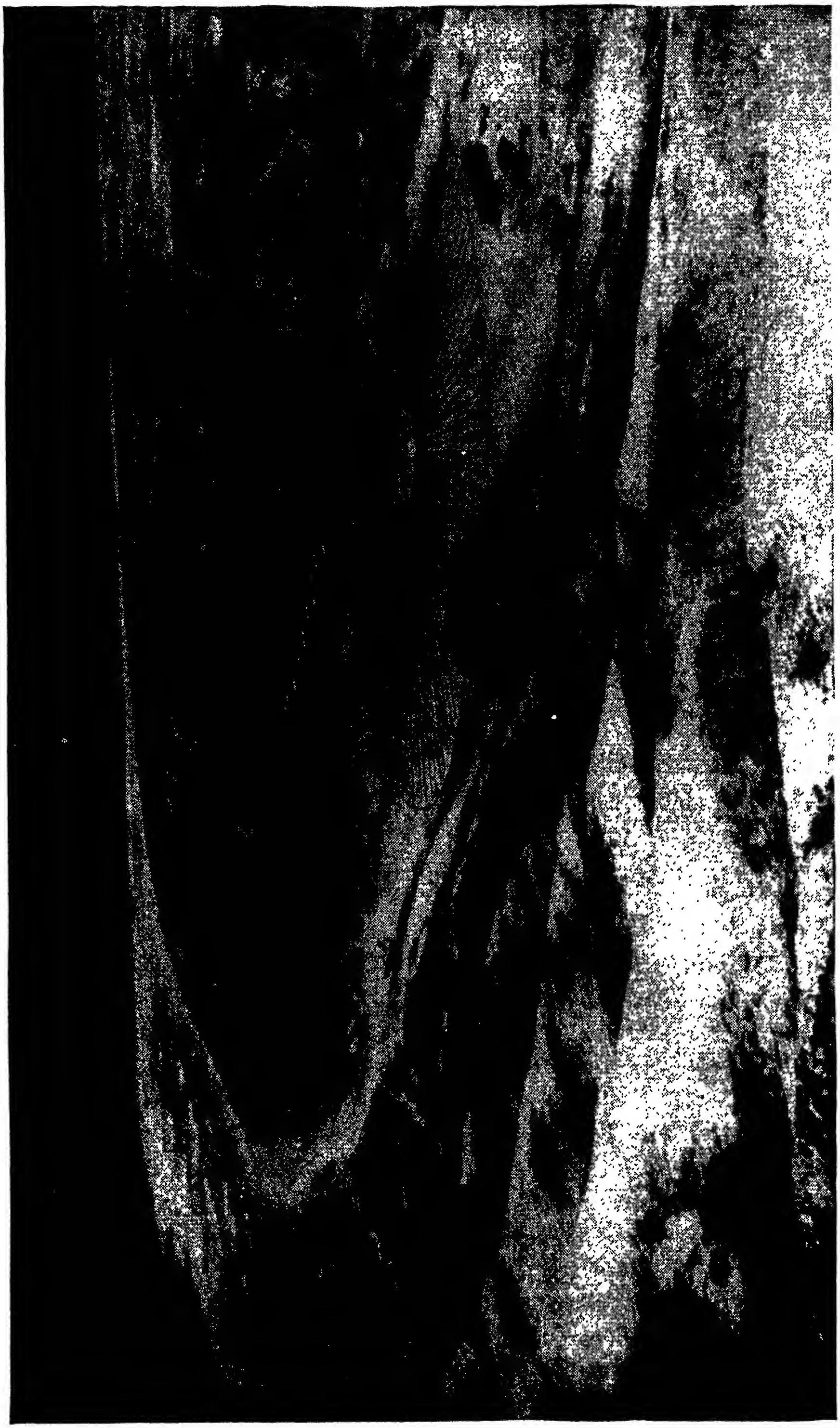


Fig. 2·3.—Aerial view of a typical ground station (located on Baker Island of the Phoenix Islands group). Note the radial ground system and the location of the various operating and emergency antennas. (*Courtesy of U.S. Coast Guard.*)

FIG. 2·4.—A station located on Sydero in the Faeroe Islands. (*Courtesy of the Royal Air Force.*)

with a view toward fitting them for their duties in operating and maintaining the Baccaro and Deming stations. The Laboratory instruction was available to officers and enlisted men of the Navy who were attached to the Loran Division as well as to an RCN group who had been sent for training. From the former group there evolved the Boston Loran Training School, operated by the Coast Guard, which in turn prepared Navy, Army, and Allied officers and men for operation of equipment and the eventual establishment of other training centers. Close liaison was possible between the Laboratory and the Coast Guard school until its later removal to Groton, Conn. Its debt to the Laboratory was repaid many times over by the pretraining of several groups, who were then sent to Cambridge for special training. Part of the success of the Groton school lay in the fact that a large number of its later instructors had actually operated stations of the Atlantic chain and in the Aleutians.

Whenever possible, the men were given an opportunity to visit and operate a field station employing equipment or techniques that they had been studying. Occasionally, it was possible to operate prototype equipment in the Laboratory; and in a few instances men were allowed to help build some of the gear that they later employed.

The Air Transportable Loran project involved the need for a quick, accurate means of charting the area to be served and the development of a rapid technique for printing many hundreds of maps in a short time. The charting requirement was finally solved so well that relatively inexperienced men with high-school education could plot Loran coordinates on a tracing from a standard Army map. The process of determining coordinates was considerably aided by the development of some standard printed forms. The printing method best adapted to the particular military requirements was the photostat process, although a silk-screen method or offset lithography might have served other requirements much better.

The important task of producing instruction books and manuals was not undertaken until early in 1943 and even then on a rather informal basis. Almost concurrent with the organization of a Sky-wave Synchronized Loran school, the importance and magnitude of this branch of instruction became apparent, and a small subgroup was formed. This Manual subgroup acted as a clearing house for information, maintained active liaison between the engineers and the Navy and Army, and furnished drawings and text to manufacturers under contract for Loran equipment developed by the Laboratory. All the earlier manuals were issued through the Navy Liaison Officer for Loran, because the Navy was the principal user of the system. At a later date, when demands for printed material began to arrive from diversified sources, all material, except that printed at Navy request, was distributed through the Document Office.

Whereas Loran system operation was the responsibility of the Chief of Naval Operations, training of Navy personnel in manipulation and maintenance of shipboard Loran equipment was under the direction of the Bureau of Personnel. Airborne Loran training was kept within the jurisdiction of the Bureau of Aeronautics. Since construction and operation of Navy Loran stations was delegated to the Coast Guard, that agency conducted its own ground-station training program.

The Coast Guard, as operating agency for the U.S. Navy, constructed, installed, and ran the Loran stations that were under the cognizance of the Chief of Naval Operations. Its association with Loran began in 1942, shortly after the Radiation Laboratory had conducted field trials on the first pair of synchronized stations. With the aid of the Laboratory, the Coast Guard inaugurated a training program on ground-station equipment at a naval Loran school in Boston. Enough men were trained so that the stations referred to could be taken over by the Coast Guard in January 1943 and so that entire complements of personnel could be engaged in the erection of stations in the far north. When the Boston school was disbanded at a much later date, the Coast Guard removed its ground-training program to Groton, Conn., not far from the Academy at New London. The basic electronics training at the Academy included instruction on many of the fundamental circuit arrangements found in Loran. Those completing the course who were going to work on Loran were transferred to Groton, Conn., to receive information on timers, transmitters, antennas, and monitors. Typical monitoring was demonstrated at Groton, and trainees were required to put in a short residence at one of the near-by Loran stations. Officers and enlisted technicians were given about five weeks of training, and operators received three-week training. The courses given were so comprehensive that other services such as the AACS, the RCN, and the Royal Navy sent trainees through this school rather than establishing formal schools of their own.

Training of Shipboard Navigators.—In the early days of Loran, all Navy and Coast Guard training was concentrated in the one school in Boston, Mass., which was organized by the Naval Liaison Officer for Loran at Radiation Laboratory, the Naval officer in charge at Massachusetts Institute of Technology, and the District Coast Guard Officer. During the introduction of Loran in the Aleutians in the latter part of 1943, a school for navigators was established at Adak, Alaska. Progress was slow at first, since the instructors were mainly self-taught and equipment was scarce. However, the Loran program expanded rapidly, and this school became inadequate because of the geographical distribution of Loran chains and personnel. In February 1944, the Bureau of Personnel established Loran schools at the following naval bases: Boston, New York, Philadelphia, Charleston, Norfolk, New Orleans, and Casco Bay. Later schools were set up at Treasure Island (San Francisco), Chicago, and Pearl Harbor. Here navigators and interested quartermasters of the fleets were trained in shipboard Loran manipulation. A comprehensive 4-day course was given, because the amount of shore time available to personnel was seldom more than this. Liberal supplies of manuals and notes were made available to these men at the conclusion of the course so that they could continue to study while at sea. Although the formal instruction was rather short, its quality was high, for the reliance placed on Loran by the members of the fleet is shown in the reports that are in the files of the Chief of Naval Operations and the Hydrographic Office.

Technicians also were trained at the bases listed above. In general, it was the Navy policy to make all radar mechanics familiar with Loran ship equipment and its circuits.

Navy Training of Air Navigators.—The Bureau of Aeronautics formed the Airborne Coordinating Group, ACG, early in the war. Civilian radar technicians were sent into all theaters where naval aviation was playing its part, and they acted as trouble-shooters, instructors, and advisers with respect to the many radar equipments in service. These men made their reports to the Naval Research Laboratories, which in turn published their comments for general distribution. Loran was one of the systems with which the ACG fieldmen were concerned. An official journal, the *Digest*, was published by the Bureau of Aeronautics and served as a medium for passing the latest information concerning airborne equipment to these men and to other interested services. Many valuable suggestions and advance information on airborne Loran were contained in this journal.

The Hydrographic Office established an informal "clinic" at the New York project office (where computations for Loran charts were performed). Navigators were invited there to discuss their results and to leave copies of their logs for analysis. Recommendations were thus easily made on the spot for improved use of the equipment and the system.

The Bureau of Aeronautics combined a good deal of its Loran work with Link trainer instruction at its Air Navigation training units, which were found at the major air-training bases. This bureau also issued some very valuable booklets on Loran operation, and these were disseminated widely. In October 1944, the Bureau of Aeronautics sponsored a Loran research flight through the North Atlantic with participants from many branches of the Naval Service and from the AAF. A thorough study of the service available from each Loran pair was made, and many useful photographs of signals were included in the report.

The Navy issued several Loran films for the instruction of both ship and air navigators that were widely distributed to all the services using

Loran. A helpful series of 35-mm slides supplemented the films and were particularly valuable for instruction of mechanics.

Training in the RAF.—The introduction of Loran to the RAF actually began in the United States in 1943 when a number of officers and enlisted men were trained by the Radiation Laboratory in SS Loran and took part in the operation of the test system. Of this group, one officer and two enlisted men later were instrumental in establishing a school in Loran for mechanics of Bomber Command; another officer carried through the initial instruction of navigators and mechanics at various Coastal Command bases; still a third officer directed the ground-station operations and training for 60-Group, the group primarily responsible for ground navigational equipment. Ground-station training was carried out at the station sites in the United Kingdom and Africa, and a large number of mechanics and WAAF operators soon became proficient in the system. By the spring of 1944 the technical standards at the RAF stations were high.

Coastal Command, using the North Atlantic chain in its U-boat campaign, relied on a traveling team of instructor and mechanic during its installation program in early 1944. It also encouraged the exchange of information among Loran-fitted squadrons. Later, a special Loran training unit was established by the Command in northern Ireland, offering a 2-weeks course in the subject and giving several training flights in the ground- and sky-wave coverage. An advantage here was that instruction was carried out in the same area where the trainees were later to use the system operationally. Coastal Command placed great emphasis on Loran, for much of their flying was at low altitudes and at latitudes where the weather was generally inclement. Early training was given to the meteorological squadrons so that the accuracy of their important weather information could be improved.

When the Bomber Command fitting program began in the fall of 1944, small groups of navigators were being trained by Bomber Command Development Unit, which conducted Service trials on equipment designed for the Command. As this was insufficient to meet the initial demands of one of the groups of the Command that was engaged in extensive night raids on the Continent, hundreds of navigators, pilots, and bomb aimers were introduced to Loran by lectures given by Loran experts of the British branch of the Radiation Laboratory. These lectures were enhanced by USN films and slides. Later on, facilities of Bomber Development Unit were enlarged.

When SS Loran became operational, it was evident that the Service plan for training of navigators was seriously behind schedule, and inadequate. Men of the British branch of the Radiation Laboratory were instrumental in conducting classes with small groups of navigators in one of the Eighth U.S. Air Force bomb groups. These navigators became familiar with Loran both in regard to the use of North Atlantic Loran for meteorological squadrons and in regard to SS Loran for night reconnaissance over the Continent. The navigators of this bomb group served as a nucleus for U.S. Air Force navigator training on Loran in the United Kingdom, since Loran training was included as prerequisite for redeployment of the Eighth Air Force to the Pacific Theater.

As soon as the RAF 5-Group of Bomber Command made known their intention of equipping the entire force of 250 to 300 planes for SS Loran operation, and when it was apparent that any school established at that time would be insufficient to meet demands of this group for immediate operation, men of the British branch of the Radiation Laboratory circulated among airdromes of 5-Group and instructed large classes of pilots, navigators, and bomb aimers. This instruction was necessarily abbreviated because of the size of classes and was therefore augmented by special training films and slides. The British branch also produced some written material on SS Loran and its peculiarities that was widely distributed among the groups of Bomber Command. Although this process was hasty, it was fairly effective, for most of the RAF navigators were well acquainted with hyperbolic navigation through their use of Gee. In the over-all training picture, a fair share of the burden of indoctrination was carried by members of the Telecommunications Research Establishment, TRE, the British organization responsible for radar and hyperbolic systems. Most of the RAF navigators were very conscientious in their interest and took advantage of their frequent raids over the Continent to learn through using; as a result there was very soon a large number of fairly skilled Loran navigators.

Army Air Force Training.—Navigators of the AAF relied at first upon facilities offered by the USN and Coast Guard for training. As Loran chains appeared in the theaters and as airborne equipment became available, schools were established with varying degrees of success. Rarely were these schools ahead of the actual operation of the neighboring Loran chain, and thus in many cases service to navigators was available before they had been adequately trained. The lack of familiarity of the average AAF navigator with hyperbolic-navigation systems or for that matter anything different from a homing beacon or radio range made it generally difficult to introduce this new type of navigation with the degree of success attendant upon the introduction of Loran to the RAF navigators, who were already well versed in Gee.

It was not until the latter part of 1944 that the Air Transport Command had an appreciable number of navigators availing themselves of Loran service in the Atlantic or the Pacific. The ATC Loran School at Wilmington, Del., organized early in 1944, had trained about 700 personnel in 1944 and a total of 1682 by August 1945. Of these, 235 were commercial air-line navigators who were members of contract carrier crews, flying military aircraft. Two mobile training units were formed by this school, one of which toured airfields in the United States, whereas the other toured several theaters.

As the flow of B-29's and B-24's increased to the Pacific, the continental air forces assumed a larger share of the burden of training air crews. Consequently, Loran instruction in the latter part of the war was included in all the major air-navigation schools of the AAF. Training flights were carried on in the area served by part of the North Atlantic chain, and in 1945 a Gulf Coast and a West Coast triplet simplified the training of B-29 navigators. Although no formal training ever took place at Guam and Saipan, a certain amount of spot-training and briefing by Loran officers did take place there.

2·7. Service Areas.—Loran operation began on the East Coast of the United States simply because the system was developed there and a pair of trial stations already existed. The expansion up the coast of North America was natural and desirable, because the Atlantic convoy route was subject to adverse weather and the rendezvous problem was acute.

Even before the completion of the Atlantic chain by the installation of stations north of the United Kingdom, the need for Loran service in the Aleutian Islands was recognized and statisfied. At this time, early 1944, a chart of the area served by Loran bore a striking resemblance to a diagram showing the parts of the world subject to mean annual cloudiness of 0.7 or more. This was no coincidence.

The operation of the SS Loran system in Europe and extensive installations in the Pacific, China, and India extended the nighttime service over two great areas. With the installation of stations on the Gulf of Mexico and California coasts (primarily to provide actual signals for airborne training of navigators) the gap between these areas has been closed. At night the service area is, as shown in Fig. 2·5, a belt extending 320° in longitude with a width varying from about 10° of latitude in the western United States to about 100° in the central Pacific Ocean. The stations that providen this service are listed in Appendix B. The total area served by Aug. 15, 1945, was about 63 million square miles, or 32 per cent of the area of the earth.

In the daytime the service area is far smaller, about 15 million square miles. Although it is possible by day to fly the northern route between the United States and the United Kingdom without losing Loran cover, the areas in the Pacific are not contiguous and serve only as essentially "local" approach systems of 700-mile radius centered in the various island groups. There is no significant daytime Loran service over land, except for the traffic guidance system over the Hump in Burma.

In the daytime the total overwater service area is about 300,000 square miles per station (neglecting stations not located to give service over water), and at night the service area is about 1 million square miles per station.

The curve relating the total area served by Loran at night to the date

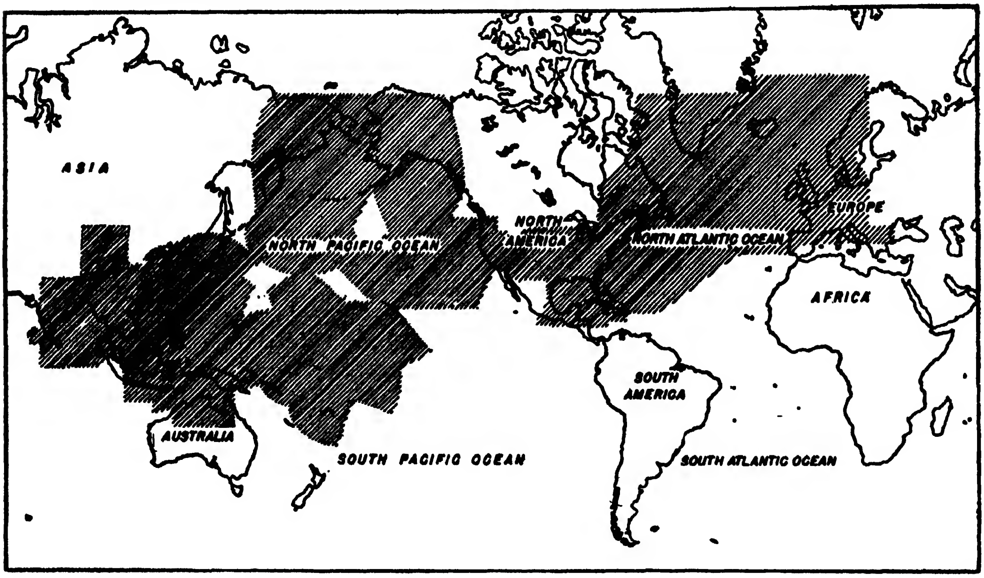


FIG. 2·5.—Nighttime sky-wave coverage at the end of hostilities.

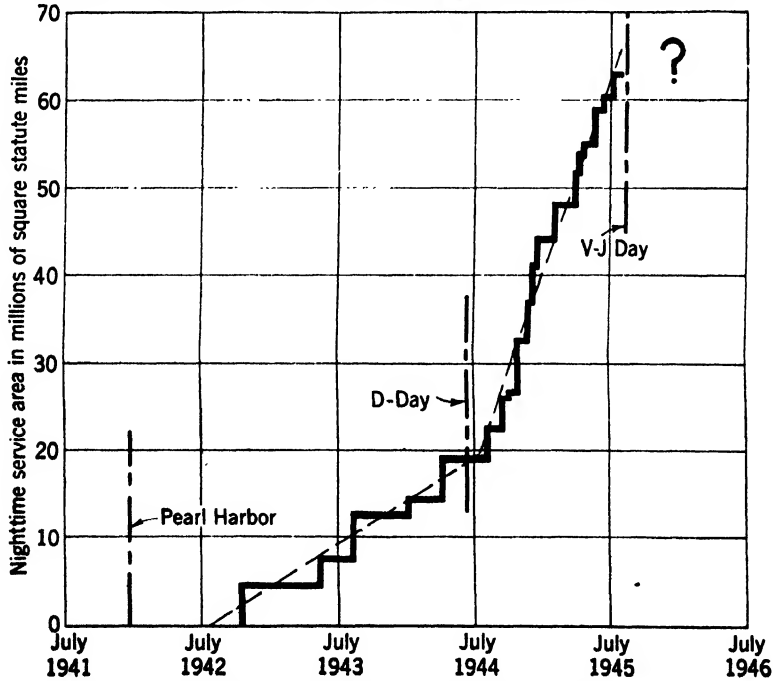


FIG. 2·6.—The total area over which Loran navigation is available has grown since its beginnings in 1942 to almost a third of the earth's surface at the end of the war.

is unusually interesting. It is shown in Fig. 2·6. The diagram begins at July 1, 1941, because, as explained in Sec. 2·1, that may be regarded as the first date in the full scale development of Loran. For a year, tests were made and equipment was developed. Then, in July 1942, the first demonstrations were given, and NDRC agreed to begin the installation of operational stations. The program went forward for two years after that at the modest rate of 10 million square miles per year. This pace seems to have been determined primarily by the rate at which procurement of transmitting equipment was had through NDRC. Another limiting factor was that installation of the system in each new area had to be sold to the potential users who, of course, could not assess the potential merit of the system because it was entirely new to them.

By July 1944, however, Naval procurement of transmitting equipment was in effect, and the system had won general acceptance. Thereafter installations proceeded at a rate commensurate with the enhanced procurement program, or about 40 million square miles per year. This rate persisted to the end of the war.

The current (November 1945) area served at night is believed to be about 70 million square miles. It is difficult to justify this figure, however. A number of new installations are being pushed forward, as they have been since August 1945, but some pairs, which had only military significance, have already been discontinued. The degree of acceptance of the Loran system for peacetime military and civil use is not at all certain. At this date, therefore, it is believed that the question mark adequately expresses the current and future coverage.

CHAPTER 3

PRINCIPLES OF LORAN

BY B. W. SITTERLY

3·1. Time Differences and Lines of Position. *Fundamental Relations.* The primary fact upon which Loran is based is that the transmission time taken by a radio pulse to travel over a distance measures the distance. The pulse travels 983.24 ft, or 0.18622 statute miles, or 0.16171 nautical miles, or 0.299692 km, in one microsecond (millionth of a second; abbreviation, μsec). The pulse takes 5.3700 μsec to travel 1 statute mile, 6.1838 μsec to travel 1 nautical mile, 3.33676 μsec to travel 1 km. Convenient approximations to these relations are 8 statute miles ≈ 43 μsec; 5 nautical miles ≈ 31 μsec; 3 km ≈ 10 μsec. It is advantageous to use 983.24 ft as a unit of length in Loran computations; this unit may be called a light-microsecond or simply a microsecond. In this unit, distance is numerically equal to transmission time.

If a pair of Loran transmitters A and B were to emit pulses simultaneously, a navigator equally distant from A and B would receive them simultaneously, but a navigator not equally distant from A and B would receive the pulse from the farther station later than that from the nearer. The *time difference* measured by the navigator from one pulse to the other would be numerically equal to the difference between the distances traveled by the pulses, measured in light-microseconds, or in form of an equation,

$$t = v, \tag{1}$$

where t is time difference and v is difference of light-microseconds. If station B were farther, its pulse would be received later than A's pulse; if nearer, earlier. The two cases may be distinguished formally by making t and v positive in the former case, negative in the latter. In observation, however, it is not possible to determine the sign, for pulses from different Standard Loran stations are exactly alike.

In order to resolve the ambiguity in practice, the pulses are emitted, not simultaneously, but alternately, from the two stations. The interval from the emission of a pulse from A to the emission of the next pulse from B is called the *absolute delay* and denoted by D. As the pulses are received by the navigator, the time difference t is greater or less than D by the same amount that B is farther or nearer than A (in light-microseconds).

That is,

$$t = D + v, \qquad (2)$$

where v is positive if B is farther than A and negative if it is nearer, as before. This relation is fundamental in Loran; it should be clearly understood (see Fig. 3·1).

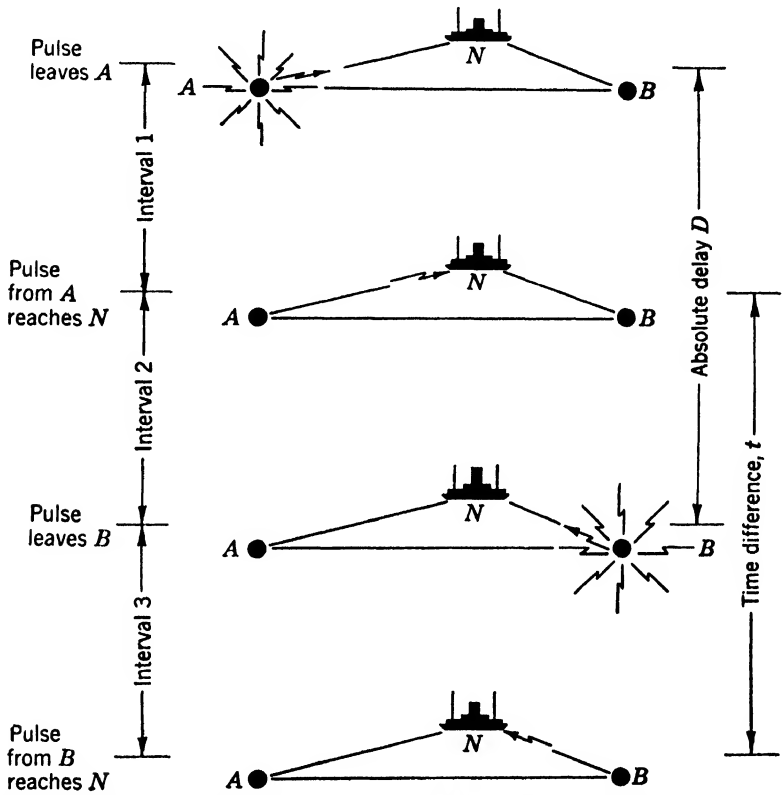


FIG. 3·1.—Time and distance relations in Loran. Absolute delay = intervals 1 + 2; time difference = intervals 2 + 3. If BN is longer than AN, Interval 3 is longer than Interval 1, and the time difference is longer than the absolute delay by the same amount: $(2 + 3) - (1 + 2) = 3 - 1 = BN - AN = v$, if distances are expressed in light-microseconds.

The range of possible values of v is evidently from $+\beta$ to $-\beta$, where β is the length of the direct line from A to B, called the *baseline*, measured in light-microseconds (for in the triangle ABN, where N is the navigator's location, the difference between the lengths AN and BN cannot exceed the length AB). The range of t is, therefore, between $D + \beta$ and $D - \beta$; and if D is made greater than β, t will always be positive, or the pulse from A will everywhere be received before the corresponding pulse from B.

The Line of Position and the Fix.—There are many points at which the *difference* between the distances from A and B is the same, although the distances themselves have various values (Fig. 3·2). These points make up a line (approximately a hyperbola) all along which v and t have con-

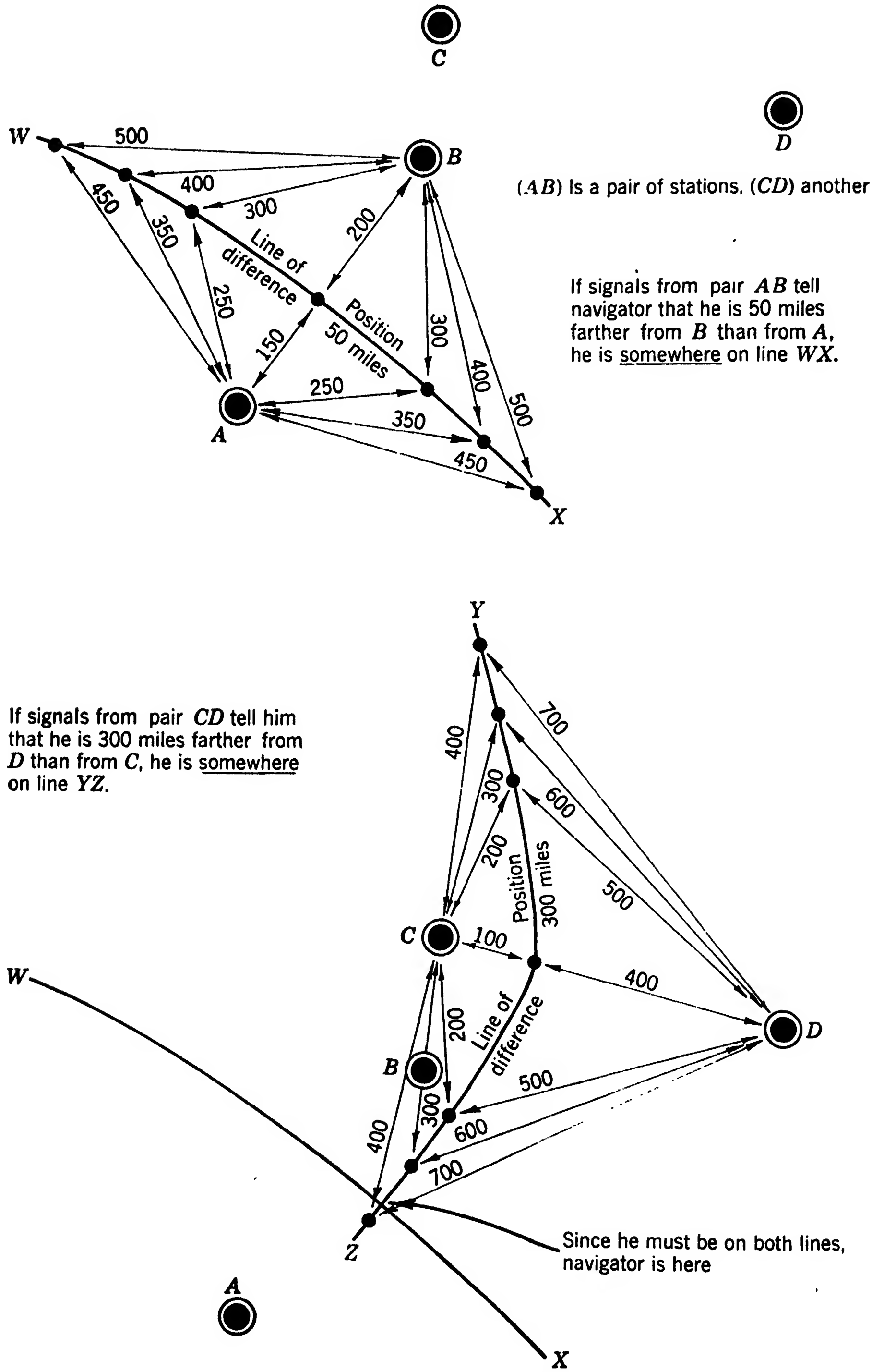


Fig. 3·2.—Determination of position by Loran.

stant values. To every possible value of v or t there corresponds one of these lines of position, passing between A and B and slightly concave toward the nearer of them. All the lines make up a *family*, generated by the two stations. An observer, measuring a certain value of t, can deduce which of these lines he is on but not where he is on it.

To locate himself definitely, the observer must also measure the time difference between the pulses emitted by a second pair of stations. This pair generates a second family of lines of position, which intersect the first family. Every intersection represents a pair of measured time differences (one from each pair of stations) and defines a point that is the location or fix of the navigator who made the measurements. Conversely, two pairs of stations are required to provide a navigator with a fix. This does not necessarily mean four stations, for three stations may operate so that one of them forms a pair with each of the others. So arranged, the stations make up a *Loran triplet.* Four or more stations may similarly form three or more pairs, every station except the end ones being common to two adjacent pairs; this is called a *Loran chain.* In some situations, four stations operating as two pairs, with their baselines crossed nearly at right angles, form an advantageous configuration; this is a *Loran quadrilateral.*

Since the locations of Loran lines of position depend only upon the positions of the stations generating them, the lines are fixed on the surface of the earth. It is a task to calculate their course (see Chap. 6), but the calculation may be made once for all, and the lines printed on charts and labeled with the appropriate values of the time difference. Any two intersecting families will then form a *Loran coordinate system,* as definite as the geographical system of latitude and longitude and independent of it. The navigator, having read two time differences, need find only the intersection of the two corresponding lines on his chart to locate his position without any computation. Three or more intersecting Loran families will afford a check or double check on position, like three or more star sights in celestial navigation.

Numerical Values of β, D, and Other Quantities.—The value of β, the electrical length from A to B, is limited by the fact that the stations keep to their correct time relation by receiving each other's pulses and by maintaining constant time differences between the received and emitted pulses. To do this, the stations must be near enough together so that each receives the other's pulses clearly. The nature of the surface over which the pulses pass and the level of atmospheric electrical "noise" prevalent in the region of operation, as well as the power and radio frequency of transmission, are the factors controlling the practicable separation of stations. At this writing (January 1946), all regularly operating Loran transmitters employ radio frequencies between 1700 and 2000 kc/sec. This range of frequencies constitutes the *Standard Loran* band. The pulse power radiated at the transmitting antenna is normally about 100 kw, and under average conditions the pulses will carry over water to a distance of 400 or 500 nautical miles with 24-hr reliability and sufficient strength to enable two stations at that separation to hold to their timing. In fact, one pair (Labrador-Greenland) operates over a baseline of 590 nautical miles. To obtain a wide area over which both stations of the pair can be received, however, the baseline should be considerably shorter than the maximum range. Three hundred nautical miles (1855 μsec) has been found to be about the optimum baseline length for effective coverage. Stations separated by land must be much closer together because with Standard Loran frequencies the low conductivity of soil and rock greatly reduces the range. An overland baseline of 100 nautical miles (618 μsec) is about the longest practicable.

A Loran network operable only by night was employed in the strategic bombing of Germany, with baselines 1130 and 1300 nautical miles long (6980 and 8050 μsec). These great separations were obtained by the use of sky-wave transmission of pulses (see Sec. 3·2) between stations, at some sacrifice of precision and reliability, and with complete interruption of service during the day.

Trials of a Low Frequency Loran triplet, transmitting on 180 kc/sec with peak radiated power near 100 kw, are in progress. Data so far obtained indicate that reliable continuous operation can be maintained even in the tropics with 600 miles of water separating the stations. If the baseline is principally over land, the distance should probably not exceed 400 miles.

The value of D, the absolute delay, is dictated by the form of the receiving and measuring apparatus (the *Loran receiver-indicator*). This apparatus displays the received pulses as vertical deflections of a horizontal line or trace that appears on the face of an oscilloscope screen. This trace is the path of a light spot sweeping from left to right across the screen, then snapping back and sweeping again. The spot sweeps across many times in a second so that the trace is steadily visible and does not flicker.

During each sweep of the light spot across the screen, electrical impulses from a crystal clock are impressed upon the moving light spot, producing time markers on the trace. The position of a received pulse among these markers indicates the interval between the beginning of the sweep and the time at which the pulse arrived. If the pulse and the sweep are made to recur exactly the same number of times per second, successive pulses will always appear at the same place on the trace, persisting as a single stationary mark whose time may be accurately read. To effect this, each transmitting station sends out its pulses in a steady, equally spaced succession; the number of pulses per second is called the *pulse recurrence rate, PRR*. The time interval between successive pulses from the same station is called the *recurrence period, L*. The indicator sweep is adjusted to recur at exactly the recurrence rate of the stations. In present Loran systems, two basic recurrence rates are used; 25 per second (*low* rate) and $33\frac{1}{3}$ per second (*high* rate). Corresponding values of L are 40,000 and 30,000 μsec.

The time sequence of pulses, as alternately *emitted* from a pair of stations, is $ABAB$ . . . . The interval between successive A's or successive B's is L. The transmission interval AB is the absolute delay D, which must therefore be less than L. The time sequence of pulses as *received* is also $ABAB$ . . . , and the interval between successive A's or B's is L, but the reception interval AB is the time difference t, which varies with the location of the navigator, between the values $D + \beta$ and $D - \beta$.

In order that no ambiguity may occur in identifying pulses on the screen of the indicator, D is made of such length that AB as received will always be greater than $(L/2)$ and less than L, which will make AB everywhere longer than BA. This will be true if

$$D - \beta = \frac{L}{2} + \delta,$$

where δ is some arbitrary time interval, less than $(L/2) - 2\beta$. That is,

$$D = \frac{L}{2} + \beta + \delta,$$

which is the equation defining the value of D for a particular pair of stations. Then the fundamental relation $t = D + v$ becomes

$$t = \frac{L}{2} + (\beta + \delta) + v, \tag{3}$$

and t ranges from $(L/2) + \delta$ to $(L/2) + (2\beta + \delta)$.

With β usually 3000 μsec or less, and $L/2$ 15,000 or 20,000 μsec, there is a wide choice of δ. In Standard Loran systems it has hitherto been 1000 or 2000 μsec, but other values may be used with installations now being set up. For purposes of security in war time, δ may be changed from time to time, and consequently only those having knowledge of the changes can interpret Loran readings correctly. For this reason δ is called the *coding delay*.

It is not difficult to visualize these relations spatially. All points that are receiving a pulse at a given instant lie upon a circle, the center of which is the station that emitted the pulse. This circle expands with the speed of radio transmission, 0.16171 nautical mile per microsecond.

Figure 3·3 shows successive positions of the "pulse circles" emitted by a station pair. Figure 3·3*a* and *b* shows the position of the pulse circles at the instant when station *A* emits a pulse and when the pulse emitted

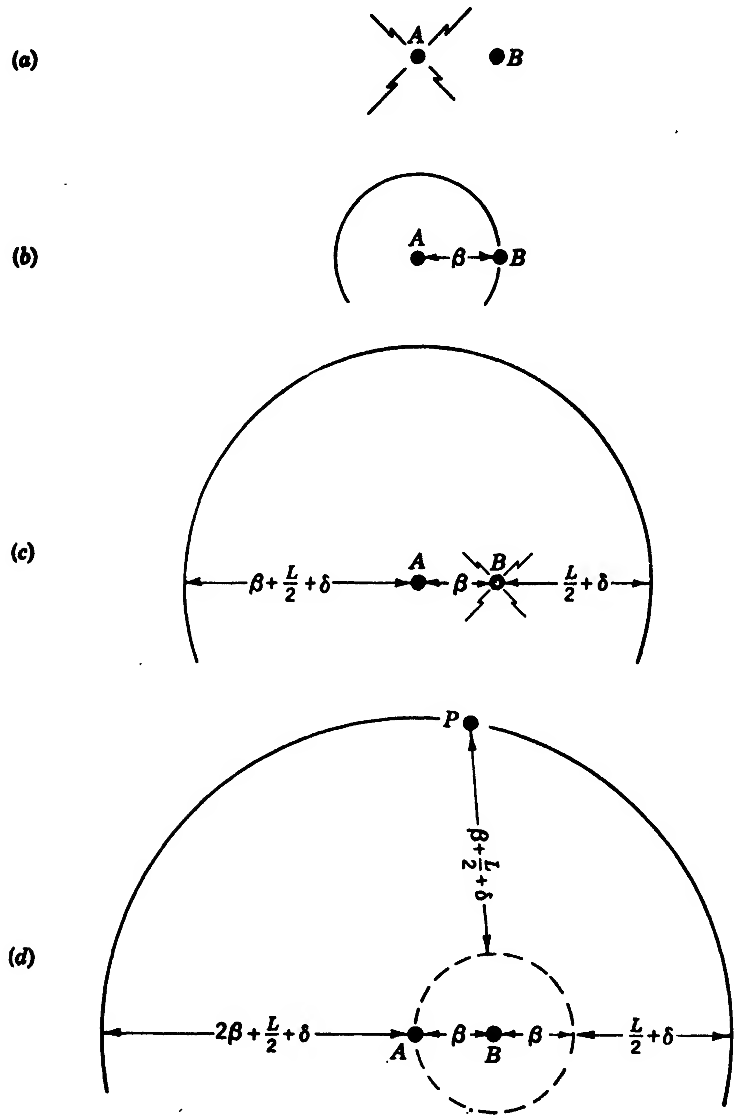


FIG. 3·3.—Time differences and space relations.

by station *A* is received at station *B*. The position of the pulse circles at the instant when station *B* emits a pulse and when *B*'s pulse is received by *A* is shown in Fig. 3·3*c* and *d*. From instant *a* to instant *c* is the absolute delay $[\beta + (L/2) + \delta]$; it is the radius of *A*'s pulse circle when *B*'s pulse is emitted. From instant *b* to instant *c* is the time difference $[(L/2) + \delta]$ *observed at B,* whereas from instant *a* to instant *d* is the time difference $[2\beta + (L/2) + \delta]$ *observed at A*. Note that the first of these intervals is the shortest distance in light-microseconds between the two circles and that the second is the greatest distance. Since the circles expand at the same rate, these distances will remain the same as the pulses move on. Note also that at any point over which the pulse circle from A is passing, the time that will elapse before the circle from B will arrive is the distance to the B-circle, measured along the radius to B from the point. This is the time difference at that point, and it is evident that the extreme values of this difference occur at points on the extended baselines and that at a point P equidistant from A and B the value is $[\beta + (L/2) + \delta]$.

The form of the display on the Loran indicator and the method of reading the time difference are such that the actual number measured is not t but $t - (L/2)$. This reading is called the *indicated time difference* and denoted by T. In practical operation, T is always used instead of t and referred to as *the* time difference. The Loran lines on the charts are labeled, therefore. with values of T instead of t. From Eq. (3) it is evident that

$$T = (\beta + \delta) + v \tag{4}$$

and that its extreme values are δ and $(2\beta + \delta)$. Along the continuation of the baseline beyond station B, $T = \delta$; along the center line, $T = \beta + \delta$; and along the extended baseline beyond station A, $T = 2\beta + \delta$. For a typical Standard Loran station pair, numerical quantities might be $\beta = 1855$ μsec (corresponding to 300 nautical miles), $\delta = 1000$ μsec, and T would range from 1000 μsec, at or behind station B, to 4710 μsec, at or behind station A.

In all the preceding relations, note that the stations are not denoted by the letters A or B indifferently. Station A is always that one of a pair whose pulse begins the absolute delay $(L/2) + (\beta + \delta)$; station B is the one whose pulse ends it. Station A is usually also the one whose crystal oscillator defines the recurrence rate; station B must regulate the frequency of its crystal oscillator to match A's. In this case station A is called the *master station* of the pair, and station B is called the *slave station*. Sometimes the initials M and S are used to represent them, instead of A and B.

3·2. Propagation and Range. *Ground- and Sky-wave Transmission.*—Up to this point it has been assumed that the Loran radio pulses travel close to the surface of the earth and consequently that their time delays measure ground distances. This is true but not the whole truth. Loran pulses travel upward as well as outward; and, when they reach the *ionosphere* (an electrically charged region in the upper atmosphere), they are reflected back to earth in considerable strength. A transmitter at point

X (Fig. 3·4) will, therefore, send a pulse to a receiver at point R by two paths, the direct path $\overline{XR}$ and the indirect path $\overline{XIR}$, where I is a point in the ionosphere. The pulse taking the direct path is said to be carried by *ground waves;* that taking the indirect path is carried by *sky waves.*

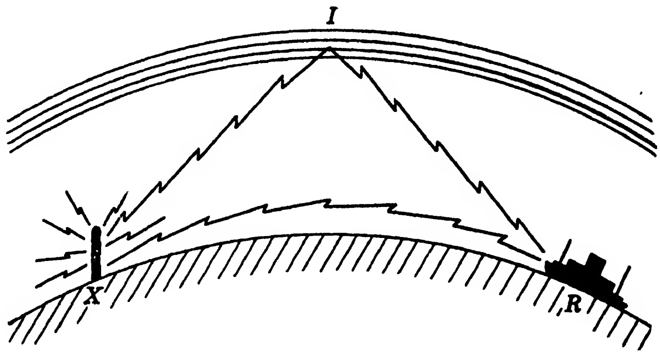


FIG. 3·4.—Ground waves and sky waves.

The distance $\overline{XIR}$ is obviously greater than the distance $\overline{XR}$. The sky-wave transmission time is, therefore, longer than the ground-wave transmission time, and a single pulse from the transmitter, arriving at the receiver over the two different paths, will be received as two pulses, the sky-wave component coming after the ground-wave component by an interval equal to the difference $\overline{XIR} - \overline{XR}$ in light-microseconds. This difference is called the *sky-wave transmission delay;* it may be denoted by E.

Actually, there are several possible paths for sky waves. The ionosphere contains two principal layers of electrified particles at different heights above the earth's surface; the lower (called the E-layer) is partially transparent to waves of the Standard Loran frequency band, with the result that these waves are both reflected from it and transmitted through it to be reflected from the upper or F-layer. Moreover, multiple reflections between ionosphere and ground occur (see Chap. 5, Fig. 5·13). The various paths are of different length, producing a series or train of sky waves following the ground wave. But only the sky wave traveling by the shortest path, the one singly reflected from the E-layer, is reliable enough in its persistence and timing to be used in Standard Loran, and all of the following discussion refers to it. In the special case of Low Frequency Loran, the pulse put out by the transmitters is so long that the ground wave and various sky waves are not resolved in reception. The behavior of this composite pulse is discussed in Chap. 5.

The *greater* the direct or ground-wave distance the *less* the indirect or sky-wave distance *exceeds* it. That is, if R (Fig. 3·5) is a receiver, X_A a near-by transmitter, and X_B a distant transmitter, then $(\overline{X_BI_BR} - \overline{X_BR})$, or E_B, is less than $(\overline{X_AI_AR} - \overline{X_AR})$, or E_A. This is evident from the figure, for the first of these differences is the length of the dotted portion of the indirect path in the neighborhood of I_B, and the second is the length of the dotted portion near I_A. On a flat earth, E would approach zero as $\overline{XR}$ increased; on the actual earth, it does not, because of the earth's curvature and other factors, but instead becomes practically constant at long distances. The amount of the sky-wave transmission E-delay is determined by observation of actual Loran pulses (see Chap. 5). It is somewhat variable, both from season to season and from hour to hour. The larger E is, the larger its range of variation.

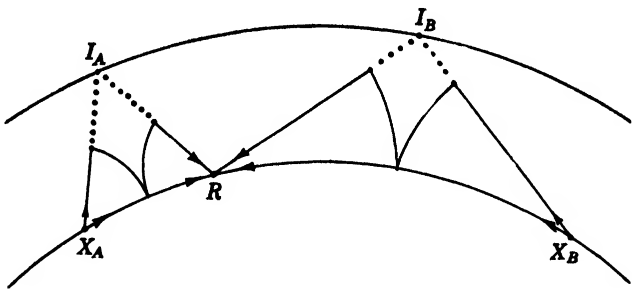


FIG. 3·5.—The sky-wave- transmission delay.

The Sky-wave Correction.—Reflection from the ionosphere is weak and erratic by day at the standard frequency, but by night sky waves can be received in usable strength three times as far as ground waves. Loran coverage at night is, therefore, greatly extended if the navigators use time differences obtained from pairs of sky-wave pulses to define lines of position. These sky-wave time differences may be denoted by T_S. In general, T_S will be different from the time difference T between ground-wave pulses that would be observed at the same place, and, conversely, a sky-wave measurement and a ground-wave measurement that are the same in amount will define lines of position that are different. Separate charts showing sky-wave Loran lines may be furnished to the navigator, in addition to the ground-wave Loran charts, or the same charts may carry both sets of lines. But many charts are inconvenient, and many sets of lines on a chart are confusing. Therefore the standard procedure hitherto has been to put on the charts only ground-wave lines representing values of T and to provide the navigator with tabulated *sky-wave corrections*, such that a correction, applied to an observed value of T_S, will reduce it to the value of T at the same place.

The quantitative relation between T_S and T may be developed as follows:

$$
\begin{aligned}
T_S &= (\beta + \delta) + (\overline{X_BI_BR} - \overline{X_AI_AR}) \\
&= (\beta + \delta) + (\overline{X_BR} + E_B) - (\overline{X_AR} + E_A) \\
&= (\beta + \delta) + (\overline{X_BR} - \overline{X_AR}) + (E_B - E_A). \\
T &= (\beta + \delta) + v = (\beta + \delta) + (\overline{X_BR} - \overline{X_AR}).
\end{aligned}
$$

Comparing the last two equations,

$$T = T_S - (E_B - E_A) = T_S + (E_A - E_B) = T_S + C, \qquad (5)$$

where C, the sky-wave transmission delay from A minus that from B (note the order of subtraction), is the sky-wave correction. C always has the same sign as v, positive if station A is nearer than B, negative if it is farther.

On the center line C is zero, as is v, for there $E_A = E_B$. Across the hyperbolas, away from the center line, C becomes positively or negatively greater as the nearer station is approached. Along a hyperbola, it approaches zero as the distance from the baseline increases, vanishing at great distances. Over the larger part of the region within which sky-wave time differences are reliable, C is less than 10 μsec. It becomes larger when the navigator is near both stations and largest when he is close to one station and far from the other. For example:

Distances of stations, nautical miles	C, μsec
Both > 600	< 12
500 and 800	16
400 and 700	26
300 and 600	42
300 and > 1000	53

The transmission delay from a near station varies unpredictably, sometimes by as much as 20 μsec, making the corrections that involve this station correspondingly uncertain. As a general rule, 250 miles may be considered the shortest distance from a station at which reasonably reliable lines of position may be obtained from its sky-wave pulses.

The Range of Loran Transmission.—The greatest distance at which Loran pulses can be received in strength sufficient for measurement is different at 1950 and 180 kc/sec, different for ground waves and sky waves, different by day and by night, and different over water and over land. The ground wave at 1950 kc/sec, by day, has a usable range of 700 or 800 nautical miles over salt water, under low-noise conditions. At night the normal increase in natural noise cuts this down to approximately 450 miles. Over land of average conductivity, the ranges are one-half to one-third of these, at considerable elevation above ground; on the surface, they are even less.

The one-hop E-layer sky wave at 1950 kc/sec is not normally observable by day over the most generally navigated regions of the earth, except at extremely short ranges (at which its time delay is unreliable). Southeastern Asia in the dry season, however, seems to be an exception to this statement.

At night this sky wave carries pulses to a range of 1400 nautical miles over water and only slightly less over land (because the land attenuation is effective only in the regions near the transmitter and receiver, where the wave is near the ground).

At 180 kc/sec, the ranges are much greater than at the standard frequency. Data obtained over several months of experimental trials indicate that by day the ground-wave range over sea is at least 1200 nautical miles and over land 1000 miles. As at the higher frequencies, the sky waves are largely absorbed by the ionosphere. At night, over land or sea, the sky-wave range usually exceeds 1500 nautical miles.

These ranges vary from day to day, seasonally, and with the locality, since they depend upon ionization in the upper atmosphere, severity of natural electrical disturbance, and surface conductivity.

3·3. Principles of Operation. *Time-difference Measurement.*—As has been mentioned, the time difference is presented to the observer visually as a length between marks on a line, which appears on the oscilloscope screen of the *Loran receiver-indicator* (see Chap. 11). The *Loran transmitter timer*, which controls and regulates the emission of pulses by the transmitting stations, is described in detail in Chap. 7. These two instruments embody the same principles, although they make different use of them. A brief and simplified description of a widely used form of the receiver-indicator is given here, followed by a statement of the additional elements that the transmitter timer requires to perform its functions.

The Loran receiver is a conventional superheterodyne with four rather broad fixed-tuned channels. The indicator contains a cathode-ray oscilloscope. The horizontal deflection of the beam and the graduating vertical deflections are precisely controlled by a crystal clock; other vertical deflections are produced by the pulses from Loran stations communicated to it through the receiver. The combination acts as a stop watch with a graduated dial (the oscilloscope trace, graduated by pulses from the crystal) and two independent hands (the delay circuits described below) that may be set to mark the times of arrival of the two pulses, after which the relative position of the hands measured by the graduations shows the time interval between pulses.

The cathode-ray beam striking the oscilloscope screen produces a spot of light. Potential differences for deflecting the cathode-ray beam are regulated by the crystal clock in such a manner that their variation swings the beam back and forth across the tube, sweeping the light spot over the screen in a regular pattern. This pattern is the *slow-trace pattern*, and the period of its repetition is called the *recurrence period L*. A typical value of L is $\frac{4}{100}$ sec, or 40,000 μsec. During this interval the moving spot goes through this sequence:

1. It sweeps steadily from left to right across the upper part of the screen. This *upper trace* is traversed in about 19,930 μsec—almost half of L.

2. It snaps downward and to the left. This *retrace* takes about 70 μsec.
3. It sweeps from left to right across the lower part of the screen. This *lower trace* takes about 19,930 μsec.
4. It snaps upward and to the left. This *retrace* takes about 70 μsec.

The sequence, repeated twenty-five times a second, is rapid enough to make the path of the spot visible as a continuous line, 1 and 3 being bright and 2 and 4 almost invisible (Fig. 3·6). As the spot sweeps across the screen, slight vertical displacements are imparted to it at 10-μsec intervals by the vibrating crystal, and greater displacements every 50 and 500 μsec. This action causes graduations, or time markers, to appear along the trace.

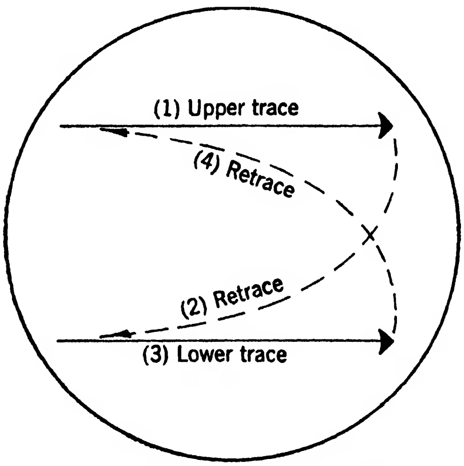


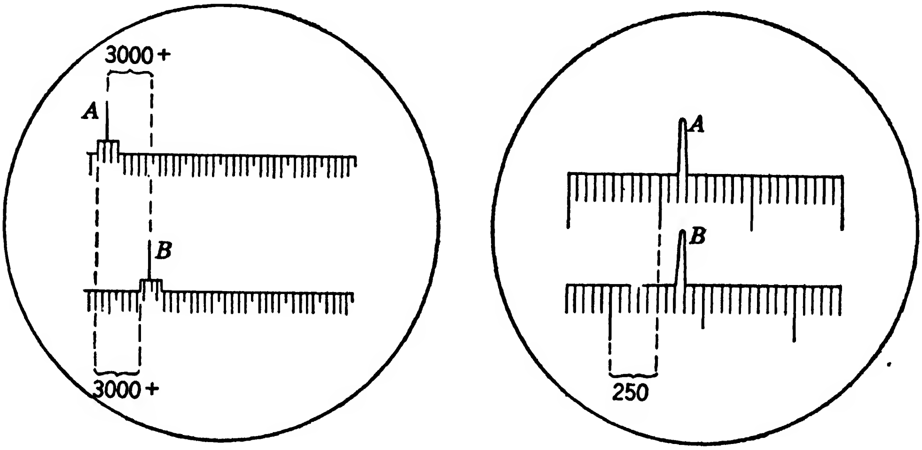
FIG. 3·6.—Indicator oscilloscope traces.

The pulses from the Loran transmitters are passed to the oscilloscope by the receiver and also appear as vertical displacements of the moving spot. Since the duration of a pulse, as distorted in the receiver, is about 75 μsec, a hump with this length and with a height depending on the intensity of the pulse is seen on the trace in a position corresponding to the position of the spot at the time of the reception of the pulse. The interval between pulses from the same station is L. During this time the light spot runs through its entire cycle and returns to the same point. The hump, therefore, is repeated at this point in every cycle and appears as a stationary feature of the trace.

Between a pulse from station A and one from station B, the interval is t, or $(L/2) + (\beta + \delta) + v$. During this time the spot traces a little more than half its path on the screen; therefore, if the hump caused by the pulse from A appears on the upper trace, the hump caused by the pulse from B will appear on the lower trace, a little to the right of the other (Fig. 3·7). For example, if t is 23,250 μsec, the pulse from B will appear to the right of that from A by the distance over which the spot moves in 3250 μsec. It is this displacement to the right which the observer measures. The time difference that he reads from it is T.

The crystal of the indicator is in no way locked to the incoming pulses. When the indicator is turned on, the A-pulse may appear at any point of the trace, and the recurrence period of the indicator may not exactly match that of the pulse, in which case the pulse will drift slowly along the trace. But an adjustment is provided to alter the effective crystal frequency (regulate the clock) so as to stop the drift. There is also a LEFT-RIGHT switch to retard or accelerate the crystal momentarily (set the clock); by its use the A-pulse may be caused to drift rapidly to the left or right until it occupies its proper position on the upper trace.

Ideally, the measurement might be made by simply counting time markers from the beginning of each trace to the hump on that trace and taking the difference. Actually, on the linear scale imposed by the size of the screen, only the 500-μsec markers can be counted, because those which are only 50 μsec apart blend together. Furthermore, the pulses



(a) (b)

FIG. 3·7.—Reading time difference from the indicator. (a) The complete traces, without magnification. Markers are 500 μsec apart. True time difference 23000+. Time difference as read, 3000+. (b) The sections adjacent to the two pulses, as magnified. Markers are 50 μsec apart. Displacement as read, 250. Total reading, 3250.

might drift appreciably along the traces while the two measurements were being made successively. To avoid these difficulties, means are provided to select a short section of each trace (distinguished from the rest of the trace by being slightly elevated above its line and, therefore, called a *pedestal*) and to display the pedestal in place of the whole trace, on a scale greatly expanded in time. The effect is as though the selected sections of trace were viewed with a magnifying glass. This display is called the *fast-trace pattern;* the unmagnified, complete display is called the *slow-trace pattern.* The upper pedestal is fixed near the beginning of the upper trace, whereas the lower pedestal may be moved along the lower trace by *coarse and fine delay controls.* With the LEFT-RIGHT switch the A-pulse is drifted to a position on the upper pedestal; with the delay controls the lower pedestal is moved under the B-pulse (Fig. 3·7a). Then the complete traces are replaced by the pedestals alone (Fig. 3·7b), and the fine delay control manipulated until the B-pulse occupies exactly the same position on the lower pedestal that the A-pulse occupies on the upper pedestal. To make this adjustment precise, the lower pedestal is raised and the upper brought down until they coincide; the pulses can then be superposed with a normal reading error of less than 1 μsec, roughly 1 per cent of the apparent width of the pulse.

When this has been done, the relative horizontal displacement between the pedestals is exactly the same as that between the pulses. This displacement, therefore, measures the time difference T at the moment when the pulses are superposed. The stop-watch analogue to this operation would be to set one stop-watch hand to the time of arrival of one pulse and the other hand to the time of arrival of the other pulse, and to make the settings simultaneously. Drift of the pulses does not matter as long as superposition is effected (just as in a sextant observation, where sun and horizon may swing back and forth together in the field of view as long as they are brought to tangency). Once the setting has been made, the displacement of the lower pedestal relative to the upper is read by counting the markers occurring after the start of the top pedestal and before the start of the lower pedestal. The 500-μsec markers are counted from the slow-trace display, and the 50- and 10-μsec markers are counted from the fast-trace display (see Fig. 3·7, which is simplified and schematic, and Fig. 11·2 of Chap. 11, which shows the complete procedure of measurement).

Maintenance of Delay between Stations.—The two transmitting stations that make up a Loran pair are electrically independent. The pulses emitted by a station are triggered by a free-running quartz-crystal oscillator, carefully controlled in temperature to maintain frequency within 1 part in 300 million (1 μsec in 5 min). The vibration frequency of the crystal is 50 kc/sec and is reduced by divider circuits to the chosen recurrence rate for the pair. The crystal-oscillator and divider circuits are similar to those of the navigator's indicator, but somewhat more elaborate and stable. They actuate a display of traces, time markers, and pedestals on two oscilloscope screens (so as to present both slow and fast traces at the same time), and both pedestals are controlled by separate delay circuits. At the master station, the circuit that controls the upper pedestal also triggers the transmitter. The pulse would be emitted exactly at the instant indicated by the left end of the pedestal if the transmitting system acted instantaneously. A receiver is connected to the timer oscilloscope, as with the indicator; if the receiver also acted simultaneously, the transmitter pulse that is received after traveling only a few hundred feet would appear on the pedestal just at the beginning of the pedestal. Actually, transmission and reception take about 50 μsec because of lag in the circuits, and consequently the pulse is displaced to the right on the pedestal by this distance.

At the slave station an exactly similar timer operates, but here the transmitter is triggered by the circuit that controls the lower pedestal, and hence the local pulse appears on it.

When the timers at the two stations are adjusted so that each pulse emitted from the slave transmitter follows the corresponding pulse emitted from the master transmitter by the absolute interval $(L/2) + (\beta + \delta)$, the stations are said to be in *delayed synchronism*. As has been explained, the indicated time difference observed at the slave station is then equal to δ, whereas at the master station it is $(2\beta + \delta)$. Maintenance of synchronism is the duty of the operator at the slave station, who adjusts his timer to keep step with the pulse received from the master station. With the two timers and transmitters running independently, the oscilloscope at either station will show the pulse emitted at that station (*local pulse*) at a fixed point on its pedestal, but the pulse received from the other station (*remote pulse*) will be drifting along the traces, for the crystals will not, in general, be vibrating at exactly the same frequency. The slave operator synchronizes his transmitter with the other in two steps. First, he sets his lower pedestal (carrying his local pulse with it) to a position δ μsec to the right of his upper pedestal by means of the delay controls. Next, he varies the frequency of his oscillator in order to drift the remote pulse onto the upper pedestal and to bring it to rest at the same place on this pedestal at which the local pulse is fixed on the other pedestal. He makes this adjustment by superposition, as does the observer on a ship or airplane, but instead of bringing this about by varying the delay to fit two remote pulses, he leaves the delay at its fixed setting and varies the oscillator phase, carrying the local pulse with it, until it fits the remote pulse. When this has been accomplished, the two pulses have the same time relation as the two pedestals and are therefore in delayed synchronism. They will remain so as long as the two crystals hold the same frequency. Generally this will be of short duration, since neither oscillator is perfectly stable. For this reason the slave oscillator must be made to follow the slight variations of the master. The slave operator may do this manually, watching the superposed pulses on the fast-trace display and advancing or retarding his oscillator slightly as the remote pulse begins to slide out from coincidence with the local. Coincidence may also be maintained by the *Loran automatic synchronizer*, an electrical network linking the receiver input with the oscillator control. This device "views" a portion of the rising slope of the remote pulse after it has been manually set in its proper place on the upper trace and accelerates the oscillator if the average elevation of this slope becomes greater (because the pulse has drifted to the left) or retards it if the elevation becomes less (because of a drift to the right). In either case the effect is to counteract the drift. The synchronizer cannot set the pulses in coincidence—this must be done by visual inspection of the pulse images—but it will hold coincidence within 1 or 2 μsec if there is not too much electrical noise. Under noisy conditions manual control is necessary. The stability of the oscillators is such, however, that synchronism may be maintained by an experienced operator through long periods of electrical disturbance if he can glimpse the remote pulse for a few seconds from time to time.

While the slave operator maintains synchronism, the master operator keeps a continuous watch over the timing by means of his own oscilloscope. He sets the delay controls so that the lower pedestal is at a distance $(2\beta + \delta)$ to the right of the upper pedestal (on which his local pulse is fixed). If the slave transmitter is timed correctly, the remote pulse coming from it will appear on the master's lower pedestal, in position so that the two pulses will coincide in the fast-trace display. If they do not, the master operator actuates a device that "blinks" his pulse (causes it to jump regularly back and forth), telling the slave to make a correction and warning observers not to make readings. The master does not, however, change the frequency of his own oscillator.

Generally, the master is the station called *A* whose pulse initiates the delay, and the slave is *B* whose pulse terminates it. In emergencies, *A* may act as slave and *B* as master, with respect to dependence and independence of the frequency of the oscillators, but they do not exchange positions in the sequence. If they should do so, the time order of the Loran lines around the stations would be reversed, making the charts useless.

At each station a switched electronic *attenuator* is inserted between the receiving antenna and the receiver, which allows the remote pulse to come through undiminished but cuts down the extreme intensity of the local pulse so that on the oscilloscope screen it can be matched in amplitude with the remote pulse. The attenuator is designed to act on the pulses without introducing any differential delay; but since it is the one circuit in the timer that does not treat them exactly alike, such a differential may well creep in, falsifying the timing at the two stations in opposite senses. To detect such an effect and to check the operating personnel, the equipment, and propagation conditions, it is highly desirable that a *monitor station*, equipped with a standard indicator, be maintained in a known position within good receiving distance of both ground stations and far enough from both so that neither pulse has to be greatly attenuated for comparison with the other. The synchronism, pulse shapes, and signal strengths should be observed, and routine reports should be submitted to the operating authorities.

Distinction between Pairs of Stations.—The navigator cannot determine his position unless he can receive pulses from two pairs of stations. In many areas he may be within range of three or more pairs. In order that he may obtain readings from several pairs in rapid succession with as little readjustment of his instrument as possible and without losing time in search of the pulses, chains of adjacent pairs of Loran stations operate on the same frequency and at nearly the same recurrence rate. All pulses strong enough to be detected appear together on the screen of the navigator's indicator; and, if the recurrence rate of the indicator is properly adjusted, they will all be steadily visible.

If the indicator and all the station pairs operated at exactly the same frequency and same recurrence rate, the pulses would all look and behave alike and identification would be impossible. To avoid this, different pairs of the same chain of stations operate on rates that differ but slightly; they are distinct but are all near the same *basic rate.* The two basic rates now in use are 25 cps (the *low,* or *L,* basic rate) and $33\frac{1}{3}$ cps (the *high,* or *H,* basic rate). A chain or series of pairs operate on *specific rates* that are related to the basic rate as follows:

Basic rate	. . .	*L*	*H*
Specific rate, cps	0	25	$33\frac{1}{3}$
	1	$25\frac{1}{16}$	$33\frac{4}{9}$
	2	$25\frac{1}{8}$	$33\frac{5}{9}$
	3	$25\frac{3}{16}$	$33\frac{2}{3}$

and so forth, up to specific rate 7, $25\frac{7}{16}$, or $34\frac{1}{9}$ cps. These values are close approximations but are not exact. The exact relations are defined in terms of the recurrence *period,* as follows. For the *L*-rates, the specific recurrence periods are $(40{,}000 - 100n)$ μsec and for the *H*-rates $(30{,}000 - 100n)$ μsec, where n takes the integral values from 0 to 7. Thus under each of the basic rates there are eight specific rates, called by the numbers 0, 1, 2, . . . , 7. These are the *station-selection* numbers.

On the indicator panel there are two switches, one of which may be set to *H* or *L,* the other to any number from 0 to 7. If these are set to *H* and 4, for example, the indicator will run at recurrence rate $33\frac{7}{9}$ cps. A pulse coming in at this rate will appear stationary on the trace, for the moving light spot will just complete a circuit of the screen between recurrences of the pulse. But pulses at the slower rates *H*0, *H*1, *H*2, or *H*3 will drift to the right along the trace, for between recurrences of a pulse the light spot will complete a circuit and go on a little way, and hence the pulse will recur later and later on the trace. Similarly, pulses at the faster rates *H*5, *H*6, or *H*7 will drift to the left. Pulses on all the much slower *L*-rates will go to the right by long jumps; they will flicker erratically over the screen and can easily be ignored.

Although all Loran stations operating at present use the same band of radio frequencies, between 1700 and 2000 kc/sec, they all do not use the same frequency. Four different frequencies have been used—1750, 1850, 1900, and 1950 kc/sec. These radio frequencies are referred to as *channels*, and they are numbered. Channel 1 is 1950 kc/sec; Channel 2 is 1850; Channel 3 is 1900; and Channel 4 is 1750. The Loran receiver may be tuned to any channel by turning a *channel switch* to the proper number.

A pair of Loran stations bears a designation made up of the channel number, basic-rate letter, and station-selection number. The first two of these characterize an entire group, or chain, of stations that are to be used by navigators in a particular area or in connection with particular operations. Such a group of stations might include pairs designated 2*H*0, 2*H*1, 2*H*2, 2*H*3. For all these the channel is 1850 kc/sec and the basic rate is $33\frac{1}{3}$ cps; the specific rates are $33\frac{1}{3}$, $33\frac{4}{9}$, $33\frac{5}{9}$, and $33\frac{2}{3}$ cps. The designation is prefixed to any value of T read by a navigator from the pulses of a pair and is part of the label of any charted Loran line. Such a line might be labeled 2*H*2-3380; the four-figure number being the value of T, the prefix the designation of the pair.

It has been mentioned that in a triplet of Loran stations, one station acts as a member of two pairs and that in a chain of stations, all members but those at the ends act in this way. Sometimes the three stations of a triplet use the same recurrence rate (as explained in Sec. 3·5 in the discussion of systems), but usually they use different specific rates. In a chain, adjacent pairs always use different rates. This means that a station which is a member of two pairs sends out two independent sequences of pulses, one slightly more closely spaced than the other. These pulses must be triggered by different timers but may be sent out from the same transmitter. *Double pulsing*, as this method of operation is called, decreases peak power somewhat by altering the duty cycle of the transmitter and slightly disturbs the timing of both pulses at the moment when the one of higher rate overtakes the other. It has been widely employed, however, in Loran operation because of its economy of equipment, of which there was a critical shortage throughout the war period in which Loran grew up.

3·4. Loran Geometry: the Pair. *The Loran Hyperbolas.*—A hyperbola is by definition the locus of points all of which are farther from one fixed point than they are from another fixed point by the same distance. The two fixed points are the foci. A Loran line of position is therefore a hyperbola with its foci at the two transmitting stations A and B.

If the surface of the earth were a plane, the lines generated by a pair of stations would form a family of *confocal plane hyperbolas* (Fig. 3·8). The baseline, connecting the stations, would be a straight line. The line $T = \beta + \delta$ or $v = 0$ would be a straight line called the *center line*, bisecting the baseline perpendicularly, a hyperbola of zero curvature. The actual lines of constant time difference approximate these hyperbolas and have very much the same properties. It is, therefore, convenient to discuss them as if they actually were such confocal plane hyperbolas. The hyperbolas in the neighborhood of the center line curve slightly away from it; the hyperbolas in the neighborhood of a station curve sharply

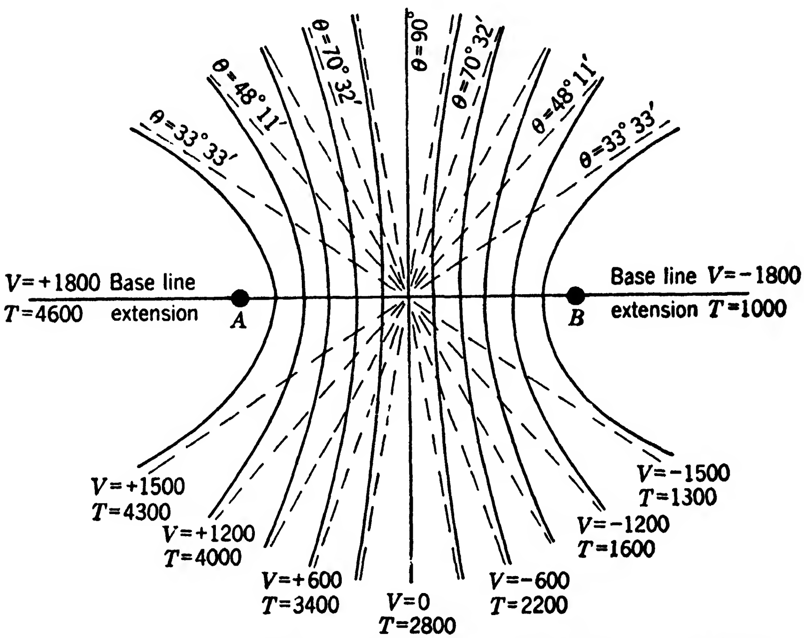


FIG. 3·8.—A family of plane hyperbolas. $\beta = 1800$ μsec; $\delta = 1000$ μsec.

around it. The lines $T = 2\beta + \delta$ and $T = \delta$ or $v = +\beta$ and $v = -\beta$ are straight lines continuing the baseline beyond A and beyond B, respectively, and are called the *baseline extensions*. They are hyperbolas folded together, with curvature degenerated into 180° angles at the respective stations. At large distances from the baseline (more than 5β or so) all the hyperbolas are very nearly straight, becoming asymptotic to radii extended from the intersection of baseline and center line and defined by the equation

$$\cos \theta = \frac{v}{\beta} \tag{6}$$

where θ is the angle between radius and baseline. A Loran reading made at a great distance from a pair of stations is, therefore, an indication of the direction of the observer from the pair, but the change of angle with a given change of reading varies from a minimum on the center line to a maximum on a baseline extension, and two directions that are not opposite correspond to one reading.

If the earth were a true sphere, the baseline would be a great circle. The center line and extended baselines would also be great circles, and the other Loran lines would form a family of confocal *spherical hyperbolas.* The earth is actually not quite spherical, so the Loran lines are slightly (but quite perceptibly) distorted from spherical hyperbolas to more complex curves. This distortion must be allowed for in precise charting over large areas. The Loran hyperbolas are discussed further in Chap. 6.

The Factor of Geometrical Precision.—Since no observation is exact, an observed reading will differ from the true value of the measured quantity by an amount that cannot be predicted for the individual observation but may be estimated as an expected or "probable" value derived from many comparisons between observed and "true" values. This expected error is usually taken as $0.67 \sqrt{\Sigma r^2/n}$, where Σr^2 signifies the sum of the squares of the deviations of a typical series of n observed values from the true values found by some more accurate method. If the distribution of deviations follows the gaussian normal law, the result thus derived is also the median of the deviations. There are as many deviations that are greater than the median as there are deviations that are less; therefore the median is called the *probable error.*

If the probable error of a Loran measurement of time difference is x μsec, an observer who obtains the reading T from his indicator is as likely to be actually located between the Loran lines $T - x$ and $T + x$ as to be outside this region. As far as he is concerned, the reading does not represent a sharp line but a strip at least $2x$ μsec wide between two hyperbolas. The width of this strip in units of length is obviously a matter of importance to the observer, since he desires to obtain his location on the earth. The width is not $2x$ times 0.1617 nautical miles, as might be assumed without due thought. In fact, the conversion factor cannot be a constant, for it is obvious that two hyperbolas of the same family are farther apart at a long distance from the baseline than they are close to it. It is also true that hyperbolas which cross the baseline near a focus diverge more sharply than those which cross near the center line.

We may, therefore, write for y, the probable error in the position of the observer's Loran line corresponding to a probable error of x in the measurement of the time difference, $y = kwx$. In this, k depends on the unit of length and is, for example, unity if distance is measured in light-microseconds. The other factor, w, that depends on the observer's position may be called the *factor of geometrical precision.* It equals $\frac{1}{2} \csc \frac{1}{2}\psi$, in which ψ is the angle between the two directions from the observer to the transmitting stations. See Appendix C·1 for the proof of this relation.

We have, therefore,

$$
\begin{aligned}
kw &= 0.08086 \csc \tfrac{1}{2}\psi && \text{(nautical miles}/\mu\text{sec)} \\
&= 0.09311 \csc \tfrac{1}{2}\psi && \text{(statute miles}/\mu\text{sec)} \\
&= 0.14985 \csc \tfrac{1}{2}\psi && \text{(km}/\mu\text{sec)} \\
&= 491.62 \csc \tfrac{1}{2}\psi && \text{(ft}/\mu\text{sec).}
\end{aligned} \tag{7}
$$

Small values of ψ, the angular separation of the two transmitting stations from the observer's position, correspond to large values of kw and correspondingly large values of y, the probable error of location of his line of position.

The curve of constant w, on a plane, is a curve of constant ψ and is therefore one of the two arcs into which a circle passing through the two transmitting stations A and B is divided by the stations. The two arcs are characterized by two different values of w that correspond to two values of ψ whose sum is π. The complete locus for one value is the figure eight or lens formed by corresponding arcs of two circles, symmetrically placed with respect to the baseline (Fig. 3·9). If P is a point where one of these circles intersects the center line, w is given by

$$w = \frac{d}{b}, \tag{8}$$

where d is the length AP or BP and b the length of the baseline AB. At any other point Q on the arc, the angle AQB is equal to the angle APB, by the elementary geometry of the circle. Thus an approximate value w can be quickly found for any point Q on a Loran chart by constructing the circle ABQ, finding the point P where the arc AQB intersects the perpendicular bisector of the line AB, measuring the lengths AB and AP or BP, and computing the ratio. Neither a table of trigonometric functions nor a protractor is necessary.

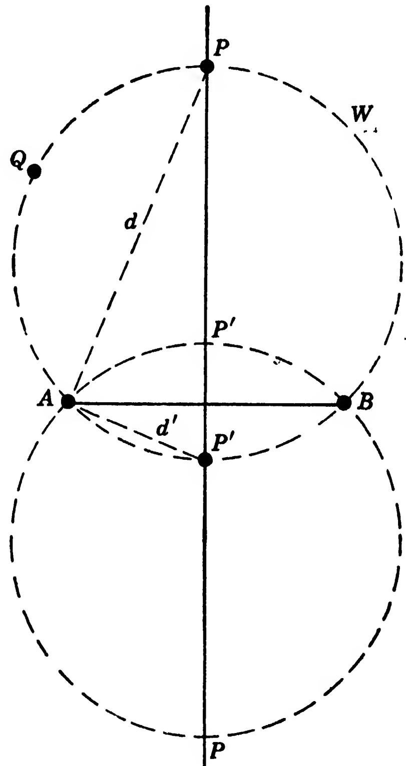


FIG. 3·9.—A graphical construction for determining w.

The corresponding curve on a sphere is of the fourth degree, but it approximates a spherical ellipse passing through A and B and having its semimajor axis a and semiminor axis a' in the ratio $\sin a = \tan a'$. The major axis lies along the center line, but, of course, the minor axis does not lie along the baseline except in the special case $\psi = 90°$, $w = \frac{1}{2}\sqrt{2}$. In this case only is the approximation exact.

An approximate expression for w, in terms of the distance r and direction θ of the observer from the point midway between the stations, is often useful. It is close to the truth if the distance is several times the baseline length, but it breaks down at short distances. The expression is

$$w = \left(\frac{r}{b}\right) \csc \theta, \tag{9}$$

where r is the distance from the midpoint, b is the length of the baseline, and θ is the angle that the line from midpoint to observer makes with the baseline. This is the formula for the spacing of the *asymptotes* of the plane hyperbolas and is obtained by differentiating the equation of an asymptote, $\cos \theta = v/\beta$ (Sec. 3·4), and noting that in this case $w = r\, d\theta/dv$.

Although w increases without upper limit as ψ decreases or r increases, its lower limit is not zero but unity. This is its value along the baseline, where $\psi = 180°$. Here the conversion factor kw is equal to the numerical coefficient in Eq. (7). Over a considerable area near the baseline, w is not much greater than unity and the precision is nearly constant. The optimum geometrical precision is therefore the same for all hyperbolic coordinate systems, whatever the length of baseline, and improvement in the accuracy with which an observer may locate himself can be effected only by decreasing the probable error of a time-difference reading in microseconds. The precision falls off, however, with distance from the baseline less rapidly if the baseline is long than if it is short.

To recapitulate: Slight departures from synchronism at the stations, slight variations in time of travel of the pulses, and slight errors in pulse-matching by the observer combine to build up the probable error of a measured Loran time difference. Let the measured value be T' μsec and the probable error x μsec. The probable error of the line of position designated by T' is represented geometrically by the strip on the earth, bounded by the hyperbolas $T' - x$ and $T' + x$. The distance across this strip in linear units is $2kwx$. If the line of position on which the observer is actually situated when the measurement is made is T, it is equally probable that T differs from T' by less than x or by more than x, in either the positive or the negative direction, and equally probable that the observer's actual line of position lies within or without the strip and that it is distant from the hyperbola T' by less or by more than kwx, in linear units. The value of x must be determined experimentally or by statistical analysis of large numbers of readings taken in actual Loran operation.

The Service Area of a Pair.—The area within which an observer can receive measurable pulses from *both* stations of a Loran pair is the area common to two circles described around the stations with radii equal to the effective range of a transmitter. This is called the *service area of the pair*. It is symmetrical about the center line of the pair, which is its longest dimension. The two stations must be within the area in order to maintain synchronism. If β is much smaller than the range, the service area is almost round (Fig. 3·10*a*); if β is nearly equal to the range, the area has a lenticular form (Fig. 3·10*b*).

As has been shown, an observed reading designates a line of position more precisely in some parts of the area than in others. This inherent inequality of precision is expressed by the variation of the factor w over the area, which is indicated in the figure by contours of constant w, with the regions bounded by them stippled and shaded appropriately. Values of kw in nautical miles per microsecond are appended to the contours. In the solid black regions, where kw is more than 2 miles per microsecond, the precision is so low that we may practically count these regions out of the area of useful service; the rest of the area is thus given a characteristic "butterfly" shape.

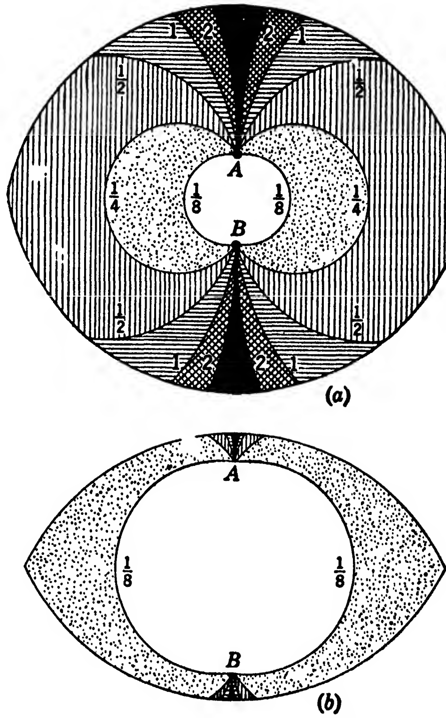


FIG. 3·10.—Service area of a pair.

It is evident that the precision is relatively high over a much larger part of the service area when the stations are near maximum separation than when they are close together. However, overlap between adjacent service areas, which is obviously necessary to provide navigational fixes, is obtained in the Standard Loran chain arrangement only by making the baselines relatively short (see Sec. 3·5). Short baselines are also conducive to reliable synchronism of stations under adverse conditions.

The symmetrical forms of Fig. 3·10 only hold if propagation is equally good in all directions. If sea water extends on one side of a pair and land on the other, the arcs bounding the area must be drawn with the appropriate different radii. With Standard Loran frequency, the daytime ground-wave extent of the service area on the landward side is less than half that to seaward. But at night the sky-wave ranges are nearly equal. If the regions covered are partly sea water and partly land or fresh water (the propagational characteristics of which are not much better than those of land), the ranges are intermediate. They depend so much upon the local conductivity that they are troublesome to calculate even if data are available.

Since the ground-wave range by day is greater than the ground-wave range by night and less than the sky-wave range by night, the boundary of the service area can be defined only with reference to the time and the form of propagation. The same pair may have a nighttime sky-wave area of the form *a*, a nighttime ground-wave area of the form *b*, and a daytime area of intermediate form. The contours of precision remain fixed with respect to the stations, since they depend upon geometry, not propagational characteristics.

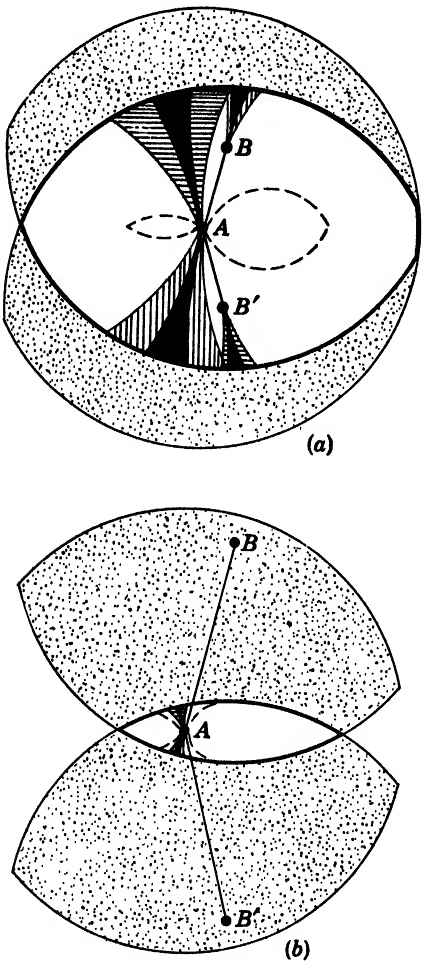


FIG. 3·11.—Standard form of a Loran triplet.

3·5. Loran Geometry: Triplets, Chains, and Quadrilaterals. *The Common Service Area of Two Pairs.*—The region within which an observer can obtain a *fix*, or determination of position, from Loran measurements must be the region common to the service areas of *two pairs* of stations. Evidently the size and shape of this region depends upon the arrangement of the pairs with respect to each other; evidently it is smaller than the service area of either pair and may be much smaller. The first Loran installations and those of the British hyperbolic system "Gee" were set up to provide service over an area with the transmitting stations all on one side of it—for the British, northwestern Europe with stations in England; for the Americans, the western end of the North Atlantic sea route with stations along the coasts of New England and Canada. The region to be covered in either case had length and width much greater than the practicable length of baseline. In these cases the only feasible arrangement of pairs was with baselines end to end—the *chain* arrangement mentioned earlier, the special case of only two pairs being the *triplet*. Since any chain is a succession of overlapping triplets, the triplet may be considered the type form.

The typical service area of a triplet of this type is depicted in Fig. 3·11*a*, where it is the area within the heavy boundary. In the stippled areas, the signals of only one pair are measurable. Within the common service area, the vertically shaded regions are those in which geometrical precision for the pair *AB* is worse than 1 nautical mile per microsecond, the horizontally shaded regions those in which this is true of the pair *AB′*. In the solid black regions precision is worse than 2 nautical miles per microsecond for one pair or the other. Only within the dashed boundary is the precision better than $\frac{1}{4}$ nautical mile per microsecond for both pairs.

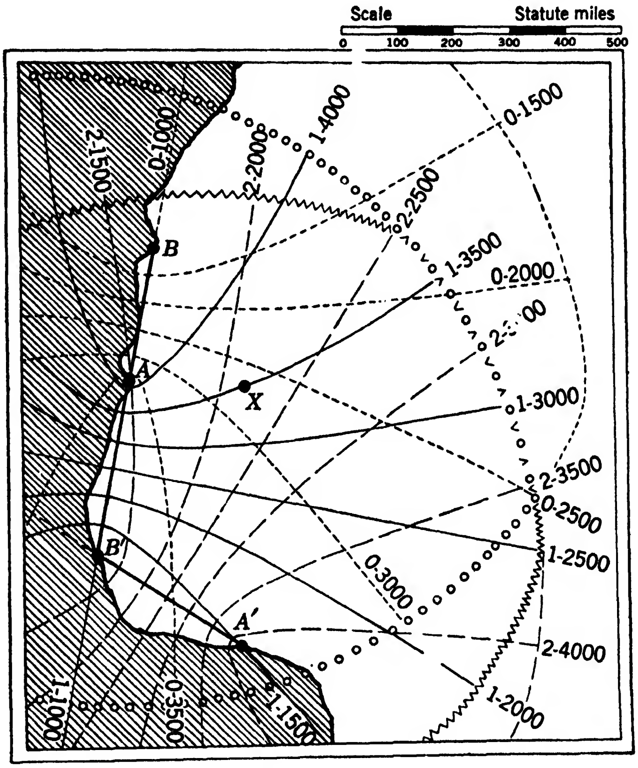


FIG. 3·12.—A Standard Loran chain of three pairs.

Figure 3·11*a* would be symmetrical with respect to the baselines *AB* and *AB′* if these formed a single straight line. As they are placed, with an angle between them, the common service area is larger and the precision better on the side where the angle is less than 180°. A triplet of stations placed along a coast line gives better service if the shore presents a concave curve toward the sea over which the traffic passes. Note that close to the baselines on the convex side the precision is very low.

The manner in which the service areas of successive triplets overlap in a Loran chain is illustrated by Fig. 3·12. The chain here has three pairs forming two triplets, and over a considerable region the navigator can obtain three lines of position, which should concur in a point at his location. Errors of operation or observation will cause the point to become a triangle, the smallness of which will indicate the amount of confidence that the observer may give to the result of his measures. The North Atlantic Loran system, a series of chains and triplets extending from Florida to the Faroes, provides in some regions as many as five con-

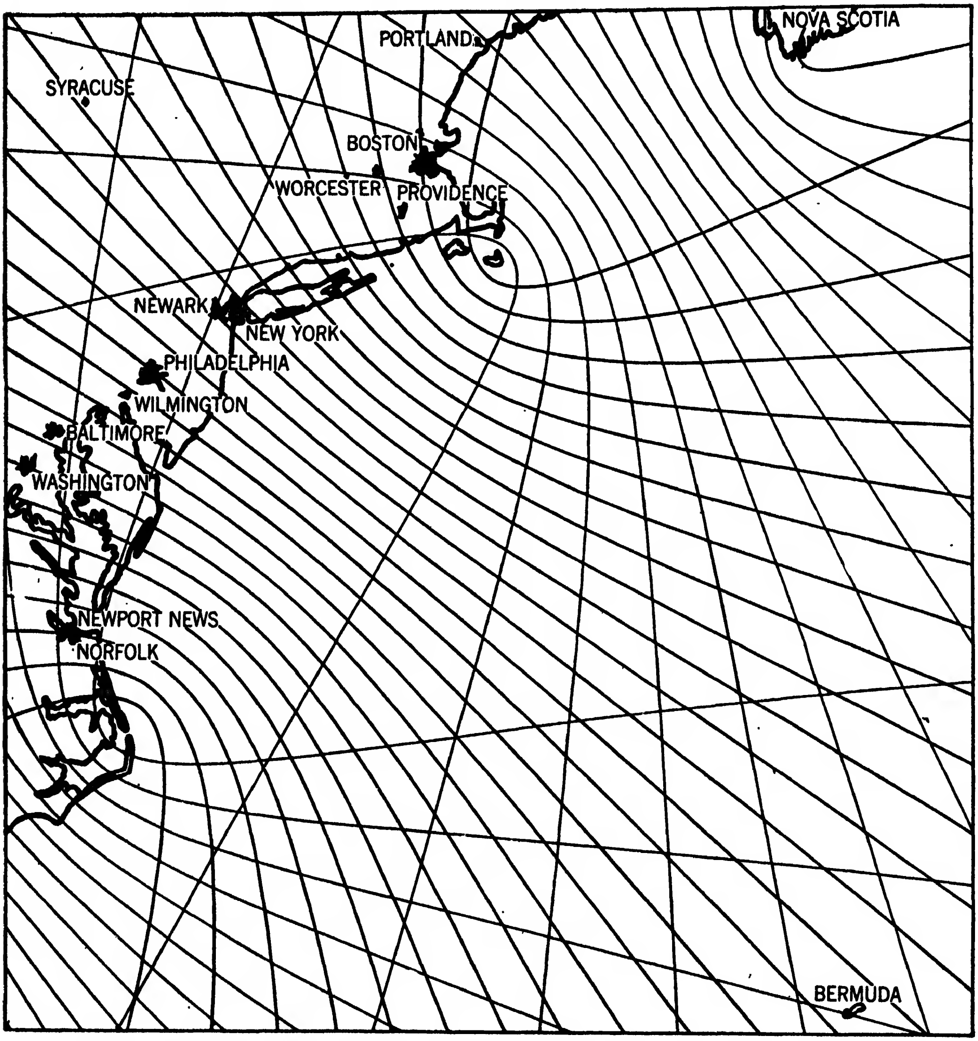


Fig. 3·13.—Part of the Standard Loran service area in the western Atlantic.

current lines of position—but, of course, some of these are of low precision and cross the others at poor angles. A part of this area off the East Coast of the United States is shown in Fig. 3·13 which is traced from a Standard Loran chart.

The common service area is greatly narrowed if the baselines are made almost as long as the range (Fig. 3·11*b*) so long as the angle BAB' is very obtuse. For this reason, as well as the necessity for reliable synchronism between stations under all conditions, baselines in most Loran installations have been kept much shorter than the range in spite of the advantage in precision that long baselines afford. If the baselines can be of length comparable to the diameter of the region over which service is required so that they may *surround* it, making the angle BAB' between 60° and 90°, the service area will have both good shape and good precision, as shown in Fig. 3·14. In both forms shown, the factor kw is smaller than $\frac{1}{4}$ nautical mile per microsecond all over the common service area except in the corners behind the stations. The equilateral triangle *b* may be operated with particular advantage if all three stations transmit at the same pulse rate, *A* sending out a single succession of pulses with which both *B* and *B′* are synchronized. In this case the two latter stations will necessarily also be in synchronism with each other, and time differences measured between the *B*- and *B′*-pulses will define a family of hyperbolas of which the baseline is the line *BB′*. With this family and the other two (*AB* and *AB′*) three-line fixes are available to the navigator, giving a check against reading errors.

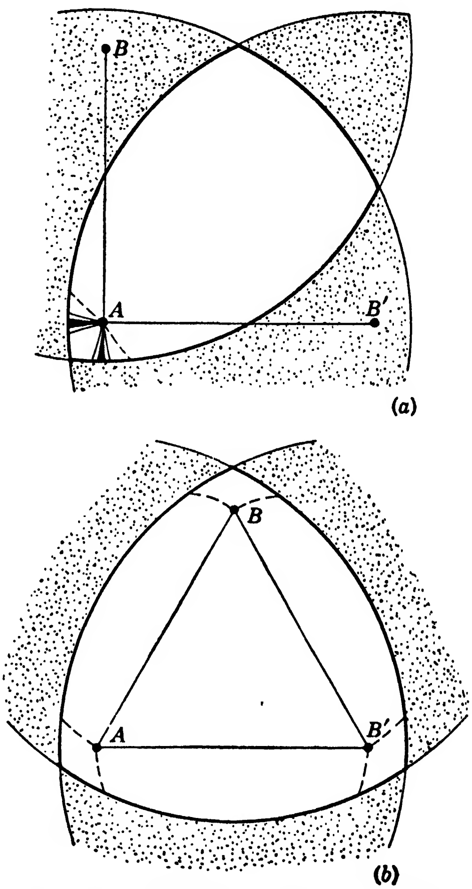


FIG. 3·14.—Triplets with long baselines.

Four-station Configurations.—A still more advantageous arrangement of two pairs with long baselines is possible if four stations are used. This is the *Loran quadrilateral*, the ideal form of which is given in Fig. 3·15*a*. Here the baseline of one pair is the center line of the other, and the center of the service area is the region of optimum precision for both families of position lines. Practical considerations of station siting will generally modify this configuration.

The stations of the night-bombing Loran installation mentioned in Sec. 3·1 were arranged in a quadrilateral. Stations in the north of Scotland and at Bizerte, Tunisia, formed one pair, and the other pair were located at Oran, Algeria, and Appollonia, Cyrenaica (Chap. 2, Fig. 2·1). Though it was necessary to place the first baseline entirely north of the other, the geometry of the lines of position over Germany, where the two center lines intersected, was excellent. No other Loran system has been set up to contain or span the area of operations by the baselines, but it is probable that some future Low Frequency installations may take this form.

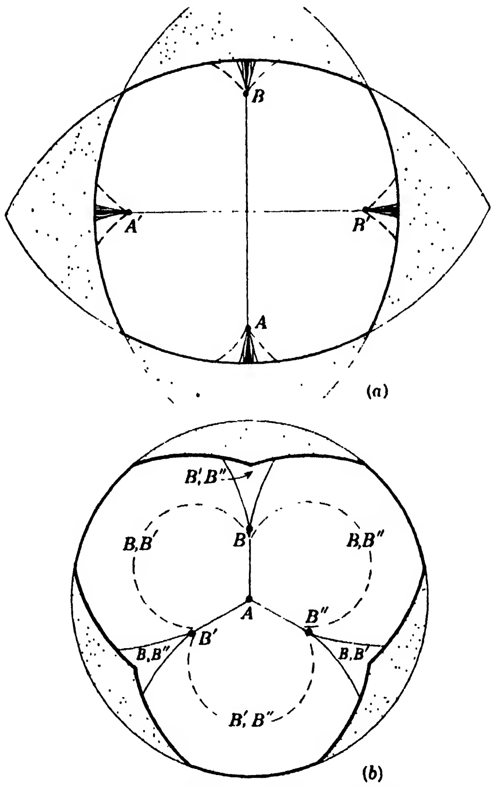


FIG. 3·15.—Quadrilateral and star chain.

The British Gee system has frequently used a configuration of four stations called a *star chain*. The master station is at the center, and three slaves, all on the same pulse rate, are placed around it in directions roughly 120° apart (Fig. 3·15*b*). This provides three triplets of the form of Fig. 3·11*a*, "back to back," so that good service is provided all around the chain. Three-line fixes are theoretically provided, but they are not practically worth while because the region of best fixes from any triplet (two pairs) is crossed by the extended baseline of the third pair. The regions served by each triplet are labeled in Fig. 3·15*b* by the letters denoting the two slave stations concerned (the master *A* being a member of all pairs).

The Crossing Angle of Two Lines of Position.—The degree of precision with which a line of position is determined by an observation has been represented by replacing the line by a strip of specified width. Similarly the degree of precision with which the crossing point of two lines of position is determined by two observations may be represented by replacing the point by a surface of specified size and shape. Two intersecting strips define a four-sided figure, which may be considered a parallelogram, since it is so small that the curvature and divergence of the pairs of hyperbolas which form its sides are inappreciable along its length and width. The area of this parallelogram is $4x_1x_2 \csc \Phi$, where $2x_1$ and $2x_2$ are the widths of the two strips and Φ is the angle at which they intersect (see Fig. 3·16). This *crossing angle* is therefore as important a criterion of the precision of a fix as are the values of w that characterize the hyperbolas at the intersection (to which the x's are proportional).

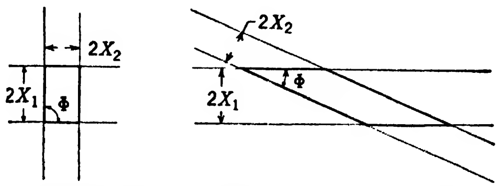


FIG. 3·16.—The parallelogram is larger when the crossing angle is smaller.

In the case of a triplet, Φ is half the angle between the directions to the end stations (B and B') from the point. This is made evident by recollection of the demonstration (App. C·1) that each hyperbola bisects the angle Ψ between the directions to the two stations (A and B or A and B') whose pulses define the hyperbola. The angle between the hyperbolas is therefore $\frac{1}{2}\Psi_1 + \frac{1}{2}\Psi_2$. But $\Psi_1 + \Psi_2$ is the angle between the directions to the two end stations, which is therefore 2Φ.

The curve of constant Φ for a triplet, on a plane and therefore approximately on a chart, is one of the two arcs into which a circle passing through the two end stations is divided by the stations (see the description of the curve of constant w, Sec. 3·4). If the distance between the end stations is g and G is the angle at the center of the circle, between the directions of the end stations, the radius of the circle is $\frac{1}{2}g \csc \frac{1}{2}G$. Then $\Phi = \frac{1}{2}G$ along the greater arc of the circle, and $\Phi = 90° - \frac{1}{2}G$ along the smaller arc. As in the case of w, the complete locus for one value of Φ is in general a figure eight or a lens. If $\Phi = 45°$, it is a circle with center on the line connecting the stations. If $\Phi = 90°$, the locus is the connecting line.

The distribution of crossing angles for a Standard triplet and a triangle with long baselines are shown in Fig. 3·17*a* and *b*. Within the lens-shaped blank areas Φ is between 60° and 90°; along the dot-and-dash lines it is 90°; in the stippled areas it is between 30° and 60°; and in the shaded areas, between 15° and 30°. For the triangle, the crossing angles are those of the two families AB, AB' only. It is evident that for any two pairs the best angles (near 90°) are in the neighborhood of the baseline of the third pair so that by always obtaining a fix from the two more distant pairs and using the line from the third only as a check, an observer will have crossing angles better than 60° practically all over the service area shown in Fig. 3·13*b*.

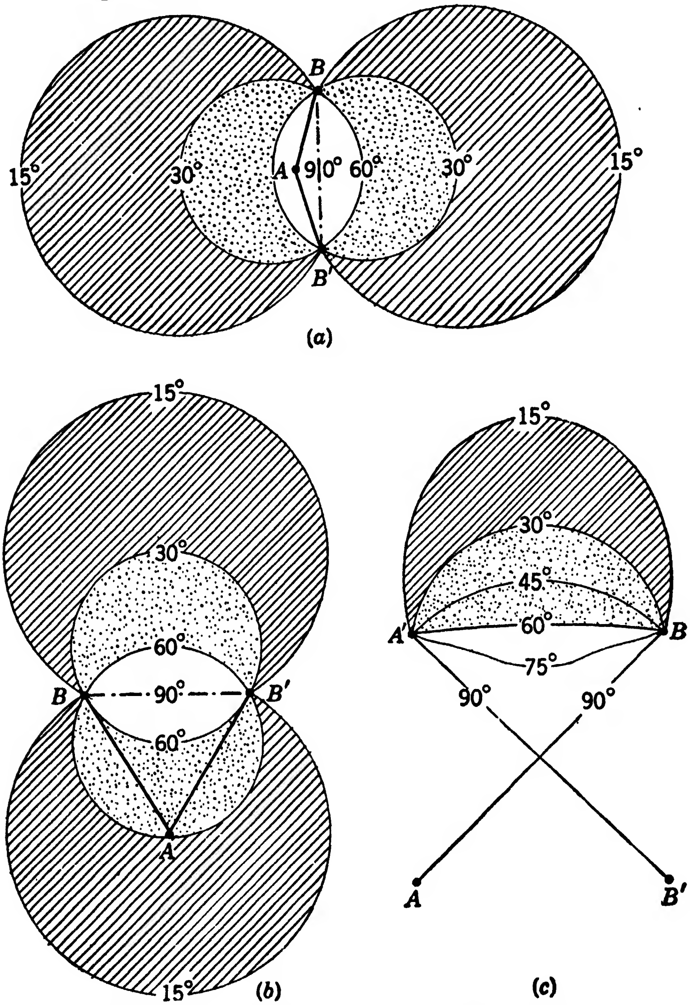


Fig. 3·17.—Curves of constant crossing angle.

The crossing angle at a given point is not so simply specified if a quadrilateral or two separate pairs generate the lines. But three simple rules may be stated for finding Φ in these cases. Denote the stations of one pair by S, s and of the other pair by S', s' (which are masters and which slaves do not matter). Take the directions in order, clockwise or counterclockwise around the point. If the order is S, s, S', s', then

$$\angle Ss' + \angle sS' = 2\Phi.$$

If the order is S, S', s, s', then

$$\angle Ss' - \angle S's = 2\Phi.$$

If the order is S, S', s', s then

$$\angle SS' - \angle s's = 2\Phi.$$

The sign of Φ is to be disregarded in the last formula. These formulas give values of Φ from 0° to 180°, whereas the rule for drawing the circular loci of Φ in the case of a triplet always gives less than 90°. But since the crossing of two lines results in four angles, two equal and less than 90° and two that are supplements of these, we may always take Φ as denoting the first-quadrant angles.

The curves of constant Φ for four stations are not circles (except in the special case of the four stations lying on the circle). They are the curves obtained by connecting the appropriate intersections between the family of circles, $\angle I$ = constant; and the family of circles, $\angle II$ = constant, where $\angle I$ is the first angle and $\angle II$ the second in any of the formulas of the last paragraph. Figure 3·17c, depicting crossing angles for the quadrilateral, was constructed in this way. The contours for only one quarter of the area are shown, since they are the same in the other three. This symmetry is, of course, a consequence of the symmetry of arrangement of stations.

In regions far enough from the two pairs so that the hyperbolas are very close to their asymptotes (Sec. 3·4) the curves of constant crossing angle approximate closely the greater arcs of circles passing through the midpoints of the two baselines and having radii $\frac{1}{2}m \csc \Phi$, m being the distance between the midpoints. The circle for 15° has the radius $1.93m$. Fifteen degrees may be considered about the smallest crossing angle that will yield a usable fix. If the angle is smaller, the rectangle representing the precision becomes so elongated that it practically degenerates into a single line of position (of high weight, of course, because it results from the concurrence of two measures).

Measures of the Precision of a Fix.—Let T' and T'' be measured time differences, obtained at the same place from different pairs of stations. Let the corresponding hyperbolas P and Q intersect at C, forming the acute angle Φ. If these measures were without error, the true location of the observer would be at C. In fact, the measures differ from the correct values T_1 and T_2 by unknown errors, and the true location is at a perpendicular distance $kw_1(T_1 - T')$ from P and at a distance $kw_2(T_2 - T'')$ from Q, where kw has the same meaning as in Sec. 3·4. If we call these distances p' and p'', the distance d of the true location from C is

$$d = \sqrt{(p')^2 + (p'')^2 \pm 2p'p'' \cos \Phi},$$

where the plus sign is used if p' and p'' have the same sign within the acute angles, the minus sign if their signs are different.

Assume that the errors affecting T' are independent of those affecting T'' and that for a great number of measures both sets of errors have a statistically normal distribution. The measures will then have standard deviations $\sigma_1 = \sqrt{\Sigma(T' - T_1)^2/n_1}$ and $\sigma_2 = \sqrt{\Sigma(T'' - T_2)^2/n_2}$ and probable errors $\epsilon_1 = 0.6745\sigma_1$ and $\epsilon_2 = 0.6745\sigma_2$. The sums of the squares of the residuals are determined from a large number n of observations made in actual operation of a Loran system. The distances p' and p''will have standard deviations $s_1 = kw_1\sigma_1$ and $s_2 = kw_2\sigma_2$ and probable errors $p_1 = 0.6745s_1$ and $p_2 = 0.6745s_2$.

Let AB and DE in Fig. 3·18 represent the hyperbolas $T' + f\epsilon_1$ and $T' - f\epsilon_1$ and AD and BE the hyperbolas $T'' + f\epsilon_2$ and $T'' - f\epsilon_2$, respectively, f being an arbitrary factor. If f is given the value 1, then by the

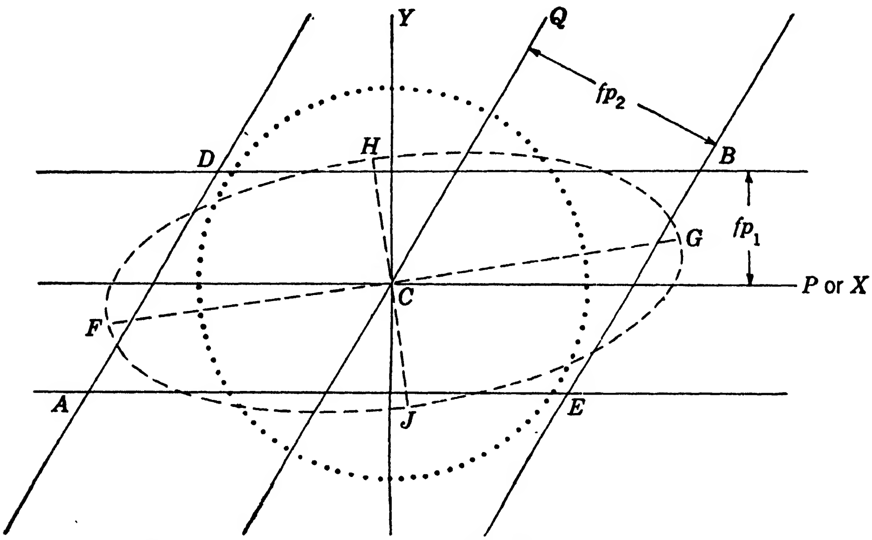


FIG. 3·18.—The error parallelogram, ellipse, and circle.

definition of the probable error, the chance that the observer's actual line of position T_1 lies between the lines AB and DE is $\frac{1}{2}$; the chance that the actual line T_2 lies between AD and BE is also $\frac{1}{2}$. Therefore the probability that the observer's true location is within the parallelogram $ABCD$ is $(\frac{1}{2})^2$, or $\frac{1}{4}$. If f is taken as 1.56, the probability that either hyperbola lies between the limits given is 0.707; consequently the chance that their intersection is within the parallelogram is 0.707^2, or $\frac{1}{2}$. This latter *probable parallelogram* (by analogy with probable error) rather simply and conveniently visualizes the accuracy of a fix and can easily be sketched on a Loran chart, interpolating by inspection between the printed lines of position. The perpendicular distance between AB and DE in linear units is $3.12p_1$; that between AD and BE, $3.12p_2$. The length of the sides of $ABCD$ parallel to the hyperbola P is $3.12p_2 \csc \Phi$; the length of sides parallel to Q is $3.12p_1 \csc \Phi$; and the diagonals have lengths $3.12 \csc \Phi \sqrt{p_1^2 + p_2^2 \pm 2p_1p_2 \cos \Phi}$.

The probable parallelogram is convenient because for a given locality it may be sketched on a Loran chart without computation. It is not theoretically very satisfactory, however, for its boundary is not a contour of constant probability. The chance that the true point is within a small area of given size, situated in the middle of one side of the parallelogram, is greater than the chance that it is within an area of equal size at a corner. It may be shown (Appendix C·2) that contours of constant probability are ellipses, and a *probable ellipse*, of such dimensions that the chance is even that the true point is within it, may be determined. This is the ellipse having conjugate axes along the hyperbolas P and Q and tangent to the four hyperbolas $T' \pm 1.74\epsilon_1$, $T'' \pm 1.74\epsilon_2$. The lengths of the major and minor axes of this ellipse are functions of p_1, p_2, and Φ. Expressions for them are given in Appendix C·2. The probable ellipse is drawn as a dashed curve in Fig. 3·18.

The *probable error in distance* may be denoted by P and defined as follows: If d is the actual distance between the point corresponding to the observed readings and the observer's true location, the chance is even that d is less than P. The length of P is a function of p_1, p_2, and Φ. It may be expressed as an integral, but the integration can be performed only numerically. However, P is approximated closely enough for practical purposes by the expression

$$P = \frac{1.15}{\sin \Phi} \sqrt{p_1^2 + p_2^2}. \tag{10}$$

The dotted circle in Fig. 3·18 has the radius P. The derivation and the validity of Eq. (10) are discussed in Appendix C·3, which gives references to more detailed and comprehensive treatments of the precision of a fix.

3·6. Standard Loran. *Location of Standard Loran Stations.*—Loran was originally developed as a wartime radio system of navigation for the U.S. and Canadian Navies. It was intended to provide reliable service over sea water, by day or night, to distances of roughly 500 nautical miles and to give fixes as accurately as good celestial navigation. To attain the range desired with reasonable transmitter power, the frequency had to be much lower than those employed by radar; to provide pulses that could be matched with the requisite precision (within a few microseconds), the frequency had to be above the ordinary broadcast band. The choice of approximately 2 Mc/sec as the frequency to use was made partly on theoretical grounds and partly because experiment showed that a remarkably low level of noise at this frequency permitted reception of ground-wave pulses beyond 500 nautical miles by day whereas steady and reliable E-layer sky-wave transmission at night multiplied the daytime ranges by two. In order to confine transmission to a narrow band the pulses had to be extremely long by radar standards, but their shape could be so well controlled by proper transmitter and receiver design and the amplitude-balance matching technique that two pulses from different stations might be matched with a probable error of setting near 1 per cent of the pulse width.

The frequency once chosen and satisfactory prototype equipment developed, it was necessary to "freeze" the basic specifications and designs so that production might be speeded up. Consequently only three varieties of the Loran system, all using similar equipment, have actually been used, and four-fifths of all stations are of one variety—the "original" system developed for naval use and called *Standard Loran.*

Standard Loran transmitting stations are located along seacoasts or on islands. Pairs are arranged in chains or in triplets with obtuse angles between the baselines, so that coverage may be provided as far to seaward as possible along thousands of miles of coast line or from island chain to island chain. The continuity of service provided by the overlapping of service areas along a long chain or a succession of triplets was considered fundamental in the development of the Standard Loran system. The scheme of assigning to each pair its own recurrence rate, described in Sec. 3·3, was devised so that pairs might be chosen for measurement in any convenient combination. To obtain this flexibility, the possibility of simultaneous measurement of two pairs of pulses (one of the most advantageous features of the British Gee system) was sacrificed. The optimum baseline length is considered to be about 300 nautical miles. This gives a common daytime service area for two pairs of the form described in Fig. 3·11*a*. The area extends 800 nautical miles to the right of *A* and 650 to the left, and its greatest vertical dimension is 1000 nautical miles. If the baselines are longer, the common area is smaller. Furthermore, high accuracy in synchronism must be maintained throughout the night and through the highest noise levels that may be expected. Such conditions may reduce the range by nearly half; and if the distance between stations becomes comparable to the range, the quality of the received pulses may not permit accurate matching by the slave operator. On the other hand, if the baselines are shorter, the area of good geometrical accuracy for each pair is smaller in proportion, as is the area of good crossing angles for the triplet.

In practice, geographical considerations force departures from the norm. The Labrador-Greenland pair, mentioned earlier, forms with a station in Newfoundland a nearly right-angled triplet, with its service area resembling that shown in Fig. 3·14*a*. Maintenance of synchronism over twice the optimum baseline length is possible because the noise level in northern latitudes is lower than farther south. A still more widely separated pair was operated between Iwo Jima and Okinawa (725 nautical miles) during the final stages of the war with Japan. However, it could not maintain a 24-hr schedule, although advantage was taken of very low noise and good station sites. The other extreme in separation of a standard pair is that between Guam and Saipan, with a baseline of only 130 nautical miles.

To attain the maximum range, Loran transmitting stations must be sited carefully. The imperfect electrical conductivity of rock and soil acts to attenuate the signal rapidly with distance traveled, and the attenuation is exponential in form, reducing signal amplitude to something like $\frac{1}{20}$ for each hundred miles traversed at standard frequency. Over salt water, the conductivity of which is good, the amplitude is reduced only to about $\frac{3}{10}$ for each hundred miles. Land close to a transmitting antenna, therefore, greatly decreases its range of transmission. Accordingly, a Loran station is placed as close to the actual water line as possible, and an extensive ground system of copper wires or straps is laid on the ground around the antenna. No island or cape should lie across the path of desired transmission, within a considerable distance. A salt marsh, however, may intervene without serious effect, for its conductivity approximates that of the sea.

The combined conditions imposed upon Loran station sites by geometry, geography, and conditions of terrain affecting transmission have resulted in the location of many of these stations in extremely inaccessible and uncomfortable places.

Equipment of a Standard Loran Station.—At a Standard Loran station that serves in two pairs, there are two 100-kw transmitters, four transmitter timers, at least two gasoline or diesel power generators, and auxiliary equipment. The transmitters and timers are housed in a single building, the timers being placed in an enclosure of wire netting to shield them from the field of the transmitters. In operation, two timers are connected to one transmitter, which is fed by one power plant; the other instruments are stand-bys and are frequently alternated with the first set so that the equipment may be periodically overhauled and components replaced without interrupting service. Transmitting and receiving antennas are separate and placed several hundred feet apart. The former is nondirectional, either a vertical wire or steel tower about 110 ft in height or an inverted-L 55 ft or so along each arm. The receiving antenna is usually a single nondirectional vertical one about 50 ft long; but, if reception from the other member of one of the pairs is difficult, a long horizontal (Beverage) antenna, extended toward the distant station, is used to pick up its signals. Generally complete living and supply-storage quarters must also be provided, and therefore the whole station occupies several acres.

Equipment in a station that belongs to only one pair is the same, except that there are only two timers, one in use and one standing by.

Sky-wave Matching in Standard Loran.—Over the greater part of the regions frequented by ships and aircraft, only ground waves are transmitted by day to any considerable distance at the Standard Loran frequency, and the identification and matching of the pulses from two pairs of stations present no difficulty. During the war it was found that in west China and Burma at some seasons the E-layer sky-wave pulse persists all day except for fading periods near sunrise and sunset, with practically the steadiness of a ground-wave pulse, and is frequently just preceded by a pulse of smaller amplitude, apparently reflected from the D-layer of the ionosphere. But in general it is only at night that the complex pulse trains sketched in Fig. 5·13 appear. These multiple images, varying in timing and amplitude, present a serious problem of identification to the Loran observer. A single pulse may show six or more images, spread over 10,000 μsec along the trace. The first of these may be the ground wave, the first E-reflection, or one of the F-layer images. From two such trains he must pick out the two ground-wave pulses (G-images) if present, or the two first E-reflections (E1-images), and match them. If only F-images are visible, no match must be made. Mismatching will give a false reading, which will not always be far enough from the expected true value to be recognized as erroneous.

If the ionosphere were a perfectly reflecting surface at a constant height above the earth, sky-wave pulses would be as easy to measure and as reliable as ground-wave pulses. Actually, "reflection" is a complex process, and the pulse that is measured is often the resultant of components that have travelled into the ionosphere and out again by several slightly different paths. The recombination of these components at the receiver gives rise to superposition and interference effects, which vary rapidly as conditions vary within the ionospheric layer traversed and constantly change the form and size of the pulse as it appears on the viewing screen. At times the pulse may split into a doubly or multiply humped shape or may fade into invisibility. Furthermore, the ionospheric layer rises and falls, diurnally and seasonally, with variations in the magnetic field of the earth, and irregularly over long and short intervals. The irregular variations in particular tend to be local, and hence regions not very far apart rise and fall almost independently. This change of height causes the transmission delays and sky-wave corrections to vary in a largely unpredictable manner.

Matching pulses that are splitting and fading requires patience and watchfulness and development of the habit of ignoring momentary forms and setting the pulses so that their fluctuating leading edges rise to about the same "ideal" envelope on the display screen. The establishment of a good match takes time; a single snap measure at a predetermined instant is reliable only if conditions are momentarily good, but a series of settings yields a much better average than appearances would lead the measurer to expect. When the technique has been mastered, matches made with sky-wave pulses are unlikely to be more than 3 μsec in error.

Some general precepts, for the identification of pulse images at night, may be stated:

1. Within 500 or 600 statute miles of the station emitting the pulses, the G-image is the first in order, the El-image next. From the ground-wave limit to 1500 or 1600 miles the E1-image is first, followed by E2 or F1 (the E2-image is often imperceptible except at long distances).
2. Normally the ground-wave image does not split or fade, though when it is not much stronger than the "noise," it appears to fluctuate in a manner that sometimes resembles splitting, and the image height will also vary with any oscillation of the receiving antenna owing to motion of the ship or aircraft. The E1-image splits and fades, but less violently than do later images and over longer cycles. At times it is as steady as a ground-wave image.
3. The time interval in microseconds between the G- and El-images is roughly

$$40 + \frac{250}{d} \qquad d \leqq 10,$$

where d is the distance of the emitting station in hundreds of nautical miles. The interval between E1 and E2 is roughly

$$40 + \frac{750}{d} \qquad d \leqq 10;$$

that from E2 to F1, a little more than this.

The limit of ground-wave reception varies with the amount of noise above which the pulse must rise and with the location of the station. Consequently a zone exists within which the first image may be G or El, and it must be identified by its behavior and its interval from the next image. If both images appear, their separation is 75 to 100 μsec in this zone. An occasional extra El-image ("sporadic E"), immediately after the regular one or overlapping its following side, may confuse the picture. Similarly, the outer boundary of the sky-wave service area takes the form of a similar zone, within which the first image may be E1 or E2; if both appear, their separation is 75 to 100 μsec in this zone. It is important to turn up the receiver to the highest practicable gain when identifying the first image of a train, to make sure that there is not another weak image to the left of it. A steady scrutiny is necessary, for unusually high noise may obscure a ground-wave image, or prolonged fading may obscure an El-image for some time.

The characteristic difference between the splitting and fading of E1- and later images is recognizable after a little experience. The splitting cycle of the E1-image is usually less than a minute, and the distortion commonly takes the form of a depression that appears at the peak of the pulse and runs down one side and up again, as shown in Fig. 3·19. Distortion of the leading side of the image is "dangerous splitting"; of the following side, "harmless splitting." At the climax, the side affected is displaced by as much as 10 μsec, but the pulse shape is nearly enough normal to tempt the observer into an incorrect match unless he watches the pulse for 10 or 20 sec at least. E1-images from near stations are subject to more complicated distortion. The rippling of the trace due to noise is, of course, superposed upon all images also. Fading causes the E1-images to rise and fall, and those from distant stations sometimes disappear into the noise for some minutes.

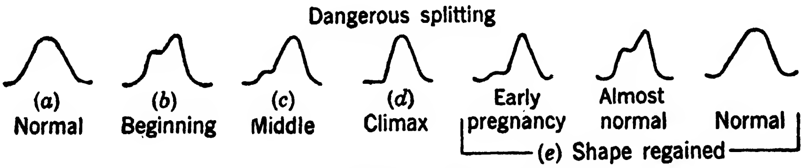


FIG. 3·19.—Splitting of an E1-image.

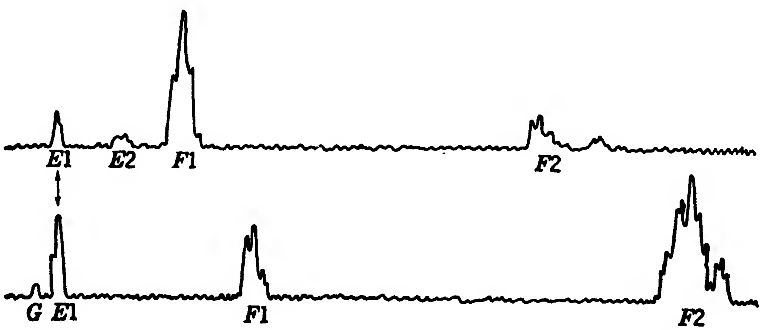


FIG. 3·20.—Pulse trains from a pair of stations approximately matched for sky-wave readings.

The E2- and F-images suffer more complex and violent splitting than does E1, and they undergo long slow rises and falls as well as abrupt changes. The F's tend to be wide and multiply peaked and sometimes occur in groups. A long series of them, at intervals of 1000 to 2000 μsec, may extend over nearly half a recurrence interval. The leading F-images are sometimes more conspicuous than G or E1 and may be the only ones to appear above a high noise level if they come from stations near the service limit.

The navigator will facilitate correct identification of pulse images if he presets his indicator to the expected sky-wave time difference for his position, as estimated by dead reckoning. This setting will in most cases be close enough to the true one to align the two pulse trains, and thus corresponding images will be near each other on the oscilloscope screen (Fig. 3·20). The navigator may then resolve doubts by observing the behavior and spacing of the images, being especially careful that one of the E1's is not missed because of momentary fading.

Probable Errors in Standard Loran.—Experience has shown that a pair of Standard transmitters can be held to synchronism with a probable error a little less than a microsecond and that the probable measuring error of an observer with an indicator, matching ground-wave pulses, is about the same. The combined probable error of a Standard Loran ground-wave reading may therefore be taken as about 1 μsec, the probable error of a line of position as $0.162w$ nautical mile, and the probable error of a fix between two ground-wave lines of position as $0.186 \csc \Phi \sqrt{w_1^2 + w_2^2}$ nautical miles.

If the observer is matching sky waves, his probable error of measurement is a little greater, because of the fluctuations mentioned above; but if he makes no measurements when the leading edges of the pulses are noticeably distorted, the error will be less than 2 μsec. An additional uncertainty is present, however, because of the variation of the sky-wave transmission delays from the mean values used to compute sky-wave corrections. The observer must use the unvarying computed corrections, and therefore an additional random error is introduced into the finding of the line of position. Its probable value depends upon the distances of the observer from the two stations, because the amounts of the delays depend upon these distances, and their variations are nearly proportional to themselves. The farther the observer is from the stations, therefore, the more reliable is the sky-wave measurement; at the limit of range its probable error due to ionospheric variation is less than 2 μsec. But at 250 nautical miles from either station this probable error is at least 5 μsec, and more if the stations are quite unequally distant. The combined probable error of a sky-wave reading made on a Standard pair, as indication of a line of position, may be taken as 2 μsec near the range limit and 6 μsec within 300 nautical miles of either station. Within 250 nautical miles of a station, the sky-wave delay is so affected by ionospheric fluctuations that sky-wave measures are not considered usable.

Generally speaking, the regions where the sky-wave probable error is high are those where w is small, and vice versa, and it is a roughly true statement that at all distances from the stations, along the center line of a pair, the probable error of a line of position in nautical miles is the same, about 400 divided by the baseline length in nautical miles. Though the probable error does not increase appreciably with distance in a given direction from the mid-point of the baseline, it does change with that direction, increasing approximately with the secant of the angle that the line from midpoint to point of observation makes with the center line. This angle is the complement of θ [see Eq. (9)], and this rule is simply an application of that equation, the distance factor (r/b) dropping out because of the decrease of measuring error with distance.

If W denotes the probable error of a sky-wave line of position in nautical miles, we may then write $W = 400/b \csc \theta$ and take $1.15 \csc \Phi \sqrt{W_1^2 + W_2^2}$ as a fair approximation to the probable error of a skywave fix.

A more precise evaluation of the probable errors of Standard Loran sky-wave lines of position is exhibited in Fig. 5·22.

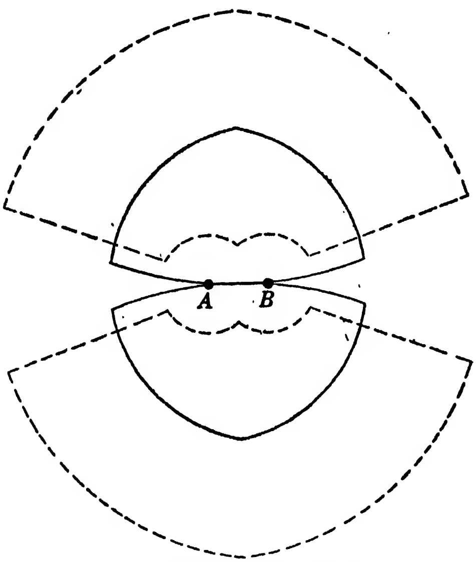


FIG. 3·21.—Useful service areas of a Standard Loran pair. Solid line: ground-wave boundary; dashed line: sky-wave boundary.

Service Areas in Standard Loran.—Although Loran readings on a pair of stations may be made wherever both pulses can be received, they are of little value if made in regions where the probable error is large. It has been customary to consider the useful ground-wave service area of a Standard pair to be those regions where kw is less than 2 nautical miles per microsecond. The areas thus excluded are shown in black in Fig. 3·10. Their boundaries are arcs of circles, with centers on the center line at a distance of six baseline lengths from the stations. From the useful sky-wave service area are excluded the region within 250 nautical miles of each station (two circles which usually overlap) and also the region adjacent to each extended baseline, bounded by the lines $\theta = \csc^{-1}(b/100)$, where b is in nautical miles. This angle is 30° if b is 200, 19.5° if b is 300, 14.5° if b is 500. In these regions, according to the formula for W stated above, the probable error of a sky-wave line of position exceeds 4 nautical miles. The two areas, delimited in this way, are shown in Fig. 3·21.

The useful common service area for a triplet or two pairs consists of those regions which fall within the boundaries for both pairs, as described above, and in addition are included inside the figure eight along which Φ for the two pairs is 15°. For a triplet, the two lobes of this contour are circles drawn through the end stations, with radii equal to the distance between these stations. For two separate pairs with the midpoints of their baselines not too close together, the lobes are nearly enough circles drawn through the midpoints, with radii equal to twice the distance between these points. When these various boundaries have been laid out for two pairs, those areas included inside all of these will form an irregular figure such as that shown in Fig. 3·22.

Of course, these conventional limits are somewhat artificial, especially the crossing-angle limit. More correctly, this and the limit $kw = 2$

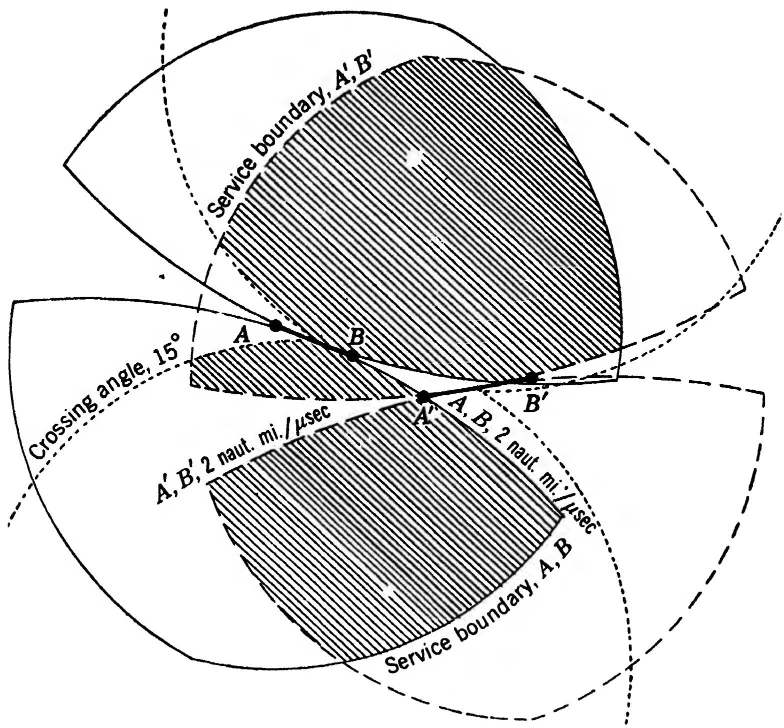


FIG. 3·22.—Common ground-wave service area for two pairs.

nautical miles per microsecond should be replaced by the curve 0.186 csc $\Phi \sqrt{w_1^2 + w_2^2} = 2$, for ground waves, or 1.15 csc $\Phi \sqrt{w_1^2 + w_2^2} = 4$, for sky waves, a curve that would have to be plotted laboriously by points. But any hard-and-fast limit is artificial, and the conventional construction gives a fair indication of the advantages and disadvantages of a given or proposed station configuration. A more detailed exhibit of the variation of W with position is given in the chapter on wave propagation (Chap. 5).

Air Transportable Loran.—A form of Standard Loran employing special lightweight equipment was developed at the Radiation Laboratory for the Army Air Forces. It was intended for use inland, in the rugged territory of northern Burma and southwestern China. Over land, Standard Loran has no advantage in range or geometrical precision over the higher-frequency British Gee system and has some disadvantage in ease and precision of time-difference measurement. In mountainous country, however, its signals can be received behind the mountains, whereas propagation at the Gee frequency is limited to the line of sight.

Timers and transmitters were designed to be transportable by air completely assembled, and tactical use of the system, advancing the stations with the advancing armies, was envisaged. The timers were adaptations of the navigator's indicator. Their crystal oscillators and divider circuits were less stable than those of the standard timer, but when properly handled they gave reliable service with only a small decrease in timing precision. The light transmitters were somewhat disappointing in power output and in other respects and were not actually used in the field; instead Standard transmitters were used. In operation, ground-wave ranges by day from 240 to 350 nautical miles were obtained and 220 to 270 by night (for high-flying aircraft). Because all baseline lengths were less than 60 nautical miles, the geometrical precision at the daytime ground-wave limit was no better than 1 nautical mile per microsecond, and the crossing angles were small. Greatly increased range given by sky waves at night was not useful practically, and therefore sky waves were used as substitutes for ground waves only when high noise made the latter unusable.

3·7. Sky-wave Synchronized Loran.—The successful use of sky waves in extending the coverage of Standard Loran at night showed that a nighttime Loran system, using sky-wave transmission for synchronizing the pairs of stations as well as for position finding, was feasible. Though necessarily inoperative by day except under special conditions, such a system would permit long baselines to be set up across land, giving high geometrical precision and good crossing angles to great distances, advantages that would offset the decrease in timing accuracy resulting from the use of sky waves to link the stations. These advantages recommended the system for the guidance of night bombers over central Germany; and as described in Chap. 2, such a system was tested in the eastern United States in the autumn of 1943 and operated over Europe during the last year of the war. A Standard Loran frequency and Standard Loran equipment were used. Two separate pairs of stations were arranged in a modified quadrilateral, the form of which (Fig. 2·1) gave the best geometrical characteristics obtainable while all western Europe was still held by the Central Powers. The system was called Sky-wave Synchronized, or SS, Loran. In the spring of 1945, two SS pairs began operation in southeast Asia. They were not arranged in a quadrilateral but gave separate families of position lines, one over the region of eastern China held by the Japanese, the other over Burma and Malaya.

The variability of the ionosphere affects Loran measurements in two ways. The varying density of the layer and its departure from homogeneity cause the total intensity of sky-wave signals to increase and decrease, the pulses rising and falling, changing their shape, and fading out completely at times, by reason both of energy absorption and of interference between components of the signal traversing slightly different paths. The varying effective elevation of the layer above the earth lengthens and shortens the time of travel of a pulse from station to observer. The variation of intensity and form is not a great handicap to the maintenance of synchronism at a slave station by matching the sky-wave pulse received from the master. The slave operator need only exercise patience and restraint, comparing pulses when the remote pulse is strong and of proper shape and relying on the stability of the two oscillators to bridge intervals of poor transmission.

The time variation is more serious. When sky waves from a pair of Standard Loran stations are measured by a navigator, the allowance that he makes for the extra delay in sky-wave transmission is the sky-wave correction C, which is the difference between the two sky-wave delays E_A and E_B. If the E-layer of the ionosphere rose and fell as a unit, both the E's would change in the same direction by amounts roughly proportional to the reciprocals of the corresponding distances, and the change in C would be the arithmetic difference of the changes in the E's and would usually be less than the smaller of these, unless one station were much closer than the other. In its seasonal and diurnal variations, the E-layer does tend to rise or fall in this way, but observations show that the short-time and irregular fluctuations in height at different places are strongly correlated only if the places are within a couple of hundred miles of each other. For regions separated by more than 500 miles, the variation may be in opposite directions. As Fig. 3·23 shows, the points of reflection, X, Y in the figure, of sky waves traveling from two stations A, B, to a navigator N are about half as far apart as the stations. In Standard Loran, X and Y are usually less than 200 miles apart, and their random variations in height show considerable correlation. The variation of C about its calculated value, as indicated by operational data, has a median absolute value of a few microseconds, and this is practically the probable error of a navigator's time difference, for the probable error

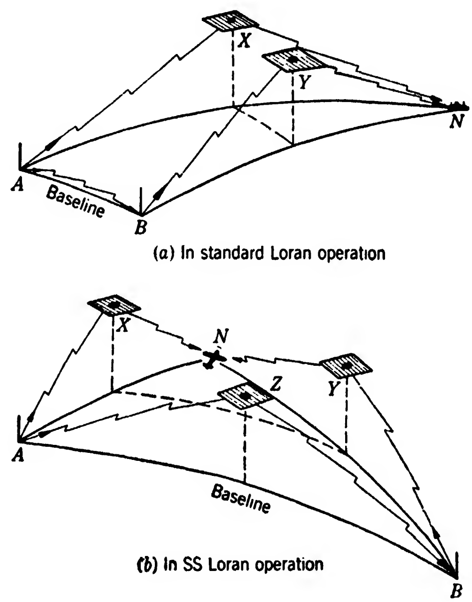


FIG. 3·23.—Sky-wave reflections.

of synchronism between stations (maintained by ground-wave transmission) is less than 1 μsec.

The absolute delay between a pair of SS Loran stations, as the slave operator holds his timer to a time difference δ, is

$$\frac{L}{2} + \beta + E_A + \delta,$$

E_A being the extra length of time taken by the sky-wave pulse from the master transmitter to traverse the path AZB (Fig. 3·23) instead of AB. As the elevation of Z above ground fluctuates, E_A varies, but the longer AB is the smaller is the variation (by reasoning similar to that used in the explanation of Fig. 3·5, Sec. 3·2). For this reason, as well as to obtain the most advantageous geometry, SS baselines are made as long as possible. The longer baseline in the European quadrilateral was 1300 nautical miles. Even with this length, the observed median absolute variation of E_A from its calculated amount, regarded as a probable error, is about 5 μsec. This variation enters into the absolute delay D in its full amount, for there is no E_B to balance E_A in the expression above, since the local pulse at the slave station is not reflected from the ionosphere. The observed time difference at N varies with D as well as with C; moreover, C fluctuates more widely in SS observations than in Standard ones, because if AB is 1300 nautical miles, XY is 650, and the changes in the elevation of Y are to a large extent independent of those of X. The combined effects of the variations at Z, X, and Y give a probable error of about 8 μsec for a measured time difference in the SS Loran system, according to observations made when the first experimental SS stations were operated in the eastern United States, in 1943.

When enough is known about the systematic variations in ionospheric elevation to predict its value to some extent, it may be possible to vary δ at the slave station so as to correct in part the changes in E_A and hold D nearer to constancy. The data collected during the experimental operations in 1943 did not give much encouragement in this direction. Without any such correction, the probable timing error of 8 μsec resulted in a median discrepancy of about $1\frac{1}{2}$ nautical miles between SS Loran fixes and visual pinpoint locations. This very satisfactory accuracy was due to the low average value of the geometrical factor kw within most of the area served by the quadrilateral, less than $\frac{1}{4}$ nautical mile per microsecond, and the large crossing angles, between 60° and 90°, as well as to rather expert handling of well-adjusted indicators and low speed of the aircraft. In actual use of the system over Germany, the accuracy of fix was not quite so good.

The "blind spot" close to each transmitting station, due to the unreliability and large delay variation of sky waves traveling short distances, is unimportant in Standard Loran because there is 24-hr ground-wave service in this region. But in SS Loran, the neighborhood of a station is beyond the ground-wave range of the other station of the pair. It is quite possible, however, to match the ground-wave pulse from the near station and the sky-wave pulse from the distant one, just as the SS slave operator does in maintaining synchronism and the master operator in monitoring.

Charts for SS Loran navigation do not carry ground-wave lines of position and numerical values of C as do Standard charts. Instead, the sky-wave corrections are incorporated in the calculations, and the given lines of position represent sky-wave time differences, so that the navigator need make no correction to his reading. Ground-against-sky lines of position, appropriately distinguished from the others, are provided within 250 miles of each station.

3·8. Low Frequency Loran.—When Standard Loran was first developed, it was felt that precise measurement of time intervals between pulses would not be practical at frequencies much below 1 Mc/sec, because the pulses would have to be extremely slow in rise and fall in order to avoid use of an excessive bandwidth. Furthermore, natural noise at low frequencies was known to be high. But the remarkable precision with which the Standard pulses (themselves very long in comparison with radar pulses) could be matched and the success of Loran operators in measuring through noise of much greater amplitude than the pulses encouraged a reconsideration. A system with longer ranges and longer baselines than Standard Loran was desired for covering the great spaces of the Pacific, particularly near Japan and the Chinese ports, and a 24-hr overland service over eastern China, from stations either to seaward or in western and southern China, would have been of material assistance in an East Asia land campaign against Japan. Equipment for such a system was designed and constructed during the winter and spring of 1944–1945 on an emergency basis, using the Standard timer with some modifications and incorporating some sections of the Standard transmitter into the LF transmitter. The transmitting antenna was a 1300-ft vertical wire supported by a barrage balloon, to be used temporarily and replaced as soon as practicable by a 625-ft steel tower supporting a top-loaded umbrella-type antenna. A converter was provided for the navigator, by the use of which signals at the frequency chosen, 180 kc/sec, would be received by the Standard Loran receiver-indicator. Low Frequency experimental transmitting stations were placed on Cape Cod, Mass., Cape Fear, N.C., and Key Largo, Fl., and operated as a triplet during the summer of 1945, with generally satisfactory results. But before the equipment could be transferred from these stations to the Pacific, the war ended.

Data obtained from the experimental operations are discussed in detail in Chap. 5. Some general characteristics of the system are stated here. The peak power of the transmitters was about 100 kw, which gave summer daytime ranges near 1200 and 1000 nautical miles over sea and land respectively and a summer nighttime range of 1500 or more. These figures are subject to large variations with time of day and season because of the very great fluctuations in the natural electrical noise at 180 kc/sec and the variability of the sky-wave transmission also. The former may be expected to decrease, and the latter to improve in winter, giving greater ranges.

The length of the pulses as received is more than 300 μsec; requirements of efficient antenna radiation and the need to keep the bandwidth narrow to avoid interference with adjacent communication channels preclude a sharper pulse form. Pulse-matching accuracy is therefore lower than in Standard Loran; but, when ground waves are matched, the probable error is only a few microseconds. With these long pulses and a sky wave that is apparently reflected from the E-layer only, the ground-wave and sky-wave pulse images, when both are present, overlap in a single composite envelope. The long trains of pulses characteristic of Standard Loran by night are not present at the low frequency—a great advantage, since a principal cause of large errors in Standard pulse-matching has been mistaking a sky wave for the ground wave or an F-image for an E.

The coalescence of ground wave and sky wave has a serious disadvantage, however. At ranges between about 400 and 1200 nautical miles, the proportion of ground- and sky-wave components in the observed pulse varies with distance, with the momentary intensity of the sky wave, and with the r-f phase difference between the ground and sky waves. The rising slope of the pulse is composite or discontinuous (see Figs. 5·31 and 5·32), and the time difference obtained by matching it with another pulse is somewhere between the values for pure ground wave and pure sky wave, varying with the conditions and with the point on the slope at which the match is made. Beyond 1200 nautical miles the ground wave is absent, but the first- and second-hop sky waves combine in a similar fashion, and beyond 1800 miles the second and third combine. Measured time differences at all distances greater than a few hundred miles must be considered as including a transmission delay increasing with distance (contrary to the pure first-hop sky-wave delay of Standard Loran, which decreases). The curve of increase has a wavy or "step" form (Fig. 5·30), and the height and spacing of the steps differ by day and night, over land and water (Fig. 5·46), and probably in summer and winter. The short-time variation of the delay curve contributes to measured time differences a probable error of apparent delay similar to that given to Sky-wave Synchronized Loran measurements by changing layer height, but somewhat greater, particularly where the delay curve is steep.

The baseline lengths of the experimental LF triplet were 535 and 606 nautical miles. Over these distances, the ground wave received at the slave stations from the master was always strong enough to control the first 30 or 40 μsec of the visible pulse form, even at night when the sky wave dominated the top of the envelope. Therefore the slave operator could always hold synchronism by ground wave. A specially designed receiver-indicator, displaying the pulses at the i-f heterodyne stage, without rectification, enabled him to superimpose the individual i-f cycles of the two pulses instead of their rectified envelopes. The cycles could be matched with a probable error of setting of about 0.1 μsec when the signal strength was well above the noise, so that synchronism could be maintained with several times the precision of Standard Loran once an operating technique had been devised for detecting and correcting occasional mismatches of one or two whole cycles. Unfortunately, cycle matching is not practicable at distances where the ground wave is too weak to rise well above the noise before the sky wave joins it, because in the composite part of the pulse, interference between ground and sky wave introduces a variable and unpredictable r-f phase shift.

With synchronism accurately maintained by ground wave and transmitters arranged in line with double master station between the two slaves, the LF system as operated resembled a Standard triplet on twice the scale rather than a day and night SS system. The 24-hr service area provided over water was about twice that of a Standard triplet, and the land service area was roughly two-thirds of that over water. Ground-wave accuracy of fix by Low Frequency was at least equal to Standard accuracy at equal distances from the baselines, for the greater timing error with the long pulses was compensated by the more favorable geometry provided by the long baselines. The accuracy might have been increased if time differences had been measured by cycle-matching, but no method was found to avoid errors of one or more whole cycles in these measures (the navigator could not have the ground-station operator's advantage of knowing the true value in advance). Low Frequency sky-wave accuracy at long distances was less than that given by Standard or SS Loran. Accuracy figures obtained at some monitor stations are given in Table 5·4.

The advantage of being able with equal facility to choose any two of several families of position to obtain a fix is not very great in a system where two pairs of stations command as large a common service area as does an LF Loran triplet or quadrilateral. On the other hand, a system with a large land coverage, extensively used by fast-moving aircraft, should require as short an interval as possible between the two time-difference readings necessary for a fix. Two simultaneous readings, as provided by the Gee system, are, of course, the ideal, but to incorporate this feature into the Loran indicator would necessitate complete redesigning, which was out of the question in view of the wartime urgency, and the alternative of carrying two indicators in an aircraft was prohibited

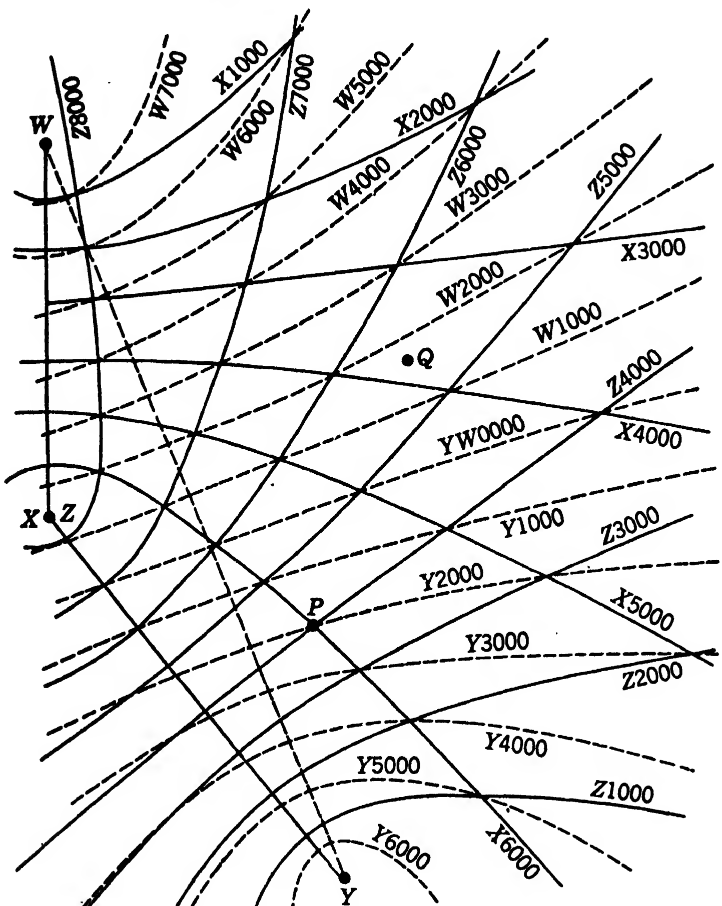


FIG. 3·24.—A Low Frequency Loran triplet. Time differences at *P* are *X*6000, *Y*2000, *Z*4000; at *Q*, *X*3800, *Z*5500, *W*1700.

by weight and space limitations. In Standard Loran a considerable part of the interval between readings is consumed in changing specific recurrence rate between pairs, and this change was eliminated in the LF system by running all three stations on the same rate. Since sky-wave trains did not appear, a scheme for distinguishing pulses by position was feasible. Loran navigators had been trained to read time differences from master to slave, and the indicator was designed to read intervals greater than $L/2$. To preserve these features in the LF time relationships, the master station was pulsed at twice the recurrence rate of the slaves. Two master pulses, separated by the interval $L/2$, and one pulse from each slave were emitted during a recurrence period L; one slave maintained synchronism with the first master pulse; the other with the second. Denoting the two master pulses as X and Z and the two slaves as Y and W, the order of emission was X-Y-Z-W, W being synchronized with X and Y with Z. In this way the intervals X-W and Z-Y, read by the navigator, were always greater than $L/2$, as required by standard reading procedure.

Since W and Y both maintained synchronism with the master XZ, on the same rate, they were in synchronism with each other, and the interval from one slave pulse to the other defined a family of hyperbolas with respect to the very long baseline between the slave stations. Figure 3·24 shows the relationship of this WY family to the other two. The time difference between W and Y at any point (P or Q) is the difference between the time differences X-W and Z-Y. Where these two are equal, W and Y are separated by just $L/2$, one appearing directly above the other on the indicator, and the time difference between them is zero. Where X-W is greater than Z-Y (as at P), Y appears to the left of W, the time difference is read from Y to W and labeled Y; when Z-Y is greater than X-W (as at Q), W is to the left of Y, the reading is from W to Y and labeled W.

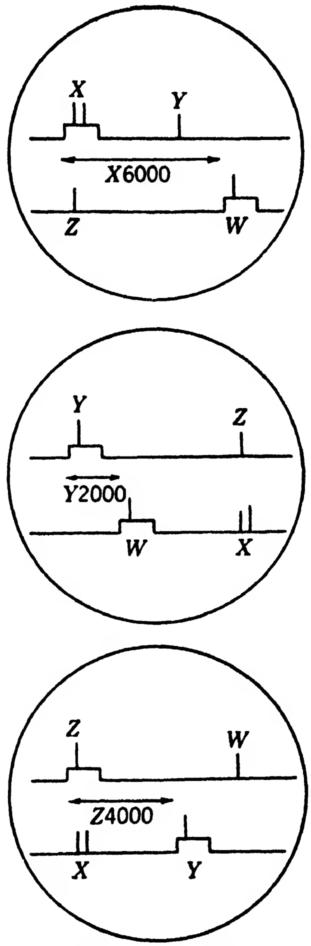


FIG. 3·25.—Low Frequency Loran readings.

The appearance of the pulses as the navigator viewed them is sketched in Fig. 3·25. In order that slaves and navigator might distinguish between the X- and Z-pulses of the master, the X-pulse was followed by an identifying "ghost," produced by delaying X by 1000 μsec in every third recurrence period. The procedure of time-difference measurement had three steps. (1) The pulses were placed on the indicator as in the upper figure of 3·25, and the interval X-W read; this was called reading X and denoted a hyperbola generated by the master and slave W. (2) The pulses were slid to the left if Y appeared on the screen to the left of W, until Y mounted the upper pedestal, and the interval Y-W read, as in the middle figure. This reading, called Y, devoted a hyperbola of the family generated by the two slaves, on the side of the zero reading toward Y. (The dashed line through P in the figure is an example.) If W

appeared on the screen to the right of Y (not shown in the figure), the pulses were slid to the right until W mounted the upper pedestal and the interval W-Y read. This reading W denoted a hyperbola of the same family, on the side of the zero toward W (e.g., the dashed line through Q). (3) The pulses were slid again to the left (or right) to bring Z to the upper pedestal, and the interval Z-Y read, as in the lower figure. This reading Z denoted a hyperbola generated by the master and slave Y. The relations $X\text{-}Z = Y$, $Z\text{-}X = W$ checked the consistency of the readings.

The hyperbolic family W-Y possesses greater geometrical precision (smaller w) at a given distance from the baseline than either of the other two families because of the greater baseline length. In the experimental system, W and Y were within sky-wave range of each other and were able to act as a low-frequency SS pair at times when the master station was inoperative and the noise was not too high. Station W, acting as slave in this case, maintained as a negative coding delay the same time difference that was obtained by reading the Y-pulse against the local W-pulse while both stations were synchronized with XZ. The delay had to be negative, whether W matched Y or Y matched W, because at either station the local pulse was emitted less than half a recurrence period after the remote pulse came in (because of the transmission time over the long baseline).

Though 700-mile baselines for ground-wave synchronism are short compared with SS baselines, they are long enough to surround an area of half a million square miles, over which the geometrical advantage of the quadrilateral, triangle, or L-arrangement of stations can be provided, with 24-hr ground-wave service over land or sea. A considerably larger area could be covered with accurate station synchronism by arranging five stations in a semicircle and operating them as two triplets, each on one rate, the middle station acting as a double slave. The baselines between the middle station and the two end ones would be some 1200 miles long and make nearly a right angle. Each of these pairs would hold accurate synchronism by maintaining ground-wave matches with their intermediate master. To run all five stations on the same rate would give great flexibility and the advantage of speedy fixes, but the problem of identifying pulses would be serious. With four stations on the arc of a circle, pulse identification would be feasible with operation on one rate. A W-form of arrangement, operated in the same manner as the semicircle, would give sky-wave coverage to great distances.

3·9. Procedure in Loran Navigation.—The Loran navigator may use a measured time difference and the corresponding watch reading to lay down a line of position upon a standard navigational chart, just as he uses a radio bearing or a celestial observation. Loran tables have been prepared, giving the intersections of the Loran lines with the meridians and parallels. By interpolating in these tables, three points of the line corresponding to his reading may be plotted on the chart, and a curve drawn through them and labeled with the reading, rate (to identify the family), and time of the observation. (Two points may serve in some regions and on some forms of chart, but in general the line is curved on the chart.) If he uses a Loran chart, the tables are unnecessary. Lines at convenient intervals of time difference (every 20 or 50 μsec is most usual) are printed on the chart, and the line representing the reading is interpolated by estimation between them.

A reading on another pair of stations gives the navigator a second line of position intersecting the first line. It is similarly drawn and labeled. If the navigator is on a slow ship, the change of position of the ship is negligible during the interval between observations, and the point where the lines intersect is the navigator's location at *both* the recorded times. But a fast ship moves a considerable part of a mile in a minute, and an aircraft moves several miles. In these cases, the lines of position must be considered to move over the earth, and their intersection *at the same time* must be found.

One way to do this is to advance the first line of position to the time of the second, according to standard plotting practice for all kinds of lines of position—lines obtained in piloting, radio bearings, or celestial lines. From any arbitrary point on the first line (conveniently near the navigator's estimated location) is measured a distance equal to the product of the speed of the craft and the time interval between observations and taken in the direction of the motion. This distance and direction locate a new point through which a new line of position is drawn parallel to the first line. The intersection of the new line with the line representing the second observation is the position of the craft at the time of the second observation.

Another way is to make observations in groups of three—the first and last on one pair of stations and the middle one on the other pair. An experienced observer can make the time intervals between readings nearly equal. Then the average of the first and last readings will be practically equal to the reading that would be obtained if this pair had been observed simultaneously with the other pair. The line representing the average reading is drawn upon the chart and labeled with the average watch time. If the time intervals are decidedly unequal, an interpolated reading is taken instead of the average. This method may be used with any number of observations greater than two if they are taken in a symmetrical order.

A graphical variant of this procedure is useful when a number of observations are taken under poor conditions so that accidental errors produce a considerable scatter. Observations on two pairs are taken alternately or in alternate groups and plotted directly against time on cross-section paper—both pairs on the same sheet or on different sheets as convenient. Smooth curves are drawn to represent the series of measures on each pair, and points on the two curves, for the same time, give the fix at that time.

All these methods tell the navigator where he was in the past, not in the present. An experienced observer, using a Standard airborne indicator, can make two readings and plot the fix on a Loran chart in less than 3 min if conditions are good. If the two pairs of pulses matched are on the same recurrence rate, as in the Low Frequency triplet described above, the time is somewhat shortened. The recently produced direct-reading indicator for shipboard use exhibits the time difference numerically on a dial as the observer matches the pulses. This eliminates the separate operation of counting markers on a screen and further shortens the time required to make a reading, but the instrument as now produced is too bulky and heavy to use in an aircraft. The only really satisfactory method of observation in an aircraft is simultaneous matching of two pairs. If space can be spared for two airborne indicators, it is possible for one observer to do this. A lightweight double direct-reading indicator is a technical problem that will undoubtedly be solved in the near future; by its use a continuous indication of the track followed would be given as long as the observer held the pulses in coincidence by turning the controls. The further step from this to linkage of the delay controls of the indicator with a tracer moving over a chart is a short one, which has already been successfully taken in trials with somewhat crude instrumentation.

The device was called the *Loran plotting board*. It consisted of a pen, moving over a board to which a Loran chart was clamped, and connected to linkages by which linear motions of the pen, parallel to two guides, were made proportional to the rotary motions of the setting controls of two indicators. The guides were set parallel to Loran lines on the chart, and the linkages adjusted so that when either of the indicators was set upon a given reading in microseconds, the tracer was set upon the corresponding Loran line; and when the indicator setting was turned through a given interval in microseconds, the tracer, sliding along the appropriate guide, passed over a corresponding number of miles on the chart. In operation, once this correspondence between indicators and chart was established, the observer simply picked up the proper pairs of pulses, matched them, and maintained the matches by turning the controls as the pulses drifted with the progress of the craft. No numerical readings were taken; the linkages continuously transferred the readings to the chart.

As used, the plotting board had a limited range; and since it translated the time differences mechanically into rectilinear coordinates, it was accurate only to the extent to which the Loran lines in the area approximated families of straight parallel lines uniformly spaced on the chart. The approximation was fairly good in the experimental Sky-wave Synchronized system in connection with which the trials were made. Means for correcting these defects and lines of future development are discussed in Chap. 4.

Several automatic plotting boards have been developed, which trace the path of a ship or aircraft by combining the velocity vector furnished by the instruments with current or wind data, and integrate over the elapsed time. It is the distinctive feature of Loran plotting that no extrapolation from past to present occurs nor is any correction for motion of the medium involved. The instantaneous position with respect to fixed stations is constantly displayed; and with a proper chart projection and a correctly designed linkage between delay circuit and tracer, the only appreciable errors should be those of pulse timing and matching. These are not cumulative, but on the contrary tend to average out over a period of time.

Loran may be used simply as an aid to conventional navigation by compass and log or air-speed indicator, furnishing check points for dead reckoning. It may also be used as a complete system for guiding the vessel along a track defined by Loran readings to a destination located by Loran readings. The simplest way to do this is to seek that hyperbola which passes through the destination and to follow it in. The reading defining this hyperbola is preset into the indicator, and the craft directed so that the pulses from the corresponding stations, widely separated where the craft is distant from the line, drift into coincidence and remain so. Progress along the line is determined by switching the indicator periodically to another pair of pulses, while holding the course, and noting the times at which lines of that family are crossed, then returning the indicator to the first setting and pair to continue tracking. This was the procedure used by the Royal Air Force in bombing Berlin by SS Loran. To facilitate alternation between pairs, Standard indicators were modified by the addition of a second pair of delay controls so that the controls could be set at two different readings and either switched into operation. With a double indicator, displaying both pairs of pulses at once, no alternation would be necessary. But, generally, this method strongly resembles the procedure of the days before the chronometer, when a navigator, trusting only his determination of latitude, might sail along the parallel that passed through his destination until he made his landfall. However, as lines of various slopes may be defined in rectangular coordinates, track lines that cut the hyperbolic families with various generalized slopes may be defined in Loran coordinates and directly tracked by the use of suitably modified Loran indicators. Such lines, analogues of the rhumb lines of present-day navigation, have been called Lorhumbs. The required instrumental modifications, while conceptually simple, have not yet been embodied in working models. Lorhumb navigation therefore belongs to the future and is discussed in Sec. 4·4.

CHAPTER 4

FUTURE TRENDS

By J. A. Pierce

4·1. Potential Accuracy and Range.—The factors that control the accuracy of timing with which two pulses can be compared do not, in general, vary except with radio frequency. If the pulses are superimposed visually and have their amplitudes made equal, and if the signal-to-noise ratio is really good, the precision of measurement is about 1 per cent of the length of the pulses. This accuracy can be realized in practice because in the hyperbolic systems, the two signals to be compared pass through the same receiving networks and encounter exactly the same artificial delays and distortions, and therefore their time difference is not at all affected by the circuit parameters, except to the extent that the pulses are lengthened beyond their proper duration.

A considerable number of experiments indicate that the length of pulses which can be used effectively cannot easily be made less than some 50 or 60 cycles of the radio frequency employed. Combination of this estimate with that of the preceding paragraph indicates that a Loran system should yield matches that are accurate to about half a wavelength. This accuracy corresponds to a minimum error in a line of position of a quarter wavelength, or 125 ft at the frequency used for Standard Loran. Actually the minimum error in Standard Loran is about 500 ft, an increase due in part to the use of pulses about twice the length suggested above and in part to the use of reading techniques that are not so precise as they might be.

The accuracy of Loran, in the ground-wave service area, could no doubt be quadrupled by the use of shorter pulses and navigators' indicators having more stable circuits and more closely spaced families of marker pips, but these improvements would not enhance the sky-wave service (which contributes a large part of the usefulness of the system) because in that case the accuracy is controlled by propagational variations that seldom permit an average error of less than 2 μsec, which is twice the current reading error.

The Low Frequency Loran system that was under development at the end of the war should, according to this argument, give average errors of about $\frac{1}{4}$ mile in the best areas. Unfortunately, propagational factors as well as geometrical ones will probably operate to increase the errors over a large part of the service area.

Transmission ranges and service areas also depend primarily on frequency, but in this case the lower the frequency the better. Throughout the microwave region the reliable range is little more than the optical range. Even in the very high frequency band, ranges are not more than, say, one and a half times the optical range. This often results in good cover for high-flying aircraft, but the distances usable at the surface of the earth are too small for the system to be of much use for navigation.

As the frequencies decrease through the high- and medium-frequency regions, ground-wave ranges increase and the differential between behavior at high and low altitudes grows smaller, especially over sea water, but the propagation of signals is no longer simple because of the complex structures of multiple sky-wave reflections that vary tremendously with the time of day and, at the higher frequencies, are extremely unpredictable.

These sky-wave phenomena become simpler and more predictable in the lower part of the medium-frequency range, but only at the low frequencies is there such a degree of stability that sky waves can be used without some undesirable confusion of the navigator. At the very low frequencies propagation over thousands of miles is easy and reliable, but wideband antenna systems are not available (because the required size is prohibitive) so long as current techniques prevail; therefore, the pulse methods cannot be expected to operate there. It seems at present that 100 to 150 kc/sec is about the lowest limit at which pulse systems can be used. At these frequencies ranges of 1500 miles should be obtained by day or night, over land or sea, and at any altitude.

4·2. Automatic Data Analysis.—It requires only limited acquaintance with a Loran receiver to realize that it will be simple to perform all manipulations of the set automatically. That is, there is no technical problem in producing a receiver that will automatically present on a pair of dial counters, say, the Loran readings on two lines of position at two selected rates. For military purposes there has been little or no requirement for this sort of receiver, and it has been advisable so far to apply the available research and development efforts to standardization and rapid production of manually operated sets.

With the application of hyperbolic navigation to commercial transportation, however, there will be a demand for a position-determining set that operates continuously, like the chronometer in the chart room, and at which the navigator may look when he wishes to know his position. There are many ways in which such machines can be built, but all or most of them may be so complicated that the navigator would be properly skeptical of their reliability.

The most common suggestion for a device of this kind is that the machine be made to read directly in latitude and longitude rather than in

Loran coordinates essentially by recording Loran charts or tables in mechanical form. This is a natural but misguided desire, as there is little that is inherently more desirable or informative in latitude and longitude than there is in the Loran coordinates themselves. The two facts that a navigator always wants to know are the distance and direction to one or to several points.

The next picture that comes to mind is that of a black box containing a number of push buttons and a pair of visible counter mechanisms. A navigator might push the button marked BERMUDA, whereupon the counters would spin and stop so that he could read "distance 342 miles; course 114°." This device, however fine a toy it may be, fails because the navigator should not be satisfied unless he is told his relation to a great many different places. To obtain this information he must, using either the black box or the latitude-longitude indicator, proceed to plot his position on a chart before he can understand the interrelations between his position and all other interesting points.

Obviously the only really effective automatic aid to navigation will plot the position of the vessel continuously and preferably leave a permanent track on the chart so that the navigator can see at a glance his current position in its relation to all other points on the chart and also can have the history of his voyage presented before his eyes.

There are many ways to build a device of this sort, and most of them suffer from a high degree of complexity. The desirability of such an instrument, however, will be especially obvious to the sales managers of our larger electronic corporations who, after the war as before it, may be expected to be in a position to see that the necessary development time is spent to reduce such a device to practice. The only prerequisites are that ground stations must be in operation to provide the necessary coverage and that the control of the ground stations be in responsible hands.

It is worth while here to point out only a single concept, which, although it violates sea-going tradition, may have some influence because of its simplicity. In any Loran indicator there is sure to be a shaft whose rotation is more or less linearly proportional to the Loran reading. This shaft may be connected to a pen through a mechanism such that the lateral position of the pen also bears a linear relation to the Loran reading. A second shaft from the same or a second indicator may be connected so that a rotation of that shaft in accordance with a second Loran reading produces a linear motion of the pen at an angle to the first motion. With this arrangement any pair of Loran readings that define a point on the surface of the earth also define a position of the pen point on a plane. A sheet of paper over which the pen moves is therefore a chart drawn in Loran coordinates. This simple system has the defect of considering all

Loran lines in a family to be straight and parallel and also of considering that the angles of intersection between the lines of the two families are constant all over the chart. These limitations, however, may not be too severe, especially in the case of an area at some distance from the ground stations. The angle between the two directions of motion of the pen may be set at the mean value of the crossing angle of the Loran lines in the area, and the rates of motion in the two directions may be set to be proportional to the relative separations of the lines in each family.

This plotting-board concept has the immense advantage of mechanical and electrical simplicity. In many cases, if the area on a chart is not too great and if the ground stations themselves are not in the charted area, the distortions encountered in drawing such a chart in Loran coordinates are no greater than those involved in many other projections.

Figure 4·1 is a chart in these Loran coordinates that represents nearly the worst possible conditions. In this case, as seen in Fig. 3·13, both the families of lines have a focus at a station on Nantucket Island so that the curvature and divergence of the lines are both at a maximum. Even though the distortion of Cape Cod, Nantucket, and Martha's Vineyard is extreme, the outline of southeastern New England is clearly recognizable, and the chart is useful for navigation.

4·3. Right-left Indicators.—It is mentally only a very short step and mechanically not a long one from automatic presentation of position on a map to the making of a connection between the map and the rudder of a vessel so that a predetermined track may automatically be followed. The means are easy to visualize and are already at hand. Only a little incentive and time are required, and hence, here again, commercial enterprise may be relied upon to bring a family of such devices into being.

One variant from past experience with direction finding must be pointed out. When using a direction-finding system, any change of course is immediately indicated and measured so that its correction, if it be accidental, can be made instantaneously. When a hyperbolic system is used, however, a change of course does not lead to any change of indication until after the new course has been held for a finite time. That is, the hyperbolic system gives an indication of position, not of direction, and the indication does not at all depend upon the attitude of the vehicle. This is an important point and a valuable one. It makes navigation independent of currents in sea or air because all courses and speeds directly derived from hyperbolic systems are ground courses and ground speeds.

If a simple RIGHT-LEFT indicator is built to show an airplane pilot whether he is to the right or left of a Loran line that he wishes to follow and even how far to the right or left he is, it will not be very successful as a means for aiding him to follow the line. This is so because there is no appreciable relation between the indications on the meter and the course

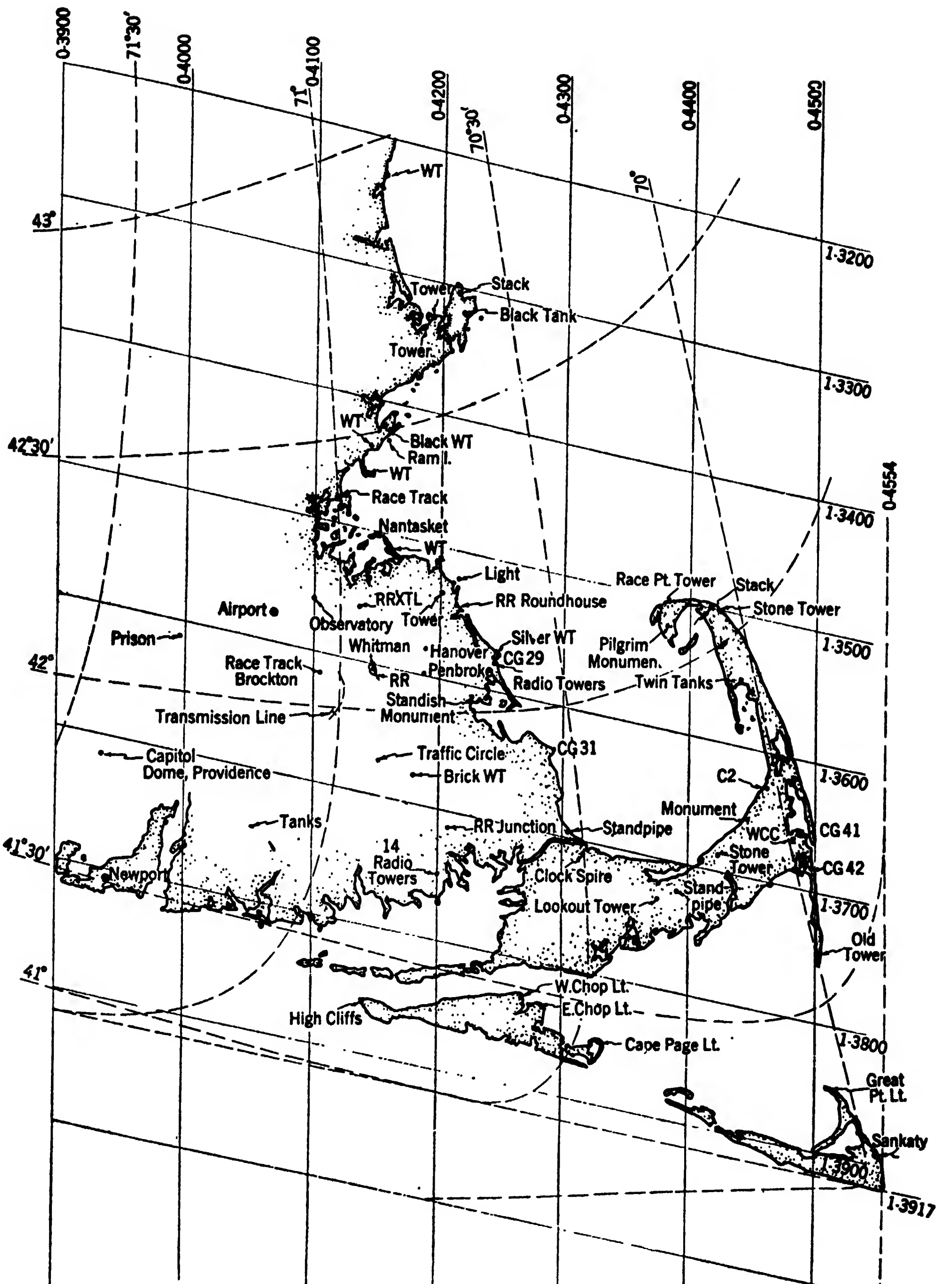


FIG. 4·1.—Rectilinear Loran projection of eastern Massachusetts.

that the pilot should follow, and thus he tends to turn more and more to the right if the meter shows him to be to the left of his desired track until he crosses the line at a large angle and has to repeat the process in reverse. The net result is a zigzag track which does, in fact, pass nearly over the objective but which wastes unreasonable quantities of time, fuel, and pilot's energy on the way.

This difficulty could theoretically be removed if the pilot would study the behavior of the RIGHT-LEFT meter in enough detail to appreciate both his displacement from the line and his rate of progress toward or away from it. With a knowledge of both these factors he could determine a reasonable course change that would bring him gently to the desired track and maintain him on it with only small excursions. The pilot is, however, too much occupied with his proper business to enter into such a study; therefore it is necessary to advance the equipment another stage and to present to the pilot both his rate of approach and the distance to the line that he wishes to follow. Thus he may be shown two meter readings, one of which tells him, say, that he is 1000 ft to the left of the line while the other shows him that he is approaching the line at 50 ft/sec. It is immediately clear that if he continues on the same course that he has been holding, he will reach the line in 20 sec and that if he wishes to come smoothly onto the line, he should begin to change course to the left. This conclusion is, of course, the opposite to that which would be derived from the simple RIGHT-LEFT indicator and shows clearly the defect in that presentation.

Within certain limits it is possible to combine the factors of displacement and rate of change of displacement automatically so that instead of two meters mentioned in the preceding paragraph the pilot could be presented with a single indicator calibrated in terms of the appropriate course correction such as "2° to the left." The only defect in this instrument would be the existence of a time constant dependent upon the time required to analyze the rate of approach to the track so that the pilot would have to learn not to make a second correction too closely upon the heels of the first.

This difficulty would vanish if the meter indication, instead of being presented to a human pilot, were connected to a gyro-controlled automatic pilot, because in that case the linkage to the automatic pilot could easily be given the appropriate time constant to prevent overcorrection.

4·4. The Lorhumb Line.—The mechanism suggested above is the simple and natural way to build a device that will automatically follow a Loran line. This is worth while because there is always a line passing through any target in a Loran service area, but it falls far short of the really desirable solution. The most important quality that the automatic equipment, like the human pilot-navigator combination, should have is the ability to proceed by a simple and reasonably direct course from wherever the vessel happens to be to wherever it should go.

This ability can stem only from simultaneous examination of two families of hyperbolas. There are many ways to make this examination, as there are many ways to make a plotting board, but one of them offers such great advantages of simplicity that it should be developed here.

Assume a Loran receiver capable of automatically following two Loran readings in two families of hyperbolic lines. The shaft rotation corresponding to either of these readings could be connected through the displacement-and-rate device mentioned above to the rudder of the vessel so that any desired Loran line in the corresponding family could automatically be followed. A Loran line passing through the initial position of the vessel could, for instance, be followed until it intersected a line passing through the objective after which instant the second line could be followed. This would produce the desired end result, but it might be by a very indirect route indeed.

A much more direct path would be one cutting across both families of lines in such a way that the rates of change of the two Loran readings would constantly bear the same ratio to each other as the total changes between initial and final readings. Along such a path, if the changes in one Loran reading were automatically followed while the delay between the second pair of cathode-ray traces (corresponding to the second reading) were constrained to vary in the designated ratio to the variation in the first reading, then the second pair of pulses, once set to coincidence, would remain so. The steering mechanism might be controlled by the second pair of pulses so as to maintain the coincidence, thus directing the vessel along the chosen path.

For example, if the readings were 3500 at the initial point and 2700 at the objective on the first Loran pair and 1400 and 1800 on the second pair, the linkage between the indications would be set at $-\frac{1}{2}$. The vessel would then follow a course such that it would successively pass through points whose Loran coordinates were (3400, 1450) (3300, 1500) . . . (2800, 1750) to the objective at (2700, 1800). The course would be quite direct unless it passed very near one of the transmitting stations. In fact, the course would differ from a great circle only in proportion as the Loran lines differed from being straight and parallel.

Figure 4·2 shows two lines of this sort drawn upon a Loran chart of part of India. The great circle from Calcutta to Benares is shown as a dashed line whereas the proposed curve, or "Lorhumb line," which crosses the East-West Loran lines at two-thirds the rate that it crosses the North-South lines, is shown as a solid line. In this case the shortest distance is 387 miles. The Lorhumb line is 1.9 miles, or 0.5 per cent, longer.

A second Lorhumb line is drawn between Benares and point Q which is about halfway from Benares to Chabua. Here the geometry of the Loran lines is less favorable, and thus the proposed course is 2.0 per cent,

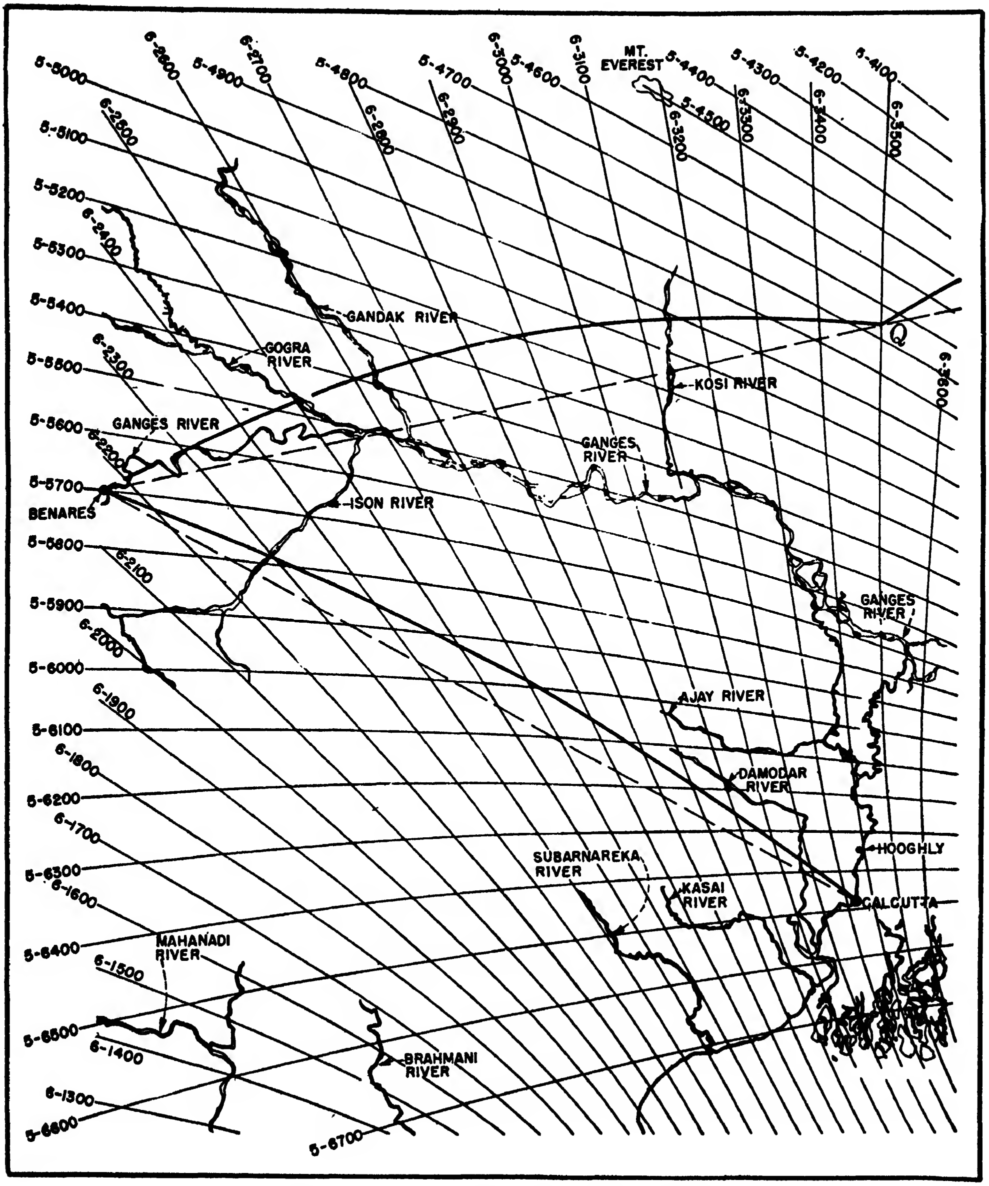


FIG. 4·2.—Lorhumb line in north India.

or 7.0 miles, longer than the great-circle distance of 358 miles. If an attempt were made to span the distance from Benares to Chabua with a single Lorhumb line, the excess distance would be about 30 miles, or 4 per cent of the total distance.

This sort of path has been called the Lorhumb line because it is the exact parallel, in hyperbolic navigation, of the rhumb line in Mercator sailing. Various Lorhumb lines might be connected by the navigator as indicated in Fig. 4·2 to form an approximate great circle or any other desired path. Devices utilizing this principle will probably be adequate for navigational purposes (as distinguished from problems of pilotage) and will presumably be more simple than others that, through more complete analysis of the exact forms of the hyperbolic lines, could follow slightly more direct paths. The advantages of the design are so obvious that devices which embody this principle may be expected to be ready for experimental operation soon after the release of engineering talent from more immediate military requirements.

4·5. Relayed Fixes.—A device for retransmitting the hyperbolic indications from the receiving point to a remote indicator may be applied to Loran. Equipment of this sort may take the form of a pulse transmitter that is triggered by the various pulses in the output of a receiver tuned for a hyperbolic system or may be essentially a superheterodyne receiver in which the intermediate frequency is sufficiently amplified and radiated. An indicator, of course, may or may not be used at the relay point.

The obvious uses for a system involving relayed fixes are those in which it is more necessary or convenient for a distant controller to have knowledge of position than it is for the occupants, if any, of the vehicle under control. Probably the only really military use might be in the control of fighter aircraft (or pilotless aircraft), where it could be expedient to relay fixes to a carrier or other base for analysis and appreciation and then to retransmit the appropriate action information through a communication circuit.

A somewhat similar use may be for extensive study of ocean currents. In this case, a number of automatic drifting buoys could relay their fixes to one or more control stations, afloat or ashore, and thus permit the gathering of precise continuous data in any weather and over long periods of time.

Probably the most important peacetime use of such a system, however, would involve the standardized installation of relay equipment in lifeboats. The information received from them would be far more useful for rescue work than directional data because it would permit potential rescuing vessels to determine at once not only the direction but the distance to those in need of assistance. Such a program must await the general use of Loran receivers on shipboard but could then easily be integrated with an automatic distress-signal receiving mechanism, provided that a frequency channel entirely devoted to such operation can be made available.

4·6. Guidance of Pilotless Aircraft.—Since hyperbolic navigation does not call for the transmission of any information from the vehicle under control, it is a mechanism with vast potentialities for the two-dimensional guidance of automatic projectiles. If flying bombs are to become the all-weather air forces of the future, no other system offers such immediate possibilities for the mass control of very large numbers of projectiles.

Systems that require some contact between a projectile and ground operators other than the launching crew may well have many tactical uses in close support operations, but the possibility of maintaining strategic bombardment by such methods is remote. A hyperbolically controlled flight of pilotless aircraft, on the other hand, could be operated without any close coordination between launching crews and the controlling groups and without saturation of the guiding facilities.

The receivers for hyperbolic operations of this sort would differ greatly from the present Loran receivers. In fact, their evolution should be in nearly the opposite direction from that suggested in the last few pages. Instead of being adapted to more flexible and versatile methods for general navigation, the equipments for pilotless aircraft should be reduced to the stage where they know only a single time difference but know it well. The corresponding ground equipment, however, must have a degree of flexibility not now in use so that the hyperbolic lines recognized by the aircraft might be made to lie across any desired target. A pair of ground stations would establish a line of position extending from the launching area to the target, while a second pair would define the intersecting line at which the projectiles would descend. Under gyroscopic control the projectiles could be launched at any time and in any number and the accuracy of their initial courses would need only to ensure an intersection with the first hyperbolic line before passing the target.

With a system of this sort, aircraft could be launched from many points in a large area. Dozens or hundreds of launching sites would independently send off aircraft sensitive to a single line of position, without any requirements for coordination except that the control system would have to be in operation. These aircraft would follow their independent courses, perhaps for half the distance to the target, until they came within the zone of influence of the hyperbolic line, whereupon each would change its course and come about exponentially to ride the line to the objective. The effect would be that of raindrops falling into a gigantic funnel and being concentrated into a steady stream playing upon the target.

Such a stream of bombs would, of course, rapidly obliterate any objective. In practice, therefore, the ground-station operators would steadily alter their timing constants so that the line followed by the projectiles would be caused to sweep back and forth over the target area, and the constants of the release line would be altered, perhaps in steps, to provide the requisite variations in range. Thus the stream could be played back and forth across the target area like the stream of a fire hose or, more exactly, like the stream of electrons scanning a television screen; all this control could be exercised without any cooperation from the launching crews who would, like the loaders on a battleship, simply maintain the flow of projectiles without giving thought to their destination.

Similarly, the beam of pilotless aircraft could be swung from target to target, to satisfy tactical requirements, without requiring any change in the launching technique or orders, provided only that the rate of sweep of the line be commensurate with the transverse acceleration available in the aircraft.

This use of the hyperbolic principle differs from Loran in that many types of transmission should be made available for it. Although coding and other features may reduce the susceptibility to jamming, the best defense is unexpected variation of the operating frequency. If this sort of mass control of pilotless aircraft is to be developed, great attention should be given to all the timing elements to ensure that none of the boundary conditions of the system shall inhibit the free choice of radio frequency. The indicating and control mechanisms should be standardized and reduced to practice in the simplest and most reliable form, but the method of transmission and detection of the hyperbolic information should be capable of alteration at a moment's notice so that, whereas Loran frequencies might be used for one tactical operation, microwaves or infrared might be used for the next.

In this respect, as in the additional flexibility of the ground stations and the simplification of the airborne equipment, the development of hyperbolic control of pilotless aircraft lies in a direction different from that in which commercial development of a general navigation system may be expected to go. It is, therefore, clear that although the exploitation of the new methods of navigation may be left to private enterprise, the development of a "hyperbolic air force" must, if it is desired, be obtained through direct and positive action by the Armed Services.

4·7. Hyperbolic Surveying.—A version of Low Frequency Loran that may become extremely important, at least for certain applications, is called "cycle matching" and consists of comparing the phase of r-f or i-f cycles of a pair of pulses rather than comparing the envelopes of the two pulses. Equipment for utilizing this technique is still in such an early stage of laboratory development that an accurate appreciation is impossible, but it seems reasonable to expect that measurements may be made to $\frac{1}{10}$ μsec over ground-wave ranges. The facility with which such readings can be taken is as yet unknown, but it is probably safe to predict that after a difficult development program, cycle matching can provide a blind-bombing system with errors in the tens of yards and with a range of 600 or 800 miles.

Whatever the merits of cycle-matching LF Loran for navigation or blind bombing, it shows great promise for the precise measurement of distances of several hundred miles. Under "laboratory" conditions, it seems reasonable to expect an error of roughly 10 ft in a single measurement of the distance between two transmitting stations, and the average of a number of observations made under good conditions in the field should exhibit about the same precision in the hands of skilled crews. This is about the accuracy with which a good trigonometrical survey measures a distance of 100 miles.

It seems probable, therefore, that radio surveying can supplement the ordinary methods for regions in which the basic triangulation system can be on a large scale. The procedure might be as follows. Three stations could be set up at the vertices of an equilateral triangle several hundred miles on a side, and the lengths of the sides determined by repeated measurements of the bounce-back time over a period of several weeks. During these measurements a number of "navigators'" receivers could be set up and operated for brief periods at points that could be identified on airplane photographs, thus providing a network of points of secondary accuracy based upon the original triangle. After thus surveying the area contained in the triangle, one station could be removed to a new location on the opposite side of the remaining baseline, and the process could be repeated. Thus a precise triangulation would be extended over immense areas in a relatively short time, and as many points as desired could be located with respect to the basic network. Neighboring secondary points would not be known, with respect to each other, with the precision obtainable by optical survey, but the absolute errors should not be more than a few yards and the speed of the whole operation should make it economically available in parts of the surface of the earth that could not otherwise be surveyed for many years to come. By this method, of course, islands and shoals that cannot be reached by optical means could be accurately charted.

Unfortunately, this is the sort of enterprise which cannot be undertaken on a small scale but must be attacked with vigor and with the expenditure of considerable money and time. It appears, however, that once in motion, the method could produce surveys of an accuracy comparable to that of any other method and produce them in a time far shorter than that now required. Good coordination of these methods with airplane photography may permit the charting, within the next few years, of very large areas that are relatively inaccessible and therefore not well known but that nevertheless may be of actual or potential military or economic importance.

4·8. The Current Problem.—Hyperbolic navigation is no longer a secret. It may develop into a great aid to international commerce, but its availability for wartime navigation is at an end. If we are faced with another war, one of the first steps taken at its onset will be to shut down all Loran stations exactly as the lighthouses were darkened at the beginning of the last war. Hyperbolic navigation must therefore be exploited commercially or reserved for occasional specialized and limited military purposes. It is obvious that the first course will lead to the greater good.

All of the equipment now in Loran operation is of 1942 design. In every category it was necessary, because of the wartime need for speed and for standardization, to adopt and build in quantity the first device that could be shown to be reasonably satisfactory. Although the present equipment is obsolete, it cannot immediately be abandoned because of the financial investment that it represents and because nothing is available with which to replace it.

The major question of the moment is this: Who is to be responsible for the development of new equipment, and, more especially, who shall control its introduction?

During the war Loran was used internationally with good success because there was only a single source of transmitting equipment—the "Navy pool"—and therefore problems of technical and operational standardization were reduced nearly to zero. As we look forward into an era of peace, this unifying force will no longer exist. Major decisions must be made on an international basis if Loran service over the oceans of the world is to be available to all. This can mean only that control of Loran in the United States must be vested in an authority that can make the necessary international commitments and enforce American compliance with them.

Even on a national basis unified control must be set up. At present, with the dissolution of the MIT Radiation Laboratory, there exists no central technical organization. The Naval Research Laboratory should accept much of this responsibility but, so far, has had to confine its activities to routine testing of equipment after the fact of its manufacture. The Bureau of Ships and Bureau of Aeronautics of the Navy and the Army's Air Technical Service Command have all made efforts to assume technical control by writing specifications for production equipment and, to some extent, by writing development contracts with commercial manufacturers. These steps, however successful, will not lead to the establishment of a single qualified technical group having cognizance of the operational needs of all services. The system planning, which should be similarly unified and based upon the knowledge of such a technical group, has hitherto been exercised by arbitration between the Chief of Naval Operations Office and the Air Communications Office of the Army Air

Forces, with some independent action by the Royal Air Force. The U.S. Coast Guard, which has done well as the Navy's operating agency, has made some attempts to conduct research leading to improved equipment but has been forced by circumstances to spend most of its available energy on day-to-day operation, as have the Royal Navy and Royal Canadian Navy. The latter service has dealt magnificently with the simultaneous problems of Loran transmission, navigation, and training but has had to follow the lead of the U.S. Navy in all technical matters.

The problem of integrating all the varied activities that have contributed to make up Loran as we know it and, we hope, of adding other activities in the future is complicated by the fact that most of the Army and Navy officers who have been closely associated with the program are now returning to varied civilian activities. They must be replaced. Ways must be found for giving civil aviation and maritime groups a voice in the technical and administrative decisions of the future. The organizational problem is severe enough on a national basis. Internationally it is acute.

CHAPTER 5

PROPAGATION

By J. A. Pierce

INTRODUCTION

5·1. Ground-wave Transmission at 2 Mc/sec. *Field Strength and Noise Factors.*—If no errors are made in the estimation of radiated power, the methods of calculation of ground-wave field intensity developed by B. van der Pol and H. Bremmer[1] and exhibited most simply by K. A. Norton[2] yield results that are in perfect agreement with observations at 2 Mc/sec and 180 kc/sec.

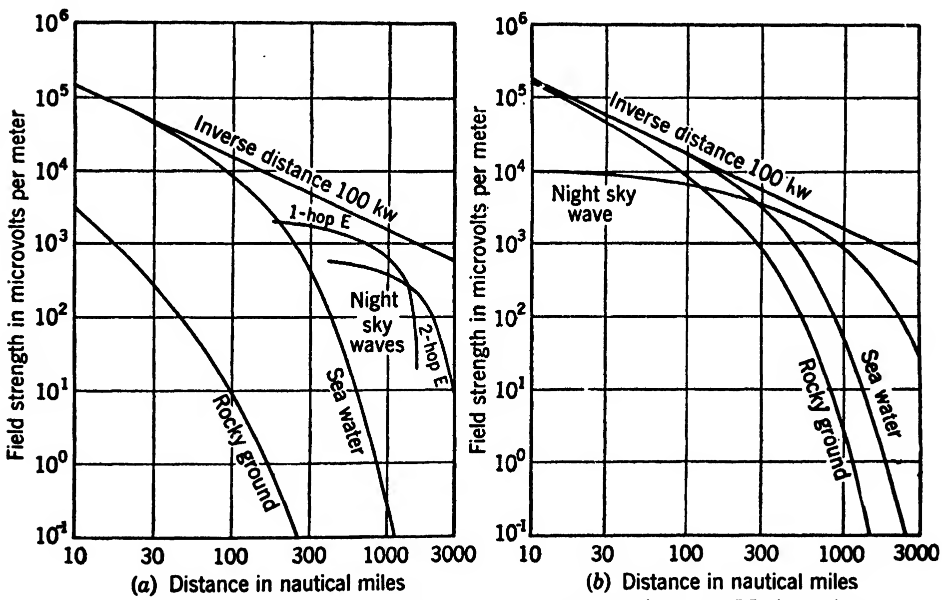


Fig. 5·1.—The variation of field strength with distance: (*a*) at 2 Mc/sec; (*b*) at 180 kc/sec. The inverse distance and ground-wave curves were computed by conventional methods, and the sky-wave curves were determined experimentally. Separate sky-wave curves are shown for one- and two-hop E-layer transmission at 2 Mc/sec because at that frequency Loran technique permits their resolution.

Figure 5·1*a* shows computed field intensities for ground-wave transmission at 2 Mc/sec, and Fig. 5·1*b* the equivalent data for 180 kc/sec. These curves are drawn for a power of 100 kw and for transmission over sea water and rocky ground. The same figures give experimental curves of field intensity of sky waves at night.

[1] B. van der Pol and H. Bremmer, *Phil. Mag.*, **24**, 141–176, 825–864 (1937).

[2] K. A. Norton, *Proc. IRE*, **29**, 623–639 (1941).

The range of transmission is dependent upon the ambient noise level. At 2 Mc/sec the signal required for satisfactory Loran operation is about 5 μv/meter in the middle latitudes in daytime. This corresponds to a maximum range of about 700 nautical miles, the nominal radius of the Loran service area. Table 5·1 shows the magnitudes of the required signals and the usable ranges for Standard Loran ground waves over sea water.

TABLE 5·1.—REQUIRED SIGNALS AND USABLE GROUND-WAVE RANGES STANDARD LORAN OVER SEA WATER

Latitude	Season	Day		Night	
		Required signal, μv/meter	Range, nautical miles	Required signal, μv/meter	Range, nautical miles
Equatorial	....	25	550	250	400
Middle	Summer	5	700	50	500
	Winter	1	850	10	650
Arctic	Summer	1	850	10	650
	Winter*	1	850	1	850

* The range in winter in quiet regions is limited by the finite sensitivity of the Loran receivers.

These ranges are approximate. There are, of course, day-to-day variations of considerable magnitude. A thunderstorm, for instance, if close to the receiver, will produce an effect very similar to tropical night conditions.

Velocity of Ground-wave Propagation.—From time to time, there have been tendencies to explain minor variations from expected Loran delay readings as indicating departures from the expected velocity of propagation. In most cases improvement in observing technique has dispelled the first opinion. One attempt was made to examine the time difference carefully at a point that involved 50-mile transmission over land from one station of a pair while the path from the other station was over sea water. Although the results indicated an extra delay of about 2 μsec in the overland transmission, there was no evidence that the probable error of the results was significantly less than that figure. In the case of the base-lines of 125 and 160 miles over land that were set up in England, the readings at the master station were about 2 μsec greater than expected, but these deviations are not greater than some that have been observed for pairs operating over sea water.

Thus, there is as yet no real evidence that transmission over land is at a lower velocity than over sea water. In the latter case the velocity of propagation is equal to that assumed within the limits of current measuring techniques.

The velocity assumed from the start of the Loran program is that determined by W. C. Anderson,[1] 299,776 km/sec in vacuum. This figure is assumed to be reduced 84 km/sec by the group retardation in the lower atmosphere. The value used is, therefore, 299,692 km/sec. Transmission time is calculated* as:

3.33676 μsec per kilometer.
5.3700 μsec per statute mile.
6.1838 μsec per nautical mile.

This value of the velocity is assumed to apply even for sky-wave transmission. There is, therefore, a slight error in all the sky-wave delay observations. This error is unimportant, however, since the sky-wave delay data must be obtained empirically.

It is probable that with the advent of cycle-matching techniques the velocity of propagation can be measured with great accuracy, but this step has not yet been taken. To date, it can be stated only that this velocity agrees with the velocity of light within a part in a few thousand.

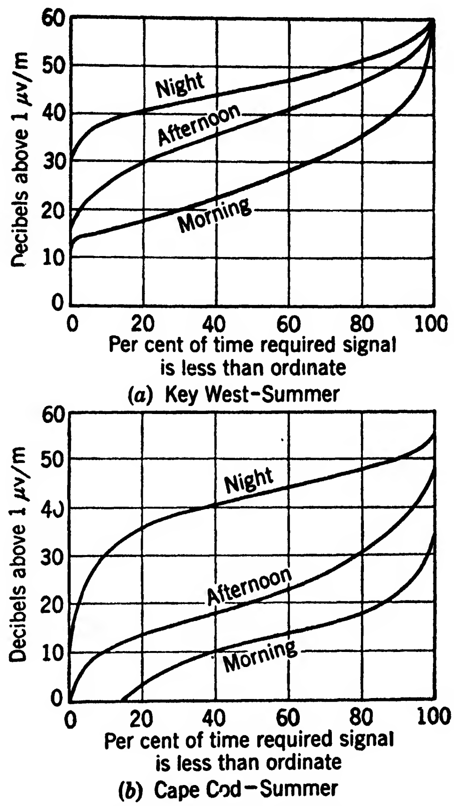


FIG. 5·2.—Diagrams showing the percentage of time that Low Frequency Loran signals must exceed certain values in order to be useful. Curves are shown for tropical summer and mid-latitude summer conditions. Each diagram shows curves for morning, afternoon, and night. For winter, or more northerly latitudes, noise conditions are less severe, and the required signals are correspondingly smaller.

5·2. Signal-to-noise Factors at 180 kc/sec.—Conditions at 180 kc/sec are more complex than at 2 Mc/sec, in that the day-to-day and even hour-to-hour noise variations are large in the summer. A simple tabulation is impossible, but a rough idea of summer-daytime conditions may be had from the statement that 100-kw signals are occasionally useful at 2400 nautical miles and nearly always useful at 1000 nautical miles. In the presence of a local thunderstorm the required signal may be 1000 μv/meter, whereas on a quiet day in winter 0.2 μv/meter has been known to be enough.

[1] W. C. Anderson, *Jour. Optical Soc. Am.*, **31**, 187–197 (1941).

* Actually, transmission time is usually calculated in terms of the oblateness and the equatorial radius of the earth which is assumed to be 21,282.5 light-microseconds (see Chap. 6).

Figure 5·2 shows measured distribution curves of the required signal (about 10 db above the mean noise) for tropical summer and midlatitude summer. Curves are drawn for the periods from sunrise to noon, noon to sunset, and sunset to sunrise. These curves were drawn taking the maintenance of synchronism between two ground stations as a criterion; the navigator can work successfully with a somewhat poorer signal.

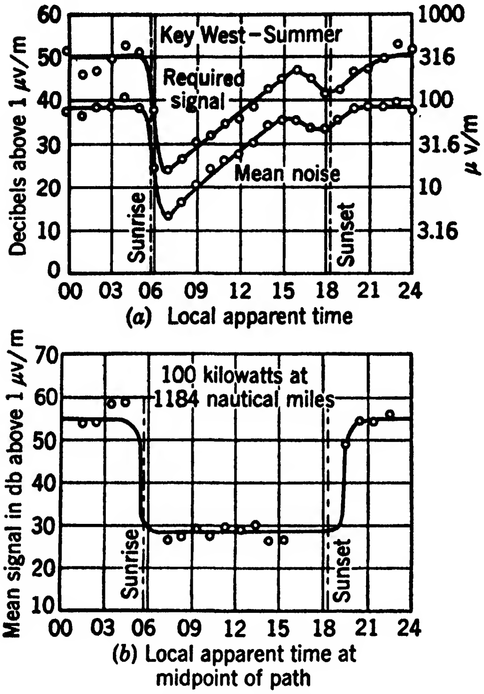


FIG. 5·3.—(a) The diurnal variation of the average noise level in the tropics in summer and the corresponding required field strength for a Low Frequency Loran signal; (b) the field strength of a 100-kw signal at about 1200 nautical miles. During the daylight hours the signal is almost entirely ground wave, but sky-wave transmission accounts for the high levels attained at night.

The most general conclusion that can be drawn is that summer noise conditions at the low frequencies are extremely variable whereas in winter the noise is fairly low and constant. Some efforts have been made to correlate noise observations made in studies of Loran transmission with the methods for estimating the required signal given in the *Radio Transmission Handbook* of the Interservice Radio Propagation Laboratory. In various experiments the signal required for Loran operation has ranged from 23 to 33 db less than the handbook estimate of the signal required for radiotelephone reception. The major part of the discrepancy, of course, is due to the difference in methods of observation. The eye is not shocked into insensitivity, as is the ear, by a sudden burst of "noise." The cathode-ray traces may be seriously disturbed by noise, but the overloading effect, with proper receiver design, is negligible. If the traces are clear and stable for a substantial fraction of a second every few seconds, Loran operation is possible (although tiring), whereas under the same conditions most other forms of radio transmission would be useless.

In general, the work on Loran has been done in terms of only two grades of circuit merit—useful and useless. This is not a desirable status in the long run, but it has led to rapid exploitation of the system under wartime conditions. As a result of this policy the most useful information on the merit of Low Frequency Loran transmission is found below in the form of data on the hours of reception of test transmissions at various distances and in the number of readings successfully made.

Qualitatively, we may roughly summarize the low-frequency transmission conditions thus:

1. In midlatitudes in summer, the daytime sky wave is almost completely attenuated by absorption; in winter, however, substantial daytime sky wave is present.
2. At night, sky-wave field strengths are only a few decibels below the theoretical inverse distance fields.
3. Transmission of both desired signals and noise is good at night and poorer by day.
4. Because generation of atmospheric noise (lightning) has a maximum in the late afternoon, the signal-to-noise ratio is poorest at that time.

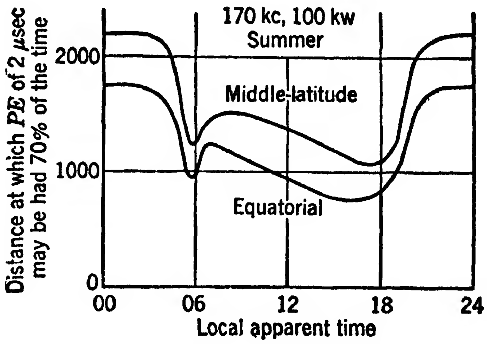


FIG. 5·4.—The approximate diurnal variation of the useful range of 100-kw Low Frequency Loran signal for tropical and temperate summertime conditions. The curves are drawn for a high degree of Loran accuracy. Useful results can be had at ranges 200 to 400 miles greater than those shown.

Figure 5·3*a* shows the diurnal variation of the noise and required Loran signal at 180 kc/sec in the Carribean area in the summer. The sharp drop at sunrise indicates that long-distance noise falls away as sky-wave transmission fails. The noise rises continuously throughout the day as the temperature rises until it passes through a maximum at about four in the afternoon. Thereafter, the noise begins to fall, but night conditions soon obtain, and the noise reassumes its nighttime value.

The corresponding behavior of a signal received over about 1200 nautical miles is shown in Fig. 5·3*b*. Although converted to a value of 100 kw, the observations were actually made at much lower power; consequently few readings could be made in the late afternoon. The character of the curve is clear, however. Only the ground wave is present in daytime, and a very substantial change in signal strength occurs at sunset and, in reverse, at sunrise. Curves of the forms shown in Fig. 5·3*b* may be drawn for various distances and compared with noise curves, similar to those of Fig. 5·3*a*, to derive curves relating distance to time of day. Two of these curves, for summer tropical and temperate zones (and for a severe accuracy criterion), are shown in Fig. 5·4.

It will be noted from Fig. 5·1*b* that the ground wave (which seems to control the field strength in summer daytime) is attenuated about 1 db for 22 nautical miles and the night sky wave decreases, on the average, about 1 db for 60 miles. The curves of Fig. 5·4 may be adjusted for various power levels through the use of these constants. Variation with the required accuracy is more difficult to estimate. It has, however, been found that a fair standard of practical operation is available at distances 200 to 400 miles greater than those shown in Fig. 5·4.

LORAN SKY-WAVE TRANSMISSION AT 2 Mc/sec

5·3. The Ionosphere.—The ionosphere is usually defined as "that region of the earth's atmosphere which is ionized sufficiently to affect the propagation of radio waves." For practical purposes it may be thought of as all the atmosphere above the stratosphere, or, more specifically, the atmosphere between 30 and 300 miles above the surface of the earth.

The atmosphere at such heights consists primarily of the same constituents as at sea level, nitrogen and oxygen. Above 60 miles the oxygen presumably exists in atomic rather than molecular form because the ultraviolet light from the sun dissociates the atoms much faster than they recombine

There is little to indicate that the heavier elements settle out at the lower altitudes. Probably all the components of the atmosphere are well mixed, except for the change from molecular to atomic oxygen at 60 miles. It may be that hydrogen and helium escape into space; there is no strong evidence that they exist at all in the upper air.

The atmospheric pressure decreases more or less exponentially with increasing height to very small values. At 60 miles it is about one-millionth of the sea-level pressure; at 200 miles it is probably thousands of times again as small. The mean free path, at 60 miles height, may be taken as 1 cm, and at 200 miles it may be as much as a mile or more. This mean free path is the average distance which a particle—molecule, atom, heavy ion, or electron—will travel before it collides with another particle. It is a very important quantity.

The temperatures in the ionosphere are high. This does not mean that there is much heat in the upper air, because there are very few particles to contain heat, but it does mean that the particles travel rapidly. At sea-level temperatures the air molecules travel at about 0.5 km/sec; at an altitude of 200 miles they move several times as fast. The temperature after falling to about $-70°F$ in the stratosphere increases to nearly the sea-level value at about 30 miles. Then there may be a sharp drop to about $-140°F$ at 50 miles. Above that the temperature (velocity of particles) rises rapidly to somewhat more than 80°F at 60 miles and to perhaps 1400°F at 200 miles.

If a certain wavelength of solar ultraviolet light excites one of the electrons in an atom so that it breaks away from the atom and exists alone, the atom is ionized. The electron is usually called a negative ion, and the positively charged remnant of the atom is called a heavy or positive ion. The electron is small and light. It will travel, independent of the heavy ion, at great speed until it finds another heavy ion with which it can unite permanently or until it finds an atom or molecule to which it can stick temporarily.

Let us assume that ultraviolet light of some ionizing wavelength is falling upon the atmosphere. There will be, in general, enough energy at this wavelength to penetrate some distance into the air but not enough to reach the surface of the earth before it has all been expended in ionization. At several hundred miles above the surface little ionization will be produced because there are very few atoms to absorb the energy. The ionization will therefore increase as the height decreases because there is more and more material that can be ionized. As the height decreases further, however, a substantial fraction of the original ultraviolet energy has been used up; thus, although the number of atoms continues to increase very rapidly, the number of electrons set free does not increase so rapidly. At still lower heights the number of free electrons actually begins to diminish and, lower yet, decreases to zero when all of the suitable incoming energy has been used up.

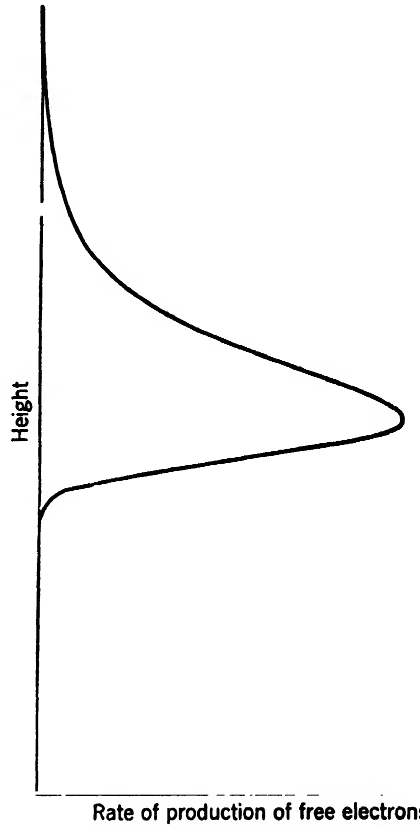


FIG. 5·5.—The vertical distribution of ionization that would be produced by a single ionizing agent acting upon a homogeneous atmosphere. The actual ionosphere may be simulated by a number of curves of this form superimposed in various ways.

This behavior can be calculated, under certain simplifying assumptions, and gives a curve of the shape of Fig. 5·5 which is known as the "Chapman distribution." The height at which the free electrons are produced and the thickness of the layer of electrons depend upon the kind of ionizing energy, the kind of atoms that are ionized, and the temperature of the air. The number of free electrons produced depends upon the same things but especially upon the total energy available in the ionizing ultraviolet light.

The true picture of the vertical distribution of free electrons is much more complicated than is indicated in Fig. 5·5. A separate distribution of the form shown in Fig. 5·5 is produced for every combination of ionizing ultraviolet wavelength and atomic constituent in the atmosphere. Many of these distributions overlap each other, but some are well separated. Furthermore, these Chapman curves define the rate at which free electrons are produced. There is some diffusion from the heights at which they are produced, and the electrons at lower levels recombine faster than those above. Both of these factors operate to cause the heights at which the density of ionization is maximum to be greater than the heights at which the electrons are set free most rapidly.

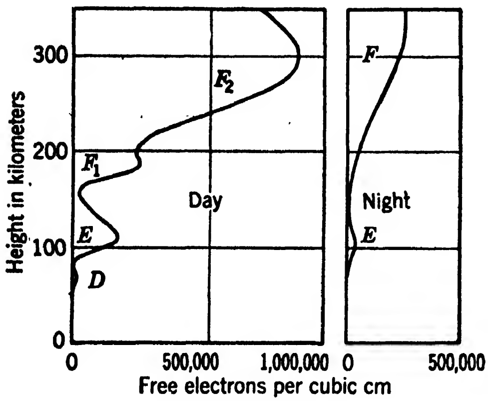


FIG. 5·6.—The approximate distribution of the density of ionization with height in the ionosphere by day and by night.

Figure 5·6 shows the approximate distribution of free electrons as they exist by day and by night. The maximum at about 250 km is called the "F-layer," or "Appleton layer." The small bump on the lower side appears only in daytime in summer, because it recombines quickly at night and is swamped in the body of the F-layer in the winter. When it appears it is called the "F_1-layer" and the remainder of the F-region is known as the "F_2-layer." The F-layer varies greatly in height, thickness, and density of ionization.

The E-, or Kennelly-Heaviside, layer, at about 100 km, is much more stable. Its density of ionization follows the altitude of the sun quite closely, except that some ionization remains throughout the night when the sunlight does not fall on the layer. We shall be primarily concerned with the E-layer.

The "tail" of the E-layer, perhaps at about 70 km above the earth, sometimes shows a small maximum which is called the "D-layer." Because the density is low, only low-frequency waves can be reflected from it. The D-layer is primarily of importance because in it energy is absorbed from radio waves.

We have been speaking of free electrons. Actually there must be about as many heavy positive ions as there are free electrons in the ionosphere. The heavy ions are unimportant in radio propagation, however (except that their existence permits the free electrons to recombine), because their relatively great mass prevents them from giving appreciable interaction with radio waves.

5·4. Reflection.—A rough model for the action of electrons in an r-f field has been given by P. O. Pederson.[1] In a qualitative way it may be described as follows.

Assume a small volume of the upper atmosphere to be equivalent to a capacitor with the space between its plates filled with air and a number of free electrons. If an r-f voltage is applied across the capacitor, there will be a displacement current proportional to the capacitance of the plates. In addition, the free electrons will be excited to vibrate back and forth along the lines of electrostatic force at the frequency of the applied voltage. Because of the inertia of the electrons, the phase of their oscillation will lag the applied emf by 90°. The moving electrons therefore constitute a current between the capacitor plates—a current in opposite phase to the displacement current. The magnitude of the electron current depends upon the magnitude of the capacitance under consideration and upon the applied emf, and it also varies directly as the number of free electrons.

The capacitor containing a volume of ionized air may now be thought of as a capacitance in parallel with an inductance that is inversely proportional to the number of free electrons. If the number of electrons is small, the inductance shunting the capacitance is nearly infinite. As the number of electrons increases, the inductance decreases and the circuit becomes more and more nearly antiresonant. The net effect is that of a capacitor whose net reactance increases as the number of electrons increases. That is to say, the capacitance can decrease to zero if the density of free electrons is properly proportioned to the radio frequency. This means that the air-plus-electrons has a dielectric constant and an index of refraction that are less than unity. If the electron current exceeds the displacement current, the reactance does *not* become inductive; the index of refraction, however, becomes imaginary. These are concepts which do not occur in simple optics.

The effect of the heavy ions that are, of course, present can be neglected because, although they are excited to oscillate (in the opposite phase to that of the electrons), their great mass limits the acceleration that can be imparted to them. Thus the amplitude and velocity of their oscillations are very small in comparison with those of the electrons. The current flow is, of course, proportional to the velocity; thus the net effect of the positive ions is very small in comparison with that of the electrons.

If a radio wave penetrates obliquely into the ionosphere, the phase velocity, which determines the direction of the wavefront, increases as the index of refraction decreases. At the same time the group velocity, which

[1] P. O. Pederson, *The Propagation of Radio Waves along the Surface of the Earth and in the Atmosphere*, "Danmarks Naturvidenskabelige Samfund," Copenhagen, 1927.

is the velocity with which the energy travels, decreases in the same ratio. Thus the upper part of the wavefront travels faster as the wave penetrates into an ionized layer because the density of ionization is increasing. The wave is therefore refracted so that it curves back toward the earth, but a pulse travels more slowly while being refracted.

In Fig. 5·7*a* we have postulated an ionospheric layer whose density (number of free electrons per cubic centimeter) is roughly indicated by the density of dots. Three rays of r-f energy are shown entering the layer. If the frequency is such that "reflection" can occur at oblique incidence on the layer but not at vertical incidence, the behavior will be as shown. A ray *C* departing at a small angle to the horizontal will

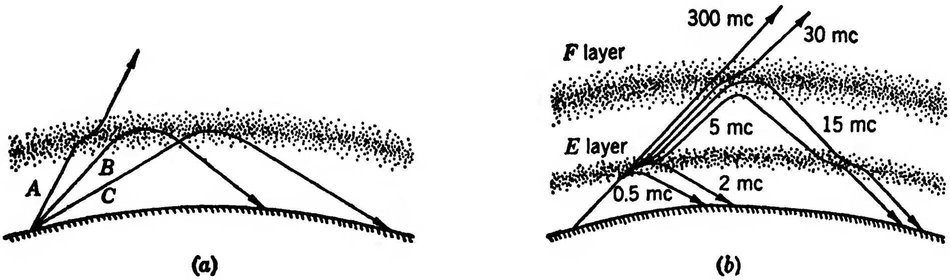


FIG. 5·7.—Qualitative diagrams illustrating the reflection of rays of energy in the ionized layers. (*a*) A possible variation of the reflection pattern with the angle of departure of the ray; (*b*) the effect of the layers at various radio frequencies, where the various rays are assumed to leave the transmitter at the same angle.

require only a modest amount of refraction before it is turned parallel to the surface of the earth. It will therefore not need to penetrate far into the layer and will span a long range in a single "hop." Another ray *B* departing more steeply from the earth will penetrate the layer more deeply because it must be turned through a greater angle. If the required bending cannot be achieved, because the frequency or departure angle is too high or the density of the layer is too low, the ray *A* will penetrate the layer, traveling on a path that is concave downward until the height of maximum ionization is reached and concave upward beyond that height. This ray, of course, leaves the earth completely unless it is turned back later by a higher layer. The effect of this penetration is to establish the well-known "skip distance" within which sky-wave signals are not received. All rays travel in straight lines except while in an ionized layer.

There is a definite maximum range that can be spanned by "single-hop" transmission. This is the distance covered by a ray departing horizontally (or as nearly horizontally as antenna radiation can be effective) and is about 1500 miles in the case of E-layer transmission. At greater distances the signal is cut off by the earth itself. This shadow effect can be seen clearly in the sharp drop in the one-hop sky-wave field-intensity curve of Fig. 5·1*a*.

A rough diagram indicating the typical action of both E- and F-layers is given in Fig. 5·7b. Here we have assumed a number of rays at different radio frequencies, all departing from a transmitter along the same path. The medium frequencies shown, 500 kc/sec and 2 Mc/sec, are both reflected by the E-layer, but the 2-Mc/sec ray penetrates much more deeply and travels somewhat farther. At 5 Mc/sec, the ray is refracted strongly in the E-layer but does penetrate it and is easily reflected by the F-layer. The 15-Mc/sec ray is less affected by the E-layer and penetrates more deeply into the F-layer, but the general behavior is much the same as at 5 Mc/sec. Under the conditions we have postulated, however, 30 Mc/sec is too high a frequency to be returned. The ray passes the E-layer with little refraction and is refracted strongly by the F-layer but without being turned back toward the earth. The energy at this and all higher frequencies, such as 300 Mc/sec, escapes into space. As the frequency increases, the deviation of the ray in the layers decreases until at microwave or optical frequencies the effect of the ionization is not at all perceptible.

The whole structure of Fig. 5·7b depends upon the density of ionization in the layers and upon the angle of departure of the orginal rays. At a lower angle the 5-Mc/sec ray might often be reflected from the E-layer and the 30-Mc/sec ray would be returned from the F-region.

5·5. Absorption.—The reflection of radio waves in the ionospheric layers is only part of the process of radio transmission by sky waves. The absorption of energy from the waves is of at least the same importance.

Some mention was made above of the mean free path of an electron (or other particle) in the upper atmosphere. This quantity, or more properly the inversely varying frequency of collision, controls the energy lost by a radio wave. Although there may be a million free electrons per cubic centimeter in a highly ionized layer, there are typically a million times as many neutral atoms or molecules with one of which an electron may collide at any instant. Suppose, for example, that on the average an electron can move freely only for a millionth of a second before colliding with a heavy atom. If the electron is being vibrated by an r-f field at 1 Mc/sec, there is only about one chance in two that the electron can complete a cycle of oscillation before a collision interferes with its motion.

Collisions are important for the following reason. Some energy is abstracted from the radio wave to provide the kinetic energy contained in the moving electrons. This energy is, in effect, lost to the radio wave only for a half cycle because the moving electron, since it constitutes a moving charge, reradiates an electromagnetic field whose energy is equal to the energy absorbed by the electron. As the radio wave passes through the ionosphere, the energy reradiated by all the electrons adds in phase to constitute a wave traveling in the same direction as the original wave.

If the electrons can move freely, tiny elements of the energy in the wave flow back and forth between electromagnetic and kinetic states, but the total energy in the wave remains the same. If, however, an electron rebounds from an atom while temporarily carrying some of the energy, two things happen. The less important is that the direction of motion of the electron is changed. The energy is then reradiated in a different orientation, with the result that the phase relation with the radiation from other electrons is damaged. Even more serious is a real loss of r-f energy because the atom is accelerated slightly and carries off part of the kinetic energy that had been loaned to the electron. This energy is completely lost to the radio wave and remains in the atmosphere in the form of increased kinetic energy, or heat.

If the probability of collision and loss of energy is high enough, the radio wave will be completely attenuated in the ionized layer. The degree of absorption is less as the frequency is increased because the electrons are more likely to be able to complete their half cycles of oscillation before a collision occurs. In the F-layer, there is little "collisional friction" because the mean free paths are long and the collisional frequency is low. In the E-layer, collisions are so frequent that waves of frequency below 2 or 3 Mc/sec are completely absorbed in the daytime. At night the density of ionization in the E-layer decreases to perhaps a tenth of the daytime value. The absorption goes down to low values because the chance of a collision between an electron and some other particle is similarly reduced.

We may summarize the situation thus: Ionization is needed to reflect radio waves, but ionization at low heights in the atmosphere absorbs energy from the waves. The higher the frequency the stronger the ionization required for reflection and the less the absorption.

Since most ionization in the atmosphere is produced by the action of ultraviolet light from the sun, there is little new ionization created at night. The free electrons recombine, but so slowly that a substantial number of them remains throughout the night. Thus the maximum ionization occurs at or soon after noon, and the minimum at sunrise. Similarly the ionization is more intense in summer than in winter because the incidence of the sunlight upon the atmosphere is more nearly perpendicular and the ionization increases as does the temperature.

Whether radio transmission is better by day or by night, in winter or in summer, is a question of frequency. At high frequencies, for example, 20 Mc/sec, the weak ionization may prevent sky-wave transmission completely in the winter or at night; in summer or daytime the stronger ionization will support transmission and absorption is relatively unimportant. At broadcast frequencies, absorption is complete in the daytime, with the result that only ground-wave ranges are useful. At night, long-distance transmission is possible, and the decreased absorption in winter makes communication better than in summer.

5·6. E-layer Transmission.—Figure 5·8 shows typical variations of the critical frequencies (which are proportional to the square roots of the maximum densities of ionization) in the E- and F-regions throughout the day. Recombination is so slow in the F-region that the maximum occurs well after noon, although all of the ionizing energy appears to come directly from the sun. The smooth decrease throughout the night is another manifestation of the fact that some free electrons have lifetimes of many hours in the F-layer.

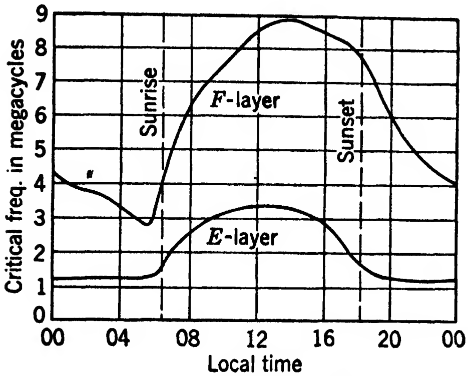


FIG. 5·8.—A typical diurnal variation of the critical frequencies of the E- and F-layers of the ionosphere. This quantity is proportional to the square root of the maximum density of ionization in a layer.

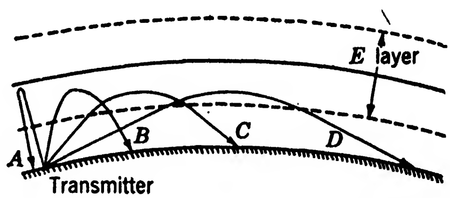


FIG. 5·9.—A diagram illustrating the variation of penetration into an ionized layer as a function of the distance traversed by a ray.

The behavior of the E-layer at night is not understood. At the height of the E-layer, complete recombination takes only a few minutes and consequently, in daytime, the density of ionization adapts itself very quickly to the amount of energy being received from the sun. The E-layer curve of Fig. 5·8, between sunrise and sunset, is nearly proportional to the fourth root of the cosine of the sun's distance from the zenith. This is so exactly true that without question the ionization would go almost to zero at night if direct ultraviolet light from the sun were its only source.

The energy brought into the earth's atmosphere by meteoric bombardment may possibly be enough to sustain this nighttime ionization.[1] In any case, meteoric effects are definitely perceptible and certainly cause many of the variations in the density and distribution of free electrons in the E-layer even though they are probably not the major cause of the ionization. The random variations in the density of the E-layer are of the first importance in the propagation of Loran signals by sky waves, because they determine the errors of the system.

The transmission time of a sky wave is greater than the transmission time of the ground wave, primarily because of the greater distance

[1] J. A. Pierce, "Abnormal Ionization in the E Region of the Ionosphere," *Proc. IRE*, **26**, 892–908 (1938).

traveled but also because the wave travels more slowly during the process of refraction. The difference between the two times is called the "sky-wave delay." Figure 5·9 shows that the sky-wave delay observed at a point very near the transmitter (if penetration does not occur) is essentially equal to the transmission time of the sky wave. As the distance increases (rays B, C, and D), the transmission time of the sky wave increases but the transmission time of the ground wave increases more rapidly. The sky-wave delay therefore decreases as the distance of transmission increases and, in fact, becomes very nearly constant at distances of a thousand miles or more. Figure 5·10 shows the standard delay curve for Loran, which is drawn for reflection from the E-layer. The curve is a mean for night conditions at a frequency just below 2 Mc/sec, and the shaded area indicates the limits of variation. It is never drawn back to zero distance because a 2-Mc/sec wave nearly always penetrates the nighttime E-layer at short distances, and because the delay becomes more variable as the distance decreases. At distances less than 200 nautical miles the delay is completely unreliable. Fortunately for Loran the ground-wave service of the system is ordinarily available at distances up to those at which the E-layer transmission becomes satisfactory.

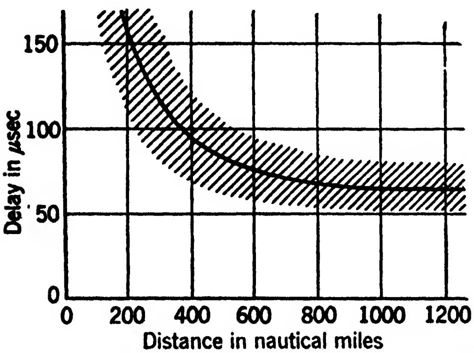


FIG. 5·10.—The Loran delay curve. Delay is the amount that a sky wave lags behind a ground wave traveling from the same transmitter to the same receiver. The shaded area shows the limits of variation of the delay.

The stability of the reflection becomes greater at longer distances partly because grazing reflection is better than reflection at a steep angle, but primarily because a change in the height of reflection does not greatly change the total distance traveled by the ray. At a distance of 1000 miles the length of the sky-wave path increases only 1.78 miles for a change in the height of reflection of 5 miles. This is a change in the time of transmission of less than 10 μsec or about one-fifth of the corresponding change at a short distance.

Variations of 5 miles in the height of reflection are rare but do occur at times. Their effect upon Standard Loran is not too large because such an extreme variation is likely to exist over a large area. It will therefore operate to increase (or decrease) the transmission times from both stations of a pair so that the time difference measured by the navigator does not vary as much as the individual delays.

The discussion in the last few paragraphs has been specifically applicable to the E-layer. Only this layer is used in Loran because the F-layer is too variable to permit prediction of the times of transmission with the necessary accuracy. A comparison between the layers is shown in Fig. 5·11, which shows the apparent variation of the line of position through a point in Bermuda. These observations were made as part of the first experiments on Loran. For obvious reasons, work involving the F-layer was discontinued after that time. The example shown is typical of the behavior of both layers, although the time of day was not favorable to maximum stability of either. The average deviations of the line of position are 18 miles for the F-layer and 2 miles for the E-layer. The distance was 625 miles from the stations; consequently the equivalent average errors in the bearing of Bermuda, as seen from near New York, were 1.7° for the F-layer experiment and 0.2° for the E-layer.

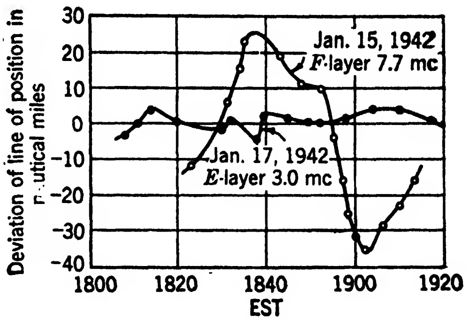


FIG. 5·11.—The variation with time of the Loran line-of-position error in Bermuda when using E- and F-layer reflection. The instability of the F-layer is so great as to preclude its use for hyperbolic navigation.

As will be seen from the notation on Fig. 5·11, the layer can be selected by proper choice of frequency. At the time of these experiments, 7.7 Mc/sec penetrated the E-layer and 3.0 Mc/sec did not. The Loran frequency is chosen as one that will be reflected by the E-layer at all times

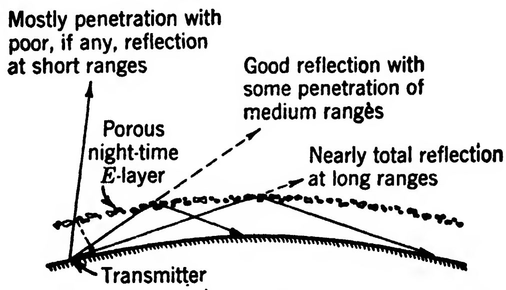


FIG. 5·12.—A diagram indicating variation with angle of the partial internal reflection obtaining at 2 Mc/sec at night.

at all distances that will not be adequately served by ground waves. It is possible that frequencies as high as 2.5 Mc/sec might satisfy this criterion, but both ground-wave range and sky-wave stability are improved by using lower frequencies. (The lower limit of frequency, incidentally, is that at which it becomes too difficult to generate and radiate a sufficiently short pulse for Loran purposes. With the criteria adopted for Standard Loran, this frequency is probably about 1 Mc/sec.)

It should be noted that the last paragraph did not state that signals at the Loran frequency would not penetrate the E-layer. They almost always do penetrate at short distances, and part of the energy may penetrate the layer at long distances. This seems to be possible because, contrary to what has been suggested above, the E-layer is not really a smooth homogeneous layer at night, although it is one in the daytime. At night the layer is porous. It seems to consist of many nuclei or clouds of ionization chiefly at about the same height—a little below the height of the daytime or normal E-layer—with either spaces or patches of sparse

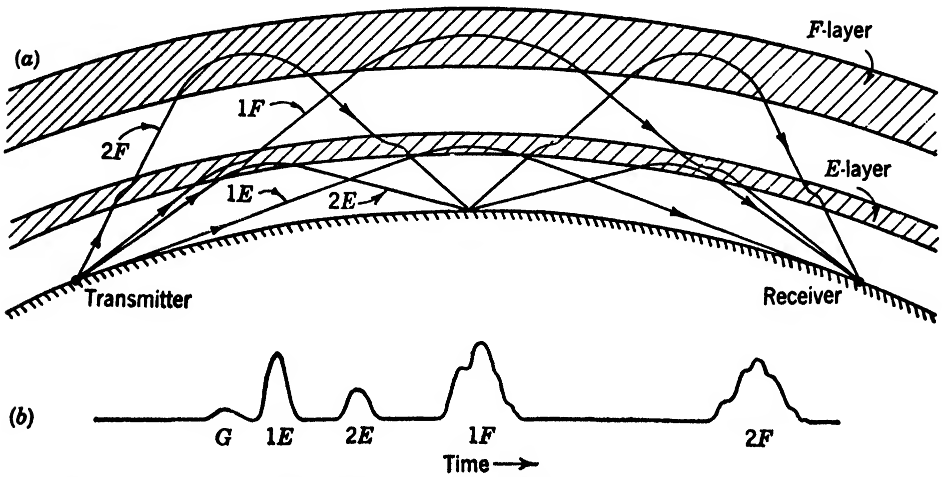


FIG. 5·13.—A diagram indicating at (a) a number of the possible ray paths between a transmitter and a receiver and at (b) the approximate pulse pattern received in this case.

ionization between them. The density of the ionization in the clouds is not very great, so that 2-Mc/sec rays pass vertically through the "layer," partly by penetrating the clouds and partly by passing between them. At angles closer to grazing incidence the probability of passing through the spaces becomes smaller and usually goes to zero for transmission over the longer distances.[1] A diagram showing this effect is given in Fig. 5·12.

In general, some energy will be reflected by the porous nighttime E-layer, and some will pass through it and be reflected from the F-layer. Multiple-hop transmission is possible in both cases, so that the pattern of received pulses may therefore be very complex. The structure of some of these components of the received pattern is shown at *A* of Fig. 5·13. The way the corresponding signals look on a linear oscilloscope trace is indicated at *B*. This diagram is idealized. A more accurate representation of a pulse train in the presence of fading and noise has been given in Chap. 3.

[1] This same result would be produced by a homogeneous layer if the layer were not thick compared with the wavelength. It is hard to believe that this is the case, however, because the layer would have to be only a few hundred yards thick at most.

The "spotty" character of the nighttime E-layer gives rise to pulses whose shape is not the same as that of the pulses when they leave the transmitter. Several of the small clouds of ionization in the neighborhood of the midpoint of the transmission path may reflect the pulse. Although each reflection may be a complete and perfect reproduction of the transmitted pulse, the overlapping components arriving at the receiver may combine to give a very complex form indeed. This is particularly true at very short distances, say up to 100 miles, where often a family of ten or a dozen contiguous or overlapping pulses may be seen. As the range increases, the weak multiple pulses move toward each other and coalesce into a single strong pulse that occasionally is seriously distorted. Figure 5·14 attempts to show some of the typical reflection patterns received between, say, 100 and 400 miles from a Loran transmitter. The reason for not using sky waves at very short distances is clear.

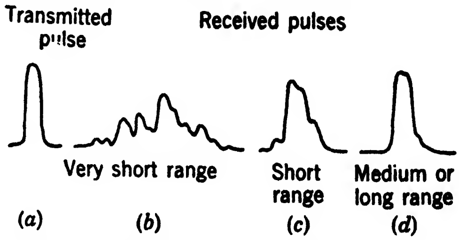


FIG. 5·14.—A representation of the complex pulse observed at short distances from a Loran transmitter. Loran sky-wave operation is uncertain and inaccurate except at medium and long ranges.

5·7. The Loran Sky-wave Delay Curve.—The standard technique in Loran is to measure to the *first* visible component of a pulse even though the pulse be complex. As seen in Fig. 5·14 this may be quite different from measuring to the dominant component. This decision was first made on theoretical grounds and was based on the belief that if a pulse should be simultaneously reflected from a number of clouds of ionization, the part arriving first must travel by the simplest and most direct path and should therefore be the most reliable. This thesis has been amply confirmed by experiment, as measurements made on the first component exhibit smaller mean deviations than those made in any other way.

At the start of the Loran program the nighttime E-layer was scarcely known to exist and its properties could not be predicted. It was necessary, therefore, in the interests of speed, to determine the necessary factors empirically. More than this has not yet been done. Fortunately the layer was found to be remarkably stable. That is, its characteristics change very little from one hour of the night to another. More surprisingly, the properties of the layer seem to be essentially the same at all latitudes and to vary only simply and moderately between winter and summer. These auspicious discoveries greatly facilitated the use of sky waves for Loran.

The sky-wave delay curve (Fig. 5·10) already cited was determined by making Loran observations on sky waves at accurately known points and comparing the observed readings with time differences calculated (for the locations where they could not be directly measured) in terms of ground-wave transmission. Figure 5·15 shows the delay curve again so that its derivation and use may be discussed.

Standard Loran charts and tables are computed in ground-wave time differences even though the distances are so great that ground waves cannot be received. A correction must be applied when sky waves are used. The correction can be read from the sky-wave delay curve if the distances to the two stations are known. Suppose that d_M in Fig. 5·15 represents the distance of the navigator from the master station while d_S is the distance from the slave. The first-hop E-layer sky wave from the master will arrive Δ_M μsec after the ground wave, and the corresponding slave pulse will be Δ_S μsec later than its ground wave. Since the navigator measures the time differences between the *M*- and *S*-pulses, his sky-wave reading will differ from his ground-wave reading (if he has made one) by $(\Delta_M - \Delta_S)\mu$sec. This amount is the sky-wave correction. In this case (closer to the master station) the sky-wave reading is smaller than the ground-wave reading. The correction is therefore called positive, so that when it is added to the sky-wave reading, the ground-wave time difference, which is shown on the charts, will be obtained.

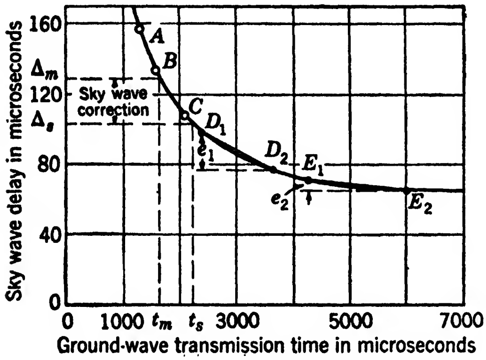


Fig. 5·15.—The derivation and use of the Loran delay curve.

The sky-wave corrections can, of course, be calculated easily at the time when the charts are prepared. They are ordinarily exhibited on the charts as small numbers printed at the intersections of the whole degrees of latitude and longitude. Since the magnitude of the corrections is small, interpolation by inspection is adequate. On the center line of the pair and at long distances from both stations the corrections are zero because the master and slave sky-wave delays cancel each other.

The delay curve was constructed through study of many thousands of Loran sky-wave readings made at various distances from the stations. At points within ground-wave range of one or both transmitting stations, the difference in the arrival times of the two ground waves and the difference in the arrival times of the ground wave from one station and the sky wave from the other station were measured, and average values for these two time differences were obtained. The difference in these two averaged time-difference measurements gave the sky-wave delay for the distance between the monitor station and the transmitting station from which the sky wave was received. Points derived in this way are shown at *A*, *B*, and C of Fig. 5·15. For longer ranges, where ground waves could not be used, an inverse process had to be employed. The sky-wave readings of a pair were averaged and compared with the calculated ground-wave reading at the monitor station. The discrepancy (e_1 or e_2 in the figure) was, of course, the sky-wave correction. Since the two distances were known, the correction gave the slope of a chord of the delay curve, as shown at D_1-D_2 or E_1-E_2. Many lines of this slope could be drawn in an effort to find the vertical position of the line that would fit its end points into a smooth curve with the end points of other similar lines at other distances. If enough observations are available, at enough distances, the curve can easily be constructed.

The curve that seems, after three years' experience in various latitudes, to be the best average approximation to the true values is shown in Fig. 5·10. This curve is represented by the following equation:

$$\text{Sky-wave delay in } \mu\text{sec} = D + 0.3\left(\frac{7000 - t}{1000}\right)^3 + 0.18 \times 10^{-6}\left(\frac{7000 - t}{1000}\right)^{11},$$

where D is the minimum sky-wave delay which varies between 65 μsec in winter and 75 μsec in summer. The transmission time of the ground wave in microseconds is represented by t.

This formula applies for distances less than about 1130 nautical miles (where $t = 7000$). For greater distances the sky-wave delay equals D. This equation is purely empirical.

As shown by the variation of the quantity D, the layer height is somewhat greater in summer. However, the delay curve, for all practical purposes, simply moves upward; thus the correction, which is always the difference between two delays, is not affected. There is an error introduced by this change in two cases; the case when the navigator may occasionally wish to measure the time difference between a sky wave and a ground wave and the case of the synchronization path in sky-wave Synchronized Loran which will be discussed below.

The only important latitude effect is that the delay curve may be used at shorter distances at low latitudes. Near the equator fairly reliable operation may be had at as little as 150 nautical miles, whereas at 45° latitude about 250 miles is the minimum safe distance. The curve itself does not seem to vary appreciably over the latitude range from 25°N to 63°N within which it has been carefully checked.

LORAN SKY-WAVE TRANSMISSION ERRORS AT 2 Mc/sec

5·8. Normal Variations in the Sky-wave Delay.—Since we propose to examine closely the averages and the mean deviations of the sky-wave delay and sky-wave corrections, it is necessary to test the accuracy with which transmitter synchronism can be maintained. An example, somewhat better than normal, is given in Fig. 5·16. This figure shows the number of the various ground-wave readings observed at a monitor station where the computed reading was 3510.6 μsec. The mean, as is usual, agrees with the computation within 0.2 or 0.3 μsec, and the average deviation is of the order of 0.6 μsec. A series of sky-wave readings usually shows an average deviation at least four or five times as great as the average error in synchronism. It is, therefore, nearly always satisfactory to assume that the synchronism of the transmitting stations is rigid and that any deviations observed are the result of variations in sky-wave propagation. Exceptions to this assumption are usually obvious.

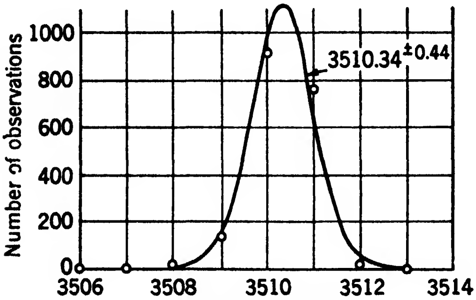


FIG. 5·16.—A distribution curve showing the normal scatter of Loran observations when ground-wave transmission is used. The average reading error is small compared with the random variations of sky-wave transmission time.

Three distribution curves of observations of the sky-wave delay are given in Fig. 5·17. The curves, which are drawn to have the same area, exhibit clearly the two important facts of sky-wave transmission for Loran. The average sky-wave delay diminishes as the distance increases, as shown by the delay curve, and the spread of the readings also decreases in about the same proportion. The probable errors in this set of observations are

9.9 μsec at 240 nautical miles.
9.0 μsec at 290 nautical miles.
5.8 μsec at 450 nautical miles.

The first two are somewhat below the normal scatter at these distances.

At long distances it is impossible to measure delay directly. Figure 5·18 shows two distribution curves of the sky-wave reading (not delay) at distances of 870 and 1350 nautical miles. The corresponding probable errors are 2.1 and 2.4 μsec, although a smaller error would be expected at the greater distance. These are errors in the sky-wave *correction*. As remarked above, major changes in the height of reflection of a sky wave may be expected to affect both transmission paths in the same way

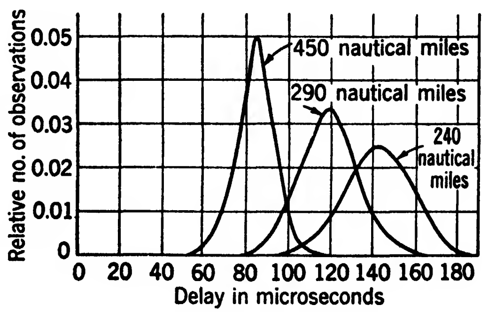


FIG. 5·17.—Three distribution curves exhibiting the way both delay and probable error of delay decrease as the distance of transmission increases.

and, therefore, to cancel to some extent. In other words, there is a correlation between the two delay patterns, and the error of a sky-wave measurement is smaller than it would be if the two reflection points behaved independently. For instance, the probable error of sky-wave delay at 1000 miles averages about 3.9 μsec. If every point in the reflecting layer varied independently, the probable error of a sky-wave reading would be about $\sqrt{2} \times 3.9$ μsec, or 5.5 μsec. Actually, for baseline lengths of about 250 or 300 miles, the probable error of a reading is usually between 1.5 and 2.0 μsec for a 1000-mile range. This indicates a fair degree of correlation in the behavior of the layer at points separated by 100 miles or more.

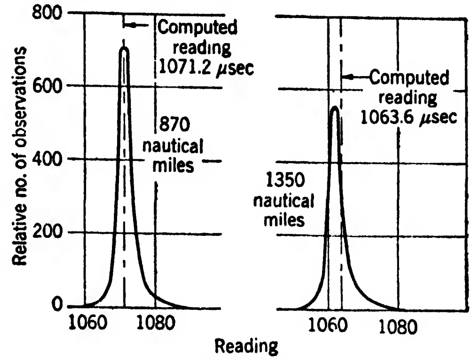


FIG. 5·18.—Two examples of the scattering of Loran sky-wave readings at medium and long distances. The average errors are four or five times those of Fig. 5.16.

The probable error of sky-wave *delay* is shown i Fig. 5·19 as determined from monitor-station readings on many different pairs of stations. The points for ranges greater than could be served by ground waves were determined during the American trials of the Sky-wave Synchronized Loran system. The equation given on the diagram defines the smooth curve but has no other significance.

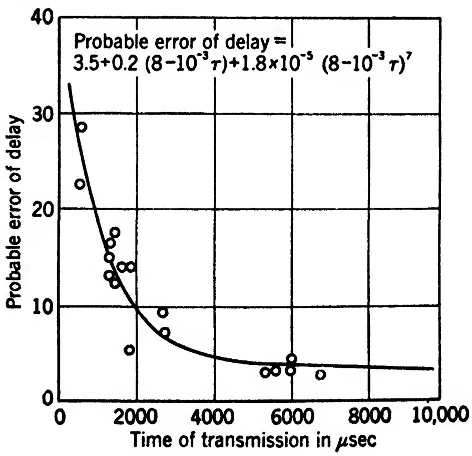


FIG. 5·19.—The probable error of a single observation of sky-wave delay at 2 Mc/sec. This is the probable error of a single transmission time, not of a Loran reading.

If no correlation existed between the layer heights at the two points of reflection, the probable error of a sky-wave reading would be found by taking the square root of the sum of the squares of the two values of probable error of delay for the two distances involved. Since there is a correlation, an estimate of the probable error of a reading can be made by multiplying the "no correlation" value by a factor smaller than unity which can be obtained by experiment. This factor is given in Fig. 5·20, where it is plotted against the length of the baseline in light-microseconds. The positive slope means simply that the greater the separation of the stations the less the variations in delay tend to cancel each other. The factor "P.E. of synchronization" is given in the equation on the figure because sometimes, as in the case of SS Loran, the absolute accuracy of synchronism cannot be assumed. In SS Loran, of course, the probable error of synchronism is equal to the probable error of sky-wave delay at the distance separating the stations.

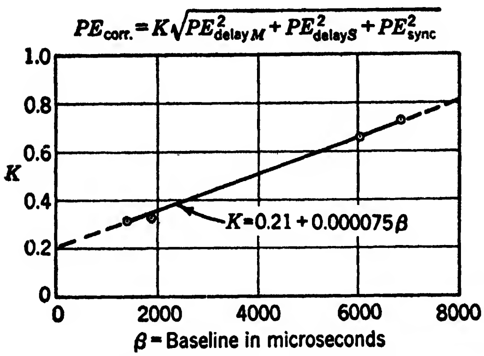


FIG. 5·20.—A form of the correlation coefficient defining the relative behavior of two points in the ionosphere, plotted against the separation between two transmitting stations, M (master) and S (slave).

Figure 5·21*a* and *b* shows the degree of approximation with which this treatment agrees with the measured probable error of readings, for short (Standard) and long (SS) Loran baselines.

5·9. Sky-wave Accuracy Patterns.—The accuracy (or average error) with which a sky-wave Loran reading can be made can be estimated by the method discussed in Sec. 5·8. This average timing error may or may not correspond to a significant number of miles, depending upon the distance from the stations and their orientation with respect to the navigator.

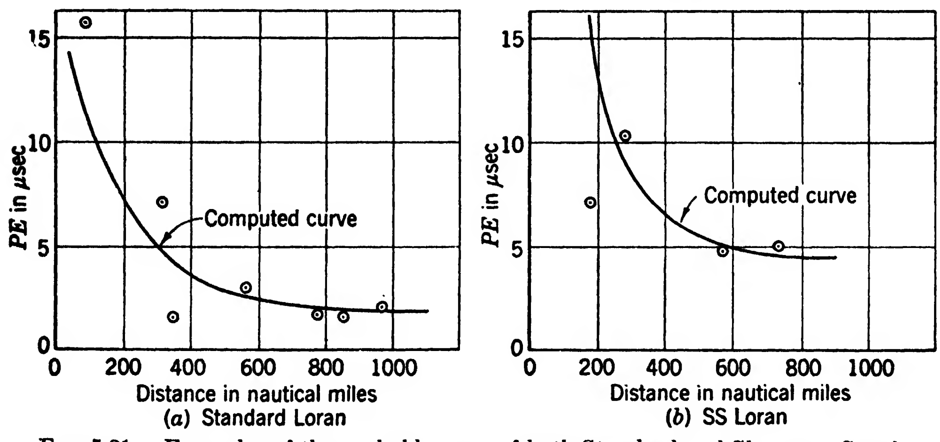


FIG. 5·21.—Examples of the probable error of both Standard and Sky-wave Synchronized Loran observations. The smooth curves are computed by empirical methods given in the text, and the circles indicate experimental observations.

The geometrical methods of Chap. 3 permit the calculation of the number of miles corresponding to a change in reading of 1 μsec. These formulas may be combined with the methods discussed in this chapter to yield the average error of a sky-wave reading expressed in miles.

Two diagrams are given, in Figs. 5·22 and 5·23, that show how the probable error of a sky-wave line of position (in nautical miles) varies over the service area of a Loran pair, whether Standard or Sky-wave

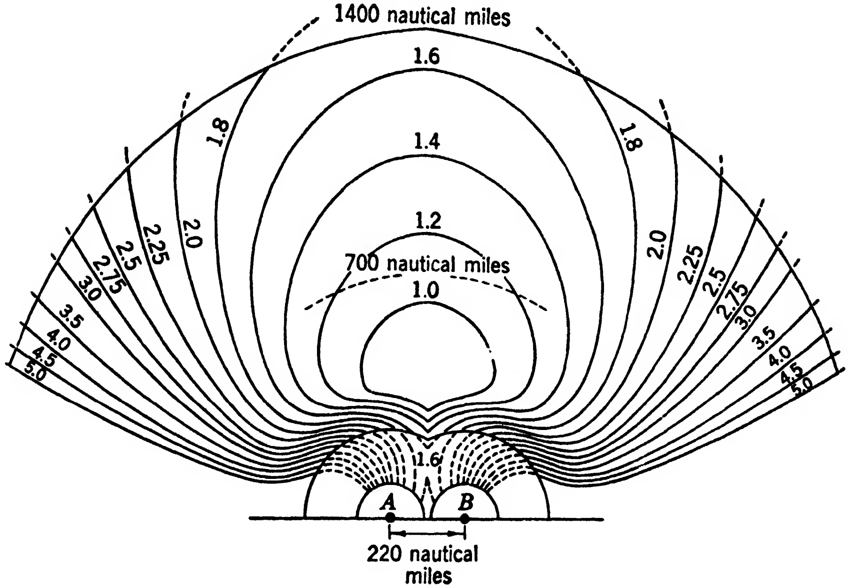


FIG. 5·22.—A contour diagram showing, as a function of the geographic position with respect to the transmitting stations, the probable error of a Stand. rd Loran line of position when using sky waves.

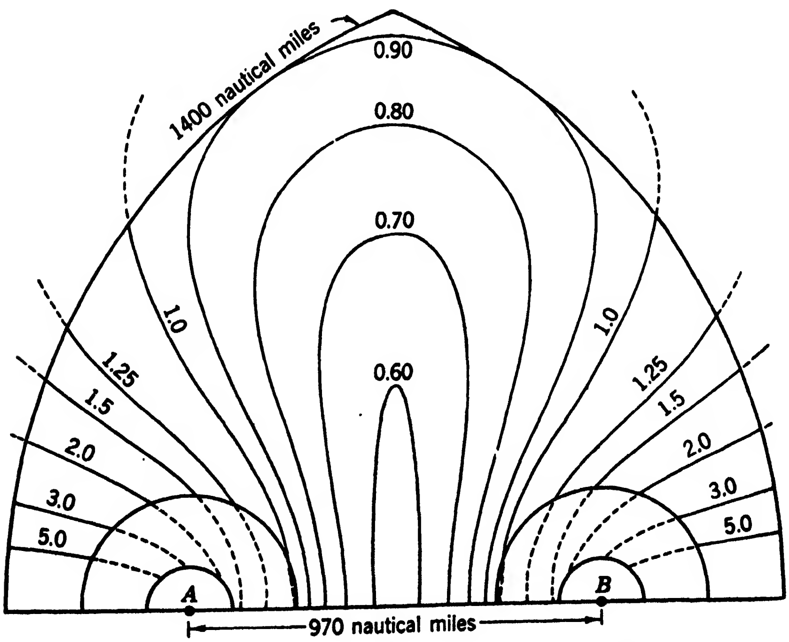


FIG. 5·23.—A contour diagram showing, as a function of the geographic position with respect to the transmitting stations, the probable error of a Sky-wave Synchronized Loran line of position.

Synchronized. The Standard Loran diagram (Fig. 5·22) is drawn for the relatively short baseline of 220 nautical miles. For modest changes in the baseline the errors would vary in inverse proportion, since the timing errors would not change appreciably.

It is of special interest to note that the errors increase very slowly with distance along the center line of the pair. This is because the timing errors due to variation of the sky-wave delay are nearly inversely proportional to distance and almost cancel the increasing geometrical error. Beyond the 1400-mile limit or within 250 miles of the stations it is not safe to use sky waves because of difficulty in sky-wave identification in the first case and erratic behavior in the second.

The accuracy of SS Loran is greater than the sky-wave accuracy of Standard Loran, as shown in Fig. 5·23, because the long baselines (in this case 970 nautical miles) greatly improve the geometrical accuracy, or miles per microsecond of timing error. The timing error itself is not so good as in Standard Loran, primarily because of sky-wave variations on the synchronizing path, but the timing error is not increased so much as the geometrical factors are improved. The total area served by an SS pair is not so great, but the errors are smaller and more constant except along the baseline extensions.

5·10. Sporadic E-region Ionization.—One of the outstanding anomalies in the E-region is the existence of sporadic ionization. This takes the form of clouds of free electrons, at a very constant height, that are sporadic in both time and space. They may appear at any time, day or night, and last for a few minutes or for hours. Their size may be anything up to hundreds of miles across. They sometimes appear to move with great velocities, and at other times they seem nearly stationary. The density of ionization is often low but occasionally is very great indeed —even greater than the greatest density ever observed in the F-layer. On at least one occasion the density has been observed to be enough to reflect signals up to 110 Mc/sec over a 1000-mile path.

These clouds are probably caused by corpuscular bombardment of the atmosphere by particles shot off by the sun, in much the same way that northern lights are formed. Although sporadic E-region ionization may appear at any time, it is most likely in summer and at times of sunspot maximum. It is most probable at high latitudes and is seldom observed at the magnetic equator—again like the aurora borealis.

In the early days of Loran it was feared that signals from one station of a pair might be reflected from a cloud of sporadic E-region ionization while the signals from the other station would be transmitted by the "normal" nighttime E-layer, thus leading to large and unpredictable errors. Fortunately this is not the case, apparently because the normal reflections occur at a height somewhat below that of the sporadic E;

consequently the signals normally are not propagated by the sporadic clouds.[1]

The best evidence to this effect is given in Table 5·2 which exhibits the average value and probable error of sky-wave readings when sporadic E-region ionization is and is not present. These data were taken in Ottawa, Canada, by the Canadian Navy in May, June, and July 1943, the season of maximum sporadic ionization. During this period the sporadic E-layer appeared about one-third of the time at Ottawa. Of course there is no proof that sporadic ionization existed at the points of reflection at the same time they were observed at Ottawa, but it is more likely to have existed there at that time than when it was not observed at Ottawa. As the table shows, there was no significant change in the Loran reading at times when sporadic E-region ionization was observed. The probable errors (or average errors) of the readings were actually smaller at those times, but the difference was not large enough to be significant.

TABLE 5·2.—EFFECT OF SPORADIC E-REGION IONIZATION ON LORAN READINGS

Pair	Computed reading	Normal			During sporadic E		
		No. of observations	Mean reading	Probable error	No. of observations	Mean reading	Probable error
MF	2932.4	561	2932.1	3.2	305	2932.6	2.9
MB	3814.7	422	3816.3	4.4	256	3816.8	3.6
DB	1342.4	368	1342.5	3.7	206	1341.8	3.1
		1351			767		

5·11. Magnetic Activity.—Sudden or large variations in the earth's magnetic field are associated with changes in the ionosphere, although both are probably secondary effects of some other phenomenon such as corpuscular bombardment of the atmosphere. In the F-region the "magnetic effects" are extreme, presumably because of the relative ease with which the free electrons can move. There are no indications that the total number of free electrons is greatly changed in the F-layer. The layer heights increase and the densities decrease during magnetic activity, much as though the atmosphere (or at least the electrons in it) were being pulled up by the top and stretched somewhat. In fact, during severe magnetic storms (extremes of activity) the F-layer is essentially "blown out of the atmosphere" and a new layer is formed underneath the remnants of the old one.

[1] At very short distances sporadic E-region ionization frequently does cause strong steady reflections. Since the height of reflection differs from the normal, this contributes to the unreliability of sky-wave transmission at short distances at 2 Mc/sec.

In the E-layer the magnetic effects are less pronounced. There is a tendency for the layer height to change, but the electron densities do not decrease much. There is usually an increase in absorption presumably due to the decrease in layer height or to the formation of new ionization at low levels through corpuscular bombardment of the sort that may produce sporadic E-region ionization or aurora. This increase of absorption is particularly severe in the auroral zones, within perhaps 30° of the magnetic poles of the earth, where it is largely responsible for extremely poor transmission by sky waves.

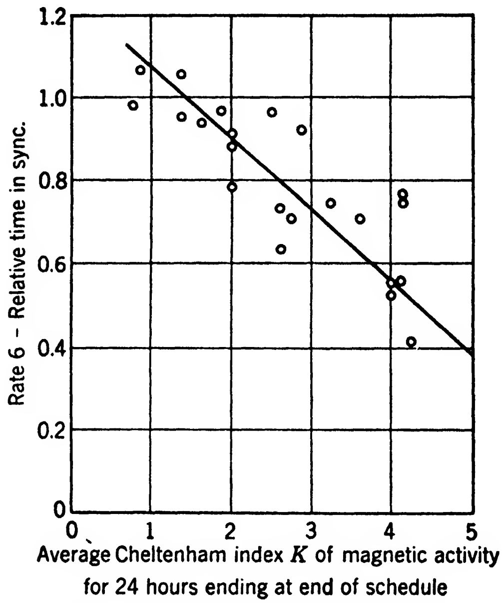


FIG. 5·24.—The reduction in the serviceability of a Sky-wave Synchronized Loran pair with increasing magnetic activity. This effect is important only when the midpoint of the pair is within about 30° of the earth's magnetic pole.

The Sky-wave Synchronized Loran trial system in the United States operated over two baselines, one (referred to as "Rate 5") about 1100 nautical miles long with its point of reflection about 120 miles east of Charleston, S.C., or 39° from the North magnetic pole. The second baseline (Rate 6) had its center over Georgian Bay, Ontario, about 26° from the pole. In the first case, variations in magnetic activity did not materially affect the ease with which synchronism could be maintained between the transmitting stations. In the case of Rate 6, however, a moderate increase in the magnetic activity was usually accompanied by a considerable decrease in the fraction of the nighttime hours within which satisfactory synchronism could be maintained. The correlation is shown in Fig. 5·24 where the abscissa displays the magnetic activity reported by the Cheltenham Magnetic Observatory. Unity on the ordinate scale is the number of hours from sunset to sunrise on the night in question.

Each dot represents a night's operation. Occasionally, when the magnetic activity was lower than average, operation was maintained from before sunrise to after sunset. On nights of high magnetic activity operation tended to start late and to be intermittent, with successful periods of an hour or two scattered throughout the night. There was no indication that the loss of synchronism was due to anything except weakness of signals; that is, this figure indicates the increase of absorption with increasing magnetic activity.

During these trials the sky-wave delay was averaged nightly for each synchronism path and compared with the magnetic activity as shown in Fig. 5·25. The data for Rate 6, at the bottom of the figure, show a fairly consistent decrease of about 10 μsec in the sky-wave delay over the normal range of variation of the magnetic index. The Rate 5 data, on the other hand, seem to show a slight increase, although that conclusion is not statistically reliable. The real decrease has not been observed outside the auroral zone.

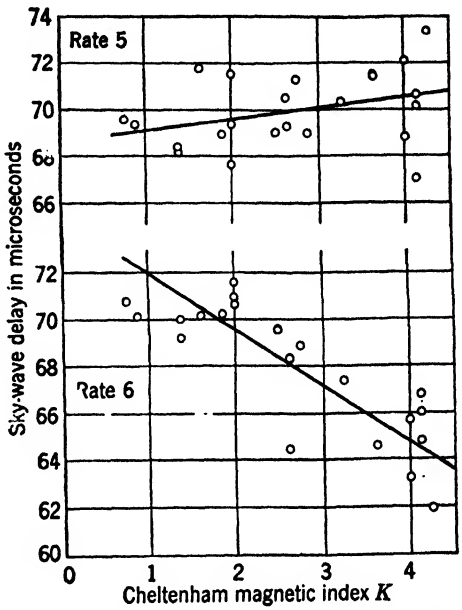


FIG. 5·25.—Variations in the sky-wave delay with magnetic activity over paths of approximately 1000 miles. The upper curve represents the behavior on a path whose midpoint was 39° from the magnetic pole; the midpoint of the other path was within 26° of the magnetic pole.

When the magnetic index is at or below 2.0, there is no difference in the average height of reflection over these two paths. When, however, the magnetic activity rises to about 4.2, there is a difference of 3.0 nautical miles in the height of the two points of reflection, which are separated by about 750 miles. This is a consistent difference of about the magnitude of many random variations.

The same change in the time of transmission is exhibited in Fig. 5·26*a* and *b* in the form of distribution curves of the double transit time plus the coding delay (minus 1000 μsec in this case). Figure 5·26*a* shows the slight but not important increase in transmission time with magnetic index for the southern pair, and Fig. 5·26*b* gives the significant decrease in time of transmission and decrease in accuracy for the northern pair when the magnetic index exceeded 3.0. This effect, it should be repeated, does not seem to be significant when the points of reflection from the ionized layer are outside the auroral zone.

It seems, therefore, that the ordinary phenomena which disturb radio transmission have no serious effect upon the accuracy of Standard Loran sky-wave readings, although the reliability of the service may suffer in the case of operation too near the magnetic pole.

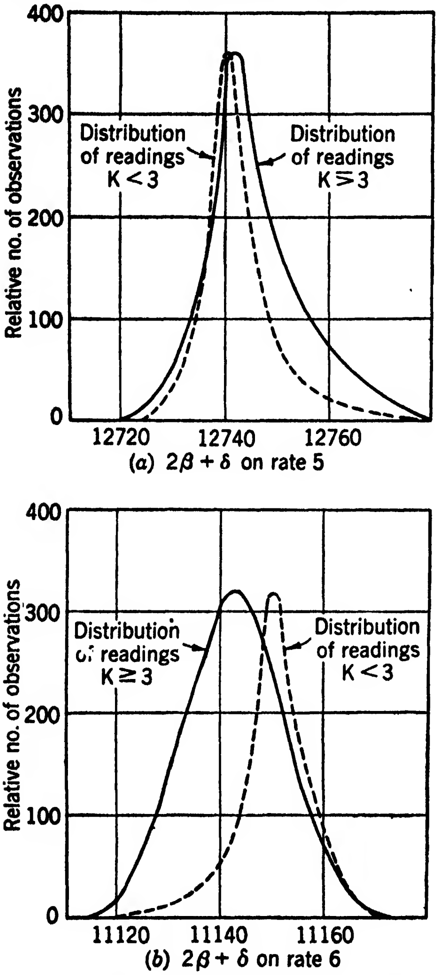


FIG. 5·26.—Distribution curves exhibiting data for the same transmission paths as in Fig. 5.25, for high and low values of magnetic activity. Here again the only serious effect is observed for operation near the magnetic pole.

LORAN TRANSMISSION AT 180 KC/SEC

Introduction.—We have suggested that the optimum Loran frequency is the lowest at which a complete ground-wave pulse can be received before the arrival of the first sky-wave pulse. This would certainly be a desirable frequency, but valuable work can be done at lower frequencies because of the greater ranges that can be had there. The concepts of the system are considerably changed, but the increased transmission range operates, much as in Sky-wave Synchronized Loran, to permit the use of long baselines and thus make the measurement of time difference less critical.

The Radiation Laboratory work on this new system was done at 170 and 180 kc/sec. A single transmitting station operated at 170 kc/sec from August 1944 to April 1945. From then until September 1945, three trial stations were in use at 180 kc/sec. These stations were monitored, as shown in Fig. 5·27, at Bermuda, Puerto Rico, Trinidad, and the Azores for determination of over-water transmission conditions. The signals over land were observed at Wright Field and Little Falls, Minn., as well as in an aircraft that spent several hundred hours of flying time investigating the range and accuracy of the system. The Army also observed these transmissions at Eatontown, N.J., and at Mobile, Ala., while the Canadian Navy and the U.S. Coast Guard operated monitor stations at Halifax (Camperdown) and Bermuda, respectively. Unfortunately, only summertime observations were recorded by this trial network.

5·12. Low Frequency Loran Pulse Shapes.—The transmission band that can be made available for any service in the neighborhood of 200

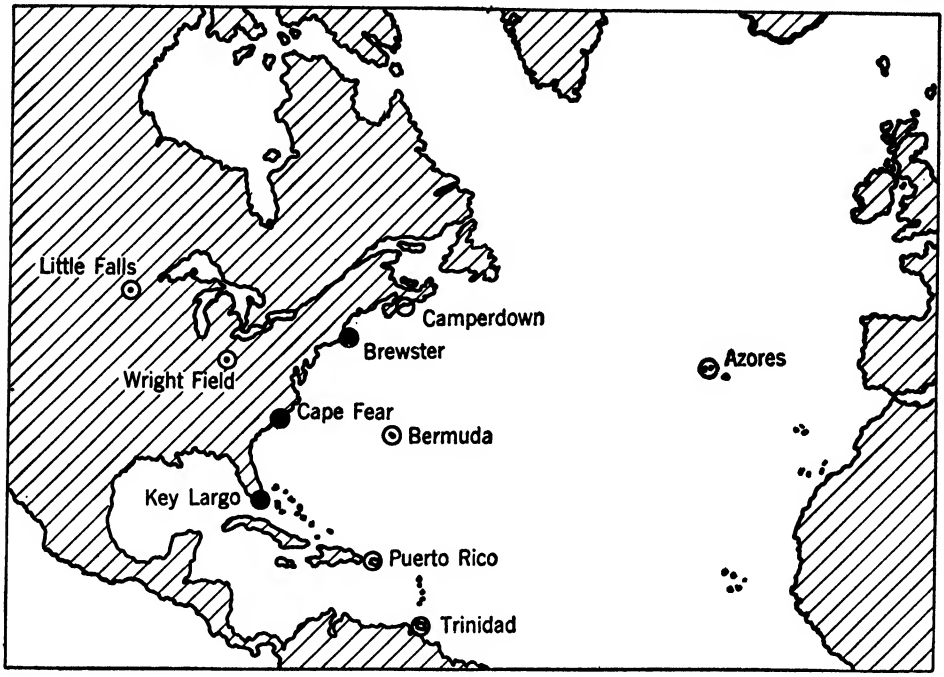


FIG. 5·27.—A map exhibiting the locations of the transmitting and monitoring stations used in the experimental Low Frequency Loran program in the summer of 1945.

kc/sec is, of course, severely limited by the requirements of other services. This means that an L-F pulse system must operate with narrow bandwidth and long pulses.[1] Since the sky-wave delay at 180 kc/sec is even less than at 2 Mc/sec, say about 50 μsec at 1000 miles, the first two or three sky-wave components of the received signal arrive before the end of the ground-wave pulse. Thus, the received pulse may be a composite of ground and sky waves, and its shape will not be that of the transmitted pulse except at short ranges where the ground wave dominates.

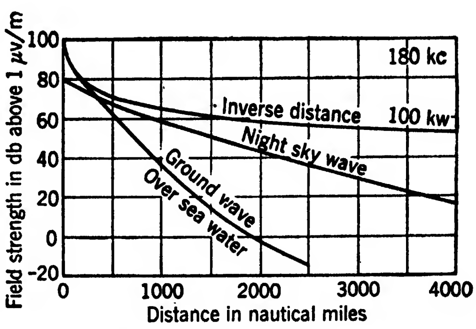


FIG. 5·28.—The variation of Low Frequency Loran signal strength with distance. The data are the same as those of Fig. 5·1*b*, except that in this case they are plotted against a linear distance scale.

As shown in Fig. 5·28 (which shows much of the data of Fig. 5·1*b* on a linear distance scale), the night sky wave, on the average, exceeds the amplitude of the ground wave at distances beyond 300 or 400 nautical miles. As far

[1] Even if this political limitation did not exist, it would be very difficult to radiate short pulses from any practical 180-kc/sec antenna system.

as is now known, the daytime sky wave may have nearly the value of the night sky wave in high latitudes in winter, but it is so completely absorbed as to be negligible at low latitudes in summer. Curves have not been shown for the daytime sky wave because of insufficient information. The night sky wave is, of course, made up of many multiple reflections. Its field strength vs. distance curve is probably made up by the summation of a number of individual curves, those for the higher multiples having lower field strengths at the short distances and extending to longer ranges before dropping sharply when the shadow

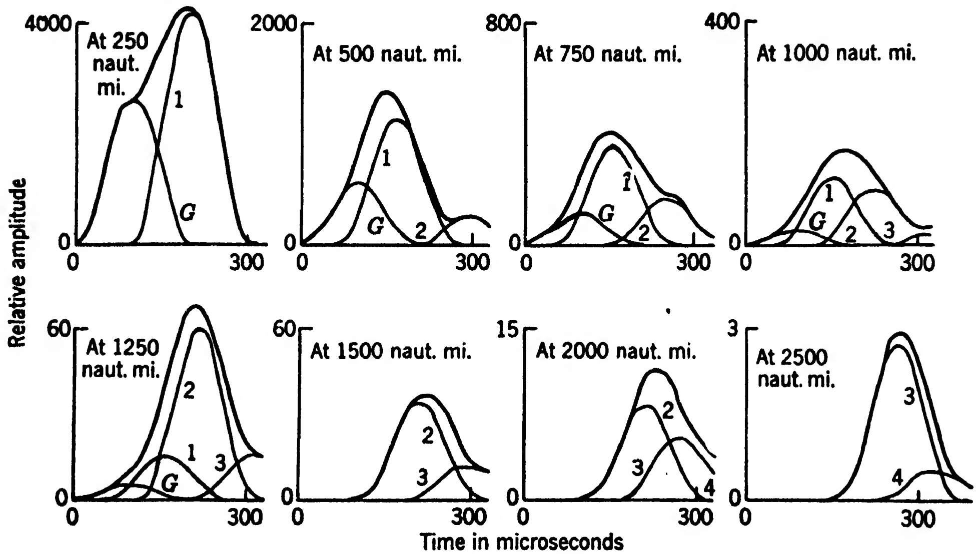


FIG. 5·29.—The way that Low Frequency Loran ground and sky waves may add at various distances. The zero of each horizontal scale marks the instant at which the first point of the ground-wave pulse arrives. The relative amplitudes are given by the changing ordinate scale.

of the earth cuts them off. A more precise experimental determination of the night sky-wave curve of Fig. 5·28 would probably show these irregularities.

The exact shape of the received pulse at any distance depends upon the length of the transmitted pulse, the amplitude of the sky-wave components relative to the ground-wave, and the sky-wave delays. Various assumptions may be made about all of these factors, and most of them lead to very similar conclusions. The effect is demonstrated in Fig. 5·29 where a pulse length of 200 μsec has been chosen. This figure has been drawn on the assumption that the ground-wave and various sky-wave pulses are always in the same r-f phase at the receiver, so that the individual pulse envelopes can be added to give the composite envelope. This assumption is contrary to fact, as will be explained below, but it yields results that are useful in understanding the problem. At 250 nautical miles the figure shows a nighttime condition where the first sky wave arrives about 100 μsec behind the ground wave and is of somewhat greater amplitude. The composite envelope exhibits a distinct shelf at the point where the sky-wave pulse begins. At 500 nautical miles the sky-wave delay is decreased to the point where ground wave and first sky wave merge into a fairly smooth pulse. The second-hop sky wave is beginning to overlap at the tail of the pulse and produces an irregularity. As the distance increases, the received pulse envelope passes through various distorted forms until at 1500 miles the ground-wave and first sky-wave components are assumed to be negligible and the pulse regains a fairly simple shape, at least throughout its first half, which is used for measurement. The pulse arrives about 110 μsec later than the theoretical time of arrival of the ground wave. At longer and longer ranges various sky-wave components drop out and the total sky-wave delay increases accordingly. The changes in amplitude with distance may be judged by the changes of scale of the ordinates in Fig. 5·29.

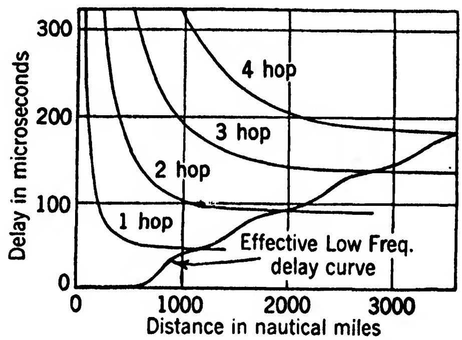


FIG. 5·30.—The way in which an approximate Low Frequency Loran delay curve can be made up from the individual delay curves for multiple-hop transmission. An explanation is given in the text.

One great advantage of L-F transmission is already clear. However complex the sky-wave components may be, nearly all the energy reaches the receiver in a single pulse because no energy penetrates the E-layer and the effective E-layer components are more or less superimposed. Thus the pulse shape may be complex, but there is only one pulse received per pulse transmitted; the navigator, therefore, is not led astray by errors and ambiguities in the choice of the pulse with which he should work.

It is already clear that the low-frequency sky-wave delay curve, if one can be drawn, differs radically from that at 2 Mc/sec because, as Fig. 5·29 indicates, the greater the distance the greater the delay. This effect may be thought of in the terms indicated in Fig. 5·30 where the delay curves for one-, two-, three-, and four-hop transmission are indicated. At 2 Mc/sec no attention is paid to the two-, three-, or four-hop delays, if they exist. The operator effectively uses the zero-delay line (ground waves) whenever he can and then when necessary makes a deliberate transition to the one-hop delay curve. This cannot be done at 180 kc/sec because the shape of the received signal pattern does not clearly show which components are being received. It is, however, possible to say that at short distances the ground wave will predominate and zero delay will be observed. At some distance, as suggested in the

1000-mile diagram of Fig. 5·29, the effective time of arrival of the received pulse is approximately that of the first-hop sky wave. At some greater distance, say 2000 miles, both the ground wave and the one-hop sky wave have negligible amplitude and the time of arrival is essentially that of the two-hop sky wave. Thus the equivalent low-frequency sky-wave delay curve, as shown by the wavy line on Fig. 5·30, will find its way across the figure with, in general, a positive slope. The tendency for this delay curve to cling to each of the separate multiple-delay curves is affected by many factors including the pulse length and receiver bandwidth but depends particularly upon the relative amplitudes of the various multiple reflections. Thus, if the two-hop component should be very weak compared with the one-hop component, the effective delay might tend to cling to the one-hop curve over a considerable distance, perhaps almost to the distance at which the one-hop signal disappears. This effect can be understood easily by reference to the night sky-wave curves of Fig. 5·1*a*.

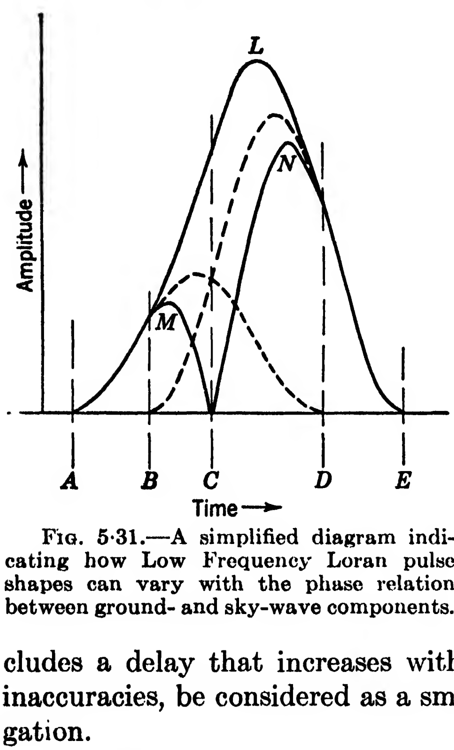


FIG. 5·31.—A simplified diagram indicating how Low Frequency Loran pulse shapes can vary with the phase relation between ground- and sky-wave components.

We are thus led to the conclusion that over long distances the time of transmission of a pulse includes a delay that increases with distance and that may, with minor inaccuracies, be considered as a small reduction in the velocity of propagation.

The assumption that the amplitudes of the various pulse components may be added to give the amplitude of the composite pulse is, of course, contrary to fact. The first-hop sky wave is in general delayed from 10 to 25 cycles (at 180 kc/sec) behind the ground-wave pulse and is just as likely to arrive out of phase as in phase. The height of reflection is not constant but is usually slowly increasing or decreasing, so that the phase of the one-hop sky-wave component may change through 2 or 3 cycles with respect to the ground-wave pulse over a period of several hours. The effects of this phase change may be examined with the aid of Fig. 5·31, which has been drawn assuming that no second- and higher-multiple reflections exist and that the ground wave has about half the amplitude of the sky wave. If these components could be seen individually, the ground wave would appear as shown by the dotted pulse between *A* and

D, and the sky wave might appear as shown between *B* and *E*. The times marked *B* and *C* are those at which the sky wave begins and at which the ground and sky waves have equal amplitude. If the ground and sky waves arrive in phase, the envelopes may be added (as shown in Fig. 5·29) to give the envelope *ALE* of Fig. 5·31. The amplitude at time *C* is twice the amplitude of the individual pulses at that instant. If, however, the sky-wave delay is an odd number of half cycles so that the components are in r-f opposition, the resultant envelope is different in major respects. There can be no change with phase between instants *A* and *B* because throughout that interval only the ground wave is being received. At time *C*, however, the two equal amplitudes of the individual components will cancel, so that the resultant amplitude of the envelope is zero. The complete resultant envelope is that shown as *AMCNE* which is, of course, the absolute magnitude of the difference between the two individual pulse envelopes. The relative amplitude of the peaks at *M* and *N* depends primarily upon the relative amplitudes of the individual pulse components, although it is affected by the ratio of the delay to the length of the transmitted pulse. The variation of the resultant envelope with r-f phase is shown in Fig. 5·32*a*. It will be observed that a 90° phase difference produces a composite envelope that is not conspicuously

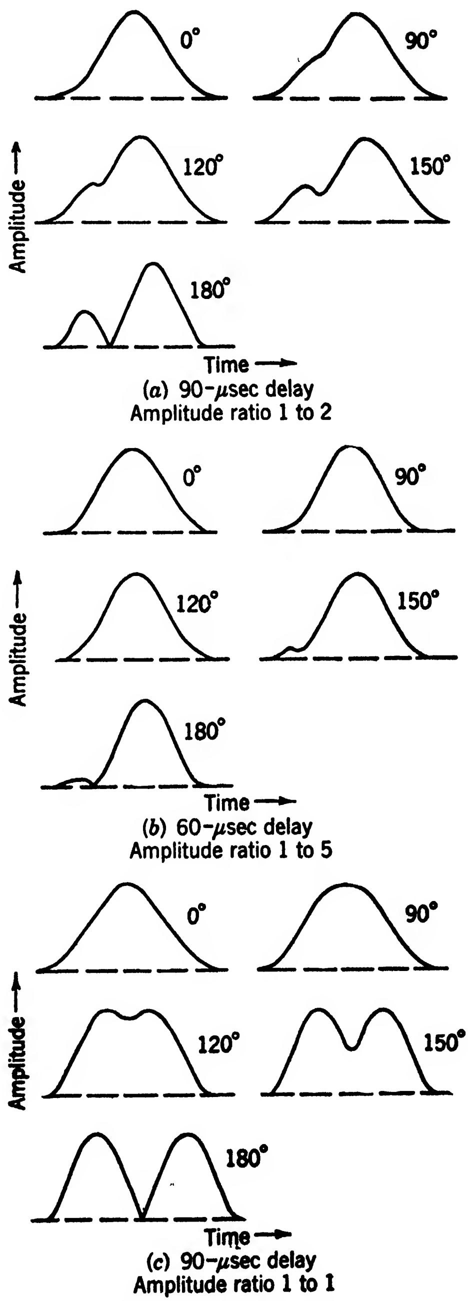


Fig. 5·32.—Diagrams of the pulse shape expected for a simple combination of ground wave and one-hop sky wave for three relative pulse amplitudes and for various phase relations.

different from that for zero degrees. Figure 5·32*b* and *c* shows the same sort of diagrams for relative ground-to-sky amplitude ratios of 1/5 and unity, respectively. In practice the patterns with plateaus or notches in them are encountered infrequently, typically for 5 or 10 min. every 2 hr. This low probability of occurrence stems from two causes: (1) With low ground-wave amplitudes, phase opposition must be attained within 30° or 40° in order to produce any significant change in the appearance of the pulse. (2) A second reason stems from the fact that the shape and length of the received pulse is ordinarily determined by the bandwidth of the receiver. The distorted shapes represented in these figures require a wider bandwidth for their satisfactory reproduction than do the simple or in-phase shapes. This can be seen most clearly in Fig. 5·32*c* where it is obvious that reproduction of the diagram for 180° will require approximately twice the bandwidth needed for the case of 0°. There is, therefore, a tendency in the receiver to smooth out the more eccentric pulse shapes, thus tending always to make the pulse look more like the in-phase pulse than it really is.

The major timing errors in LF Loran arise from the condition shown in Fig. 5·32*b* where the ground wave is relatively weak compared with the one-hop sky wave. In the 180° curves of Fig. 5·32*a* and *c* a large error is not ordinarily to be feared because the first rise of the ground-wave pulse has sufficient amplitude to permit the operator to make his reading on the ground-wave component and to disregard any peculiar shapes introduced by the sky waves. In Fig. 5·32*b*, however, the ground wave contributes only the wedge-shaped beginning of the pulse. If the noise is sufficiently low, the operator may be able to increase the gain of the receiver and make what amounts to a ground-wave match; but, if the noise is high, the navigator may miss the snout of the pulse and make his measurement on the steeply rising portion. This can result in an error of as much as 50 μsec. It is practically impossible for the navigator to estimate corrections that would make his reading more truly representative of his position, on the basis of the pulse shape that he sees. In general, the average value of the effective delay of the pulse must be incorporated in the construction of the navigator's charts, and any deviations from this average value must be accepted as errors. The chart-producing agency cannot determine in advance whether or not the navigator will identify the snout on the pulses in Fig. 5·32*b*. The charts must, therefore, be drawn in terms of the average reading made by the average operator under these conditions. This is equivalent to saying that larger errors must be expected at the distances at which the low-frequency delay curve of Fig. 5·30 is most steep. At distances where the delay curve is essentially horizontal there is little opportunity for ambiguity.

The slopes at which these pulses rise are inversely proportional to the receiver bandwidth. The degree of smoothing depends essentially upon the ratio between the reciprocal of the receiver bandwidth and the sky-wave delay time. It is therefore obvious that the effective time of arrival of a composite pulse depends upon the bandwidth of the receiver used to observe it. This is an unfortunate condition in that it, to some degree, requires the specification of the receiver to be used in the LF Loran system before the empirical sky-wave delay data can be gathered. In the case of the Radiation Laboratory experiments it appears now that the band-

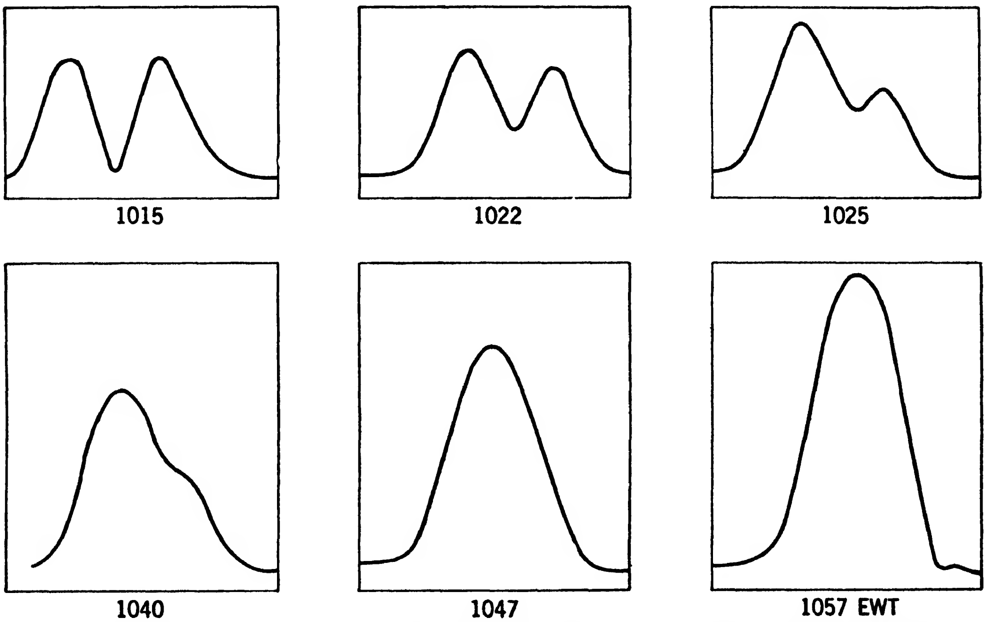


FIG. 5·33.—Low Frequency Loran pulse shapes under conditions that closely approximate those of Fig. 5·32c.

width of the converters that were built to permit operation of standard receiver-indicators for LF Loran operation should have been about 12 to 14 kc/sec rather than the 8 kc/sec that was used. A brief experiment conducted just before the end of the experimental program indicated that the average errors of an LF Loran reading could be reduced in some cases by a factor of 2 by the use of a receiver having a bandwidth of 14 kc/sec. The additional noise introduced by this increase in bandwidth did not seem materially to affect the operation of the system.

In practice, the pulse shapes observed are more complex than those shown in the last few pages because of the presence of components representing second, third, and higher multiple-hop transmission. These more complex forms, however, do not materially affect the navigator's operation, because his attention is confined to the first part of the pulse. Figure 5·33 shows a condition (Key Largo observed at Puerto Rico between

10:00 and 11:00 A.M. in June) that closely resembles that of Fig. 5·32*c*. The amplitude of a one-hop sky wave is approximately equal to that of the ground wave, and the higher multiple reflections are not of sufficient amplitude to affect the picture significantly. The figure shows a series of photographs of the traces on the Loran indicator during the transition from phase opposition to phase addition.

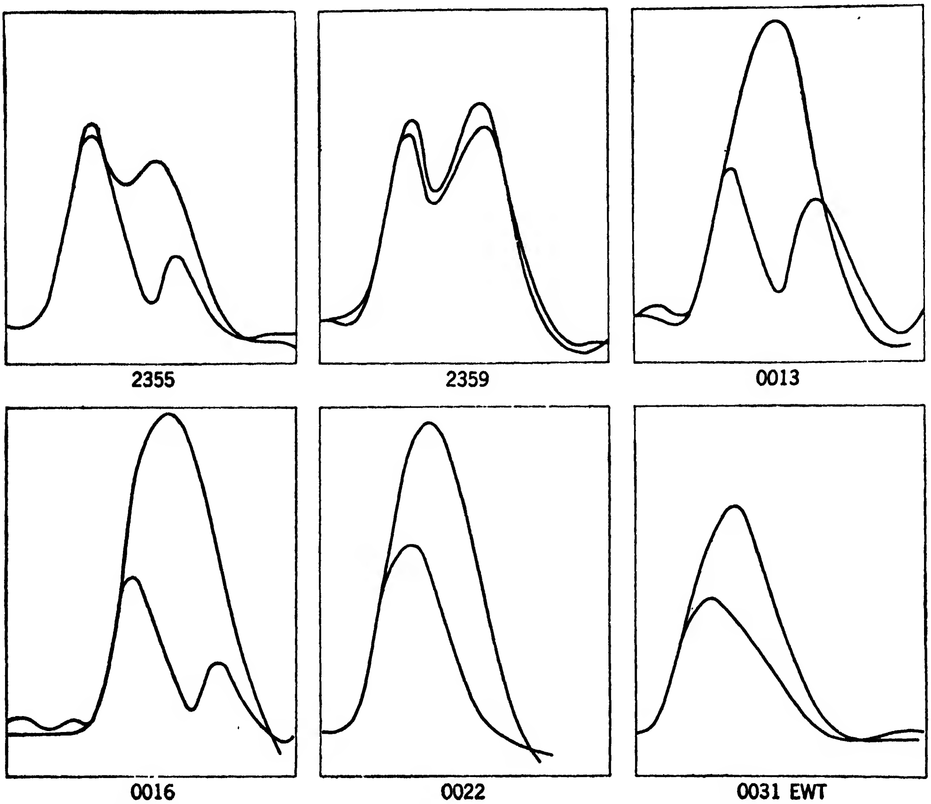


Fig. 5·34.—Two superimposed Low Frequency Loran pulses under more complex conditions than those of the last two figures. Note that the shape of the ground-wave part of the pulses (at the left) remains unchanged although there are violent changes in the shape of the remainder of the pulses.

Figure 5·34 shows the more complicated conditions obtaining at night. These pictures were made at about midnight in summer at a point about halfway between Brewster and Cape Fear. The distances are so short that the first part of the pulses, which are shown matched, is the ground-wave portion corresponding to the time interval *AB* on Fig. 5·31. The indicator was not readjusted throughout this series of photographs. Although each of the pulses passed through extreme gyrations of shape, the match of the leading edges was always good. Figure 5·35 shows the match between a pair of pulses at a greater average distance, at about the same time of night. One of the pulses exhibited a fairly strong ground-wave component, but the second one was dominated by the first-hop sky wave. The changes in shape were less rapid and extreme, but the precision of the match of the front edges was not nearly so good as in Fig. 5·34. Figure 5·35 is much more representative of the typical behavior of LF Loran pulses that are the two that precede it.

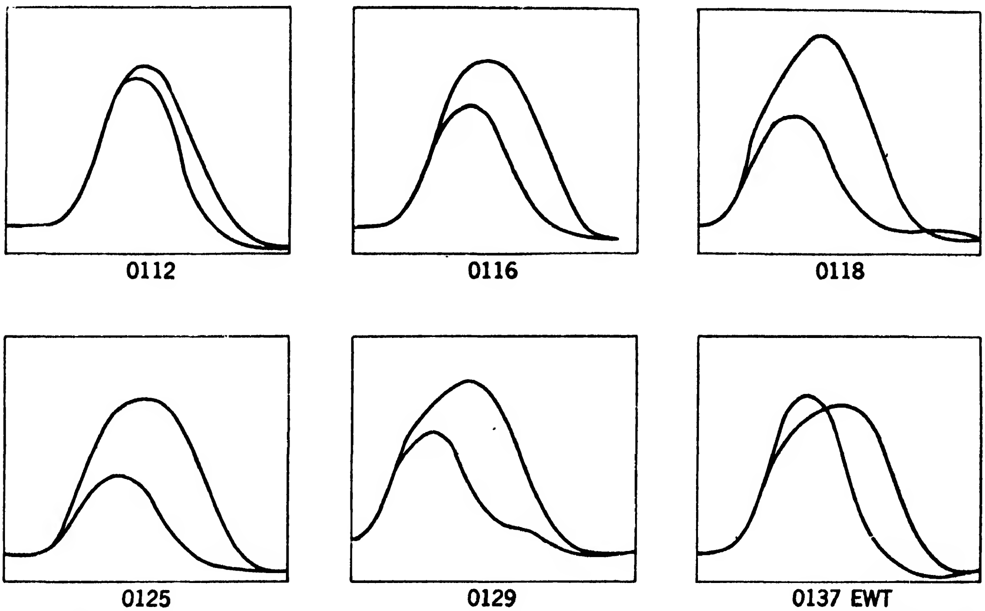


FIG. 5·35.—Low Frequency Loran pulse shapes. This figure indicates approximately the average behavior of the pulses under operational conditions.

5·13. Observations on the Experimental Low Frequency Loran Triplet.—Because of the complicated pulse structures described in the last few pages, it is necessary to adopt rather simple operating techniques for the use of the navigator and to accept as errors any variations that cannot be reconciled with the simple instructions. If any errors turn out to be consistent in certain areas or at certain distances from the transmitters, they can be incorporated in one or more sky-wave delay curves of the form shown in Fig. 5·30. Separate delay curves can be used for transmission over land and over water without difficulty because the agency that calculates the Loran charts and tables can select and use the appropriate corrections. To some extent, differing sky-wave corrections can be used for day or night and winter or summer conditions. This trend cannot be carried far before it results in undesirable confusion for the navigator, but there is a precedent for the use of sky-wave corrections to be applied at night. We are justified, therefore, in considering that four sky-wave delay curves will be used: for day and night, land and water. Charts will presumably be drawn including the sky-wave corrections applicable for daytime operation, and nighttime corrections, analogous to the sky-wave corrections in Standard Loran, will be used wherever they are necessary. Whether separate charts or separate sky-wave corrections will be required for summer and winter operation is not yet clear.

Since the sky-wave corrections could not be estimated before the start of the experimental program, the LF Loran tables were made up by the Hydrographic Office on a basis of ground-wave transmission, assuming the same velocity of propagation, 299,692 km/sec, that has been used in preparing charts for Standard Loran. Monitor-station operators were instructed to use as high a receiver gain as the noise permitted and to match the leading edges of the pairs of pulses, paying no attention to the relative amplitudes of the pulse peaks. These data, comprising some 80,000 individual readings, have been summarized and analyzed. The consistent variations of the observed readings from the predicted ground-wave readings have been used to construct the equivalent delay curves for LF Loran operation in summertime. The deviations from these average readings are summarized below as errors. This treatment is not strictly accurate, as the delay curves, of course, do not pass through all the experimental points; there are, therefore, some residual errors that would operate to increase the average deviation. It is felt, however, that this effect would be offset by the improvement to be expected from the use of a somewhat wider pass band in the receiving equipment, which has been suggested above. It is probable, therefore, that the data to be presented give a good estimate of the errors to be expected in LF Loran operation.

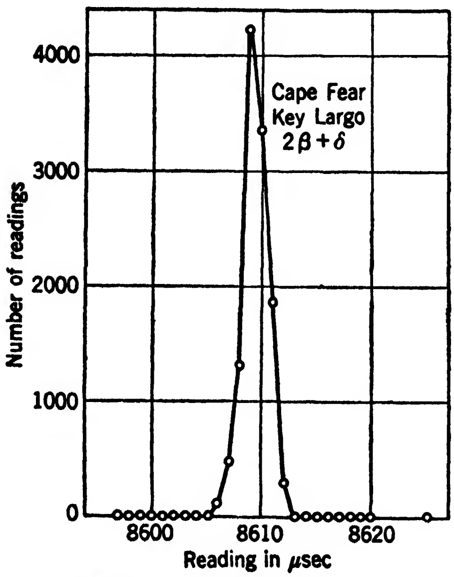


FIG. 5·36.—A distribution curve indicating the reliability with which Low Frequency Loran observations can be made at distances where the ground-wave component dominates the pulse shape.

In working up the data, it has been assumed that the synchronism of the transmitting stations is rigorous and that all of the observed variations occur in the paths between the transmitting stations and the monitoring stations. Figure 5·36, a distribution curve showing the master-station readings on the *Z*-pair, indicates that this assumption is justified. The average deviation of synchronism is not, in general, more than a few per cent of the deviations observed at any of the monitoring stations.

A very fair indication of the diurnal variatons in the usefulness of the signals received at various distances is given in Fig. 5·37. These curves represent the relative number of readings made on the *Z*-pair at various distances, plotted as a function of time of day. The habits of the operators at the transmitting and monitoring stations appear in these data but do not materially affect the conclusions. The number of readings between the morning hours of eight and nine is low, as the transmitting stations were frequently late in coming on the air, because ground fog prevented the flying of the balloons that supported the transmitting antennas. These points have been neglected in drawing the smooth curves. Two significant conclusions may be drawn from Fig. 5·37. (1) As seen in the two lower curves, there is, during the afternoon and night, a steady increase in the difficulty in making readings at distances where the ground-wave component of the received pulses is considerable. This effect is due to the steady rise of the noise level and indicates the *disinclination* of the operators to take many readings rather than the impossibility of making measurements. The peak at 17 hr. in the Puerto Rico curve is probably fictitious. (2) The curves for Trinidad and Little Falls indicate the *impossibility* of taking readings at those distances when the afternoon noise reaches its peak at about 18 hr. The signals are recovered when the sky-wave components increase in amplitude at sunset. In summer, the portions of the curves before 18 hr. represent primarily ground-wave transmission, whereas those between 18 hr. and sunrise are due mostly to the sky-wave components. There is some evidence to indicate that in winter daytime sky-wave transmission will dominate at ranges beyond 800 or 900 miles, but this suggestion needs additional verification.

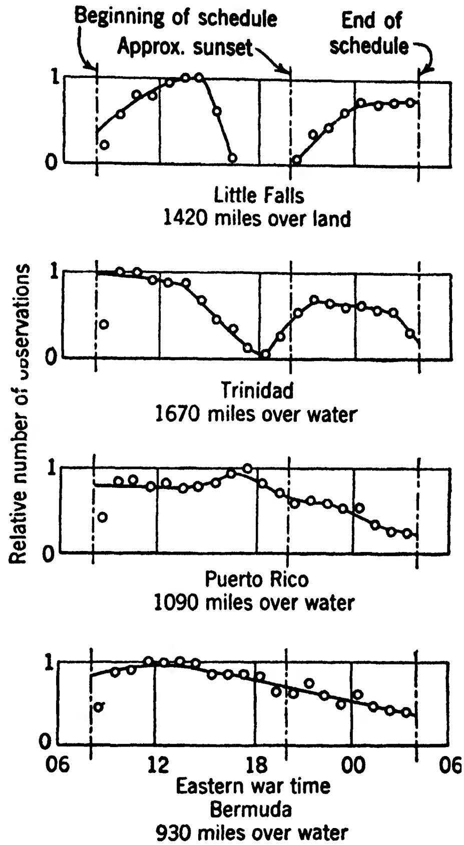


FIG. 5·37.—The diurnal variation of the serviceability of Low Frequency Loran signals at various distances in summer. The ordinates represent the average number of readings successfully made at various fixed monitor stations.

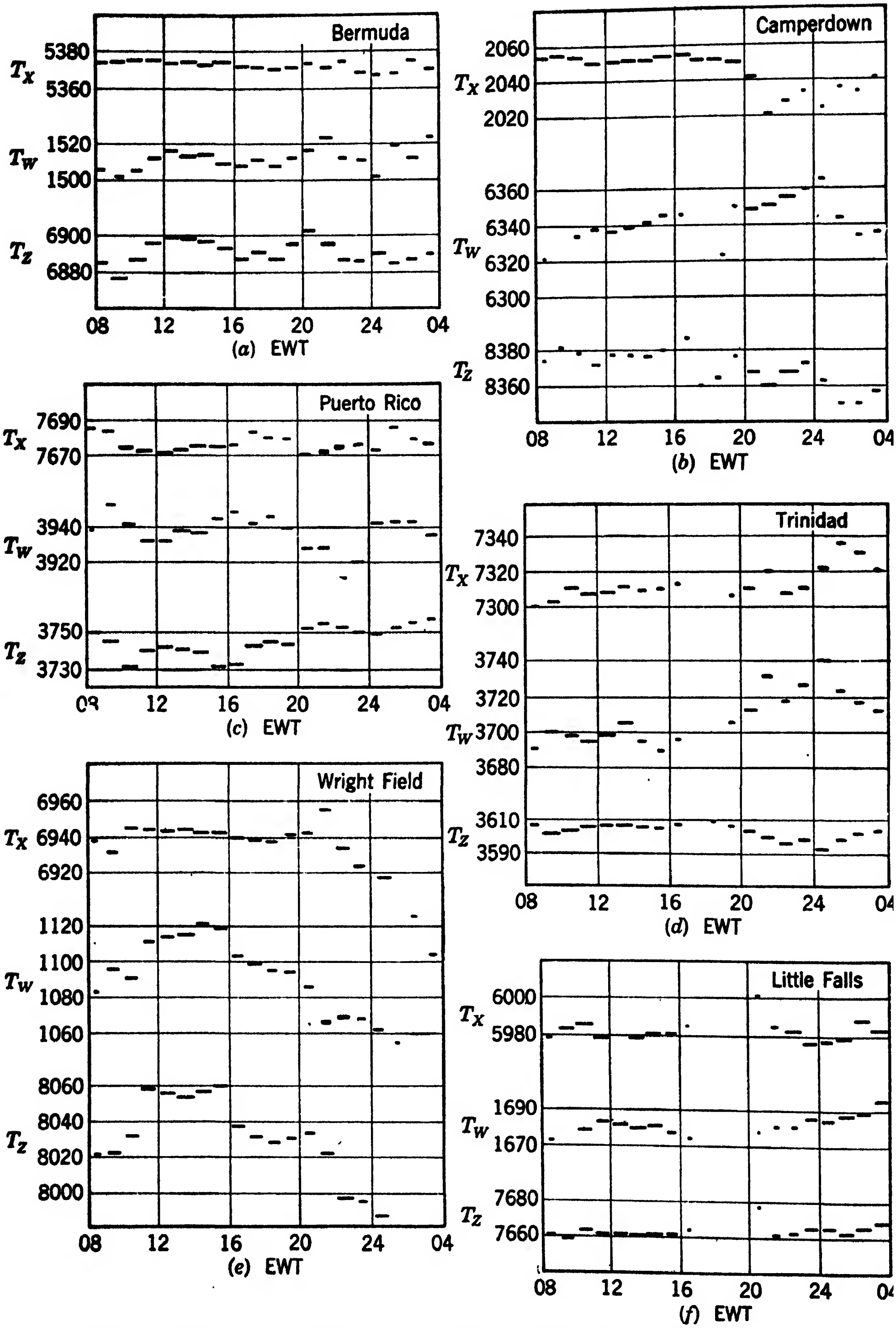


FIG. 5·38.—The diurnal variation of the various Low Frequency Loran readings at six monitor stations. The ordinates indicate the mean readings, and the lengths of the line segments are approximately proportional to the number of observations in each case.

The diurnal variations of the readings at the six regular monitor stations are exhibited in Fig. 5·38*a* to *f* inclusive. In these diagrams the vertical position of each line segment indicates the mean reading for the hour in question, and the length of the segments represents roughly the relative number of observations. That is, the lengths of the lines indicate data of the form exhibited in Fig. 5·37. In the cases of Bermuda and Little Falls (Fig. 5·38*a* and *f*) there is little indication of any diurnal trend in the readings, although the signals at Little Falls fail for 4 or 5 hr. in the late afternoon. The other figures in this series indicate either a consistent difference between daytime and nighttime readings or a fluctuation that does not appear to be statistically reliable in indicating a diurnal effect. There is, however, an indication that transmission conditions are usually more stable in the daytime. This has led to breaking the bulk of the data into two groups with a nominal dividing line at sunset. Distribution curves indicating the spread of daytime and nighttime readings at the various monitor stations are given in Figs. 5·39 to 5·45 inclusive. All of these diagrams are plotted in terms of the Loran reading in

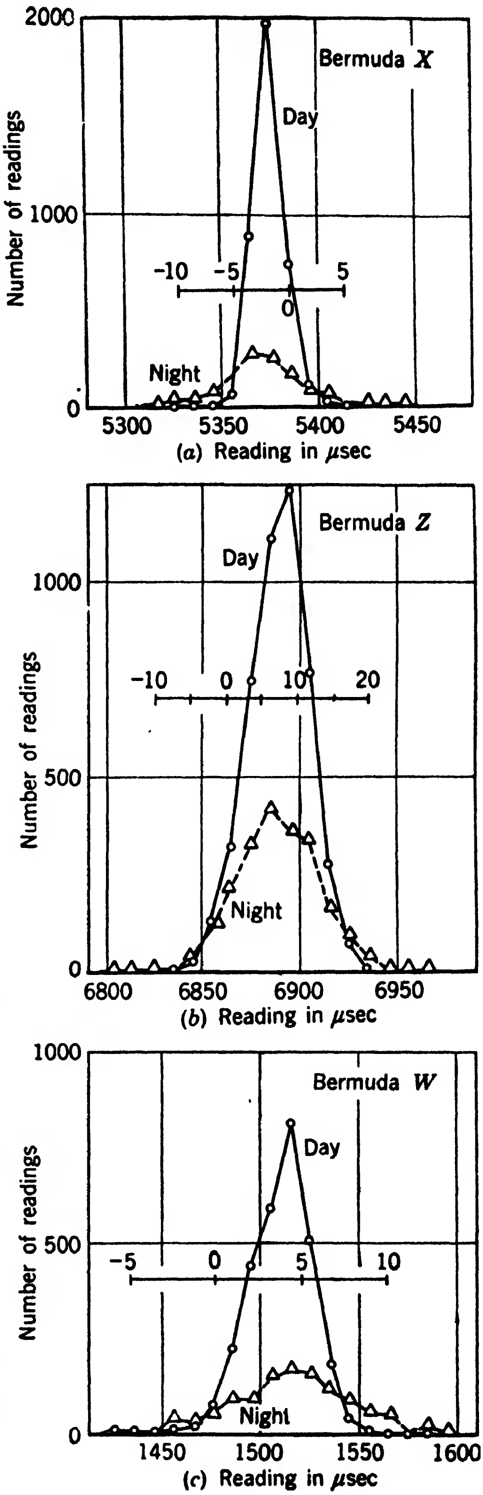


FIG. 5·39.—The distribution curves of the three Low Frequency Loran readings at Bermuda. In each case a subsidiary abscissa scale has been appended with its zero at the reading computed without benefit of sky-wave corrections. The subsidiary scale gives the line-of-position error in nautical miles.

microseconds, but to each of them is appended a scale giving the corresponding displacement in nautical miles perpendicular to the line of position. The zeros of these scales are at the computed ground-wave readings, so that a visual estimate may be made of the errors introduced by neglecting the sky-wave corrections. The algebraic signs attached to these subsidiary scales have no significance. The daytime curve of Fig. 5·39*a*, for instance, indicates that most of the readings fall within the range 5350 to 5400 μsec, or about −6 to +3 nautical miles. The position corresponding to the mean reading (on a ground-wave basis) is about 2 miles from the actual site.

In general, nighttime readings have a larger spread than those taken in daytime. They may also, as in Figs. 5·40 and 5·42*b*, exhibit a consistent shift. The Camperdown readings on the *X*-pair (Fig. 5·41*a*) are particularly interesting. In this case the slave station was at such a short distance that the received pulse was essentially pure ground-wave at all times. The master station, however, at 930 nautical miles, was received by ground-wave transmission in the daytime but was dominated by sky-wave at night. This would have caused little difficulty, since nighttime measurements could have been made on the ground-wave part of the composite pulse, except that the monitoring station was subject to periods of extreme man-made interference from neighboring installations. When this noise was high, it would cover up the ground-wave contribution to the composite pulse (see the 1000-mile curve of Fig. 5·29) with the result that the apparent time difference was changed by about 50 μsec, the amount of the sky-wave delay. Thus the night distribution curve of Fig. 5·41*a* tended to have two maxima corresponding to the reading of essentially pure ground wave or pure sky wave from the master station. It should be noted that the night maximum at 2055 μsec and the daytime maximum both agree with the computed ground-wave time difference.

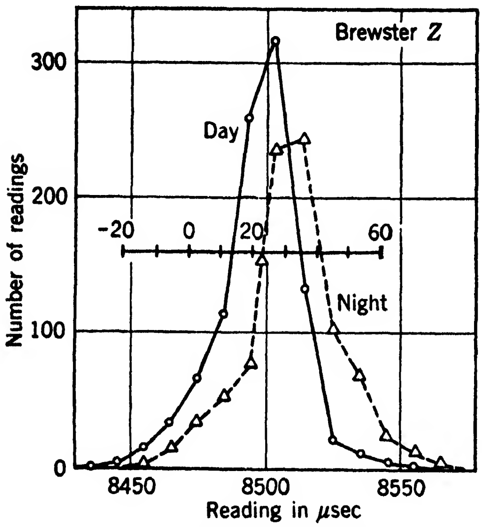
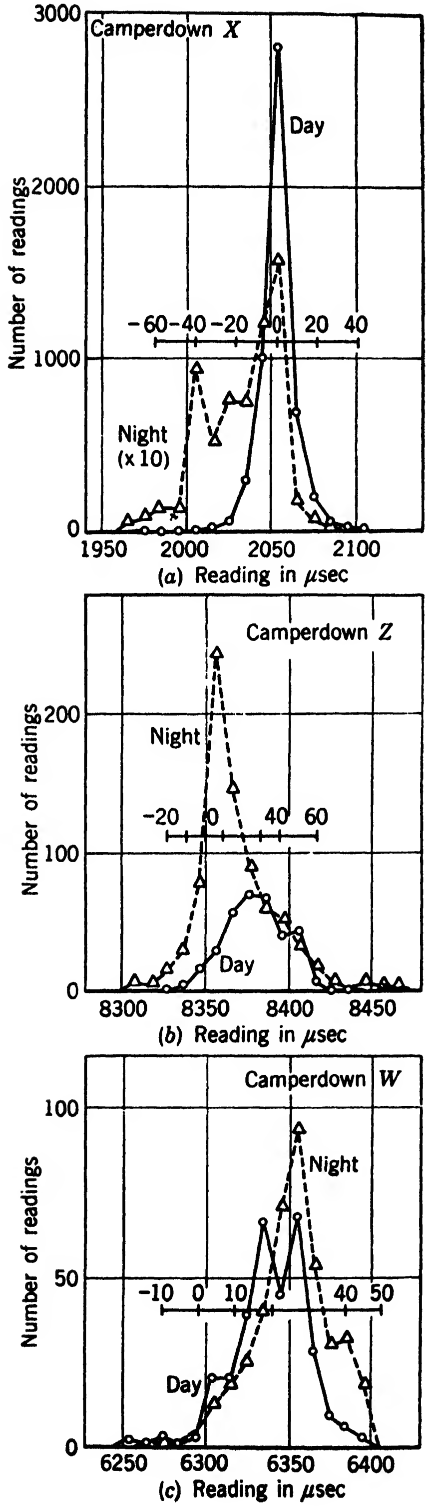


FIG. 5·40.—Distribution curves, similar to those in Fig. 5·39, of the Low Frequency Loran readings at Brewster.

It will be noticed that in general there is not a great difference in the total spread of the curves as a function of distance. On the average, half of the daytime observations fall within ±10 μsec from the median, and at night 50 per cent of the readings are within ±13 μsec. At some



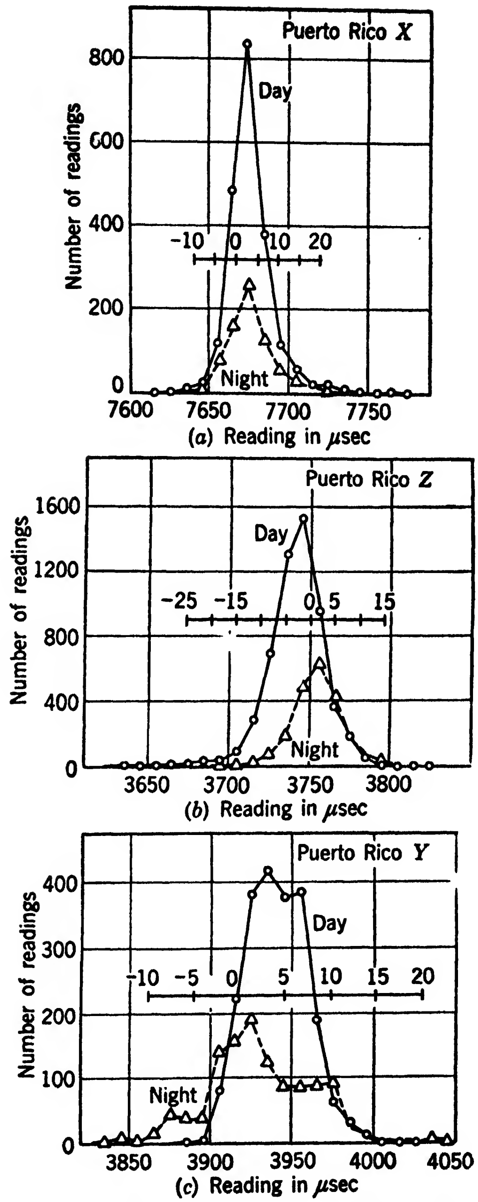


FIG. 5·42.—Distribution curves, similar to those of Fig. 5·39, of Low Frequency Loran readings at Puerto Rico.

FIG. 5·41.—Distribution curves, similar to those of Fig. 5·39, of Low Frequency Loran readings at Camper down.

distances such as in the Camperdown case quoted above or in the case of the 890 miles over land represented in Fig. 5·44*b* and *c*, there is considerable ambiguity in that the operator may read essentially a ground wave or a sky wave or a composite value. It will be realized that this distance is that at which the estimated delay (Fig. 5·30) is making its sharpest rise.

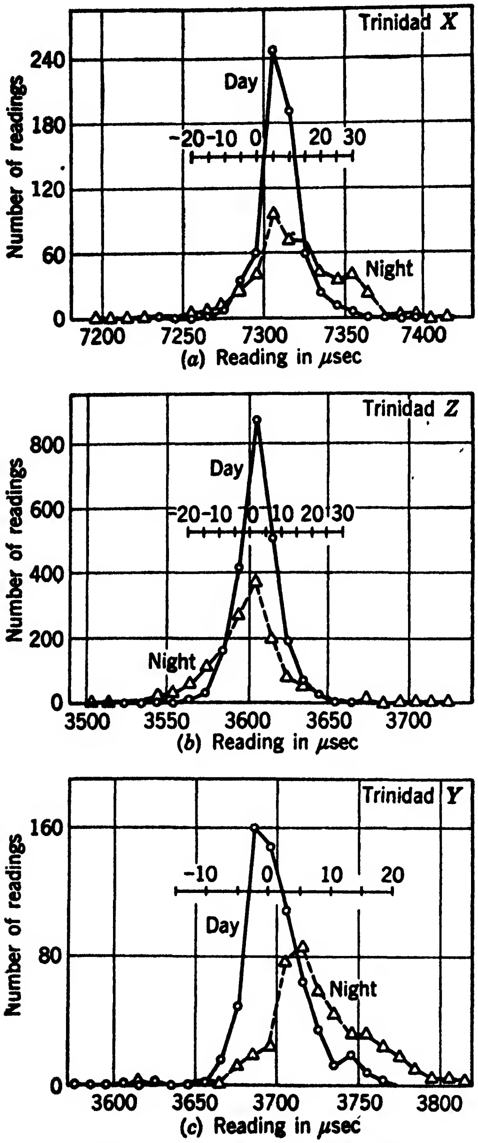
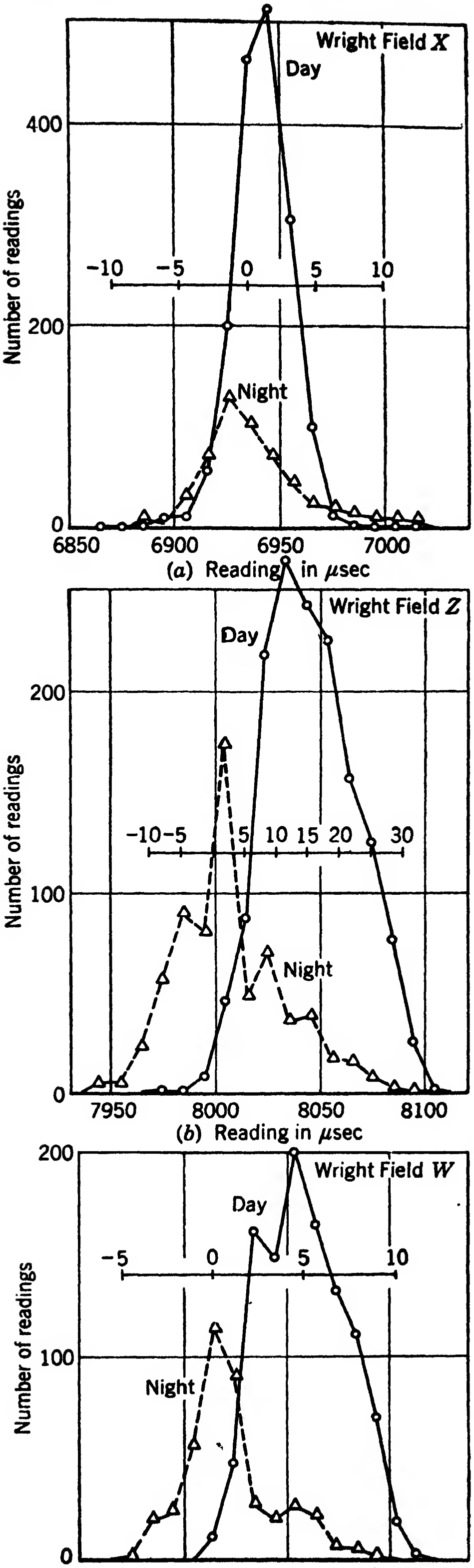


Fig. 5·43.—Distribution curves, similar to those of Fig. 5·39, of Low Frequency Loran readings at Trinidad.

The discrepancies between the observed readings and those computed for ground-wave transmission are exhibited in Table 5·3. The discrepancy in Column 7 or Column 9 is, with due regard for sign, a chord of the delay curve (see Fig. 5·30) between the two transmission times given in Columns 3 and 4. By starting at the shorter distances, at which the delay may be assumed to be zero, points may be connected to define approximately the shape of the curve, as was done to derive the 2-Mc/sec delay curve. Fitting these various data together calls for the exercise of judgment because the agreement between separate sets of observations is never so good as could be wished. In general, all of the observations except those at Bermuda fit into the delay pattern exhibited in Fig. 5·46. The Bermuda observations have been weighted very lightly in drawing these curves because the anomalies there may be attributed to a faulty amplitude-balance circuit in the receiver used at that station.[1]

The shape of the overwater curves of Fig. 5·46 resembles the curve of

[1] A receiver that was known to be satisfactory was operated in Bermuda for a few days toward the end of the program. The observations with this receiver, although few in number, were in good agreement with the curves of Fig. 5·46.



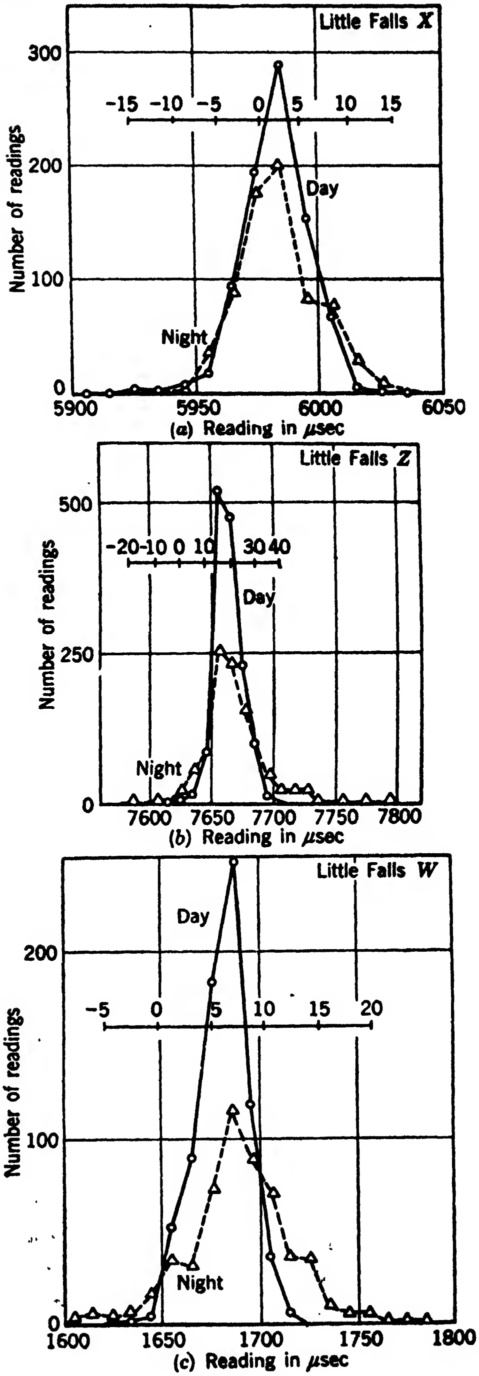


FIG. 5·45.—Distribution curves, similar to those of Fig. 5·39, of Low Frequency Loran readings at Little Falls.

FIG. 5·44.—Distribution curves, simi-

Fig. 5·30 except that the height of the steps is less than had been anticipated. It is reasonable that the night curve should resemble the day curve, displaced to the left, because any daytime ratio of first-hop sky-wave amplitude to that of the ground wave can be found at night at some shorter distance. It is possible that the initial slope of the land curves represents a decrease in the velocity of ground-wave propagation over land. The curves have been drawn as they are because there is no evidence that the land curves leave the origin along the abscissa. If the velocity is less over land, the shapes of the land curves may be very nearly those of the water curves superimposed upon a velocity slope, which here seems to be about 1 in 250. This hypothesis accounts for the shape of the night-land curve, but we should expect that the slope of the day-land curve would begin to decrease at about 7000 μsec. More overland data should be taken to clarify this question.

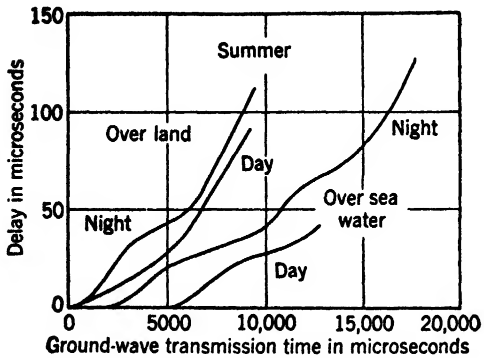


FIG. 5·46.—The four experimental Low Frequency Loran delay curves for summer operation.

That the minor variations in the delay curves of Fig. 5·46 are not of extreme importance is indicated in Columns 4 and 5 of Table 5·4. These columns give the displacements of the line of position (in nautical miles) corresponding to the discrepancies of the mean readings, from the calculated ground-wave values, which were given in Columns 7 and 9 of Table 5·3. The entries for Brewster and Camperdown in Table 5·4, Columns 4 and 5, are nearly meaningless because the monitoring stations were located almost upon the baseline extensions where the system is not expected to provide navigation. The remaining figures in these columns indicate the consistent discrepancies that the equivalent delay curves are expected to correct. That is, the position lines at distances of the order of 1000 miles are, in general, in error by less than 10 miles even if the delay curves are totally neglected.

Columns 6 and 7 of Table 5·4 give the average deviations from the mean reading observed at the various monitor stations. Here again the entries for Brewster and Camperdown are not significant from the viewpoint of navigation. The figures in Columns 6 and 7, Table 5·4, do not form a very coherent pattern because the monitor stations lie at various angles to the baselines. This effect has been removed in columns 8 and 9 where the stations are assumed to lie on a great circle that intersects the center of the baseline at an angle of 45°. The geometrical factors have also been adjusted to apply to a baseline whose length is 600 nautical miles. The only assumption involved in this treatment is that the scattering of the observed time differences does not depend upon the orientation of the baseline. This is not strictly true, but most of the adjustments are relatively minor.

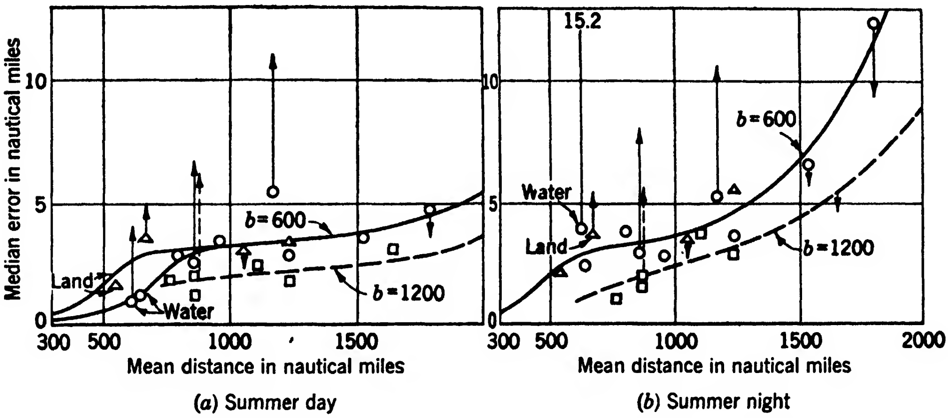


Fig. 5·47.—The median errors of the Low Frequency Loran experimental observations plotted as a function of distance. The curves are corrected to simulate operation at an angle of 45° from a 600-mile baseline. The heads of the arrows appended to many of the experimental points indicate the values before correction.

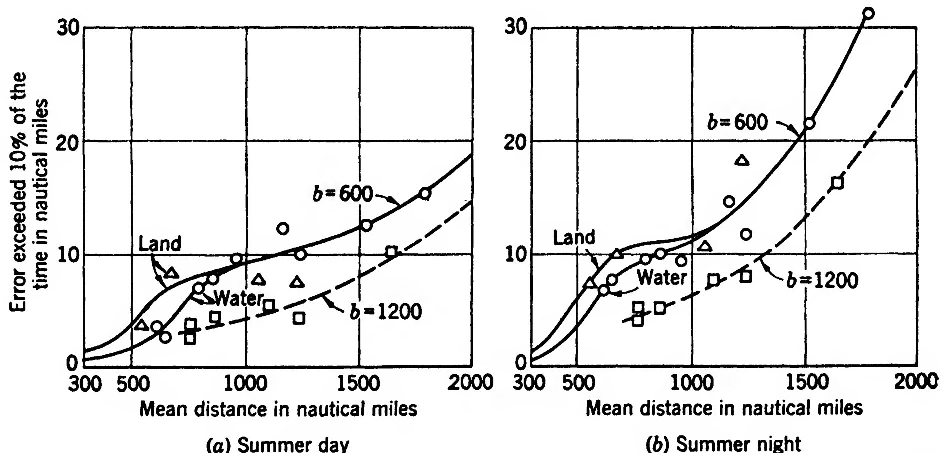


Fig. 5·48.—Error diagrams for day and night operation, similar to those of Fig. 5·47, but indicating the errors exceeded less than 10 per cent of the time.

The median errors from Columns 8 and 9 are plotted in Fig. 5·47*a* and *b*. In these diagrams the solid lines represent the errors associated with a baseline length of 600 nautical miles, and the dashed lines represent the errors associated with *Y*- and *W*-readings which have a 1200-mile baseline. The arrows attached to many of the points indicate the magnitude of the corrections that were made for the positions of the monitor stations. That is, the actual observed errors (Columns 6 and 7 of

Table 5·4) lie at the heads of the arrows. Figure 5·48*a* and *b* exhibits very similar data. In this case the curves represent the errors (of line of position) that were not exceeded in more than 10 per cent of the readings.

The observations were reduced to positions at an angle of 45° from the baseline to represent average navigational conditions. The variation of error with angle is small for short distances. At long distances, say more than one baseline, the accuracy varies approximately with the cosine of the angle that measures the navigator's position with respect to the normal to the baseline. In other words, the errors on the center line may be expected to be about 0.7 of those plotted in these figures, and the errors at 30° off the baseline should be about 1.4 times the quantity that has been plotted.

TABLE 5·3.—DATA FOR LF LORAN SKY-WAVE CORRECTION CURVES
All figures in microseconds

1	2	3	4	5	6	7	8	9
		Time of transmission			Day		Night	
Monitor station	Pair	Master station	Slave station	Computed ground-wave reading	Mean observed reading	Observed minus computed	Mean observed reading	Observed minus computed
Over sea water:								
Bermuda	*X*	4186	3838	5385.2	5374.4	−10.8	5369.3	−15.9
	Z	4186	5737	6862.0	6888.8	26.8	6887.8	25.8
	W	3838	5737	1476.8	1508.8	32.0	1514.6	37.8
Brewster	*Z*	3746	6914	8472.2	8496.8	24.6	8508.9	36.7
Camperdown	*X*	5721	2031	2053.6	2052.4	−1.2	2031.3	−22.3
	Z	5721	8766	8349.1	8377.5	28.4	8364.4	15.3
	W	2031	8766	6295.6	6338.8	43.2	6350.7	55.1
Puerto Rico	*X*	6737	8660	7667.1	7675.1	8.0	7674.4	7.3
	Z	6737	5182	3749.5	3740.1	−9.4	3753.4	3.9
	Y	5182	8660	3917.5	3938.9	21.4	3929.4	11.9
Trinidad	*X*	10332	11883	7295.5	7308.6	13.1	7317.6	22.1
	Z	10332	8629	3601.7	3605.0	3.3	3598.0	−3.7
	Y	8629	11883	3693.8	3696.8	3.0	3723.6	29.8
Over land:								
Wright Field	*X*	2828	4019	6934.9	6939.9	5.0	6934.4	−0.5
	Z	2828	5524	7999.8	8044.3	44.5	8005.2	5.4
	W	4019	5524	1064.8	1107.7	42.9	1071.2	6.4
Little Falls	*X*	6450	6680	5977.0	5981.2	4.2	5981.8	4.8
	Z	6450	8770	7624.0	7661.3	37.3	7665.3	41.3
	W	6680	8770	1647.0	1679 1	32.1	1687.1	40.1

The discussion has been limited to the errors of a line of position, because the errors of fix are complicated by the variation of the crossing angle between two lines of position. This matter is so complex that an attempt to treat it in a simple way usually fails of its purpose. The errors of fix for any proposed orientation of stations must be examined as a specific problem by the ordinary methods through the treatment outlined in Chap. 3. It should be remembered that this question of the error of fix is not peculiar to Loran but occurs in exactly the same way when celestial navigation or radio direction finding are used.

TABLE 5·4.—DATA ON THE SCATTER OF LF LORAN READINGS
All figures in nautical miles

1	2	3	4	5	6	7	8	9
Monitor station	Pair	Mean distance	Magnitude of sky-wave correction		Median deviation observed		Median deviation reduced to $b = 600$, $\theta = 45°$	
			Day	Night	Day	Night	Day	Night
Over sea water:								
Bermuda	*X*	649	1.9	2.8	0.8	1.9	1.1	2.4
	Z	802	7.3	7.0	2.7	3.7	2.8	3.8
	W	774	3.6	4.3	1.2	2.0	1.2	2.0
Brewster	*Z*	862	20.8	31.1	6.8	8.0	2.5	2.9
Camperdown	*X*	627	1.0	18.6	4.0	15.2	1.0	3.9
	Z	1171	25.1	13.5	11.1	10.6	5.4	5.2
	W	873	19.5	24.8	6.3	5.7	1.9	1.7
Puerto Rico	*X*	1245	3.0	2.7	2.3	2.9	2.8	3.6
	Z	964	3.1	1.3	3.2	2.6	3.4	2.8
	Y	1119	3.8	2.1	2.3	3.6	2.4	3.8
Trinidad	*X*	1796	6.6	11.0	3.5	9.1	4.7	12.3
	Z	1533	1.7	1.9	3.2	5.8	3.6	6.5
	Y	1658	0.8	7.7	2.7	4.5	3.1	5.2
Over land:								
Wright Field	*X*	554	0.8	0.1	1.4	1.9	1.6	2.2
	Z	675	14.7	1.8	5.0	5.5	3.6	3.8
	W	772	1.4	0.7	1.8	1.1	1.8	1.1
Little Falls	*X*	1062	1.2	1.4	2.2	2.6	3.1	3.6
	Z	1231	18.5	20.4	3.7	5.9	3.4	5.5
	W	1249	5.9	7.3	1.5	2.5	1.7	2.9

CHAPTER 6

METHODS OF COMPUTATION OF LORAN TABLES AND CHARTS

By B. W. Sitterly

6·1. Equations for Distance over the Earth.—The equation for the time difference T, which is the quantity measured by the Loran timer or indicator, has been shown to be

$$T = (\beta + \delta) + v$$

Eq. 4 of Sec. 3·1, where β is the distance between the master and the slave station and $v = s_B - s_A$, s_B and s_A being respectively the distances, from the point at which T is determined, to the slave and to the master station. The three distances are taken along geodesics over the earth's surface and expressed in light-microseconds.

For Loran computations it is not accurate enough to consider the earth as a sphere; it must be taken as an oblate spheroid. The length along a geodesic between two designated points on a spheroid cannot be calculated directly but may be approached to any degree of approximation by a somewhat lengthy step-by-step process.[1] For the purposes of Loran, great accuracy is unnecessary; the nearest hundred feet is close enough. This precision may be attained by rather simple modifications of the calculation for a sphere. Two such modifications have actually been used in Loran computations.

The first method used was one devised by Doolittle and described by Hayford.[2] In this method the true geodesic distance between a point on the earth at latitude φ_1 and a point at latitude φ_2 (where φ_1 is farther from the equator than φ_2) is approximated by the great-circle distance between a point at latitude

$$\varphi_1 - \tfrac{1}{2}e^2(\varphi_1 - \varphi_2) \cos^2 \tfrac{1}{2}(\varphi_1 + \varphi_2)$$

and a point at latitude

$$\varphi_2 + \tfrac{1}{2}e^2 (\varphi_1 - \varphi_2) \cos^2 \tfrac{1}{2}(\varphi_1 + \varphi_2)$$

on a sphere of radius

$$\frac{E}{\sqrt{1 - e^2 \sin^2 \tfrac{1}{2}(\varphi_1 + \varphi_2)}},$$

[1] See W. D. Lambert, "Effects of Variations in the Assumed Figure of the Earth on the Mapping of a Large Area," *U.S. Coast and Geodetic Survey, Special Pub.* 100, p. 16, 1924.

[2] J. F. Hayford, "The Figure of the Earth and Isostasy," *U.S. Coast and Geodetic Survey*, p. 88, 1909; F. G. Watson, "Computation of Loran Lattice Points," RL Loran System Report No. 23, p. 1, 1942.

where E is the equatorial radius of the earth and e is the eccentricity of a meridian section. It was found that this approximation was not sufficiently close in some latitudes and orientations of points, so a second method of computation, independently originated by Andoyer[1] and by Lambert,[2] has been generally adopted for computing Loran distances. In this method the great-circle distance is computed on a sphere of radius equal to the earth's equatorial radius E, between points having the same longitudes and latitudes on the sphere as on the earth. Then a small correction is applied to this distance to reduce it to its true value. If σ is the great-circle distance in radians, the true distance s in linear units is given by

$$\left.\begin{aligned} s &= E\sigma + \delta s, \\ \delta s &= \frac{E}{2}\left(1 - \sqrt{1-e^2}\right)\left[\frac{3\sin\sigma - \sigma}{\cos^2\frac{1}{2}\sigma}\sin^2\frac{1}{2}(\varphi_1+\varphi_2)\cos^2\frac{1}{2}(\varphi_1-\varphi_2)\right. \\ &\qquad \left. - \frac{3\sin\sigma+\sigma}{\sin^2\frac{1}{2}\sigma}\cos^2\frac{1}{2}(\varphi_1+\varphi_2)\sin^2\frac{1}{2}(\varphi_1-\varphi_2)\right]. \end{aligned}\right\} \quad (1)$$

Since δs is quite small, never exceeding two-thirds of 1 per cent of s, it is convenient and precise enough to find it from tables[3] or graphically.[4]

The last equation of (1) may be written

$$\left.\begin{aligned} \delta s &= p(\sin\phi_1 + \sin\phi_2)^2 - q(\sin\phi_1 - \sin\phi_2)^2, \\ p &= \frac{E}{8}\left(1-\sqrt{1-e^2}\right)\frac{3\sin\sigma - \sigma}{\cos^2\frac{1}{2}\sigma}, \\ q &= \frac{E}{8}\left(1-\sqrt{1-e^2}\right)\frac{3\sin\sigma + \sigma}{\sin^2\frac{1}{2}\sigma}. \end{aligned}\right\} \quad (2)$$

The factors p and q are tabulated against σ in the Hydrographic Office report mentioned. The computation may be made with a slide rule. The equations may also be written in the form

$$\left.\begin{aligned} s &= E\left(1 + \frac{\delta s}{E\sigma}\right)\sigma \\ \frac{\delta s}{E\sigma} &= \left(1 - \sqrt{1-e^2}\right)\left[(1-A)\sin^2\frac{1}{2}(\phi_1+\phi_2)\right. \\ &\qquad \left. - (2-B)r^2\cos^2\frac{1}{2}(\phi_1+\phi_2)\right] \\ &= C\sin^2\tfrac{1}{2}(\phi_1+\phi_2) - D\cos^2\tfrac{1}{2}(\phi_1+\phi_2), \end{aligned}\right\} \quad (3)$$

where $r = (\phi_1 - \phi_2)/\sigma$, which is practically equivalent to the cosine of

[1] M. H. Andoyer, "*Formule donnant la longueur de la geodesique*, etc.," *Bull. Geodesique*, **34**, 77 (1932).

[2] W. D. Lambert, "The Distance between Two Widely Separated Points on the Surface of the Earth," *Jour. Washington Acad. Sci.*, **32**, 125 (1942).

[3] Hydrographic Office, U.S. Navy, Loran Technical Report No. 3, 1945.

[4] B. W. Sitterly and J. A. Pierce, "Simple Computation of Distance on the Earth's Surface," RL Report No. 582, 1944.

the "average" true bearing along the great circle whose length is σ, and A and B are small quantities, functions of r and σ. A rather simple nomogram may be constructed, for reading the coefficient $E[1 + (\delta s/E\sigma)]$ directly, against the three arguments $\frac{1}{2}(\varphi_1 + \varphi_2)$, r, and σ, to a precision better than 1/100,000 of σ, or against the two arguments $\frac{1}{2}(\varphi_1 + \varphi_2)$ and r, to a precision of about 100 ft. at distances less than 1000 miles. The nomogram is described and examples given in the Radiation Laboratory report mentioned. The quantity $E[1 + (\delta s/E\sigma)]$ may be regarded as the "effective radius of curvature" of the arc σ.

In all these methods, the great-circle distance σ is calculated by one of the standard formulas

$$\cos \sigma = \sin \varphi_1 \sin \varphi_2 + \cos \varphi_1 \cos \varphi_2 \cos \Delta\lambda, \tag{4}$$

$$\text{hav } \sigma = \text{hav } (\varphi_1 - \varphi_2) + \cos \varphi_1 \cos \varphi_2 \text{ hav } \Delta\lambda, \tag{5}$$

$$\text{hav } \sigma = \text{hav } \Delta\lambda \text{ hav } [180° - (\varphi_1 + \varphi_2)] + \text{hav } (180° - \Delta\lambda) \text{ hav } (\varphi_1 - \varphi_2), \tag{6}$$

where $\Delta\lambda$ is the difference between the longitudes of the points and hav σ (the haversine of σ) is $\sin^2 \frac{1}{2}\sigma$. Since σ is usually less than 20°, seven significant figures are required to determine it to 1″ (100 ft.) from its cosine, five figures to determine it from its haversine. But, if a calculating machine is used, seven figures are not much more troublesome than five, while the five-place tables of haversines included in most collections of nautical tables[1] give only three or even two significant figures in the natural values for small angles, since the first two or three decimals are zero. Five-figure tables giving one million times the haversine, between $\sigma = 0°10'$ and $\sigma = 25°00'$, were prepared in 1944 at the Radiation Laboratory[2] for the solution of Eq. (6). This form of solution has been found convenient and rapid. If σ is less than 2°, the direct formula[3]

$$s = \sqrt{[f_1(\varphi_1 - \varphi_2)]^2 + (f_2 \, \Delta\lambda)^2} \tag{7}$$

is sufficiently accurate. Here $f_1 = R \sin 1'$, $f_2 = N \cos \frac{1}{2}(\varphi_1 + \varphi_2) \sin 1'$, where R is the radius of curvature along the meridian and N the radius of curvature perpendicular to the meridian, at latitude $\frac{1}{2}(\varphi_1 + \varphi_2)$. The differences $(\varphi_1 - \varphi_2)$ and $\Delta\lambda$ are expressed in minutes of arc, and the linear unit of s will be that of R and N. Tables of f_1 and f_2 are given in the reference[3] the linear unit being the light-microsecond. Tables of R and N appear in standard geodetic texts.

The small error in s which results from the use of the approximate correction δs may be made still smaller by using the parametric or reduced latitudes of the two end points, instead of the geographical latitudes, in

[1] For example, in the *American Practical Navigator*, Hydrographic Office, U.S. Navy, Publication No. 9, revised every few years.

[2] "Manual of Procedures for Mobile Charting Units, Air Transportable Loran System," RL Report No. M-183, 1945.

[3] Hydrographic Office, U.S. Navy, Loran Technical Report No. 3, 1945.

Eqs. (1) to (6) inclusive. In this case the second equation of (1) is modified by substituting $\sin \sigma$ for $3 \sin \sigma$ in both the bracketed terms. This substitution alters the values of p and q in Eq. (2), making p negative and very small and about halving q. In Eq. (3), $1 - A$ is to be replaced by $-A'$ and $2 - B$ by $1 - B'$, where A' and B' are small quantities slightly different from A and B. The parametric latitude, which we may denote here by θ, is defined by the relation

$$\tan \theta = \sqrt{1 - e^2} \tan \phi,$$

ϕ being the geographical latitude. According to examples worked out by Lambert, use of the parametric latitude reduces the error of the approximation by about half.

Over a small area the surface of the earth is very nearly a plane. Along a narrow strip it approximates closely a cylindrical or conical surface which may be developed into a plane. In so far as this approximation holds, the earth may be represented truly to scale by a chart, and distances directly measured between charted points. If one light-microsecond on the earth is equivalent to k mm. on the chart, the point on the earth where $v = s_B - s_A$ will correspond to the point on the chart where a circle, described about the slave station with radius ks_B, intersects a circle described about the master station with radius ks_A. If a family of such circles be described about each station and those intersections between the families selected, for which the difference $(ks_B - ks_A = kv)$ has a constant value, the curve passing through these intersections on the chart will represent the Loran line $(T = v + \beta + \delta)$ on the earth. This technique has been used in constructing preliminary charts when the utmost rapidity in production was demanded.

6·2. Equations for a Loran Line of Position. *The Plane Approximation.*—For navigational purposes, the form of the earth may be taken to be spheroidal. No direct expression for the coordinates of a line of constant difference of distance on a spheroid has been developed as far as the writer is aware. But to the extent that a portion of the surface of the earth approximates a plane, a Loran line approximates a plane hyperbola, with its foci at the two transmitting stations. Three simple equations for the plane hyperbola are the central equation in rectangular and in polar coordinates, with origin midway between the foci, and the polar equation with origin at a focus. These are, respectively,

$$\left.\begin{aligned} x^2 &= \frac{a^2y^2}{c^2 - a^2} + a^2, \\ r^2 &= \frac{a^2(c^2 - a^2)}{c^2 \cos^2 \theta - a^2}, \\ r &= \frac{c^2 - a^2}{c \cos \theta \pm a}, \end{aligned}\right\} \qquad (8)$$

where $2c$ is the distance between the foci and c/a the eccentricity of a hyperbola, x is taken parallel to and y perpendicular to the line connecting the foci (baseline), and θ is zero when r coincides with this line. When $y = 0$, $x = a$. To distinguish the two branches of the hyperbola of eccentricity c/a, which correspond to different values of T, x and a are considered positive on the side of the center line (y-axis) on which the master station lies, negative on the other, so that a has the sign of v. In the denominator of the last equation the upper sign is applied to a if the origin of polar coordinates is taken at the master station, the lower if it is at the slave station.

The constants a and c in Eq. (8) are related to the constants v and β of a Loran line by the relations

$$c = \frac{k\beta}{2}, \qquad a = \frac{kv}{2}, \tag{9}$$

where k is the length of a light-microsecond in the linear units in which x, y, and r are expressed. By means of Eqs. (9) and (8) the lines of a Loran family may be plotted by points upon a chart on which the appropriate coordinate grid, properly centered and oriented, has been constructed. The rectangular equation is the best for this purpose, because rectangular coordinates are easier to lay out than polar. The Hydrographic Office has published a table[1] giving x with arguments a and y, for $a \leq 0.75$, and y with arguments a and x, for $a \geq 0.70$. The unit of length is c; the interval in a is 0.001; and the tabulated coordinate is given to four decimal places. There are also instruments for tracing plane hyperbolas mechanically, without calculation, tables, or constructed grids; one of these is described in Sec. 6·6.

The plotted lines on the chart will depart from the course of the actual lines on the earth to the extent to which the chart projection distorts the earth's surface in representing it on a plane. This distortion is small enough in the case of the azimuthal and conic projections, within certain limits, so that corrections may be determined and applied to the plane hyperbolas, "warping" them to fit the other features of the chart. Distortion in the Mercator projection is too great to be corrected in this way, except in regions near the equator.

In theory, it should be possible to express the coordinates of Eq. (8) in terms of latitude and longitude on the chart, by an algebraic transformation, since meridians and parallels on the chart form a plane coordinate grid. Such a transformation is practicable in the case of projections on which parallels and meridians are represented by a grid of straight lines, circles, or both; for others it is not. In all cases, graphi-

[1] Hydrographic Office, U.S. Navy, "Tables for the Construction of Plane Hyperbolae," *H.O. Misc.* 11,486 (1944).

cal construction is quicker and accurate enough for charting, while determination of exact general formulas to correct the plane hyperbolas for the terrestrial curvature and the form of the projection is not practicable. Approximate correction may be made by computing true Loran readings at selected points on the earth and adjusting the hyperbolas so that they will indicate these readings at the corresponding points on the chart.

The Spherical Approximation.—A region of the terrestrial spheroid as large as the service area of a Low Frequency Loran triplet departs far from a plane surface, but it may be rather closely represented by a spherical surface. Loran lines on this surface are spherical hyperbolas. The first two equations below are, respectively, the central equation of a spherical hyperbola in spherical rectangular and in spherical polar coordinates; the last two are different forms of the spherical polar equation with origin at a focus.

$$\left.\begin{aligned}
\sin^2 x &= \frac{\sin^2 a \cos^2 c}{\sin^2 c - \sin^2 a} \sin^2 y + \sin^2 a, \\
\tan^2 r &= \frac{\tan^2 a\,(\sin^2 c - \sin^2 a)}{\sin^2 c \cos^2 \theta - \sin^2 a}, \\
\tan r &= \frac{\sin^2 c - \sin^2 a}{\sin c \cos c \cos \theta \pm \sin a \cos a} \\
&= \frac{\cos 2a - \cos 2c}{\sin 2c \cos \theta \pm \sin 2a}, \\
\tan^2 \frac{1}{2}\theta &= \frac{\sin (c \pm a) \sin [r - (c \mp a)]}{\sin (c \mp a) \sin [r + (c \pm a)]},
\end{aligned}\right\} \tag{10}$$

where a, c, x, y, and r are spherical arcs. Here y is the spherical distance of a point of the hyperbola from the baseline (which is the great circle passing through the foci), that is, the arc intercepted between baseline and point, on a great circle that passes through the point and the poles of the baseline. Similarly, x is the spherical distance of the point from the center line (which is the great circle passing through the poles of the baseline and midway between the foci). The origin for the first two equations is the intersection of baseline and center line; for the third and fourth, one of the foci; and θ is zero when r extends from this focus toward the other one, along the baseline. The first equation might have several other forms, since "spherical rectangular coordinates" may be chosen in several ways. The signs are taken in the same way as in Eq. (8).

Conversion from the coordinates of Eq. (10) to geographical longitude λ and latitude φ may be effected by standard transformation formulas of spherical analytic geometry or trigonometry. Convenient forms of these are given in Sec. 6·7 below [Eqs. (16) to (18)]. On a spherical earth of radius E, a series of points λ, φ, computed by Eq. (10) and the transformation formulas, along a hyperbola specified by constants c and a, will define a Loran line for which

$$\left.\begin{aligned} \beta' &= 2Ec, \\ v' &= 2Ea, \\ T' &= \beta' + \delta + v', \end{aligned}\right\} \tag{11}$$

where E is the equatorial radius of the actual earth expressed in light-microseconds, a and c are expressed in radians, and δ is the coding delay. The longitudes and latitudes of the stations determine c, and a may then be chosen so that T' shall have any desired value.

If the same series of points λ, φ are transferred to the spheroidal earth, the lengths of all the great-circle distances will be changed, so that instead of B', v', and T' we will have

$$\left.\begin{aligned} \beta &= 2Ec + \Delta c, \\ v &= 2Ea + \Delta a, \\ T &= \beta + \delta + v \\ &= 2E(c + a) + \delta + \Delta c + \Delta a. \end{aligned}\right\} \tag{12}$$

Here Δc is the Lambert correction to the baseline, defined by Eq. (1) with $\sigma = 2c$, and Δa is the difference between the Lambert corrections to the distances from the point λ to the two stations. The correction Δc is constant for all the points, but Δa is not; consequently T is different for different points. Near each point, however, there will be another point λ', φ', at which the time difference has the constant chosen value T'. Since the quantities Δc and Δa are small enough to be treated as infinitesimals to the accuracy required in Loran computations, the distance D from φ to φ' will be in light-microseconds

$$D = \tfrac{1}{2} \csc \tfrac{1}{2}\psi \; (\Delta c + \Delta a) = w \; (\Delta c + \Delta a), \tag{13}$$

ψ being the angle at λ, φ between the directions to the two stations. The direction A_D from λ, φ to λ', φ' will be perpendicular to the line connecting neighboring points of the series λ, φ and will extend in the direction of decreasing T (toward the slave station) if $\Delta c + \Delta a$ is positive, in the opposite direction if it is negative. Formulas for computing D and A_D are developed in Sec. 6·7. When these have been found for each point λ, φ, the coordinates of the corresponding point λ', φ' are given by

$$\left.\begin{aligned} \lambda' &= \lambda \pm 0.162D \sin A_D \sec \varphi, \\ \varphi' &= \varphi + 0.162D \cos A_D. \end{aligned}\right\} \tag{14}$$

A_D is measured from the north through the east, and the upper sign in the first equation is used if the longitude is east, the lower if it is west. The factor 0.162 converts D to minutes of arc. At the points λ', φ' on the earth, the time difference is T'. A line drawn through these points is the desired Loran line. It practically coincides with the line drawn through the points λ, φ near the baseline and diverges from it as distance from the stations increases. The divergence is greatest if the baseline is long, lies in middle latitudes, and runs nearly north and south, and if w is large. Over most of the ground-wave service area of an average standard Loran pair, it is less than a mile.

6·3. The Three Basic Methods of Computation.—Basically, the course of Loran lines of position may be determined in three ways. The first may be called the *inverse method.* An array of regularly spaced points on the earth is chosen (for example, every whole degree in latitude and in longitude) over a service area. The distances on the earth from the transmitting stations to each of these points are computed, then the difference between each pair of distances, and the corresponding value of T. The resulting nonintegral values of T are tabulated against the corresponding integral values of latitude and longitude, and from this table another table, of integral values of T against nonintegral values of latitude and longitude, is obtained by inverse interpolation. Points having the same T lie on the same Loran line. This is the standard method used by the Hydrographic Office of the U.S. Navy in preparing Loran charts and tables (see Appendix A.) It was developed under the direction of F. G. Watson, first as staff member of the MIT Radiation Laboratory and from 1943 to 1946 as Lieutenant and Lieutenant Commander in the U.S. Navy.

The second and third methods may be called *direct methods.* In these, the earth is first assumed to be plane or spherical, the constants of the hyperbolas corresponding to desired values of T are calculated, and the equations solved for the rectangular or polar coordinates of points on the hyperbolas. Then transformation to geographical coordinates and correction for departure of the surface of the earth from plane or spherical form are effected. The plane approximation is used in the second method. Rectangular coordinates are laid down on a chart, and the plane hyperbolas plotted by points. Since the geographic grid of meridians and parallels is shown on the chart and the rectangular grid superposed on it, no transformation by calculation is necessary. To correct the hyperbolas for the chart distortion, the accurate distances on the earth from the stations to chosen points and the resulting values of T are computed. The differences between these computed T's and those read from the plane hyperbolas are found and reduced to zero by shifting the hyperbolas. This method has been used by the U.S. Coast Guard and Army Air Forces for drawing preliminary Loran charts, where the required accuracy was not the highest but production of charts in the shortest possible time was desired.

In the third method the spherical approximation is used. Constants of the spherical hyperbolas are calculated. The spherical rectangular or polar coordinates of points on these hyperbolas are computed, and latitude and longitude obtained by means of the transformation equations. The latitudes and longitudes are then corrected for the spheroidal form of the earth (from λ, φ to λ', φ'), and the corrected coordinates plotted or interpolated to integral values for Loran tables. This method has never been employed in the construction of actual charts. Mathematically it is the most elegant, but it lacks the simplicity of the first method. Its practicability depends upon rapid and easy determination of the necessary large number of small corrections. If suitable tables or graphs of these were prepared, the amount of computation in the third method could be made comparable to that in the first.

6·4. The Standard Inverse Method.—At the end of 1945 the Hydrographic Office had published approximately $2\frac{1}{2}$ million Loran charts, and Loran tables for about 50 pairs of stations. Computations for all of these were made by the inverse method.

The first step in the procedure is to select the points for which distances to the stations are calculated. It is convenient to take these at the intersections of all meridians, the longitudes of which are whole degrees, with all whole-degree parallels of latitude. Near the stations and the baseline extensions it is necessary to take half-degree or quarter-degree points, because the curvature or the change of spacing of lines is too rapid for interpolation over degree intervals unless differences above the second are taken into account. The number of points included within the sky-wave service area of a pair of island stations, with oversea coverage on all sides, is generally between 1000 and 2000.

The second step is to compute the distances s_B and s_A from each point to the stations, to take the differences $s_B - s_A = v$ (in light-microseconds), and to obtain corresponding values of T by Eq. (3·4). The spherical arcs σ are calculated by Eq. (4), and the corrections δs by Eq. (2). The Hydrographic Office computers use the parametric latitudes in these calculations, converting from geographical latitudes by tables. Other special tables give $E\sigma$, p, and q directly in microseconds with argument $\cos\sigma$. The baseline length β in microseconds is computed by the same process. The T's obtained are ground-wave time differences, but they are determined for points all over the sky-wave area as well as for those within ground wave range. Loran lines representing sky-wave time differences are not shown on Hydrographic Office charts. Instead, the sky-wave corrections are given in regions where sky waves are used.

The sky-wave correction C at a point is the difference of the transmission delays, $E_A - E_B$ [Eq. (3·5)], and E is a function of s, determined by observation (Sec. 5·3) and embodied in a curve (Fig. 5·10) or a table with s as argument. When S_A and S_B have been found as described above, E_A and E_B are read from the table, and their difference C taken, if both distances exceed 250 miles (the inner limit for reliable sky wave timing). Since C is a function of s_A and s_B together, it may also be read directly from a double-entry table, graph, or nomogram, against the two values of s.

The third step is to tabulate T against the argument λ (longitude of each point) along parallels of latitude or against the argument φ (latitude of each point) along meridians. The former tabulation is made over areas in which the Loran lines intersect the parallels more nearly at right angles than they do the meridians, the latter tabulation if the reverse is the case. Where the angles are nearly equal, values of T are tabulated both ways. Then the first, second, and third differences of the T's are taken.

The result of the third step is a series of tables of the following form:

$$\begin{array}{llllll}
\lambda_{-1} & T_{-1} & & \Delta^2_{-2} & \\
 & & \Delta_{-1} & & \Delta^3_{-2} \\
\lambda_0 & T_0 & & \Delta^2_{-1} & \\
 & & \Delta_0 & & \Delta^3_{-1} \\
\lambda_1 & T_1 & & \Delta^2_0 & \\
 & & \Delta_1 & & \Delta^3_0 \\
\lambda_2 & T_2 & & \Delta^2_1 &
\end{array}$$

where the argument is λ and φ is constant, or of a similar form with argument φ and constant λ. The differences Δ follow the usual notation. The T's have nonintegral values, whereas the λ's are whole degrees or simple submultiples, having the constant difference ω.

The fourth step is to choose values T_x that are multiples or simple submultiples of 100 μsec and to interpolate for corresponding values λ_x. Everett's central-difference formula inverted [1] is used, carried to second differences only. (The third differences in the table above are taken only as a means for detecting errors.) Assume that T_x is between T_0 and T_1, and let

$$m = \frac{T_x - T_0}{\Delta_0}, \qquad n = 1 - m, \qquad d_0^2 = \frac{\Delta^2_{-1}}{\Delta_0}, \qquad d_1^2 = \frac{\Delta^2_0}{\Delta_0},$$

$$E^2(m) = \tfrac{1}{6}m\,(1 - m)\,(1 + m),$$

$$E^2(n) = \tfrac{1}{6}n\,(1 - n)\,(1 + n) = \tfrac{1}{6}m\,(1 - m)\,(2 - m).$$

The formula for λ_x is then

$$\lambda_x = \lambda_0 + \omega[m + d_0^2E^2(n) + d_1^2E^2(m)]. \tag{15}$$

(Note that the superscript 2's do not indicate squares.)
Davis gives a table[2] of values of E^2.

[1] H. T. Davis, *Tables of the Higher Mathematical Functions*, Vol. I, Bloomington, Ind., 1933, p. 82.

[2] Davis, *op. cit.*, Table D, p. 126.

Fourth differences can be taken into account by adding two more terms to the Everett formula, but it is better to make ω small enough so that Δ^4 is negligible. In regions where the higher differences of T are not small in comparison with the first difference, inverse interpolation is not feasible. This is true close to the baseline extensions. But, if, instead of T, $\sqrt{T - \delta}$ be taken as the tabulated function in the neighborhood of the extension behind the slave station and $\sqrt{(2\beta + \delta) - T}$ in the neighborhood of the extension behind the master, the differences of these quantities will generally be found quite tractable.

Tabulations of λ_x with argument T_x along the parallels and of φ_x with argument T_x along the meridians, within the service area of a pair of stations, make up a Loran table for the pair. As mentioned in Sec. 3·9, these tables are published by the Hydrographic Office for the convenience of navigators who desire to lay down Loran lines of position, along with celestial lines of position and those obtained by radio bearings, upon standard navigation charts.

The fifth step is to plot the points of the Loran tables upon charts, by means of the graduated geographical grid of meridians and parallels that appears on the charts, and to draw the Loran lines by passing a smooth curve through each set of points T_x = constant. The standard Hydrographic Office Loran charts are on the Mercator projection. In addition to the rectangular geographical grid they show the principal features of the terrain in simple outline, with important seaports and airfields and selected navigational aids, in an unobtrusive background tone. Families of Loran lines generated by two or more pairs of stations will extend over all areas in which Loran fixes can be obtained. The different families are distinguished by different colors on the charts. The interval in T between lines is 20, 50, or 100 μsec, depending upon the spreading of the lines (values of w) and upon the scale of the chart. The chart scales vary from 1 in. = 14 nautical miles to 1 in. = 70 nautical miles (approximately 1/1,000,000 to 1/5,000,000).

Values of the sky-wave correction C at all points where λ and φ are whole degrees are given as part of the Loran tables and are shown on the charts as small figures close to the intersections of the meridians and parallels. The correction for each pair is printed in the color used for the lines of that pair.

6·5. The Direct Method, Using Plane Hyperbolas. *The Coast Guard Method.*—During the "island-hopping" stage of the war in the Pacific, when Loran stations were being set up and put into operation as rapidly as possible, "Mobile Charting Elements" of the Coast Guard were sent forward into the area of operations and produced temporary Loran charts, to be used until charts of standard form could be sent from the United States over the long shipping routes. These temporary charts were prepared by plotting plane hyperbolas on special geographical grids, correcting the hyperbolas for chart distortions, drawing in coast lines, location of navigation aids, etc., and reproducing the grids photographically by the Ozalid process. Details of procedure are given in a Coast Guard Manual.[1]

The geographical grids were on transparent sheets of vinylite. These showed meridians and parallels at intervals of 1°, on a scale of 1/2,000,000. The projection was the Lambert conformal conic with two standard parallels, the same that is used in the Civil Aeronautics Authority and U.S. Army aeronautical charts. In this projection the distortion is small over regions between or near the standard parallels, so that Loran lines on the chart have nearly the form of plane hyperbolas. The parallels are shown as concentric circles; the meridians as straight lines radiating from the common center of the parallels; directions around any point are represented truly; and great circles appear as nearly straight lines if not carried too far from the standard parallels.

With the geographical grids was used another grid of rectangular coordinates, also on vinylite. The stations of a Loran pair were plotted on the geographical grid, and this was placed over the rectangular grid, so that the x-axis of the latter passed through the stations and the y-axis was midway between them. If the x-coordinates of the stations, in units of the grid, are $\pm c$ (the positive sign being given to the master station), the inverse eccentricity a/c of the hyperbola representing time difference T is given by

$$\frac{a}{c} = \frac{T - (\beta + \delta)}{\beta}$$

[from Eqs. (3·4) and (6·9)], and the coordinates x, y of points on the hyperbola are defined by the first of Eq. (6·8). In practice, x and y were obtained from the "Tables of Plane Hyperbolae" (see footnote, page 174), the tables being entered with the argument: tabular $a = [T - (\beta + \delta)]/\beta$ (since $c = 1$ in the tables). The baseline distance β in microseconds was calculated by the accurate formulas (4) and (2). The pairs of values x, y given by the table were multiplied by c and then plotted, by means of the rectangular grid, on the vinylite sheet bearing the geographical grid.

If there were no distortion, the family of hyperbolas thus plotted would be a Loran chart. It would only remain to remove the rectangular grid, to draw in coast lines and other features of the terrain, and to make prints from the vinylite sheet. But distortion is not negligible even on the Lambert projection, except over small regions and nearly midway between the standard parallels; and, even if it were, a procedure to check the plotted hyperbolas is desirable. The procedure devised for checking

[1] U.S. Coast Guard, "Mobile Loran Monitor Charting Element," *Manual of Methods and Procedure*, with Addenda Nos. 1, 2, 1944, 1945.

and correction made use of a set of "Loran Grid Tables" computed for the purpose by the Hydrographic Office. Each of these tables gave the distance in microseconds (called d) and the azimuth in degrees and tenths (called A) from a center point, the latitude of which was a given whole number of degrees, to every other point within 1500 nautical miles, the latitude and longitude of which differed from that of the center point by a whole number of degrees. These tables were the counterpart, for the spheroidal earth, of the well-known celestial navigation tables H.O. No. 214 and H.O. No. 218. With these tables the true distances, and therefore v and T, for every intersection on the geographical grid of the chart could be read directly from the tables, if the stations were located at such intersections. In actuality, a station might be as much as 40 nautical miles from the nearest center point, and every distance had to be corrected for the amount and direction of this offset, by a graphical method described elsewhere.[1]

In this way true values of T for intersections of meridians and parallels of the vinylite chart were obtained and compared with chart values, found by interpolation between the plane hyperbolas. The differences, due to the distortion, were indicated on the vinylite, and the plane hyperbolas shifted by freehand sketching so as to make the interpolated values agree with those from the tables. The original hyperbolas were erased, the geographical detail sketched in and necessary labels and text supplied; then Ozalid prints were made from the sheet to serve as charts.

The MIT-AAF Method.—The MIT Radiation Laboratory and the Army Air Forces worked out a charting procedure for use with the Air Transportable Loran system. The method is described in detail in MIT Radiation Laboratory Report No. M-183 (footnote, Sec. 6·1, page 172). It was similar in its main features to that of the Coast Guard and used the same Tables of Hyperbolae and Grid Tables but differed in several details. No special grids were employed. Each chart was drawn on tracing paper spread over a standard AAF chart of the region covered (Lambert projection, scale usually 1/1,000,000). The chart furnished the geographical grid, and the rectangular grid was drawn on the tracing paper, its meshes spaced to make the unit of x and y equal to half the distance between the plotted stations, so that c was unity and coordinates of the hyperbolas could be plotted as read from the tables.

Plotting was not done, however, until after the corrections for distortion were determined. These were obtained in the form of small quantities Q to be added to the a's and subtracted from the x's of the plane hyperbolas, bending them into approximate conformity with the distortion. The first step of the corrective process was to choose a dozen points or so, taken for convenience at intersections of the lines of the

[1] U.S. Hydrographic Office, "Graphical Methods," Loran Technical Report No. 1, 1944.

rectangular grid and forming a ring around the baseline near the margin of the chart. For each of these points the distances to the stations over the earth were computed by Eq. (6) and the nomogram embodying Eq. (3). The difference v was found and divided by β, giving the inverse eccentricity a of the plane hyperbola that would pass through the point if the chart truly represented the earth. With this value of a, the Table of Hyperbolae was entered and rectangular coordinates for the point were obtained. Any distortion would then appear as a discrepancy between these tabular coordinates and the actual grid coordinates.

The second step was to find the correction to a that would change the curvature of the plane hyperbola so that it would pass through the chosen point. The correction, denoted by Q, is a function of the discrepancy and of the geometrical factor w at the point (given accurately enough by the tabular difference for consecutive a's in the Table of Hyperbolae). The functional relation is developed in detail in Report M-183. Q was found by a slide-rule computation for each of the chosen points. Then the values of Q were plotted against corresponding values of a on cross-section paper, and a smooth curve drawn through the plotted points. From this curve Q might be read for values of a b tween those chosen, assuming that the distortion varied smoothly.

The third step was to take from this curve a value of Q for every a that represented a desired value of T and to enter the Table of Hyperbolae with argument $(a + Q)$ instead of a, obtaining a series of pairs of coordinates x, y. Then Q was subtracted from each of the x's, and the points $(x - Q)$, y were plotted on the chart. In effect, this process amounted to choosing, instead of the hyperbola a, a neighboring hyperbola $(a + Q)$ of suitable curvature and shifting it back into the place of the first hyperbola.

This corrective procedure had the advantage that no "uncorrected" hyperbolas were actually drawn and then erased. But it was a first-order approximation, sufficient only if the distortion was small, which was generally the case over the chart sheets adjacent to the baseline. For outlying chart sheets, the entire method of charting was different. The inverse method of Sec. 6·4 was used, but the distances were obtained by means of the Loran Grid Tables, with a nomographic method of correction for station offsets, and the inverse interpolation was done graphically, by plotting and reading curves. As in the case of areas near the baseline, the Loran lines were drawn on tracing paper laid over standard charts, but no rectangular grid was constructed, since the latitudes and longitudes were read from the interpolating curves.

After the Loran lines were drawn, other features of the chart were traced in, and photographic reproductions of the tracing were made by the Portagraph process.

Neither of the plane hyperbola methods has been extensively used.

They were devised to enable small charting units, located in isolated regions and supplied with limited equipment, to produce usably accurate Loran charts quickly, and under normal conditions these limitations are absent. The outlines above describe the procedures as they were planned. In actual use, various modifications were forced by unantici-

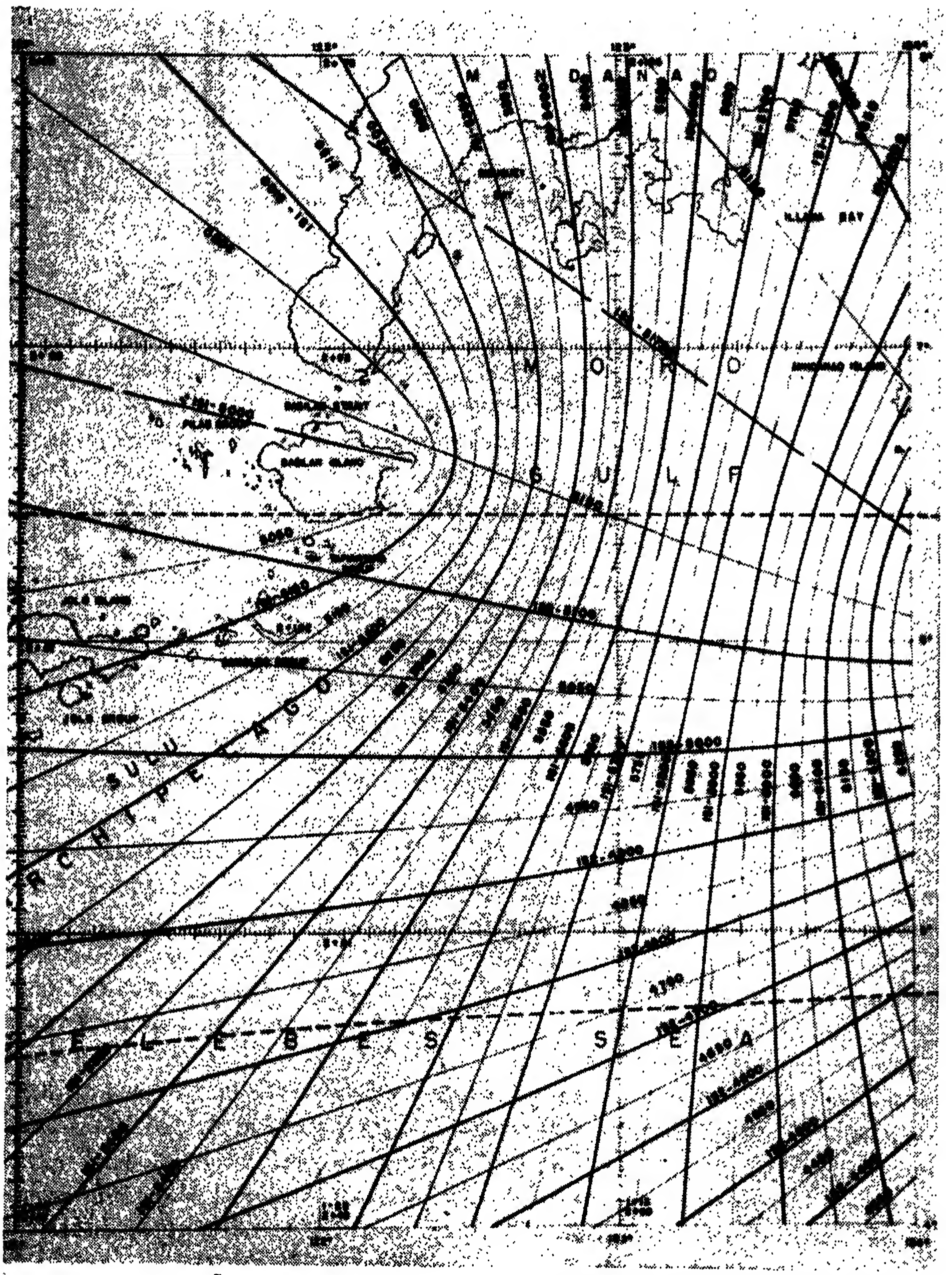
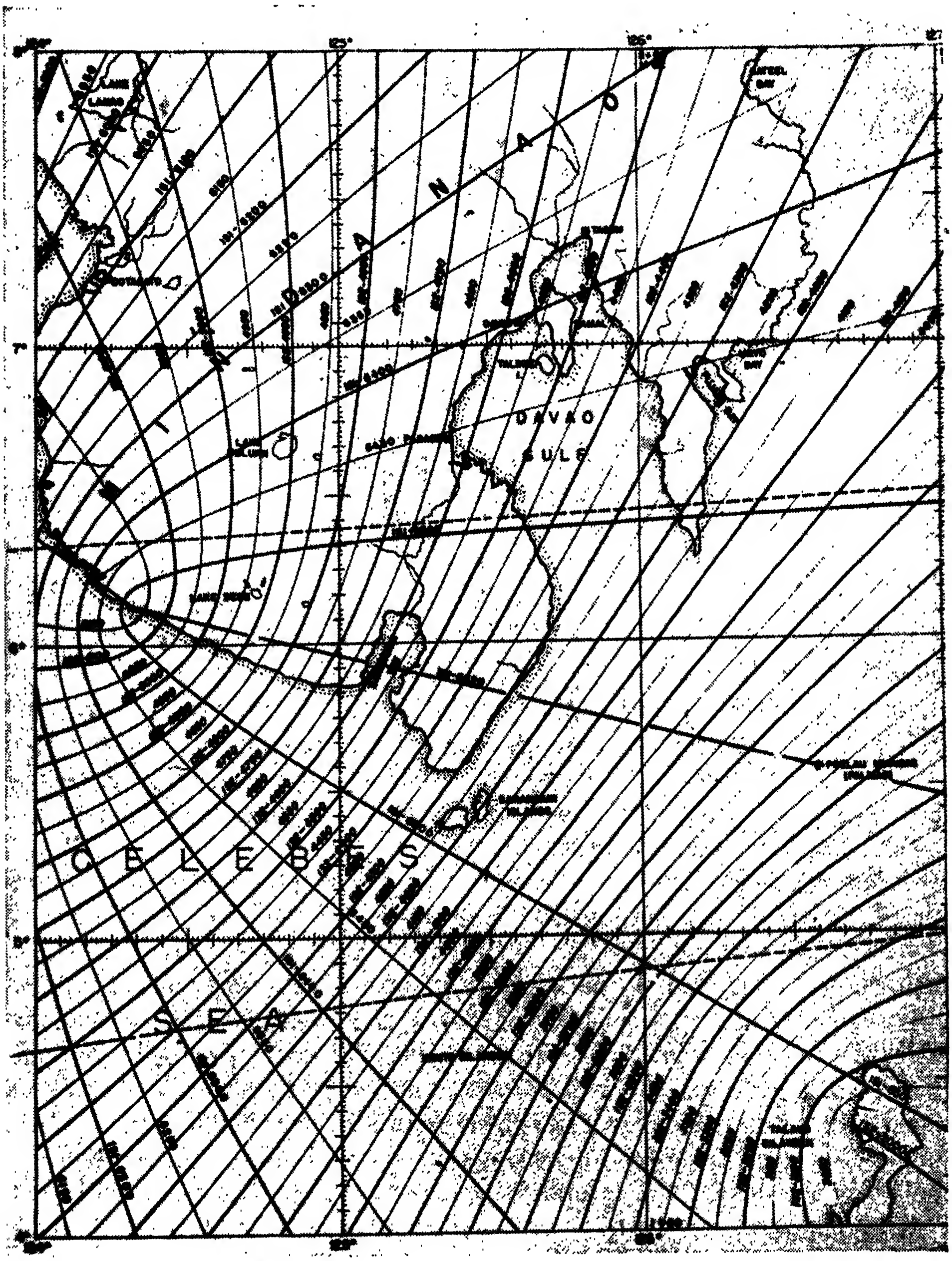


Fig. 6·1.—Loran chart of a fictitious instalpated conditions or suggested by experience. For example, the entire AAF procedure was set up for use with charts on the Lambert conformal projection, scale 1/1,000,000, covering areas about 4° by 6°. When the AAF charting units were required to produce single charts covering four times this area, at half this scale, and charts on the Mercator projection,



lation prepared by the MIT-AAF method.

the method of correcting distortion had to be revised to deal with greater departures from the plane approximation than had been expected. That revisions of this sort were successfully improvised in the field was owing to the intelligence and resourcefulness of the charting personnel, both officers and men.

A chart of a fictitious Loran installation, prepared during training by one of the AAF charting units, is reproduced as Fig. 6·1.

6·6. A Mechanical Tracer of Plane Hyperbolas.—Numerous instruments for tracing plane hyperbolas have been devised. Some of these depend upon the property that the distances from a point moving along the hyperbola to a fixed point (focus) and to a fixed straight line (directrix) bear a constant ratio, equal to the eccentricity. Some depend on

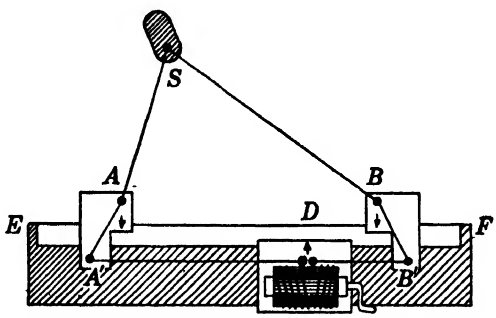


FIG. 6·2.—Diagram of the Hygraph.

the projective properties of the hyperbola. The simplest devices make use of the constant difference v between distances of points of the hyperbola from the foci. The Hygraph, a compact and accurate instrument of this type, designed at the MIT Radiation Laboratory, will be described briefly here. It was tested for use in drawing Loran charts by the method of the plane approximation and found satisfactory when kept in proper adjustment. Its construction and operation are discussed in detail in the *Hygraph Instruction Manual.*[1]

Figure 6·2 is a diagram of the essentials of the instrument. A metal bar EF carries three sliding parts, AA', BB', and D. A, A', B, and B' are swiveled bearings through which two cords run; D is a carriage that holds a rotating drum upon which the cords may be wound. On a separate carriage S a stylus is mounted, and the ends of the cords are attached to this carriage by means of rings centered on the stylus. When the drum is rotated, the two cords are pulled in together, so the equal lengths of cords $DA'AS$ and $DB'BS$ remain equal as they diminish. The points A and B are placed over the stations on a chart. The difference between the lengths $A'D$ and $B'D$ depends upon the position of the

[1] RL Report No. M-230, 1945.

movable carriage D. Since $A'D$ is longer than $B'D$ by just the same amount that AS is shorter than BS (because the total lengths DS are equal), the difference $BS - AS$ remains constant as the drum is turned, and S describes a hyperbola having the stations as its foci.

On the bar EF is engraved a scale, the units of which are half microseconds on the scale of the chart, but numbered as whole microseconds (so that the scale of the bar is half the scale of the chart); numbering is in both directions. The point A is to be set on the scale so that the index attached to it reads δ (the coding delay). Then the bar is laid upon the chart (over which tracing paper has been spread) so that A coincides with the master station, and the point B is slid along the scale and the bar turned about A until B coincides with the slave station. The index attached to B will then read $(2\beta + \delta)$. That is, the scale reading at each station is the time difference T at the other station. The direction of numbering on the scale, from A to B, is the reverse of the true direction on the chart, because D must be moved to the left to place S on the right. With this arrangement, when the carriage D is set on the scale so that the index attached to it reads any chosen time difference T, the stylus S will draw the hyperbola corresponding to T, as the drun is rotated.

Of course, since the cords must pull the stylus toward the bar, the hyperbolas on the two sides of the baseline must be drawn separately, the Hygraph being reversed in position on the chart between the two operations.

In the preceding description it has been assumed that the scale engraved on the Hygraph bar exactly matches the chart scale. If it does not, let the ratio of Hygraph scale to chart scale be $2\beta'/\beta$, instead of 2. Then if the index at A reads δ, the index at B will read $(2\beta' + \delta)$, where β' is the "Hygraph baseline length," and to draw the hyperbola corresponding to actual time difference T, the index at D must be set to the value $(\beta'/\beta)T$.

Absence of distortion was also assumed above. If distortion exists, it may be detected and adjustment made by varying the Hygraph settings. The principle of the "Q-procedure," described in Sec. 6·3, is applied. First, the instrument is set up as above, and short sections of hyperbolas drawn, for selected values of T, conveniently spaced. On these hyperbolas, points are chosen, their latitudes and longitudes read from the chart, and true distances and true time differences T_c computed, as described in Sec. 6·3. Now, if we denote by q the equivalent of Q in microseconds, it may be shown that

$$q = F(T - T_c),$$

where F is a positive factor between 1 and 2, a function of the distance and direction of the point from the center of the baseline. Usually it may be taken as 1, and in other cases it may be read from a small table. For each point q is found, and a curve of q against T is plotted. To set the Hygraph to draw the corrected hyperbola T, the two station indices A and B are first shifted. The master index A is moved from the reading δ to the reading $\delta + q$, and the slave index B from reading $2\beta + \delta$ to the reading $2\beta + \delta + q$, q being taken from the curve with argument T. Then the drum carriage index is set to read $T + 2q$ instead of T. All these shifts are in the same direction, from master to slave if q is positive.

As noted in Section 6·3, the Q method of correction is not generally adequate over the entire service area of a Loran pair even if the most advantageous chart projection is used. The Hygraph can be used, therefore, only over that part of the area which is fairly near the station. But this is just the region where the standard inverse method is most laborious, because of the sharp curvature of the hyperbolas. So the Hygraph may be found a useful tool in Loran charting, if used with judgment, and in drawing charts for hyperbolic systems of short range it should be particularly valuable.

6·7. The Direct Method, Using Spherical Hyperbolas. *Equations of Transformation.*—The formulas for a spherical hyperbola, Eq. (10) in Sec. 6·2, give rectangular coordinates x, y or polar coordinates r, θ of points on the hyperbola. The second and third of these four equations will not be considered further here. If polar coordinates are to be used, it is advantageous to place the origin at a focus, so that the radial coordinate r shall represent the length of one of the actual signal paths. The origin is at a focus for both the third formula and the fourth, but the latter leads to more symmetry and convenience in computation. In the discussion below, equations for polar coordinates are given in form to be used with the fourth formula.

Equations of transformation from the rectangular coordinates to geographical coordinates λ, φ are

$$\left.\begin{aligned}\sin\varphi &= \sin X \sin x + \sin Y \sin y \\ &\qquad + \sin\varphi_0\sqrt{1 - \sin^2 x - \sin^2 y},\\ \sin(\lambda - \lambda_0) &= \frac{\sin A_0 \sin x - \cos A_0 \sin y}{\cos\varphi}\end{aligned}\right\} \tag{16}$$

where X, Y are the rectangular coordinates of the north geographical pole, λ_0, φ_0 the geographical coordinates of the origin and A_0 the azimuth of the baseline, as defined below. These five quantities are determined from the geographical coordinates λ_1, φ_1, and λ_2, φ_2 of the foci having rectangular coordinates $+c$, 0 and $-c$, 0 respectively, by the relations

$$\left.\begin{aligned}
\sin A &= \pm \sin (\lambda_1 - \lambda_2) \frac{\cos \varphi_1}{\sin 2c},\\
\sin \varphi_0 &= \sin \varphi_2 \cos c + \cos \varphi_2 \sin c \cos A,\\
\sin (\lambda_0 - \lambda_2) &= \pm \sin c \frac{\sin A}{\cos \varphi_0},\\
\sin A_0 &= \cos \varphi_2 \frac{\sin A}{\cos \varphi_0},\\
\sin X &= \cos A_0 \cos \varphi_0,\\
\sin Y &= \sin A_0 \cos \varphi_0,
\end{aligned}\right\} \tag{17}$$

where A and A_0 are the azimuths of λ_1, φ_1 from λ_2, φ_2 and from λ_0, φ_0 respectively, measured from the north through the east, and the upper signs are to be used in east longitude, the lower in west. The half-length c of the baseline is computed by Eq. (4), (5), or (6), setting $2c = \sigma$.

Equations of transformation from polar to geographical coordinates are

$$\left.\begin{aligned}
\tfrac{1}{2}\alpha &= \tfrac{1}{2}A_0 + \tfrac{1}{2}\theta,\\
\tan F &= \tan \frac{1}{2}\alpha \frac{\sin \frac{1}{2}[(90^\circ - \varphi_0) + r]}{\sin \frac{1}{2}[(90^\circ - \varphi_0) - r]},\\
\tan G &= \tan \frac{1}{2}\alpha \frac{\cos \frac{1}{2}[(90^\circ - \varphi_0) + r]}{\cos \frac{1}{2}[(90^\circ - \varphi_0) - r]},\\
\lambda &= \lambda_0 + F - G,\\
\cos \varphi &= \sin \alpha \frac{\sin r}{\sin (\lambda - \lambda_0)},\\
A_D &= F + G + \tfrac{1}{2}\psi \pm 90^\circ.
\end{aligned}\right\} \tag{18}$$

In these equations the origin is at a focus, so that λ_0 and φ_0 are the geographical coordinates of that focus, and A_0 is equal to A as given by the first equation of (17), with $\lambda_2 = \lambda_0$, the longitude of the origin, and λ_1, φ_1 denoting the coordinates of the other focus. The angle θ is measured in the same direction as is A_0. The last equation of (18) is used with the correction formulas discussed below. It gives the azimuth A_D from λ, φ to the corrected point λ', φ'.

Formulas for Correction to the Spheroid.—As shown in Sec. 6·2 above, the time difference T' at a point with coordinates λ, φ on a spherical earth is specified by Eq. (11). But on the actual spheroidal earth T' is the time difference, not at λ, φ, but at a near-by point λ', φ', of which the distance from λ, φ is D and the azimuth A_D. D is given by Eq. (13) in terms of three quantities: the Lambert correction Δc to the baseline, the difference Δa of the Lambert corrections to the distances of the foci (stations) from the point λ, φ, and the angle ψ between the directions of the stations from the point. The correction Δc may be computed by Eq. (2), setting $\Delta c = \delta s$, taking φ_1 and φ_2 as the latitudes of the stations, and obtaining the p and q functions from the tables or by calculation for $\sigma = 2c$.

The correction Δa is

$$\Delta a = \delta s_B - \delta s_A, \tag{19}$$

where δs_B and δs_A are the Lambert corrections computed by Eq. (2) for the distances σ_B and σ_A of the slave and master station, respectively, from the point.

If λ, φ have been computed from focal polar coordinates r, θ,

$$\sigma_B = r + 2a, \qquad \sigma_A = r \tag{20a}$$

with origin at the master station, or

$$\sigma_B = r, \qquad \sigma_A = r - 2a \tag{20b}$$

with origin at the slave station. If rectangular coordinates have been used, the σ's may be computed by the formulas

$$\left.\begin{aligned} \cos \sigma_A &= \sin c \sin x + \cos c \sqrt{1 - \sin^2 x - \sin^2 y}, \\ \sigma_B &= \sigma_A + 2a. \end{aligned}\right\} \tag{21}$$

The angle ψ is given by

$$\csc^2 \frac{1}{2}\psi = \frac{\sin \sigma_A \sin (\sigma_A + 2a)}{\sin (c + a) \sin (c - a)} \tag{22}$$

for use with rectangular coordinates, or

$$\csc^2 \frac{1}{2}\psi = \frac{\sin [r + (c \pm a)] \sin [r - (c \mp a)]}{\sin (c + a) \sin (c - a)} + 1. \tag{23}$$

for use with polar coordinates. In Eq. (23) r is the radial coordinate of the last equation of (10), and the double signs have the same meaning as in that equation. The two equations (for $\tan^2 \frac{1}{2}\theta$ and $\csc^2 \frac{1}{2}\psi$) are conveniently used together, for the four sine factors are the same in both equations.

To determine the corrected coordinates λ', φ' from the spherical approximations λ, φ, we calculate Δc by Eq. (2), find σ_A and σ_B by (20) or (21) and Δa by (2) and (19), and obtain $\csc^2 \frac{1}{2}\psi$ from (22) or (23). D is then computed by Eq. (13). If polar coordinates have been used, the azimuth A_D in which D extends from λ, φ is found by the last equation of (18), interpreting the double sign so that λ', φ' shall lie on the side of the hyperbola on which the slave station lies when $\Delta c + \Delta a$ is positive, on the side of the master station when it is negative. If rectangular coordinates have been used, A_D is given to a sufficient approximation by

$$\tan A_D = \frac{\varphi_W - \varphi}{(\lambda_W - \lambda) \cos \varphi}, \tag{24}$$

where λ_W, φ_W are the longitude and latitude of the point next to λ, φ, on the same hyperbola, to the westward. Of the two opposite azimuths given by Eq. (24) that one is chosen which locates λ', φ' in accordance with the rule stated above. Finally, λ' and φ' are determined by Eq. (14).

The Complete Computation.—The computation of a Loran line representing time difference T', generated by a pair of stations having the geographical coordinates λ_1, φ_1 and λ_2, φ_2, may be recapitulated in three steps. These will be enumerated first for the method using polar coordinates, since this is the simpler and more direct. The first step is the calculation of constants for the whole family of lines, and those for the particular line T'. For the family we obtain c by Eq. (4), (5), or (6), β' by the first equation of (11), Δc by (2), and the azimuth A of the baseline by the first of (17). The true baseline length $\beta = \beta' + \Delta c$ should be determined also. An advantageous arrangement of the points λ, φ may be obtained by using each station as origin for those lines curving away from it—the master station for negative values of v and a, and the slave for positive values. There will then be two values of A, nearly opposite, each of which serves as A_0 for half the family of lines, while λ_0 and φ_0 are the coordinates of one station for half the computations, and the other for the rest. For a particular line T' is chosen, and v' and a obtained from the last two equations of (11).

The second step is to choose values of r, and to compute corresponding values of λ and φ. If the origin has been taken as stated above, the least value of r (for $\theta = 0$) is

$$r = c + |a|.$$

By making the interval between successive values of r the same as that between values of a for consecutive hyperbolas, the same numerical quantities, functions of r and its combinations with a, will recur many times in a set of computations, reducing the labor considerably. For each r, $\frac{1}{2}\theta$ is determined by the last equation of (10), $\frac{1}{2}\psi$ by (23), and λ, φ, and A_D by (18). Each angle will have two values, corresponding to positive and negative values of the tangent and cosecant. These represent points symmetrically placed on opposite sides of the baseline. The values of $\frac{1}{2}\theta$ and $\frac{1}{2}\psi$ having the same sign refer to the same point.

The last step is to determine Δa by Eqs. (20), (2), and (19), D by Eq. (13), and λ' and φ' by Eq. (14). This step is time-consuming, but since D is always small, three-figure accuracy in the computations is sufficient. If tables of p and q and tables or nomograms of $(\sin \varphi_1 \pm \sin \varphi_2)^2$ are used, Eq. (2) can be very rapidly solved to this accuracy. Over large parts of the service area, D and A_D change slowly and smoothly, and can be interpolated along the hyperbolas between separated points.

When rectangular coordinates are used, the constants c, Δc, β', and β

are found as above, and λ_0, φ_0, X, and Y by Eq. (17). The coordinates of the master station are λ_1, φ_1 in these equations. T' is chosen, and v' and a determined as before. Then the quantities

$$\sin^2 a \text{ and } \frac{\sin^2 a}{\sin^2 c - \sin^2 a},$$

which are constant for a hyperbola, are computed to be used in the first equation of (10). In the second step this equation gives values of x corresponding to a and a series of chosen values of y. Two values of x, both having the same sign as a, are obtained in each computation, one for $+y$ and one for $-y$. If a is between $\pm\frac{1}{2}c$, the same fairly widely spaced values of y may be used along all the hyperbolas, but as a approaches $\pm c$, the interval between y's must become smaller and smaller. For each point x, y Eqs. (16) give λ and φ. For determination of the corrections, σ_A and σ_B are computed by Eq. (21), A_D by Eq. (24), and $\frac{1}{2}\psi$ by Eq. (22). The last step is the same as for polar coordinates.

6·8. Factors Affecting the Correctness of Computed Loran Time Differences.—Correspondence between the time differences actually observed over a Loran service area and those given by a Loran chart or table depends upon the assumption of the correct velocity of signal propagation, upon the holding of the correct coding delay by the slave station, and upon the knowledge of the true latitudes and longitudes of the transmitting stations, as well as upon accurate computations of the Loran lines and accurate pulse matching. Analysis of Loran operation up to the present has given no evidence that the signal velocity over sea differs from that stated in Chap. 5 and used in Hydrographic Office computations. Sufficient data have not yet been obtained to evaluate the velocity over land. The land range of Standard Loran signals is small, and there are no land baselines between permanent stations along which velocity measurements could most readily be made. The effect of a diminution of velocity upon the grid of Loran lines would be a shrinking of the entire pattern, and a corresponding increase in the time difference T at a fixed point on the earth, such that

$$T' - \delta = (T - \delta)\frac{c}{c'},$$

where T increases to T' as the velocity c decreases to c', and δ is the coding delay. Existence of a proportionality of this sort between computed and observed time differences would reveal an abnormal signal velocity if this were uniform over the service area. But, if the velocity depended on the local electrical characteristics of the surface (as it might more plausibly do), the pattern of alteration of time differences might be very complex.

The operator of a slave station maintains the coding delay by keeping the time difference between the pulse from the remote master transmitter and that from his own adjacent antenna, as he observes them on his oscilloscope, equal to δ. The powerful local signal is passed through the attenuator, in order that it may appear equal in amplitude to the weak signal from the distant master; and if there are maladjustments in the attenuating circuits, the local pulse may be deformed so that the apparent delay may differ from the actual time between pulses by several microseconds. Such an error in timing will appear in all measured time differences, as a constant increment to T, independent of the observer's location, and as such it may be recognized.

The sites of Loran stations are often in places remote from accurately determined geodetic reference points, so that they cannot be tied in to such points by triangulation. The positions must be found by astronomical observations. The instrument may be either the theodolite or the prismatic astrolabe (also called the equiangulator). Both are easily portable, and either, in conjunction with a good timepiece and a radio receiver, will give positions with an internal probable error of the order of 1 sec of arc (100 ft) or better, from a few nights' work. With the theodolite, latitude and longitude are determined separately by meridian observations of stars, by the methods set forth in standard geodetic textbooks. With the astrolabe, stars in all azimuths are observed at altitude 60° (or 45° in some forms of the instrument). The time at which each star passes this altitude is determined and the line of position computed by formulas similar to those used by the celestial navigator, but with greater precision; the concurrence of lines of position from all the stars gives the observer's location.

Unfortunately, the internal probable error of a series of astronomical observations is not a reliable measure of the accuracy of the resulting position. In all such observations, the fundamental reference direction is the direction of gravity, which ideally is normal to the spheroidal surface but actually may be inclined to the normal by a considerable fraction of a minute of arc. This "station error," if not allowed for, will appear in its full size as an error in the observed position and can be detected only by triangulation or some equivalent method of comparing the positions of different points. Loran is such a method, and station errors will affect the Loran time differences; conversely, the errors may be determined from the deviations of observed time differences at accurately known positions from their computed values.

At a given position of the observer, incorrect positions of the transmitting stations will affect three signal paths: that from each station to the observer and that from the master M to slave S. These will all combine to alter the observed time difference from its computed value.

That is,

$$\Delta T = \Delta t_s - \Delta t_m + \Delta\beta,$$

where ΔT is the change in time difference, Δt the change in time of transmission from station to observer, and $\Delta\beta$ the change in time of transmission from master to slave, all in the sense, observed minus computed, and taken as positive or negative according as the transmission time is increased or diminished. Since an increase in t_m delays the beginning of the interval T, it decreases T and must be subtracted.

If D_s and D_m denote the distance in microseconds from the position of each station, as determined by observation, to its true position, it is evident that Δt_s is equal to the component of D_s in the direction from S opposite to the observer's direction and similarly for Δt_m, while $\Delta\beta$ is equal to the component of D_s in the direction along the baseline away from M, minus the component of D_m in the direction along the baseline toward S.

Since each D may be specified by two quantities, either amount and direction or rectangular components, observations of ΔT at four known points will determine the D's. If D'_s and D''_s denote the components of the displacement of the slave station along and perpendicular to the baseline respectively and D'_m and D''_m those of the master, the points of observation may be so chosen that D'_s, D''_s, D'_m and D''_m are determined separately. Let D'_s and D'_m be counted positive in the direction from master to slave. At Point 1 on the baseline, between the stations, D''_s and D''_m do not enter into ΔT, $\Delta t_s = D'_s$, $\Delta t_m = -D'_m$, $\Delta\beta = D'_s - D'_m$; consequently, $\Delta T_1 = 2D'_s$. At Point 2 on the extended baseline behind the master station, D''_s and D''_m again have no effect, $\Delta\beta = D'_s - D'_m$, $\Delta t_s = D'_s$, $\Delta t_m = D'_m$; consequently, $\Delta T_2 = 2(D'_s - D'_m)$, or $\Delta T_1 - \Delta T_2 = 2D'_m$. At Point 3 on the perpendicular through the slave station and near the station on the positive side, D''_m has no appreciable effect on ΔT, but $\Delta t_s = -D''_s$, $\Delta t_m = -D'_m$, $\Delta\beta = D'_s - D'_m$. Hence $\Delta T_3 = D'_s - D''_s$, or $\frac{1}{2}\Delta T_1 - \Delta T_3 = D''_s$. If the point is on the negative side of the slave station, $\Delta T_3 = D'_s + D''_s$, or $\Delta T_3 - \frac{1}{2}\Delta T_1 = D''_s$. Similarly, at Point 4 on the perpendicular through the master station and near the station, $\Delta T_4 = 2D'_s - D'_m \pm D''_m$, where the upper and lower signs apply respectively to points on the positive and negative sides of the master station. On the positive side $\Delta T_4 - \frac{1}{2}(\Delta T_1 + \Delta T_2) = D''_m$; on the negative, $\frac{1}{2}(\Delta T_1 + \Delta T_2) - \Delta T_4 = D''_m$. At Point 5 on the extended baseline behind the slave station, ΔT_5 is not affected by errors in the positions at all. Neither does an incorrect assumption as to the velocity of propagation affect it. A discrepancy here, if not due to observational error, must represent an incorrect delay held at the slave station.

Of course, observations at any four or more points, properly distributed, will determine the station displacements. The theory of this determination is discussed in Appendix D.

PART II
LORAN EQUIPMENT

CHAPTER 7

TIMERS

By R. H. Woodward and J. C. Williams

7·1. General Requirements.—The function of the Standard Loran timer is to control the synchronism of the pulsed transmissions of the ground stations. As explained in Sec. 3·3, a master station transmits a series of pulses at an accurately constant recurrence rate. The time required for the signal to travel from the master station to the slave station is designated as β. The transmission from the slave station is so synchronized with that of the master station that the interval of time (as observed at the slave station) between the reception of the signal from the remote master station and the reception of the locally transmitted slave signal is equal to half the recurrence period L plus the coding delay δ. The slave timer must be capable of measuring this interval of time and maintaining this synchronism with an error of less than 1 μsec. The interval of time (as observed at the master station) between the reception of the master signal and the reception of the slave signal is $(L/2) + 2\beta + \delta$. Although the operator of the master timer does not control the synchronism of the signals, he must be able to measure the time difference between the two signals with an error of less than 1 μsec. If he observes that the synchronism is incorrect, he informs the slave operator and warns navigators of this fact by blinking the locally transmitted signal.

The function of the timer in the Sky-wave Synchronized Loran system is similar to the function of the Standard Loran timer except that since the distance between master and slave stations in the SS system is greater, the value of β is correspondingly greater. The same timing equipment is used for both systems. The function of the Low Frequency timer is somewhat different and is discussed in Sec. 7·14. The Standard Loran timer must be modified for use in the LF system.

Experience has indicated that in order to measure with the required precision time differences between the relatively slow-rising pulses of Standard and SS Loran, the presentation on the cathode-ray oscilloscope should be such that one fast linear trace showing one pulse should appear directly above another fast linear trace showing the other pulse. The timing of the traces must be adjustable so that the two pulses can be made to appear on the fast traces and one pulse can be positioned directly above the other. The vertical spacing between the traces must be adjustable so that when the pulses are vertically aligned, the spacing can be reduced to zero and one pulse thereby superimposed upon the other. Furthermore, the relative amplitudes of the two pulses to be measured (one from the remote transmitter and the other from the local) must be adjustable so that they can be made equal. Under this condition of superposition the time difference between the initiations of the two fast traces is equal to the time difference between the arrivals of the two pulses. The time difference between the initiations of the fast traces is measured by means of calibration markers derived from the blocking oscillators of the divider chain.

The general requirements for the timer are that it shall be capable of providing trigger pulses to the transmitter at any one of a number of accurately constant, predetermined recurrence rates and that the trigger pulses shall bear a precise, predetermined time relationship to the pulsed signals received from a remote station. The equipment, supplemented by duplicate auxiliaries, must be capable of giving continuous service 24 hr. a day with the exception of negligible switch-over time. Appropriate monitoring facilities must be provided to permit operation as either a master or a slave timer.

For satisfactory manual operation the slave timer must be capable of precise adjustment in frequency in relation to the master timer so that one series of pulses drifts with respect to the other less than 1 μsec in 5 to 10 min. For such precise adjustment, both master and slave timers must have crystal oscillators that fluctuate in frequency less than 1 part in 10^9 over short periods of time.

The timing circuits required for initiating the fast traces and triggering the transmitter must be sufficiently flexible to cover continuously a wide range of possible time differences between the reception of the pulse from the remote station and the transmission of the local pulse. The timing circuits and associated sweep circuits must be stable. The calibration markers must be sufficiently clear to permit easy counting of time differences and sufficiently sharp to permit measurement with errors of considerably less than 1 μsec. It must be possible to check and adjust these circuits during service without interfering with their operation.

The bandwidth of the receiver must be wide enough to allow the pulse to rise rapidly for accurate timing and yet narrow enough to give satisfactory signal-to-noise ratios under severe conditions of noise. It has been found experimentally that a 6-db bandwidth of 60 kc/sec is a good compromise value and that bandwidths between 40 and 100 kc/sec are satisfactory.

The early models of the timer (Models A, B, and B-1) were composed of the following units:

1. Oscillator unit, consisting of a highly stable crystal oscillator and a phase shifter.
2. Divider unit, consisting of divider circuits with feedback, locked delay multivibrators for initiating fast traces, sweep generators, calibration-marker circuits, an attenuator circuit of the relay type, and a transmitter-trigger circuit.
3. Oscilloscope.
4. Receiver with amplitude-balance control.
5. Regulated power supply.

The later models (Models C, C-1, and UJ) have been improved in several respects. The phase-shift capacitor of the oscillator is geared to the frequency control in such a way that as it is rotated in maintaining synchronism, the oscillator frequency is automatically adjusted to reduce the rate of drift of the slave timer with respect to the master timer. The locked delay multivibrators used to initiate the fast traces have been replaced by selector circuits, each consisting of a delay multivibrator, which generates a gate of adjustable delay, and a gate-pulse mixer that permits the selecting of the highly stable pulses from the dividers for triggering other selector circuits and the fast-sweep generator. This selector circuit has the advantage that its adjustment can be checked without interfering with the operation of the timer. The single oscilloscope has been replaced by a dual oscilloscope, one cathode-ray tube displaying the two fast traces and the other displaying the complete recurrence cycle on two slow traces. An additional oscilloscope is used for checking the adjustment of the divider and selector circuits while the timer is in service. A synchronizer automatically controls the frequency of the oscillator of the slave timer to maintain the prescribed time difference between the reception of the remote signal and the transmission of the local signal.

The most recent version of the timer (Model UE-1) has been more carefully engineered than the earlier models, but it has few fundamentally new features. Probably the most important innovation is a motor-driven phase-shift capacitor that is geared to the frequency control of the oscillator. The rotation of the phase-shift capacitor is controlled by the synchronizer. The advantages of the mechanical coupling between the synchronizer and the oscillator over the earlier electronic coupling are that the high stability of the oscillator is retained and the rate of drift is reduced to a minimum by the operation of the geared frequency control. As the rate of drift is reduced, the rate of phase compensation can be reduced with the result that the synchronizer operates smoothly and reliably under severe conditions of noise.

7·2. Timer Models A, B, and B-1.—Models A, B, and B-1 are the first three series of timers that were designed for the Loran system. A

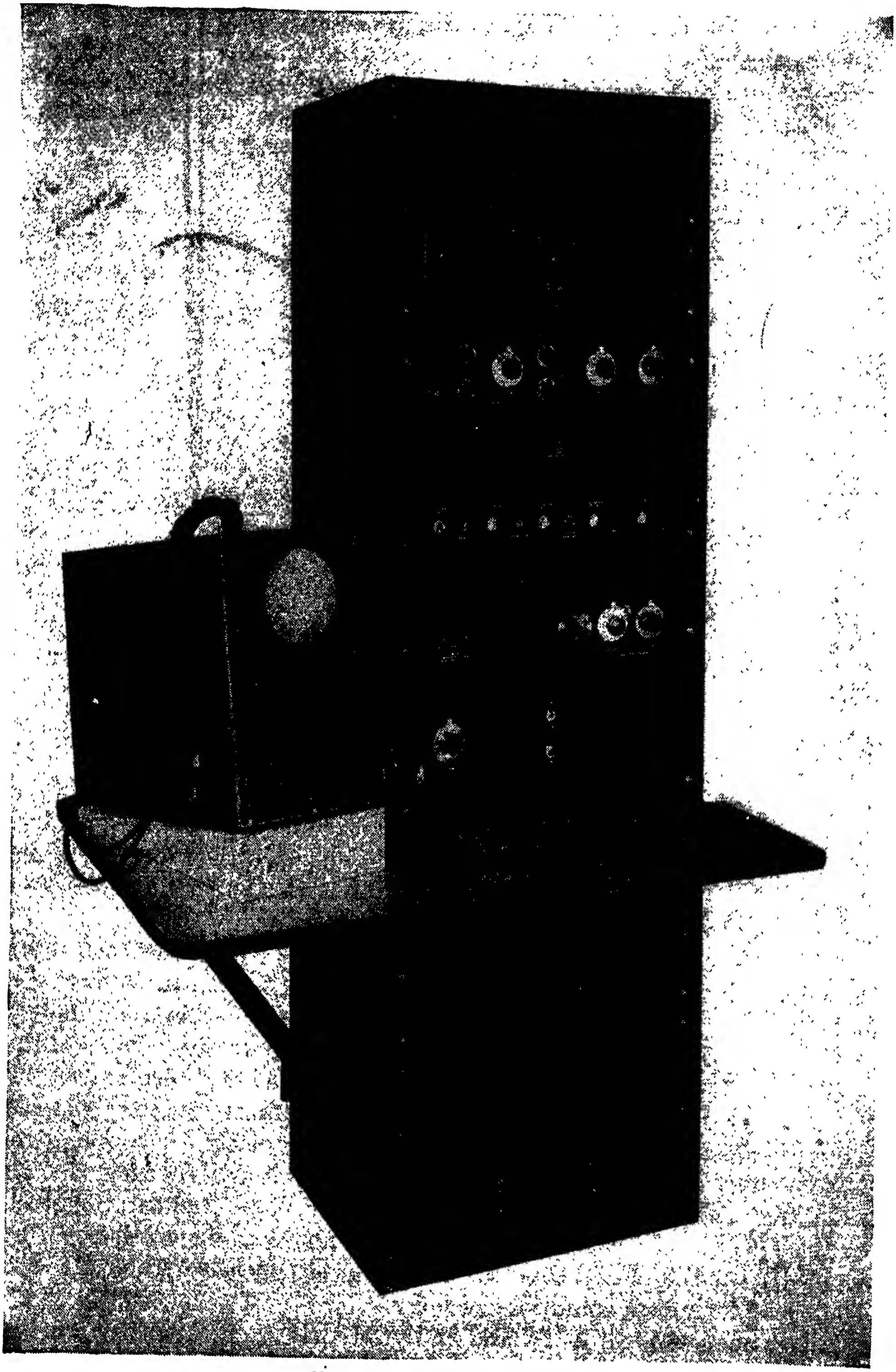


Fig. 7·1.—Model B-1 timer.

total of 56 timers of these types were constructed at the Radiation Laboratory and at Research Construction Company. Since many of them are still in active service in the North Atlantic chain, the Aleutians, and many parts of the Pacific and probably will be for some time to come, it seems desirable to give a general description of the Model B-1 timer (see Fig. 7·1) in spite of its obsolescence.

Although the construction is somewhat crude, the fundamental design is similar to that of the modern timers. The block diagram of the Model B-1 timer and attenuator is shown in Fig. 7·2. As mentioned in Sec. 7·1, one fast linear trace showing one pulse is presented on a cathode-ray tube directly below another such trace showing the other pulse. Since the local transmitter is triggered at the same instant that one fast trace is initiated, the local pulse remains stationary. The remote pulse on the other fast trace drifts slowly to the right or to the left if the recurrence rate of the local timer differs slightly from the recurrence rate of the remote timer. In operation, at a slave station, the time difference between the initiations of the two fast traces (one for the local pulse and one for the remote pulse) is adjusted to a predetermined value. The remote pulse is placed on its fast trace below the local pulse on its fast trace. The recurrence rate of the local timer is then adjusted to the recurrence rate of the remote master timer until the remote pulse ceases to drift. By adjusting the phasing of the local timer, the remote pulse is moved directly below the local pulse. The amplitudes of the local and remote pulses are next equalized, and the vertical spacing between the two traces is eliminated so that one pulse is superimposed on the other. As long as they remain superimposed, the time difference between the reception of the remote pulse and the transmission of the local pulse is equal to the predetermined time difference between the initiations of the two fast traces. This time difference between the initiations of the fast traces is adjustable and is measured precisely by means of calibration markers.

A slow-trace presentation is provided to aid the operator in placing the remote pulse on the fast trace. It consists of two slow linear traces, each of one-half the recurrence period, one placed below the other. The duration and timing of the fast traces with respect to the slow-trace pattern are indicated by pedestals on the slow-trace pattern.

The Loran technique for measuring time difference requires timing equipment of high stability. The only device with the required stability is a crystal oscillator. Accordingly, a 50-kc/sec, X-cut quartz bar, suspended in a thermostatically controlled oven, is used in the Model B-1 timer to control the oscillator frequency. The circuit consists of an amplifier, a phase inverter, and a resistance and lamp bridge which serves as an automatic volume control.

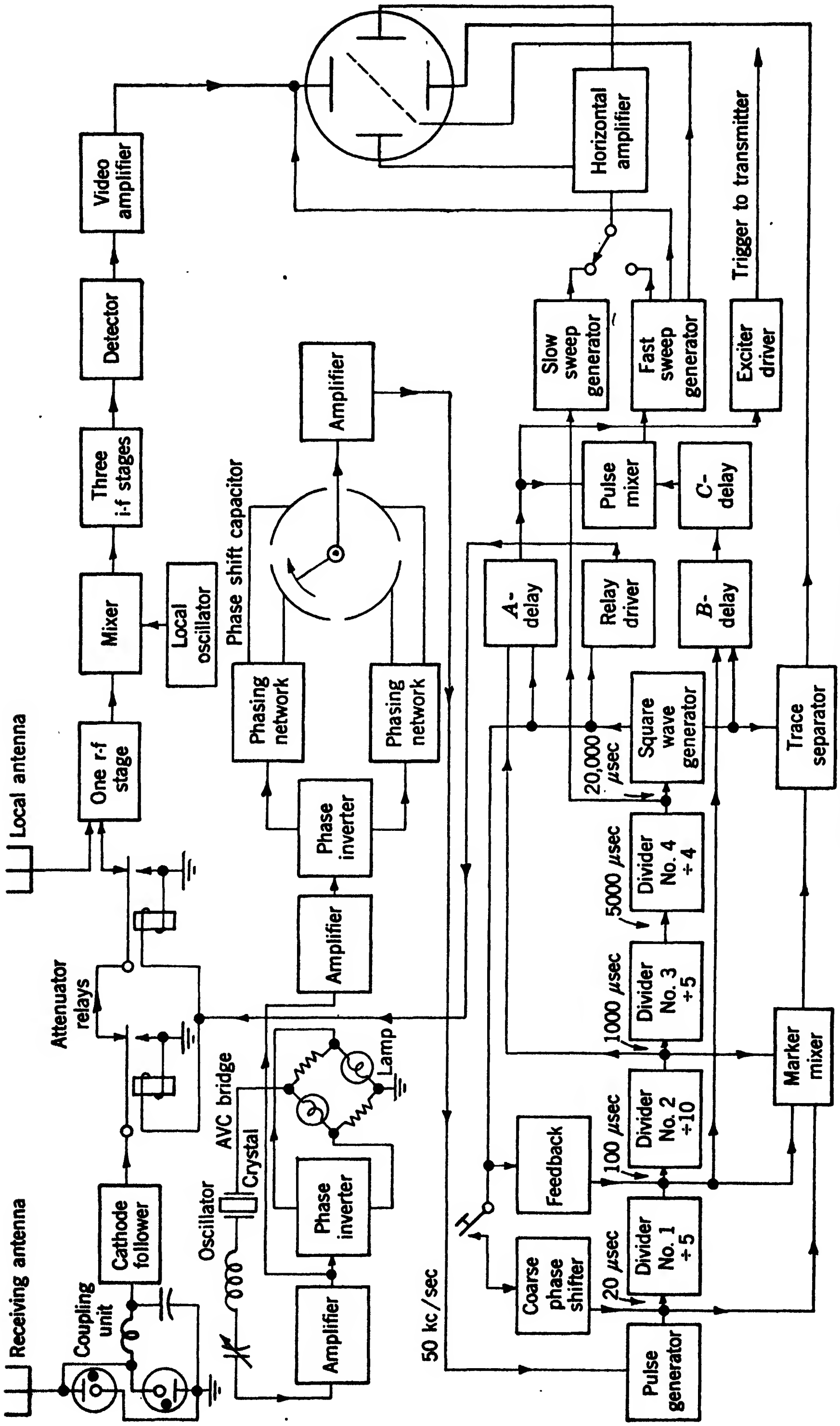


Fig. 7·2.—Block diagram of Model B-1 timer.

The phase-shift capacitor is a convenient device for precise shifting of the phase of the timer. The voltages impressed on its four sets of stator plates are mutually 90° out of phase. The phase of the voltage induced on the rotor plates varies uniformly as the rotor is turned from one set of stator plates to another. One complete turn shifts the phase of the output voltage one cycle (20 μsec) with respect to the voltage from the oscillator. In operation this causes the remote pulse to move along the trace a distance corresponding to 20 μsec. Fractions or whole numbers of rotations produce proportional positive or negative shifts of phase.

The 50-kc/sec sine wave from the phase-shift capacitor must be reduced in frequency to a pulse recurrence rate of approximately 25 pps. Because of their greater precision, pulses of short duration are used instead of sine waves. An amplifier that is rapidly driven from cutoff to saturation converts the 50-kc/sec sine waves to square waves which on differentiation become positive and negative pulses recurring every 20 μsec. The pulse recurrence rate is reduced from 50,000 to 50 pps by a series of four dividers. A divider is a device that produces a single output pulse for a given whole number of input pulses. It consists of a capacitor that is charged in steps by the input pulses acting through a double diode and of a blocking oscillator that discharges the capacitor and produces an output pulse when the voltage of the capacitor reaches a certain value. The four dividers are arranged to divide by 5, 10, 5, and 4, which produces series of pulses with recurrence periods of 100, 1000, 5000, and 20,000 μsec respectively. The recurrence period of the last divider is one-half the recurrence period required for Loran transmission.

The recurrence period is doubled by a square-wave generator to give the recurrence rate of 25 pps required for Loran transmission. The square wave is impressed on the vertical plates of the cathode-ray tube to give the vertical displacement of the slow-trace presentation. The upper section of the square wave becomes the upper trace, and the lower section becomes the lower trace. The spacing between the two traces is adjustable.

Since several pairs of Loran transmitters must operate on a single radio frequency, it is necessary that they transmit at slightly different recurrence rates to permit a navigator to distinguish the signals of one pair from those of another and to obtain time-difference measurements from any pair of transmitters. The timing of each recurrence rate must be precise; and, for the sake of economy, it is desirable that all recurrence rates be derived from a single crystal oscillator. This is accomplished by feeding a pulse from the square-wave generator back into the second divider in such a way that it charges the capacitor of the second divider. If the charge from the square-wave generator is equivalent to a single charge from the first divider, the capacitor of the second divider is discharged after receiving 9 charges from the first divider instead of the normal 10 (in 900 μsec instead of the normal 1000 μsec), and the final recurrence period becomes 39,900 μsec instead of the 40,000 μsec with no feedback. Similarly, if larger charges are fed from the square-wave generator back into the second divider, recurrence periods of 39,800, 39,700, 39,600, 39,500, 39,400, and 39,300 μsec can be obtained. The corresponding eight recurrence rates (numbered 0 to 7) are called "specific recurrence rates." A second set of eight recurrence rates is obtained by adjusting the last divider to divide by 3 instead of 4. The two different sets of recurrence rates, approximately $33\frac{1}{3}$ and 25 pps, obtained by adjusting the last divider are called the high and low, *H* and *L*, "basic recurrence rates."

A coarse phase-shift control is required for quickly bringing the slave timer into approximate synchronism with the remote master timer. For this purpose pulses from the last divider are fed back into the first divider through a push-button switch.

The oscillator, dividers, and square-wave generator produce the required recurrence period, which is represented as two slow traces, one below the other, on a cathode-ray tube. The relative timing and duration of the fast traces are indicated by pedestals on the slow traces. The receiver-output signals produce vertical deflections on the two traces and show the relative timing of the signal from the remote station with respect to the slow-trace pattern. The location of the remote signal on the slow trace can be adjusted by means of the coarse (feedback) and fine (phase-shift capacitor) phase controls.

The time difference between the initiations of the fast traces is adjusted to equal the required time difference between the remote and local pulses. At the slave station the remote (master) pulse must precede the local (slave) pulse by half the recurrence period plus a small constant time difference called the "coding delay." If necessary this delay can be changed, according to a predetermined schedule, to confuse the enemy. Thus the master pulse precedes the slave pulse over the entire coverage area and so can be readily identified by the navigator. At the master station the local (master) pulse precedes the remote (slave) pulse by half the recurrence period plus the coding delay plus twice the time required for a radio wave to travel from one station to the other.

The required time differences are obtained from the *A*-, *B*-, and *C*-delay multivibrators. Since delay multivibrators are not sufficiently stable to give long delays with the required precision, the *A*- and *B*-delay multivibrators are locked by pulses from the second and first dividers respectively. The *A*-delay multivibrator gives delays that are multiples of 1000 μsec and is adjustable from 1000 to 10,000 μsec. The *B*-delay multivibrator gives delays that are multiples of 100 μsec and is adjustable from 300 to 2500 μsec. The *C*-delay multivibrator is unlocked and is variable continuously from 30 to 170 μsec.

At the slave station the multivibrators are arranged so that the A-delay multivibrator is triggered at the start of one slow trace. This multivibrator is adjusted to give a delay of 2000 μsec after which it triggers the fast-sweep generator and the local transmitter. The B-delay multivibrator is triggered at the start of the other slow trace. It triggers the C-delay multivibrator which in turn triggers the fast-sweep generator. The B- and C-delay multivibrators are adjusted to place the master pedestal to the left of the slave pedestal by a distance corresponding to the coding delay.

At the master station the fast-sweep generator and the local transmitter are triggered at the start of the upper trace. The three delay multivibrators are arranged in series so that the A-delay multivibrator, which is triggered at the start of the lower trace, triggers the B-delay multivibrator, which in turn triggers the C-delay multivibrator. The C-delay multivibrator initiates the fast trace. Thus the time difference between the initiations of the two fast traces is variable continuously from a little more than 1000 μsec to a little more than 10,000 μsec (plus half the recurrence period). With the proper time difference $(2\beta + \delta + L/2)$ between the initiations of the two fast traces, the operator at the master station should find the remote signal directly below the local signal on the fast traces. If he does not, the signals are improperly synchronized, and he notifies the slave operator of this condition by blinking his transmitter on and off.

For the precise measurement of the time difference between the initiations of the fast traces, calibration markers are displayed on the slow and fast traces. Pulses from the pulse generator, the first divider, and the second divider are mixed and impressed on the vertical plates of the cathode-ray tube to form 20-, 100-, and 1000-μsec calibration markers. By means of the 1000-μsec markers displayed on the slow traces, the horizontal displacement of the lower pedestal to the right or left of the upper pedestal is estimated to the nearest thousand microseconds. On fast traces of approximately 1500-μsec duration, the displacement of the 1000-μsec markers on the lower trace with respect to those on the upper trace is estimated to the nearest hundred microseconds. Similarly, on fast traces of approximately 150-μsec duration the displacement of the 20- and 100-μsec markers is estimated to the nearest microsecond.

MODEL C-1 TIMER

7·3. General Description of Timer Models C, C-1, and UJ.—The first completely redesigned timer, the Model C, occupies twice the cabinet space of the earlier models but is designed for ease of operation and for reliability in service. A dual oscilloscope gives a simultaneous display of both the slow- and fast-trace pattern, and a test oscilloscope provides a convenient means of adjusting the timer while it is in service. The locked delay multivibrators of the earlier models are replaced by selector circuits that serve the same purpose but have the advantage that they

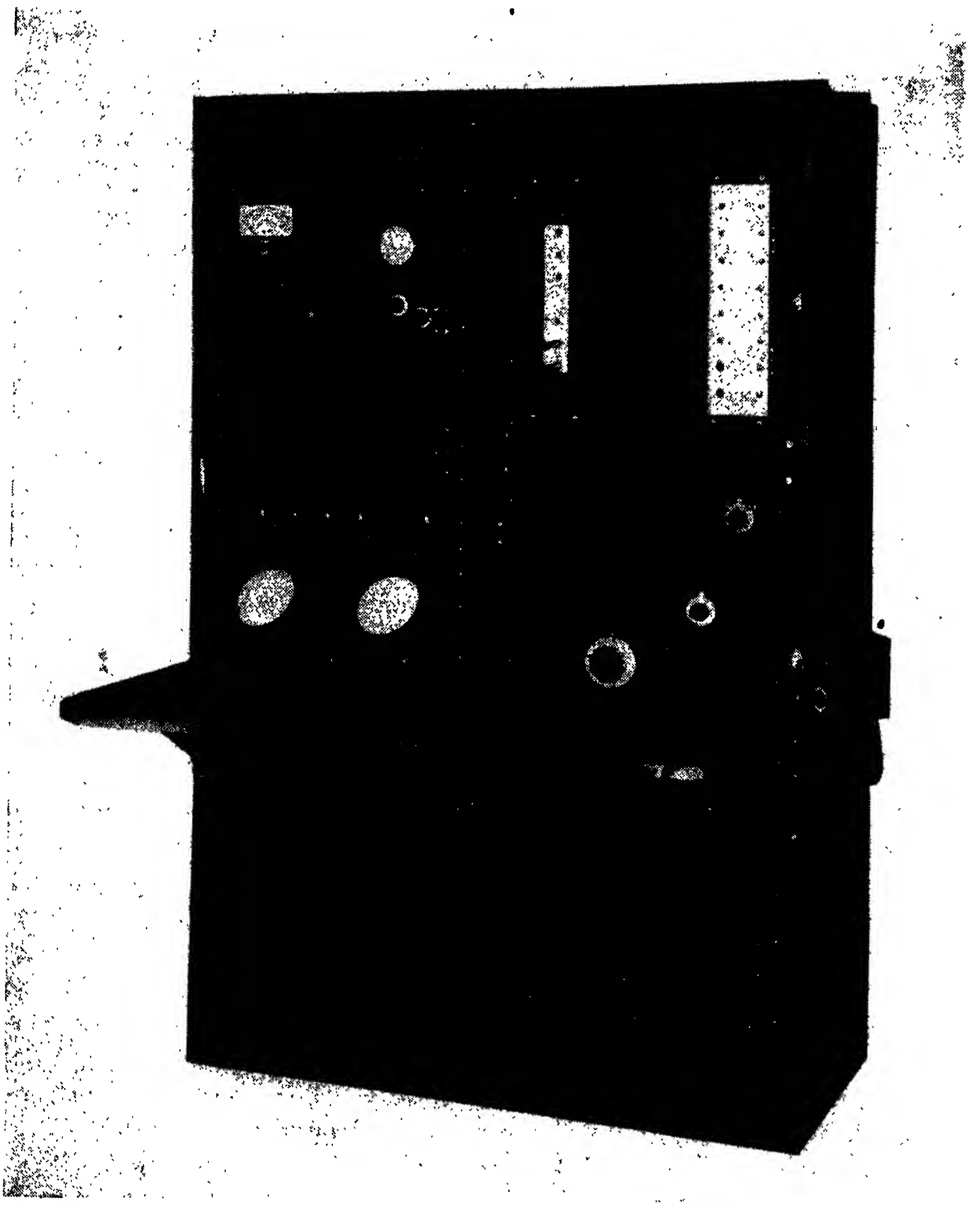


FIG. 7·3.—Model C-1 timer.

can be adjusted in service without interfering with their operation. Maintenance of synchronism at the slave station is simplified by gearing the phase-shift capacitor to the frequency control. An automatic synchronizer further facilitates the operation of the Model C timer by correcting the frequency and phase of the oscillator in the slave timer with reference to the pulsed signal received from the master station.

The 70 Model C-1 timers and the 80 Model C timers that were manufactured by Research Construction Company differ in few respects. A clutch in the geared mechanical coupling between the phase-shift capacitor and the frequency control of the Model C-1 oscillator permits the adjustment of the phase without altering the frequency adjustment. The trace-separation circuits are modified so that only the vertical separation between the fast traces is adjustable, whereas the separation between the slow traces is fixed. The 60 Model UJ timers manufactured by Du Mont Laboratories are similar to the Model C-1 timers.

As shown in Fig. 7·3 the Model C-1 timer is housed in two standard relay-rack cabinets bolted together. The cabinet on the left contains the power-distribution panel, the test oscilloscope, receiver, dual oscilloscope, and automatic synchronizer. The cabinet on the right contains the divider and selector circuits, the oscillator, and the high- and low-voltage power supplies. A small box mounted on the side of the cabinet contains the controls for the synchronizer.

7·4. Block Diagram of Model C-1 Timer.—A block diagram of the Model C-1 timer with the attenuator, antenna, and antenna coupling units is shown in Fig. 7·4. It differs from the Model B-1 timer in the larger number of dividers, the substitution of two selectors for the locked delay multivibrators, the addition of a synchronizer, and the incorporation of individual cathode-ray tubes for both the fast- and the slow-trace presentations. The test oscilloscope is not shown in the block diagram.

Crystal Oscillator.—The oscillator, similar to that of the Model B-1 timer, is controlled by a 50-kc/sec quartz bar that is mounted in a constant-temperature oven. The oscillator is sufficiently stable to maintain synchronism between the local and remote timers without adjustment for at least three minutes with an error not exceeding 1 μsec. The frequency of the oscillator can be varied several parts per million above and below the nominal value of 50 kc/sec.

Phase-shift Capacitor.—Like that of the B-1 timer, the phase-shift capacitor serves as the fine adjustment of phase, a single rotation of the phase-shift capacitor shifting the phase of the local signal one cycle, or 20 μsec, with respect to the signal from the remote station. Fractions or whole numbers of rotations produce proportional shifts of phase. The phase-shift capacitor is geared to the oscillator frequency in such a way that as the phase-shift capacitor is rotated in maintaining synchronism, the oscillator frequency is automatically adjusted to reduce the difference in the frequencies of the local and remote oscillators.

Frequency Doubler.—The oscillator frequency of 50 kc/sec was chosen because, of the available crystals, those operating at 50 kc/sec were most

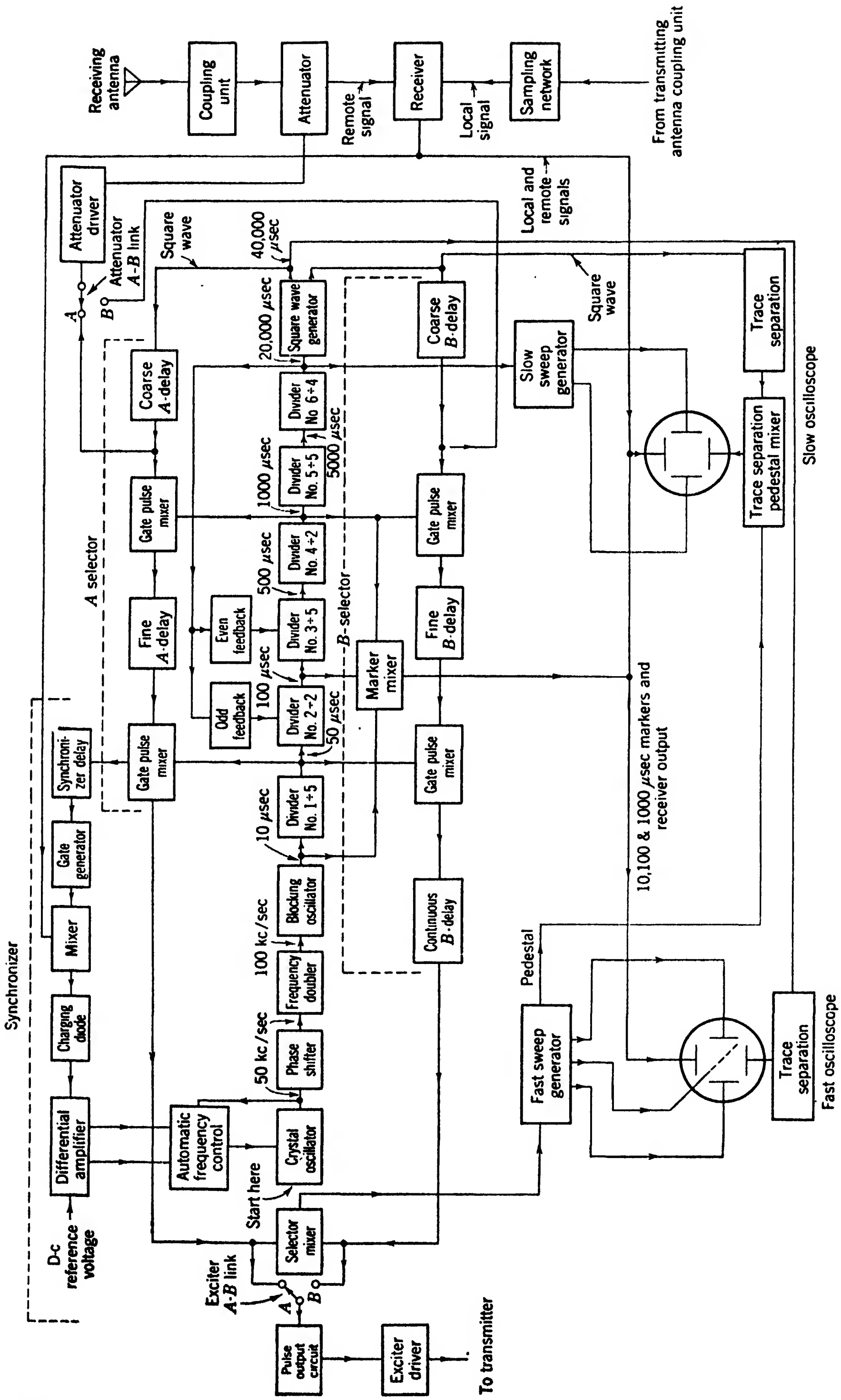


FIG. 7·4.—Block diagram of Model C-1 timer.

stable. To provide 10-μsec calibration markers and to simplify the divider-feedback circuits, the 50-kc/sec signal from the phase-shift capacitor is doubled to 100 kc/sec.

The blocking oscillator is controlled by the sinusoidal signal from the frequency doubler and produces, at 10-μsec intervals, sharp, precisely timed pulses that drive the dividers and serve as calibration markers.

Dividers.—A series of six dividers reduces the recurrence rate (100,000 pps) of the blocking oscillator to that desired for the slow and fast traces. For operation at the low basic recurrence rate (50 sweeps per second or 25 locally transmitted pulses per second), the six dividers are adjusted to divide by 5, 2, 5, 2, 5, and 4, respectively. For operation at the high basic recurrence rate ($33\frac{1}{3}$ pps), the last divider is adjusted to divide by 3. The last divider triggers the slow-sweep generator and the square-wave generator.

Eight specific recurrence rates (from zero through seven) at each of the two basic recurrence rates are derived from a single crystal oscillator by feeding pulses of adjustable amplitude from the last divider back into the second and third dividers. The second divider receives pulses from the first divider at intervals of 50 μsec and is adjusted to divide by 2. Therefore, if the amplitude of the pulse fed back from the last divider is equivalent to that received from the first divider, the recurrence period of the second divider is reduced from 100 to 50 μsec once for every recurrence period of the last divider. The recurrence period of the last divider is reduced therefore by 50 μsec. The amplitude of the pulse fed back from the last divider into the second divider can be adjusted either to reduce the recurrence rate of the last divider by 50 μsec or not to reduce it at all.

Similarly, the third divider receives pulses from the second divider at intervals of 100 μsec and is adjusted to divide by 5. The amplitude of the pulse fed back from the last divider into the third divider, therefore, can be adjusted to reduce the recurrence period of the last divider by 0, 100, 200, or 300 μsec. The combination of feedback into the second and third dividers provides for reduction of the recurrence period of the last divider by 0, 50, 100, 150, 200, 250, 300, or 350 μsec. Since the recurrence period of the square-wave generator and of the transmitted signal is twice that of the last divider, the reduction of their recurrence period is 0, 100, 200, 300, 400, 500, 600, or 700 μsec.

The square-wave generator (Eccles-Jordan circuit) is made up of two symmetrically connected triodes, one of which conducts while the other is nonconducting. Each pulse from the last divider reverses the conducting and nonconducting states of the triodes. The plate circuits of the triodes provide two square-wave output voltages that are mutally 180° out of phase. The square-wave generator divides the recurrence rate of the last divider by 2, provides the vertical displacement of alternate traces of both the fast- and slow-sweep oscilloscopes, and triggers the A- and B-selectors, one of which in turn triggers the transmitter.

Selectors.—A selector is a series of circuits that, after being triggered, selects a pulse from one of the dividers and emits a pulse following the trigger pulse by an adjustable period of time. It permits the introduction of an adjustable time delay that has the inherent stability of the dividers. It has the further advantage that its adjustment can be observed and corrected without interfering with the operation of the circuits.

Two selectors, both triggered by the square-wave generator, are used to initiate the fast traces and so to establish the time difference between the reception of the signal from the remote station and the transmission of the local signal.

The A-selector, which is triggered at the start of the upper trace of the slow-trace pattern, initiates the fast trace which is represented by the upper pedestal shown in Fig. 7·5*a*. It can be adjusted to introduce a time delay equal to $1000M$ μsec plus $50N$ μsec, where M is an integer from 1 to 12 and N is an integer from 1 to 13.

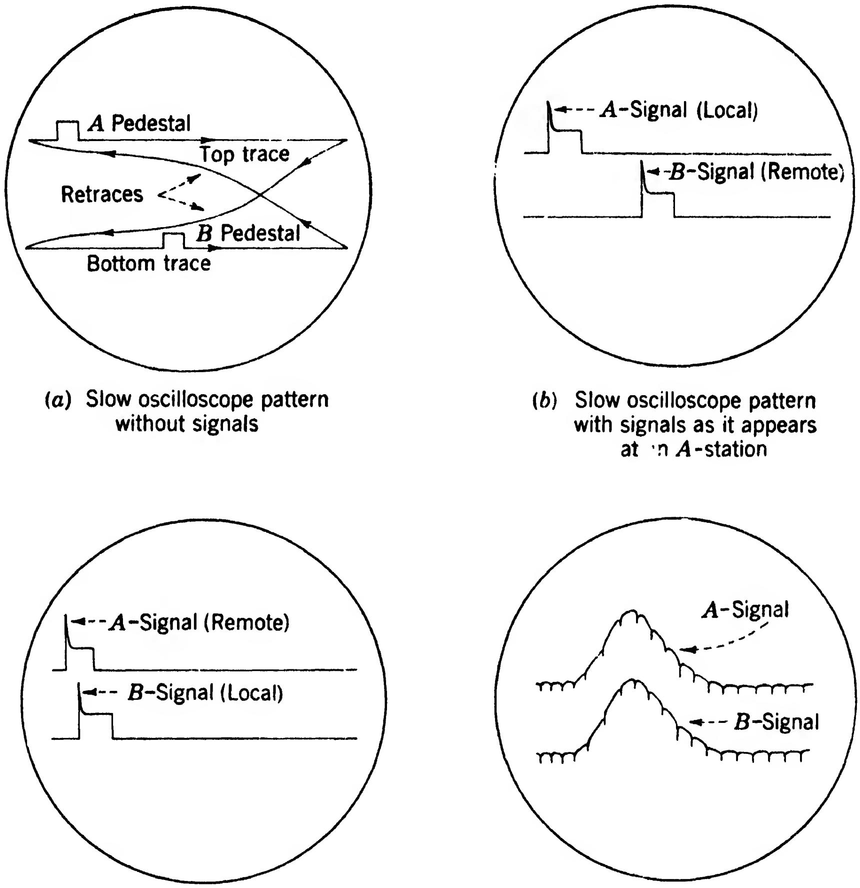
Likewise, the B-selector, which is triggered at the start of the lower trace, initiates the fast trace which is represented by the lower B-pedestal. It can be adjusted to introduce a delay equal to $1000M$ μsec plus $50N$ μsec plus P μsec, where M and N have the values given above and P is a number, not necessarily an integer, between 40 and 120. Thus, although neither selector can be continuously varied over the range, the time difference between the two fast traces can be adjusted to any value between 0 and 11,500 μsec (plus one-half the recurrence period). As shown in Fig. 7·5*b* and *c*, the B-pedestal is placed to the right of the A-pedestal at both the master and slave stations.

The coarse delay is a delay multivibrator that is triggered by the square-wave generator and that can be adjusted to introduce a time difference between 1000 and 12,000 μsec. The differentiated output voltage, called a "gate," cuts off one triode of the mixer for a period of approximately 1000 μsec.

The gate-1000-μsec pulse mixer is a coincidence mixer which consists of two triodes whose plates are connected (the so-called Rossi "coincidence circuit"). When both triodes are cut off at the same time, a large positive output pulse is produced; a relatively small pulse is produced when only one triode is cut off. Negative pulses recurring every 1000 μsec from the fourth divider are applied to one grid; the differentiated negative gate from the coarse delay multivibrator is applied to the other grid. Thus, adjustment of the coarse delay permits the selection of a particular pulse from the divider to trigger the fine delay.

The fine delay is a delay multivibrator that can be adjusted to introduce a time difference of 50 to 650 μsec. The output signal is differentiated to produce a gate approximately 50 μsec long.

The gate-50-μsec pulse mixer is similar to the coincidence mixer described above. It selects a particular pulse from the first divider.



(a) Slow oscilloscope pattern without signals

(b) Slow oscilloscope pattern with signals as it appears at an A-station

(c) Slow oscilloscope pattern with signals as it appears at a B-station

(d) Fast oscilloscope pattern with markers and with A- and B-signals aligned

FIG. 7·5.—Basic oscilloscope patterns.

The continuous delay is a multivibrator whose delay can be varied continuously from 40 to 120 μsec.

Exciter Driver.—At a master station the pulse-output circuit is connected to the A-selector so that the local pulse appears on the upper or A-pedestal. At a slave station it is connected to the B-selector so that the local pulse appears on the lower or B-pedestal. The pulse-output circuit and exciter driver amplify and shape the pulse that drives the local transmitter.

Marker Mixer.—Calibration markers derived from the dividers are mixed and applied to the vertical plates of the fast and slow oscilloscopes for the measurement of the time difference between the initiations of the two fast traces. The 10-μsec markers are derived from the 100-kc/sec blocking oscillator; the 100-μsec markers are derived from the second divider; and the 1000-μsec markers are derived from the fourth divider.

Sweep Generators.—The output pulses from the *A*- and *B*-selectors are mixed and applied to the fast-sweep generator to produce the upper and lower traces on the fast-sweep oscilloscope and the upper and lower pedestals on the slow-sweep oscilloscope.

When the fast-sweep generator is triggered, it produces two equal and opposite voltage outputs that vary linearly with time and are applied to the horizontal deflecting plates of the cathode-ray tube. The intensifying grid of the cathode-ray tube is so biased that the electron beam is blanked out except for the duration of the fast trace. In this way the short intervals of time represented by the pedestals on the slow-trace pattern are expanded to form the fast-trace pattern of Fig. 7·5*d*, which shows the remote and local signals and the calibration markers.

The slow-sweep generator is synchronized by pulses from the last divider and produces two voltage outputs that vary linearly with time during the interval between the synchronizing pulses. These equal and opposite voltage outputs are impressed on the horizontal plates of the slow-sweep oscilloscope to produce the two linear traces of the slow-trace pattern shown in Fig. 7·5*a*.

Trace Separator.—The voltage output of the square-wave generator is applied to the vertical plates of both the slow- and fast-sweep oscilloscopes to produce the separation between the upper and lower traces. On the fast-sweep oscilloscope the separation is variable, whereas on the slow-sweep oscilloscope the separation is fixed.

An output voltage from the fast-sweep generator is mixed with that from the trace separator and impressed on the vertical plates of the slow-sweep oscilloscope to produce the upper and lower traces and pedestals shown in Fig. 7·5*a*.

Attenuator-bias Driver.—Since the attenuator does not respond instantaneously, it is necessary to apply the attenuating bias some time before the transmission of the local signal. The attenuating bias is initiated, therefore, by a pulse from the coarse *A*- or *B*-delay multivibrator, the choice depending on the operation of the timer as master or slave. The operation of the attenuator is described in Sec. 8·3.

Receiver.—The attenuated local signal from the sampling network and the signals from the receiving antenna are amplified in the receiver and impressed on the plates of the fast- and slow-sweep oscilloscopes to produce vertical deflections.

The receiver is a superheterodyne with one stage of r-f amplification, a frequency converter, three stages of i-f amplification, a video amplifier, and an output cathode follower. A ganged tuning capacitor tunes the receiver over a frequency range of 150 kc/sec. By the adjustment of three slug-tuned coils the center of the capacitor tuning range can be set at any frequency between 1750 and 2100 kc/sec. The intermediate frequency is 1600 kc/sec. The over-all bandwidth is approximately 65 kc/sec at 6 db down from maximum response and 140 kc/sec at 30 db down. The receiver noise is equivalent to an input signal of less than 3 μv, and the sensitivity is such that a 15-μv signal saturates the video amplifier and gives a deflection of 2 in. on the dual oscilloscope.

The signals from the electronic attenuator are introduced to the receiver through a resistance network. The electronic attenuator eliminates all signals induced on the receiving antenna for a short time (approximately 1800 μsec) during which the local signal is transmitted. The local signal is picked up on a small loop located near the transmitting-antenna coupling unit and is introduced to the receiver through a potentiometer in the resistance network. The potentiometer permits the equalization of the amplitudes of the local and remote signals as they appear on the cathode-ray tubes.

Synchronizer.—The synchronizer automatically controls the frequency of the oscillator of the slave timer in order to maintain the prescribed time difference between the reception of the remote signal and the transmission of the local signal. A gate, adjustable in time to give the prescribed time difference, is used to sample, for the duration of the gate, the voltage of the signal from the master (remote) station. The sampled voltage is applied to the crystal oscillator to control the frequency in such a way that the gate seeks a position a third of the way up the leading edge of the signal from the master station. The same equipment is used at the master station (but disconnected from the oscillator) to sound an alarm when the synchronism is incorrect.

Test Oscilloscope.—The test oscilloscope is designed for checking the operation of the timer and especially of the dividers and selectors, which are so designed that they can be checked while the timer is in service without interfering with its operation. The schematic diagram is shown in Fig. 7·6.

The test oscilloscope consists of a 3-in. cathode-ray tube, a video amplifier, a sweep generator, and a delay multivibrator. A selection of three sweep speeds giving full deflection in approximately 130, 2400, and 22,000 μsec is available. Pulses from any one of the last four dividers or from the square-wave generator can be used to trigger the delay multivibrator which in turn triggers the sweep generator. The time difference introduced by the delay multivibrator between the input trigger pulse

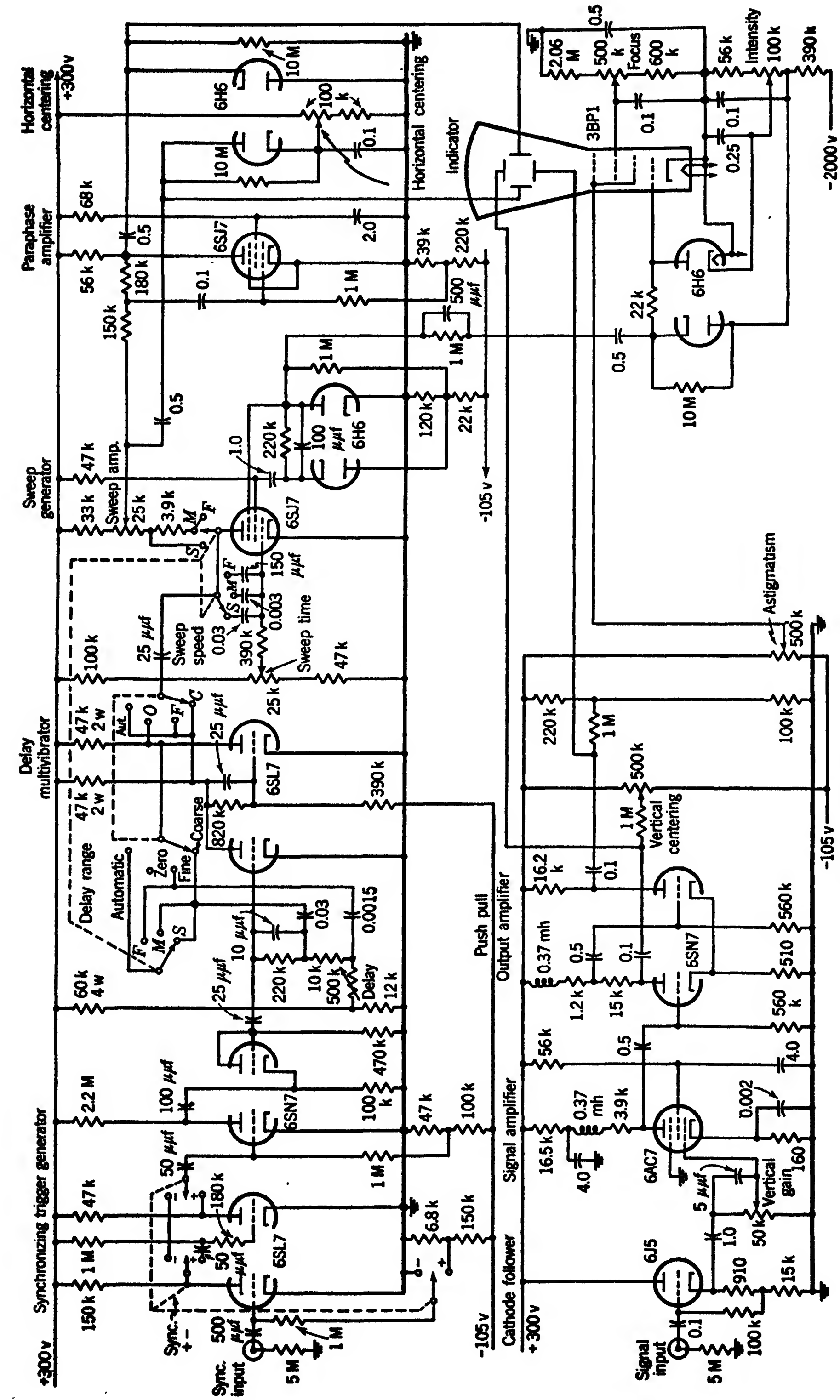


Fig. 7·6.—Schematic diagram of Model C-1 test oscilloscope.

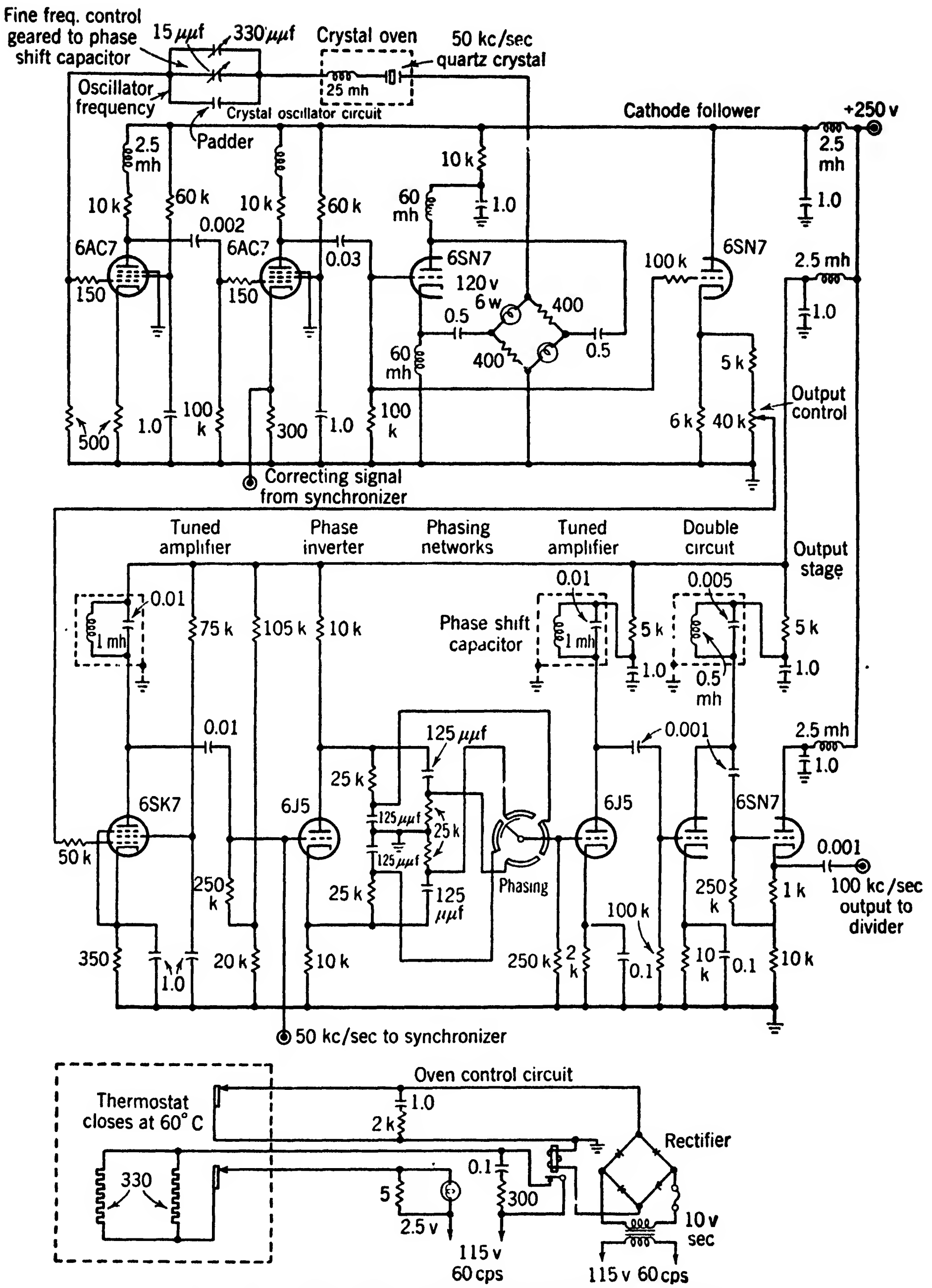


FIG. 7·7.—Schematic diagram of Model C-1 oscillator.

and the initiation of the trace can be adjusted from 25 to 18,000 μsec so that almost any desired portion of the period between trigger pulses can be displayed on the cathode-ray tube.

7·5. Model C-1 Oscillator.—As shown in Fig. 7·7, the oscillator consists of a crystal, an amplifier, an automatic volume control, and a series inductance, capacitance, and resistance circuit. A signal applied to the amplifier is increased about one-hundred fifty times and applied to the automatic volume control, which maintains a constant amplitude of oscillation. The output of the automatic volume control drives the crystal at its natural frequency of 50 kc/sec. In series with the crystal, tuning coil, and resistor is a variable capacitor that controls the frequency. The signal generated across the resistor and applied to the amplifier completes the oscillator circuit.

The oscillator must be stable to 1 part in 100 million for an hour or two at a time. This requirement means that the Q of the crystal must be high lest its frequency of oscillation be appreciably influenced by variations in the electrical driving circuit. It must have a low-temperature coefficient; the oven temperature must be constant; and the electrical driving circuit must be so designed that any phase shift which it introduces will be small and stable.

The crystal is an X-cut quartz bar that oscillates at 50 kc/sec. The dimensions are 54 mm along the Y-, or mechanical, axis; $9\frac{1}{2}$ mm along the X-, or electrical, axis; and $7\frac{1}{2}$ mm along the Z-, or optical axis. The upper and lower surfaces ($7\frac{1}{2}$ by 54 mm) are electroplated, and electrical contact is made to them through very fine wires that are soldered to the metallic plating at the center of each surface. The crystal is supported between a cork pad and a felt pad of small cross section, which clamp the plated surfaces at the center points to which the wires are soldered. Since these points are nodes of vibration at the desired frequency, the clamping does not seriously affect the vibration of the crystal. The clamping pressure is controlled by a screw adjustment on the crystal mount.

The dimensions of the crystal are chosen to give a high Q and a low temperature coefficient. If the crystal is represented by its equivalent electrical circuit of an inductance, capacitance, and resistance in series, Q is the ratio of ωL to R. The Q is approximately 65,000, and the resistance is approximately 3500 ohms. The temperature coefficient is negative, about 1 part per million per degree centigrade at an operating temperature of 60°C.

Baffle plates are mounted at short distances from the ends of the crystal to serve as sound reflectors. They reduce the amount of sound energy uselessly radiated and so increase the Q of the crystal. Since at reflection the sound wave is reversed in phase, the reflected wave at the end of the crystal should be in phase with the transmitted wave to reinforce the normal vibration. The baffles are therefore adjusted for a distance of a quarter wavelength of 50-kc/sec sound in air.

The crystal oven consists of an outer aluminum case, an insulating layer of asbestos, and an interior aluminum case that contains the crystal, its mount, and the inductor. The outer aluminum case is heated by six heater cards, one attached to each side. A mercury thermostat, mounted on one side of the outer aluminum case, controls the temperature by opening and closing the circuit through the heater cards. A balsa-wood box encloses and thermally isolates the whole assembly.

Heat is applied to the outer case for about 1 min out of a 4-min cycle when the room temperature is 20°C. The heat "ripple" caused by the on-and-off heating cycle is smoothed by the filtering action of the alternate conducting and insulating layers. The aluminum cases can be considered as having large thermal capacitance, and the insulating layer can be considered as offering resistance to the flow of heat.

A mercury thermometer extending into the inner case indicates externally the temperature of the crystal. The absolute value under normal stable conditions is not important as long as it is within a few degrees of 60°C. After the crystal temperature has reached equilibrium, it should be stable to within $\frac{1}{10}$°C.

The oven temperature is raised when a relay allows current to flow in the heater cards. This relay is actuated by the mercury thermostat that consists essentially of a glass tube of fine bore into which a pair of fine contact wires are sealed. The contacts are so placed that they complete a circuit through the mercury column at about 60°C. Mounted on the outer aluminum case, the thermostat assumes the temperature of the metal. A rise in temperature of the outer oven closes the circuit through the relay coil, pulls up the armature of the relay, and opens the contacts of the heater circuit. Upon cooling, the circuit through the relay coil opens and allows the armature to fall back and close the heater circuit again.

Because of its location, the thermostat has no immediate control over the temperature of the inner oven, and at least three hours are required for the crystal to reach a stable operating temperature.

Because of the small size of the mercury thermostat, the short-circuit current must be limited to 10 ma and the voltage, when the circuit is open, to 12 volts.

A selenium bridge rectifier converts 10-volt alternating current from the transformer to 8-volt direct current for the purpose of operating the relay. The transformer is protected by a fuse against short circuits in the rectifier.

The amplifier, which furnishes the power to drive the oscillator, consists of two pentode tubes. Each tube operates under Class A conditions and has a gain of about 13. Small inductances have been introduced in the plate circuits to minimize the phase shift, and the unbypassed cathode resistors provide degenerative feedback to reduce distortion.

The automatic volume control consists of a phase-inverting tube and a bridge composed of two fixed resistors and two lamps whose resistance varies with temperature. The phase inverter is a triode with equal impedances in plate and cathode circuits. The cathode-output signal is in phase with the input signal on the grid; the plate-output signal is 180° out of phase with the grid signal. Since the same current is flowing in the plate circuit as in the cathode circuit, and since the plate and cathode impedances are equal, the 50-kc/sec alternating voltages at the plate and cathode are equal.

When the oscillator is turned on, the lamps are cold, their resistance is low, and the bridge is unbalanced; consequently a large signal is impressed on the crystal. The mechanical vibration of the crystal and the piezoelectric signal associated with it build up with a time constant (Q/f) of about 1 sec. As they increase, the amplified signal and the output from the phase inverter also increase and cause the temperature and the resistance of the lamps to rise. As the bridge approaches balance, the signal transmitted through it to the crystal decreases (the attenuation of the bridge increases) until a stable state is reached. In the stable state, the bridge is slightly unbalanced. The gain of the amplifier is then equal to the attenuation of the bridge plus the loss in the crystal and tuning circuit. The bridge is thus a variable attenuator that acts like an automatic volume control without introducing the usual shift of phase and associated shift of frequency.

The amplifier and automatic volume control are designed to minimize the shift of phase between the amplifier input and output, especially the shift of phase that might depend on variable quantities such as line voltage, temperature, or tube characteristics. Since the Q of the crystal is finite, the frequency at which it vibrates can be pulled slightly higher or lower by applying a driving voltage that either leads in phase or lags behind the crystal oscillation. (This is the principle by which the synchronizer controls the frequency of the oscillator.) The variable capacitance in series with the crystal, inductance, and resistance provides such a frequency control. This capacitance controls the phase of the signal applied to the amplifier input with respect to that derived from the crystal. It therefore regulates the phase of the voltage from the automatic volume control that drives the crystal and, hence, controls the frequency at which the crystal vibrates.

Rotation of the oscillator frequency control through one division on the dial varies the frequency by roughly 1 part in 3 million. This represents a change in rate of drift of 20 μsec/min. These figures are only approximate because the sensitivity of the oscillator to the frequency control depends on the fixed capacitor and on the Q of the crystal. The fine-frequency control has a much smaller effect upon the circuit, its complete range corresponding to a little more than three divisions of the coarse frequency dial. A clutch may be engaged so that the rotation of the phase-shift capacitor rotates the fine frequency capacitor, one complete rotation of the phase-shift capacitor corresponding to about seven divisions of the dial of the fine frequency capacitor. In this way, the difference between the frequencies of the local and remote oscillators is automatically reduced in maintaining synchronism.

Since the oscillator is sensitive to loading, the output is taken from a cathode follower that draws no current from the oscillator. A signal from the grid of the phase inverter is impressed on the grid of the cathode follower.

A potentiometer controls the amplitude of the signal applied to the grid of the tuned amplifier and therefore controls the output of the oscillator unit. The tuned amplifier improves the waveform of the signal that is applied to the grid of the phase inverter. The purpose of the phase inverter is to provide two output signals that are equal in amplitude and 180° out of phase. These two signals are applied to four phasing networks to produce four signals that are mutually 90° out of phase. If an alternating voltage is impressed across an impedance composed of a resistance and a capacitance in series, the voltage across the resistor leads the voltage across the capacitor by 90°. The voltage across the combination is the vector sum of the voltage across the resistor and the voltage across the capacitor; in phase it lies between the two component voltages. Since the capacitive reactance $1/2\pi fC$ equals the resistance, the voltage across the capacitor is equal to the voltage across the resistor. Under this condition the voltage across the resistor leads the voltage across the combination by 45°; the voltage across the capacitor lags behind the voltage across the combination by 45°. Thus the four phasing networks produce four voltages that are mutually 90° out of phase. These are impressed on the four stator plates of the phase-shift capacitor, which is the same as that of the Model B-1 timer described in Sec. 7·2.

The tuned amplifier amplifies the signal from the rotor of the phase-shift capacitor and improves its waveform.

The frequency doubler differs from the tuned amplifier in that the plate antiresonant circuit is tuned to 100 kc/sec, and the positive bias of the cathode is larger (because of the high cathode resistance). The tube is nonconducting except for about a quarter of the 50-kc/sec period. The short pulse of current causes the tuned circuit to oscillate at its resonant frequency of 100 kc/sec. Since the amplitude of the oscillation decreases slightly between pulses, it is necessary to improve the waveform in a 100-kc/sec tuned amplifier located in the divider unit.

The output stage is a cathode follower with cathode self-bias.

7·6. Model C-1 Divider Unit.—In the divider schematic diagram (Fig. 7·8), the tuned amplifier, blocking oscillator, and six dividers with feedback are shown together with the marker mixer, square-wave generator, trace separator, and pedestal mixer.

The output of the frequency doubler is a 100-kc/sec sine wave with alternate cycles of decreased amplitude. The tuned amplifier converts this output to a 100-kc/sec sine wave of constant amplitude.

Since the sine-wave output signal of the 100-kc/sec shaper is not suitable for generating calibration markers or for driving the dividers, it

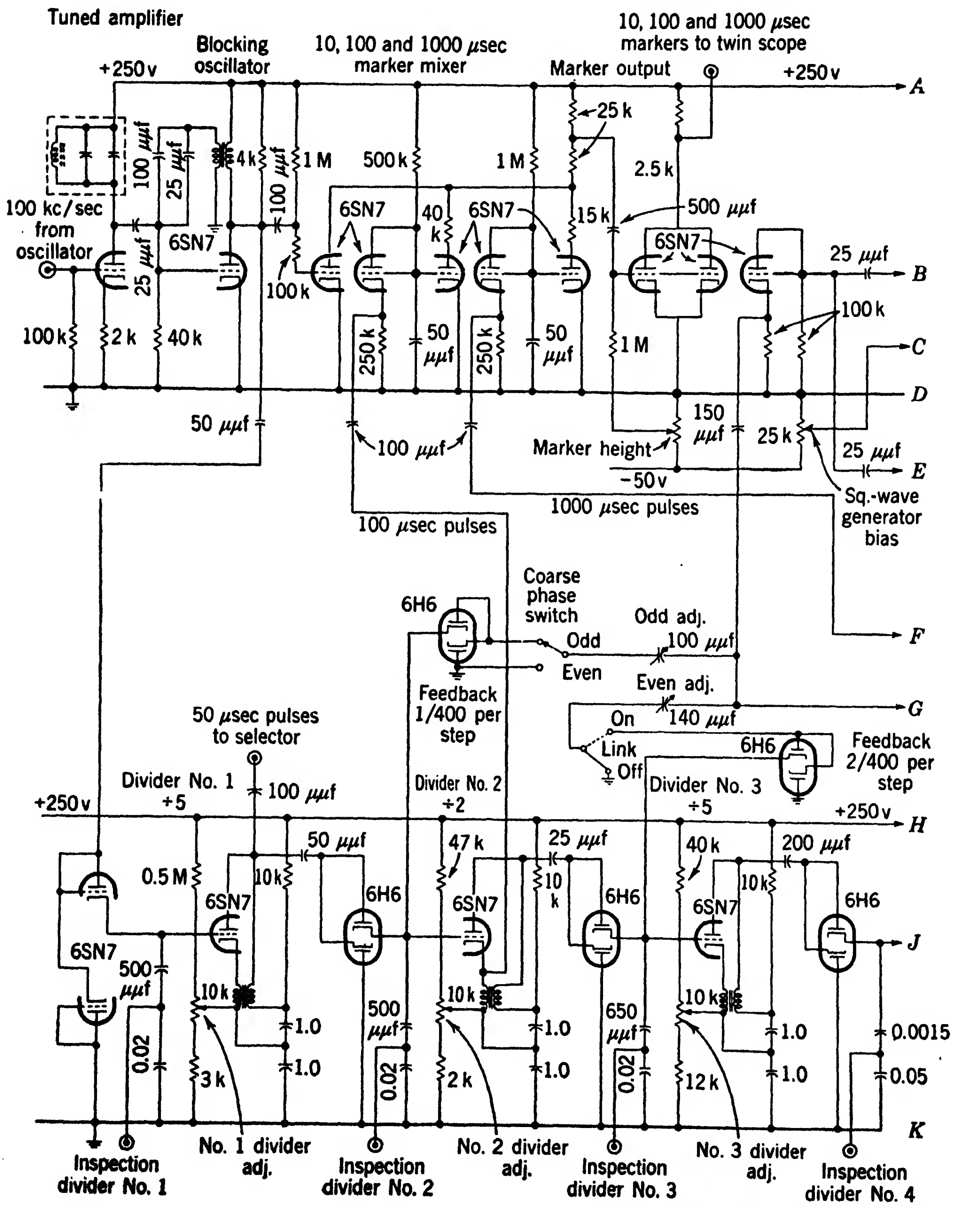
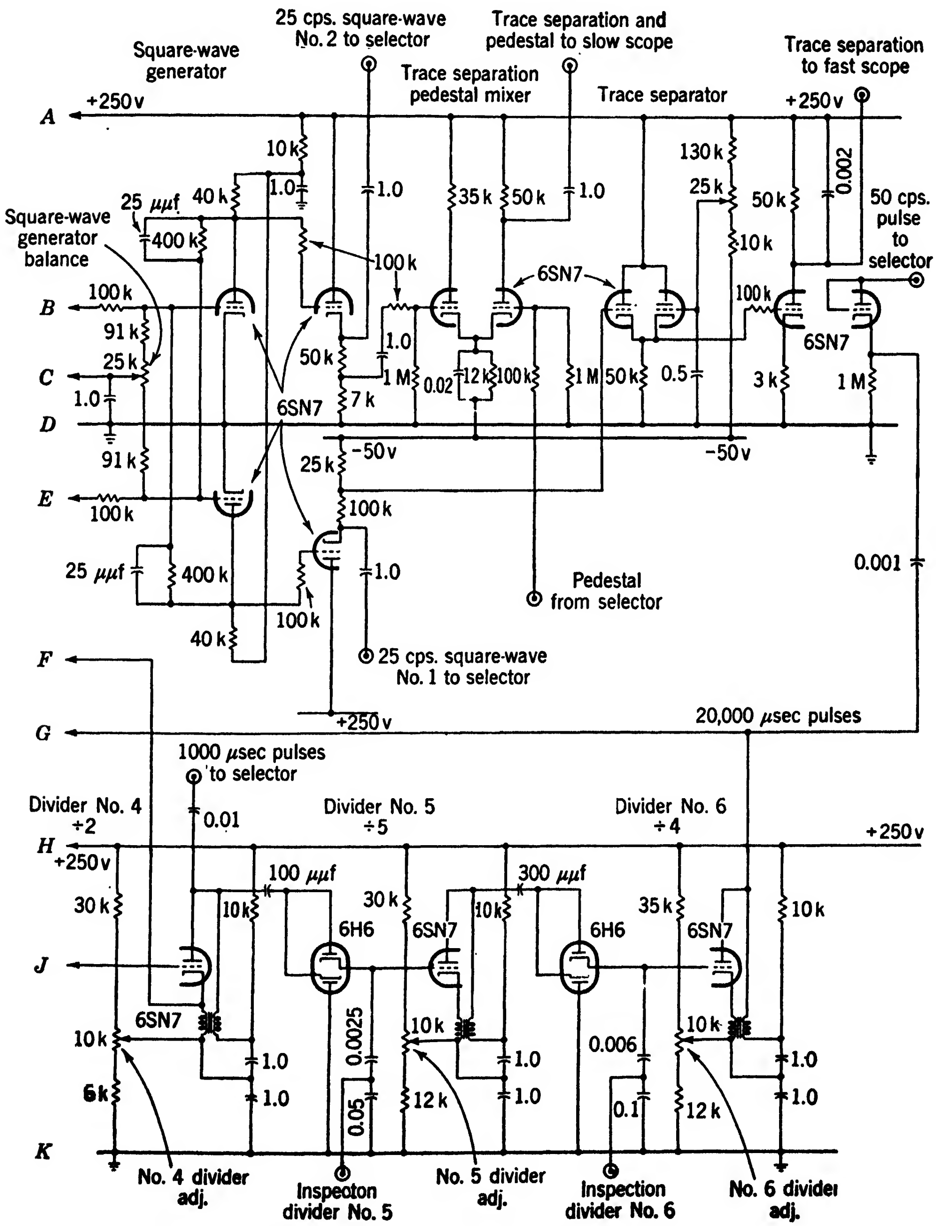


FIG. 7·8.—Schematic diais used to synchronize a blocking oscillator that generates accurately timed pulses of short duration recurring every 10 μsec. When the grid of the triode is driven to the potential at which plate current flows, the plate current flowing through the transformer induces a voltage on the grid. The polarity of the transformer windings is such that the increase of plate current drives the grid of the tube to a positive potential. The



gram of Model C-1 divider unit.

grid-voltage rise brings about a further increase in plate current which, in turn, causes an additional increase in grid potential. This regeneration continues until grid current is drawn and the grid capacitor is negatively charged. Its capacitance is small, and consequently it becomes charged very rapidly once the grid of the tube is driven into the high grid-current region. When the rate of change of potential on the capacitor caused by flow of grid current exceeds that caused by transformer action, the grid voltage begins to decrease. This causes the plate current to decrease and hence reverses the polarity of the potential induced on the transformer secondary. The decreasing secondary voltage augments the grid-voltage decrease until the cutoff voltage is exceeded and the flow of plate current ceases. The magnetic field that has been developed in the transformer by plate current collapses and induces an overshoot voltage. Since the grid has been driven below cutoff, additional oscillations are prevented until the grid capacitor is discharged, at which time the cycle is repeated.

There are six dividers with feedback which reduce the recurrence rate (100,000 pps) of the pulses from the blocking oscillator to the recurrence rate of the traces (which is twice the recurrence rate of the transmission of the local *A*- or *B*-signal).

A typical divider circuit consists of a charging capacitor, a double diode, a storage capacitor, and a blocking oscillator. The input pulses, through the action of the charging capacitor and the double diode, build up a charge on the storage capacitor in steplike fashion, each input pulse raising the charge and the voltage one step. When the storage capacitor, which is connected to the grid of the blocking oscillator, reaches the potential at which plate current flows, the cycle of the blocking oscillator is triggered, an output pulse is produced, and the storage capacitor is discharged. This steplike accumulation of charge on the storage capacitor followed by its discharge is repeated indefinitely.

The number of steps between discharges, or the dividing factor of the circuit, is inversely proportional to the input charge per step (which is proportional to the total positive input voltage applied to the charging capacitor and to the capacitance of the charging capacitor). It is directly proportional to the capacitance of the storage capacitor and directly proportional to the difference between the discharged potential and the potential at which the cycle of the blocking oscillator is triggered. When the storage capacitor is discharged by the blocking oscillator, it is first driven below ground potential but is immediately restored to ground potential by the double diode. The potential at which the cycle of the blocking oscillator is triggered is determined by the cathode bias, which is controlled by a potentiometer.

Feedback is applied from the last divider to the second and third dividers. By means of a second double diode connected to the storage capacitor of the third divider, for instance, every output pulse from the last divider supplies a charge of adjustable amount to the storage capacitor. This feedback reduces the recurrence period between output pulses of the third divider once every recurrence period of the last divider and thereby reduces by the same amount the recurrence period of the last divider.

The functions of the square-wave generator are to divide the recurrence rate of the last divider by 2 and to produce an output square wave for the vertical displacement of the upper and lower traces of the fast- and slow-oscilloscope patterns. The square-wave generator is an Eccles-Jordan circuit similar to a multivibrator, and it consists of two triodes whose plates are cross-coupled to the grids through resistors as well as through capacitors. It is a balanced circuit, each component associated with one triode corresponding to an identical component associated with the other triode. There are two stable states of operation, in which all currents and voltages remain constant. In one state one triode conducts while the other is nonconducting; in the other state the conducting and nonconducting conditions of the triodes are reversed. The negative portions of the output pulses from the last divider are applied through a diode to both grids of the square-wave generator. Each pulse causes the states of operation of the triodes to reverse, producing at the two plates square-wave outputs that are equal in amplitude but opposite in phase. Since the square-wave generator is sensitive to loading, the outputs are taken from two cathode followers.

In the trace-separation pedestal mixer the square wave is mixed with the flat-topped intensifier pulses from the fast-sweep generator (shown in Fig. 7·9). The output is applied to one of the vertical deflecting plates of the slow oscilloscope to produce the upper or *A*-trace with the *A*-pedestal and the lower or *B*-trace with the *B*-pedestal. The vertical separation between the upper and lower traces of the slow oscilloscope is fixed. The square-wave and pedestal signals are applied to the grids of two triode amplifiers that are cathode-coupled. The signals applied to the grids are relatively small positive and negative voltages, and consequently both triodes operate over approximately linear portions of their characteristics. The current through the cathode resistor is controlled by the grid that is momentarily more positive. The voltage waveforms that appear on the plates of the triodes are similar although unequal and opposite in phase.

The operation of the trace-separation circuit that gives adjustable vertical separation between the upper and lower traces of the fast oscilloscope is similar to that of the trace-separation pedestal mixer. The circuit consists of two cathode-coupled triodes that operate as cathode followers. An adjustable d-c potential is applied to one grid, and the

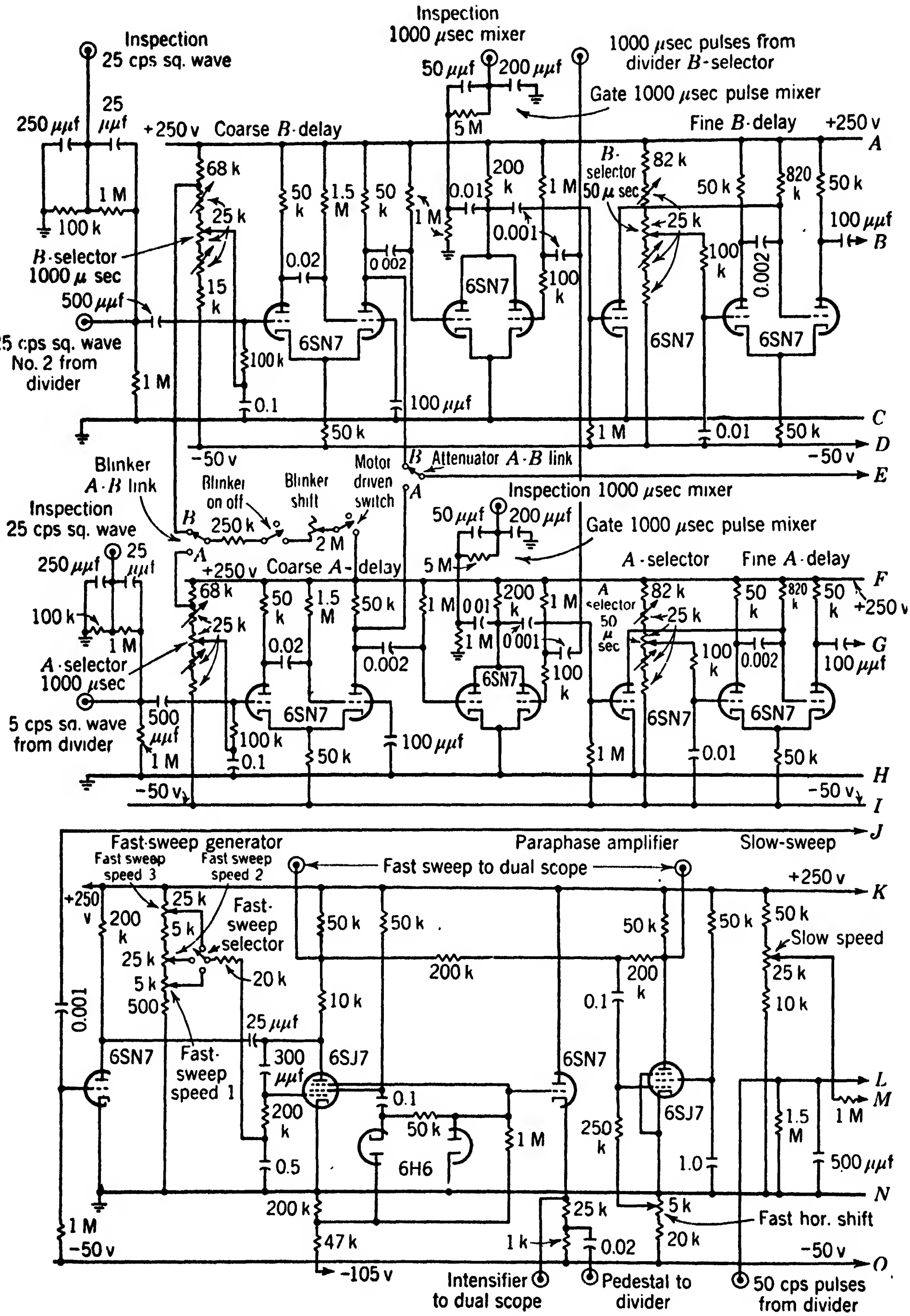
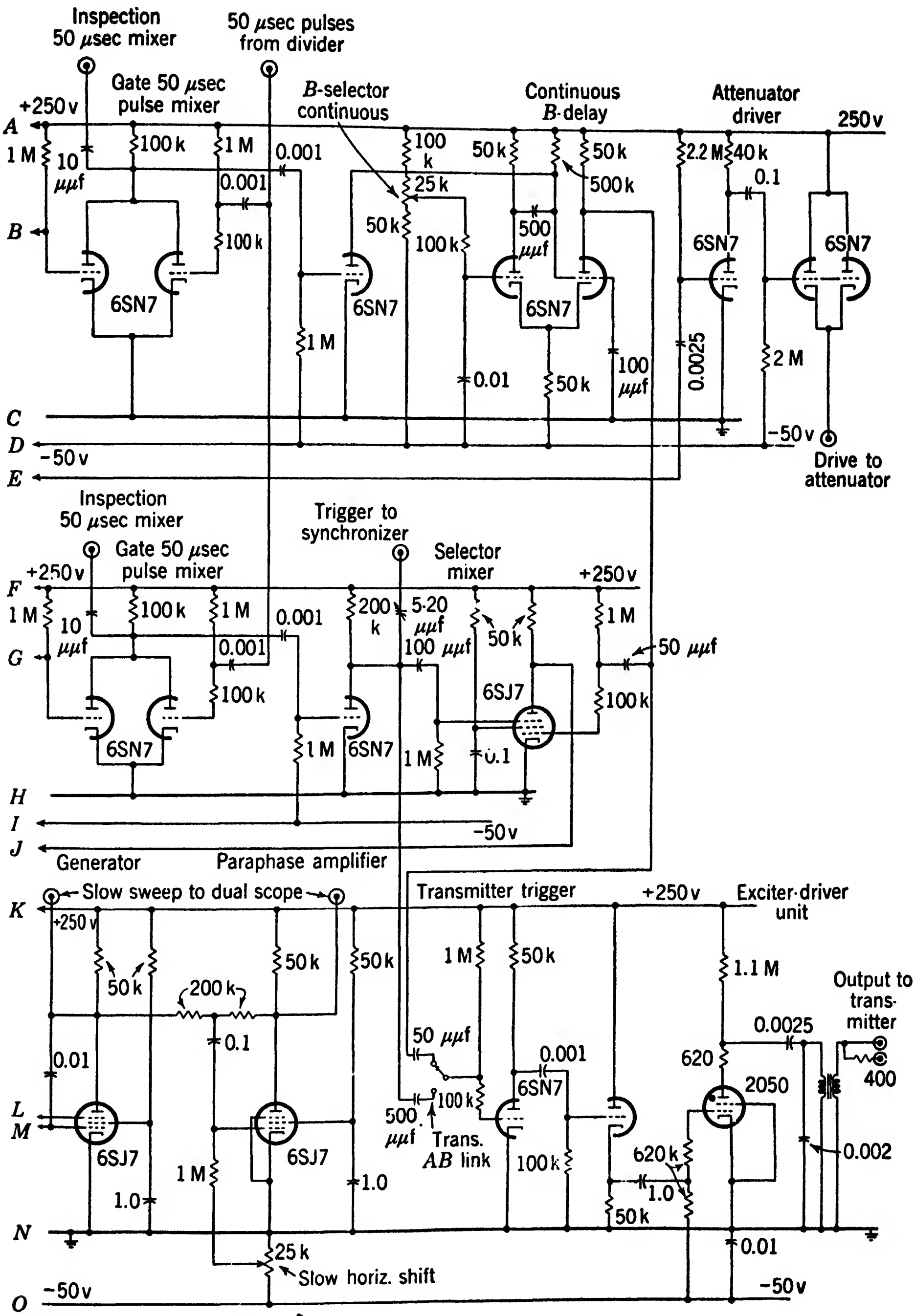


FIG. 7·9.—Schematic diagram



of Model C-1 selector unit.

square wave is applied to the other. The cathode potential cannot fall appreciably lower than the higher of the two grid potentials. When the d-c grid potential is low, the cathodes are free to follow the square wave impressed on the other grid; when it is high, the cathode can follow only the positive portion of the square wave. The output from the cathode is amplified and applied to one of the vertical deflecting plates of the fast oscilloscope.

The 10-, 100-, and 1000-μsec marker mixer is a triple-coincidence mixer. The plates (with limiting resistors) of three normally conducting triodes are connected so that the combined plate currents determine the potential difference across the common plate resistor. The output positive pulse is very small when one triode is cut off, somewhat larger when two are cut off, but very large when all are cut off. Negative pulses from the blocking oscillator recurring every 10 μsec are applied to the grid of the first triode and produce small positive output pulses. Once every 100 μsec a pulse from the second divider is rectified and applied to the grid of the second mixing triode, which cuts it off for a period of approximately 10 μsec. A pedestal on the output waveform results, and one of the 10-μsec pulses is effectively amplified. Similarly, a pulse from the fourth divider produces a pedestal approximately 30 μsec long and effectively amplifies three of the 10-μsec pulses. The pedestals, which are appreciably smaller in amplitude than the 10-μsec markers, are eliminated by the limiting action of the marker output amplifier. Thus, the output waveform is a series of marker pulses recurring accurately every 10 μsec. Every tenth pulse is a 100-μsec marker of increased amplitude. Every tenth 100-μsec marker is identified as a 1000-μsec marker by a series of three pulses following the 100-μsec marker and spaced 10 μsec apart.

7·7. Model C-1 Selector Unit.—As shown in Fig. 7·9, the selector chassis contains the *A*- and *B*-selectors, the selector mixer, the fast- and slow-sweep generators and paraphase amplifiers, the exciter driver, and the attenuator driver.

The function of the selectors is to permit the introduction of an adjustable and highly stable time difference between the initiations of the fast *A*- and *B*-sweeps (see Sec. 7·3). After being triggered by the square-wave generator, one selector circuit selects one of a series of pulses (recurring every 1000 μsec) from one of the dividers. The selected 1000-μsec pulse in turn triggers another selector circuit, which selects a particular one of a series of 50-μsec pulses. The selected 50-μsec pulse of the *B*-selector triggers a continuously adjustable multivibrator whose output pulse initiates the fast sweep.

A typical selector circuit, such as the coarse *A*-delay and the associated gate-1000-μsec pulse mixer, consists of a delay multivibrator and a coincidence mixer. The delay multivibrator is a double-triode cathode-coupled multivibrator that is inactive until it is triggered by a positive pulse on the first grid or a negative pulse on the second grid. In the normal quiescent state the first triode is nonconducting while the second triode is conducting. The grid of the second triode is returned to the B-supply voltage through a high resistance so that the grid-to-cathode voltage is essentially zero. Therefore, the cathode potential is determined by the flow of current through the cathode and plate resistors and a triode operating at zero grid-to-cathode voltage. The bias of the first grid, which controls the time delay, must be negative with respect to the quiescent cathode potential. A positive trigger pulse applied to the first grid or a negative trigger pulse applied to the second grid causes the first triode to conduct and the second to be cut off. The cathode potential and also the change in the plate potential from the nonconducting to the conducting state are determined by the grid bias. The change in plate potential determines the amplitude of the negative pulse impressed on the second grid. The potential of the second grid, therefore, varies exponentially with time and returns toward the B-supply potential with a time constant equal to the product of the grid resistance and the coupling capacitance. When it approaches the cathode potential (as adjusted by the grid bias), the second triode again conducts and produces a negative output pulse, the first triode is cut off, and the circuits assume their normal quiescent state. The time delay, therefore, is a function of the time constant and the adjustable grid bias. Actually it is an approximately linear function of the grid bias.

The gate-pulse mixer is a double-triode coincidence mixer of the type previously described. The negative output pulse of the delay multivibrator is differentiated to cut off the first triode for a time determined by the product of the grid resistance and the coupling capacitance. Negative pulses from one of the dividers are impressed on the other grid. When both triodes are cut off, the resulting positive pulse is large enough to cause current to flow through the biased amplifier and trigger the following selector circuit.

The purpose of the selector mixer is to produce for each negative pulse from the A-selector and each negative pulse from the B-selector a positive output pulse to trigger the fast-sweep generator. It is a pentode amplifier that is normally conducting. Positive and negative differentiated pulses from the A-selector are impressed on the suppressor grid, and positive and negative differentiated pulses from the B-selector are impressed on the control grid. A positive pulse on either grid does not appreciably affect the flow of plate current; a negative pulse on either grid cuts off the plate current and produces a positive output pulse. This positive pulse is applied to a negatively biased amplifier that triggers the fast-sweep generator.

The fast-sweep generator when triggered generates an output voltage that varies linearly with time and deflects the cathode-ray beam horizontally to produce the A- and B-traces of the fast oscilloscope. By means of a three-position switch and potentiometers the sweep speed can be adjusted from a speed that gives full deflection in 60 μsec to one that gives full deflection in 1400 μsec. The sweep generator also provides positive flat-topped intensifier pulses, which are applied to the intensifier grid of the cathode-ray tube. The cathode-ray beam is cut off except for the duration of the sweep.

The fast-sweep generator is a sharp cutoff pentode amplifier whose plate is capacitance-coupled to the control grid. The potential of the suppressor grid is limited by diodes to the region between ground and 85 volts below ground potential. In the quiescent state, the suppressor grid is held at −85 volts, and the control grid is connected through a high resistance to a positive potential. Consequently, no plate current flows, but there is a large flow of screen-grid current, and the screen-grid potential is low.

A negative pulse applied to the plate and control grid momentarily cuts off the flow of screen-grid current, raises the screen-grid potential, and, through capacitance-coupling, raises the suppressor-grid potential from −85 volts to ground potential. The control grid immediately returns to a potential at which space current flows. Since the suppressor grid is at ground potential (where it remains for the duration of the sweep), less current flows to the screen grid, and the screen-grid potential remains higher than in the original quiescent state. The plate potential tends to decrease from the quiescent nonconducting value; but, because of the capacitance coupling of the plate to the control grid, the change in plate potential maintains the control grid at the potential (a few volts below ground) at which the plate current is controlled by the grid potential. Thus the plate potential is controlled by the potential difference across the coupling capacitor—a difference that is determined by the flow of charging current through the grid resistor. Since the grid potential and the adjustable positive bias are practically constant, the flow of current through the grid resistor is also constant, and the potential difference across the coupling capacitor (which is equal to the charge divided by the capacitance) is a linear function of time. Consequently, the plate potential is a linear function of time, and the rate of change of potential which determines the sweep speed is directly proportional to the difference of potential between the adjustable positive bias and the grid potential (approximately ground) and inversely proportional to the grid resistance and the coupling capacitance. As the plate potential approaches the knee of the characteristic curve of the tube, the screen-grid current increases and thereby reduces the screen-grid potential, drives the suppressor grid to negative potentials, and cuts off the plate current. As the plate current is cut off, the plate potential rises rapidly and causes grid current to flow in the coupling capacitor, thus further increasing the screen-grid current and returning the circuit to its original quiescent state.

The output of the sweep generator is applied to one horizontal deflecting plate of the fast cathode-ray tube, and the output of the paraphase amplifier is applied to the other. The output waveform of a paraphase amplifier is similar and equal to the input waveform (in this case the wave from the sweep generator), but it is inverted. The potential at a point midway between the deflecting plates of the cathode-ray tube remains practically constant, therefore, and defocusing at the ends of the trace is minimized.

The slow-sweep generator and its associated paraphase amplifier are rather similar in operation to the fast-sweep generator and paraphase amplifier. They are triggered by pulses from the last divider and deflect the beam of the slow oscilloscope horizontally to produce the upper and lower traces of the slow-trace pattern.

The exciter-driver circuit can be triggered by output pulses from either the *A*- or *B*-selector, the choice depending on the function of the timer as a master or a slave. The pulse is amplified to trigger a gas-filled tube, the output pulse of which is shaped in a resistance and capacitance network and transformer to drive the transmitter.

Similarly, a negative output pulse from either the coarse *A*-delay multivibrator or the coarse *B*-delay multivibrator is chosen to control the bias of the electronic attenuator. The attenuator driver generates a positive flat-topped pulse so timed that the transmission of the local signal falls within its limits for all adjustments of the selectors. The duration (approximately 1800 μsec) of the flat-topped biasing pulse is determined by the differentiation of the negative output pulse from the coarse *A*- or *B*-delay multivibrator.

As a warning to Loran navigators, the transmitted signal is caused to blink if the synchronism is incorrect. This is done by a motor-driven switch (controlled from the panel of the dual oscilloscope) that changes the bias of the coarse delay multivibrator and therefore changes (ordinarily by 1000 μsec) the time difference introduced by the selector for $\frac{1}{3}$ sec every second. Viewing the slow-trace pattern, a navigator sees the signal shift periodically to the right or the left. The signal as viewed on the fast oscilloscope disappears for $\frac{1}{3}$ sec every second.

7·8. Model C-1 Synchronizer.—The purpose of the synchronizer is to control the frequency of the oscillator of the slave timer automatically so that the prescribed time difference between the reception of the remote signal and the transmission of the local signal is maintained. The information obtained from the sampling of the leading edge of the received remote signal is applied to the crystal oscillator in such a way that the position of the remote signal as it appears on the fast oscilloscope is held stationary.

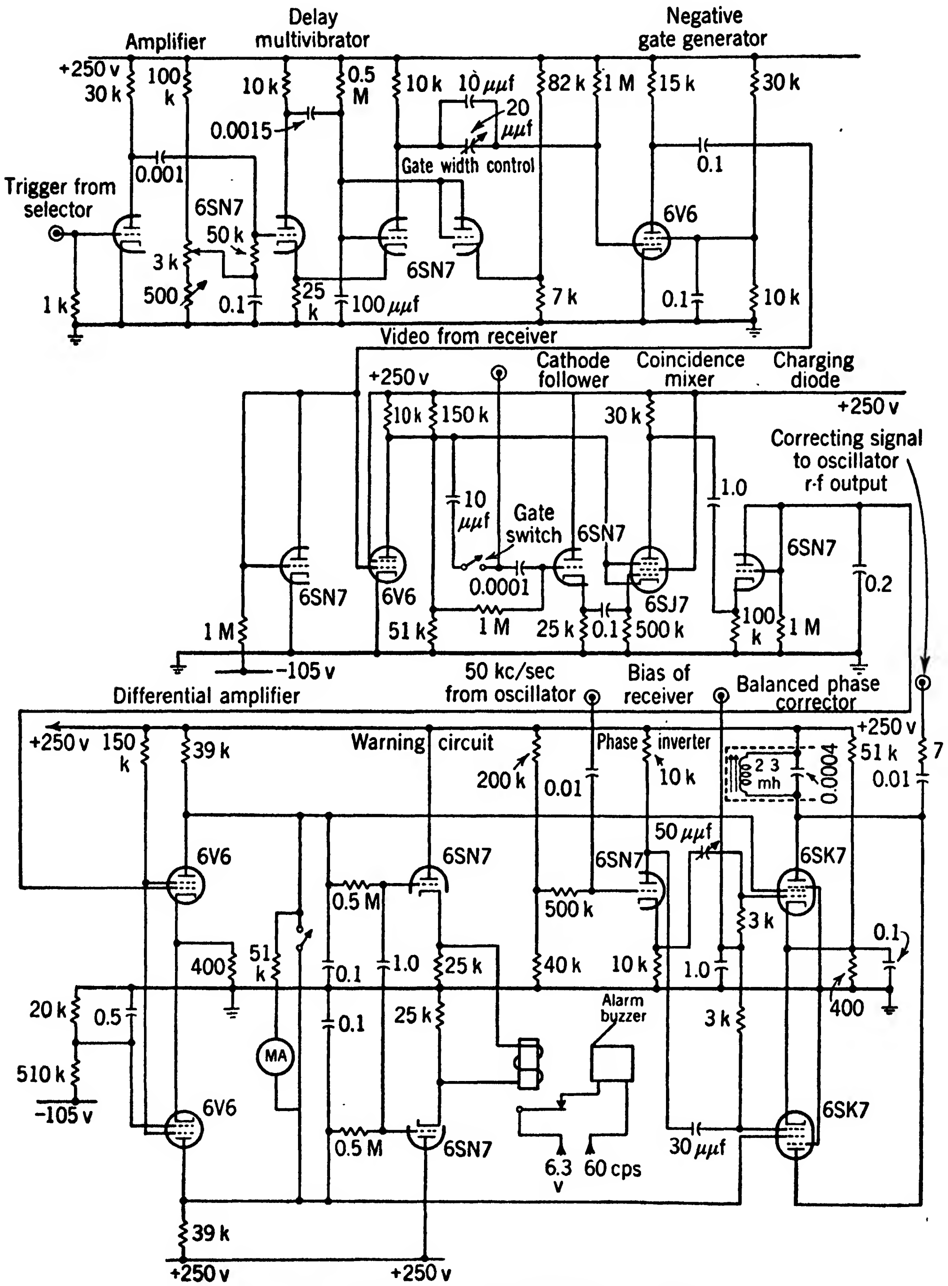


FIG. 7·10.—Schematic diagram of Model C-1 synchronizer.

As a result of the delays in the transmitting and receiving systems, the local pulse does not appear precisely at the start of the fast trace but is displaced to the right by a distance corresponding to a delay of approximately 50 μsec. When the signals at the slave station are properly synchronized, the remote signal appears on the fast *A*-trace directly above the local signal on the fast *B*-trace. An adjustable time difference of 50 μsec or so, therefore, must be introduced between the start of the fast *A*-trace and the initiation of the gate that samples the voltage of the leading edge of the remote signal. The delay multivibrator shown in Fig. 7·10 controls the position of the gate and of the remote signal on the fast *A*-trace. The delay multivibrator is a cathode-coupled double-triode multivibrator similar in operation to those in the selector unit.

The positive flat-topped signal generated by the delay multivibrator is differentiated and applied to the grid of an amplifier. Since the grid of the amplifier is returned to the *B*-supply through a high resistance, the positive pulse at the start of the delay (coincident with the start of the fast *A*-trace) does not appreciably affect the flow of current through the amplifier. However, the differentiated negative pulse following the delay cuts off the flow of current through the amplifier for a period of time determined by the product of the grid resistance and the coupling capacitance. The resulting pulse of approximately 20-μsec duration is inverted and amplified to produce the negative gate that is applied to the cathode of the coincidence mixer. The video signal from the receiver is applied to the grid of the coincidence mixer. The amplitude of the negative output pulse from the coincidence mixer is determined by the average amplitude of the video signal for the duration of the gate. In normal operation the gate falls approximately a third of the way up the leading edge of the remote signal. If it occurs a few microseconds early, the output is less than normal; if it occurs a few microseconds late, the output pulse is greater than normal. The output pulse, which is applied through a diode to a capacitor, charges the capacitor negatively. The capacitor is allowed to discharge to ground through a high resistance, the combination having a time constant that is many times longer than the recurrence period of the charging pulse. Thus a sawtooth voltage is generated on the capacitor, the amplitude of the teeth and also the average negative potential depending on the timing of the gate in relation to the remote signal.

The negative sawtooth voltage is applied to one control grid of the differential amplifier. The other control grid is maintained at a fixed negative reference potential. The two tetrodes are coupled through a common cathode resistor and a common screen-grid resistor so that the two amplified output signals at the plates are sawtooth in form and opposite in phase. The relative average voltages at the plates depend on the relation between the average negative sawtooth bias and the negative reference bias and are applied directly to the two screen grids of the balanced phase corrector. These average voltages are equal when, in normal operation, the gate is located one-third of the way up the leading edge of the remote signal. A 50-kc/sec signal from the crystal oscillator is impressed on the grid of a phase inverter, yielding two equal and opposite 50-kc/sec signals which are applied to the control grids of the balanced phase corrector. The small coupling capacitances and small grid resistances produce a shift of phase of approximately 90°. This provides the proper phase of the frequency-correcting signal, which is applied to the crystal oscillator, to control the oscillator frequency. The control grids are normally biased at approximately ground potential, but they are connected through a high resistance to the detector of the receiver, and hence during large bursts of noise the grids are negatively biased and the synchronizer is paralyzed. Since the 50-kc/sec signals impressed on the control grids are opposite in phase, the phase of the output signals at the antiresonant common plate impedance depends on the relative average voltage on the screen grids. This output signal is applied to the cathode of one of the amplifiers in the crystal-oscillator circuit in such a way that it changes the phase of the signal impressed on the crystal and therefore tends to increase or decrease the frequency of the oscillator. The increase or decrease in the frequency depends on the unbalance of the differential amplifier, which in turn depends on the timing of the gate in relation to the remote signal.

Thus at a slave station the synchronizer holds the remote signal at a predetermined position on the fast *A*-trace by controlling the frequency of the crystal oscillator. When the differential amplifier becomes unbalanced, a buzzer that is connected between the plates of the differential amplifier sounds an alarm indicating an error in synchronism. At a master station the automatic synchronizer is not connected to the oscillator, but it is used to sound the alarm when the synchronism is incorrect.

A voltmeter connected between the plates of the differential amplifier provides an indication of the unbalance of the differential amplifier and of the amplitude of the frequency-correcting signal that is applied to the crystal oscillator. When the meter reads zero (and also during bursts of noise), no frequency-correcting signal is applied to the crystal oscillator. If the operator adjusts the oscillator fine frequency control so that the average reading of the voltmeter is zero, there is then no false correction applied if the synchronizing signal is momentarily removed by the paralyzing effect of a burst of noise.

MODEL UE-1 TIMER

7·9. General Description of Model UE-1 Timer.—In consultation with representatives of the Radiation Laboratory and the Bureau of Ships, the General Electric Company developed the Model UE-1 timer. Because it is constructed of Navy-approved components to meet Navy

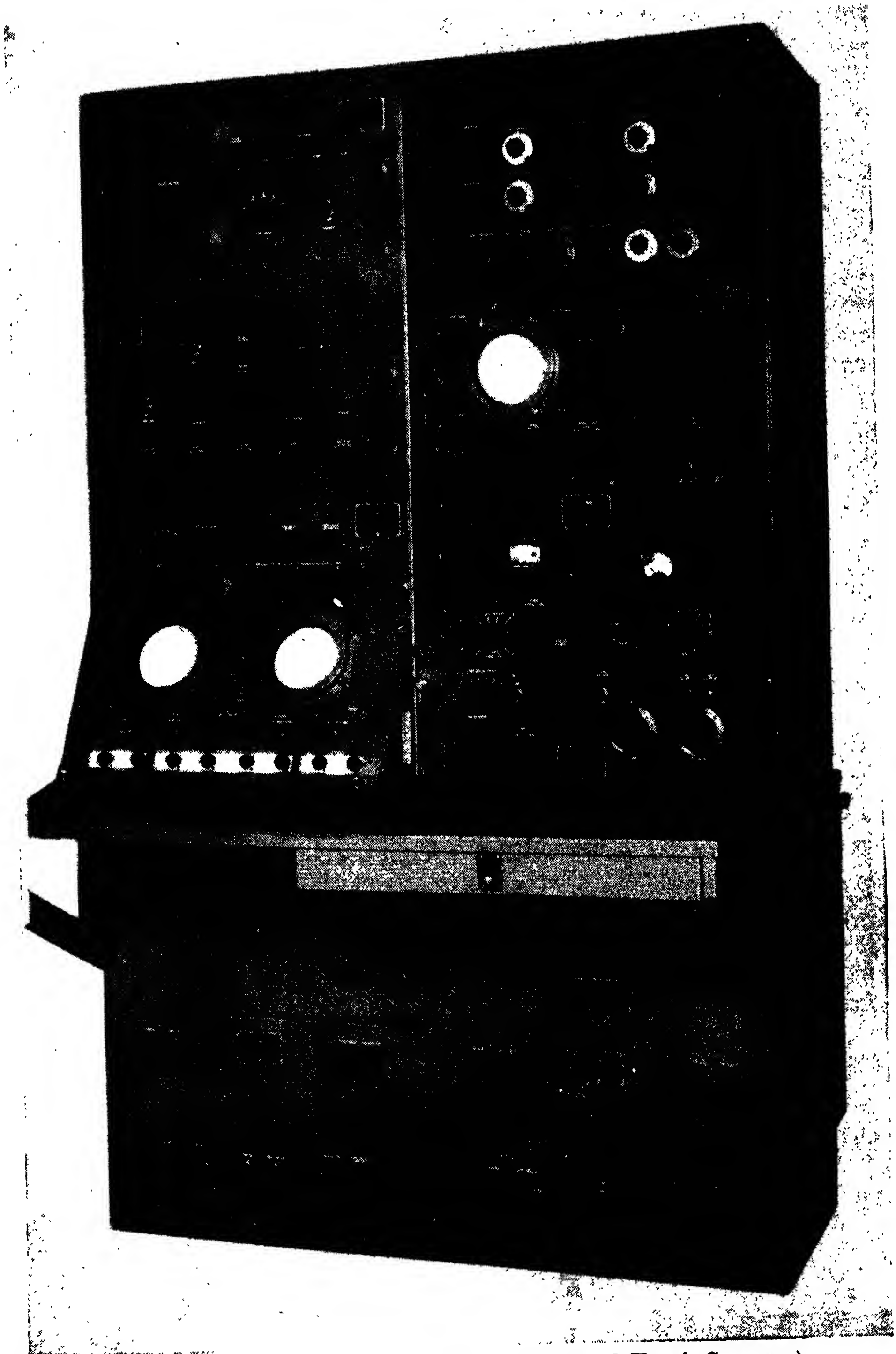


FIG. 7·11.—Model UE-1 timer. (*Courtesy of General Electric Company.*)

specifications, it is somewhat larger and heavier than the Model C-1 timer. Blowers circulate air through the cabinet to keep the components cool, and space heaters are provided to keep the equipment dry when it is idle. The mounting of all chassis on drawer slides facilitates the servicing of the equipment.

There are few fundamental changes in circuit design. The oscillator, designed at the Bell Laboratories and manufactured by the Western Electric Company, is more stable than that of the Model C-1 timer. The phase-shift capacitor and oscillator frequency control are motor-driven and are mounted in a separate chassis. Also the dividers and selectors are mounted in two separate chassis. The use of locked delay multivibrators in the test oscilloscope permits the stable presentation of any portion of the recurrence period on the fast trace, and an internal system of cabling and switching provides a convenient means of observing waveforms at a number of test points. An infinite rejection wave trap incorporated in the receiver serves as an antijamming and anti-interference device.

The synchronizer differs from that of the Model C-1 timer. The phase-correcting voltage, instead of electronically controlling the frequency of the oscillator, controls a motor that drives the phase-shift capacitor and the oscillator frequency control. Thus, as the synchronizer automatically maintains the prescribed synchronism, it also adjusts the oscillator frequency in such a way as to reduce the difference between the frequencies of the master and the slave oscillators. As the frequency difference is reduced, the operator can reduce the rate at which the synchronizer corrects errors in synchronism. This procedure permits the maintenance of stable and reliable synchronism even under severe conditions of noise.

Figure 7·11 is a photograph of the Model UE-1 timer. The cabinet on the left contains the selector unit, receiver, dual oscilloscope, automatic synchronizer, and high-voltage power supply. The cabinet on the right contains the divider unit, test oscilloscope, crystal oscillator, phase-control unit, main power supply, and bias power supply.

Altogether 192 Model UE-1 timers have been ordered to replace timers of the earlier designs in most of the permanent stations.[1]

Block Diagram of Model UE-1 Timer.—As shown in Fig. 7·12, the block diagram of the Model UE-1 resembles that of the Model C-1 timer. Since the oscillator frequency is 100 kc/sec, no frequency doubler is required. The dividers, feedback, and square-wave generator are essentially unchanged. The introduction of an additional delay multi-

[1] The Model UE-1 timer is described in detail in the "Preliminary Instruction Book for the Model UE-1 Timer," *Navships* 900, 427-IB, which is distributed by the Bureau of Ships, U.S. Navy Department, Washington, D.C.

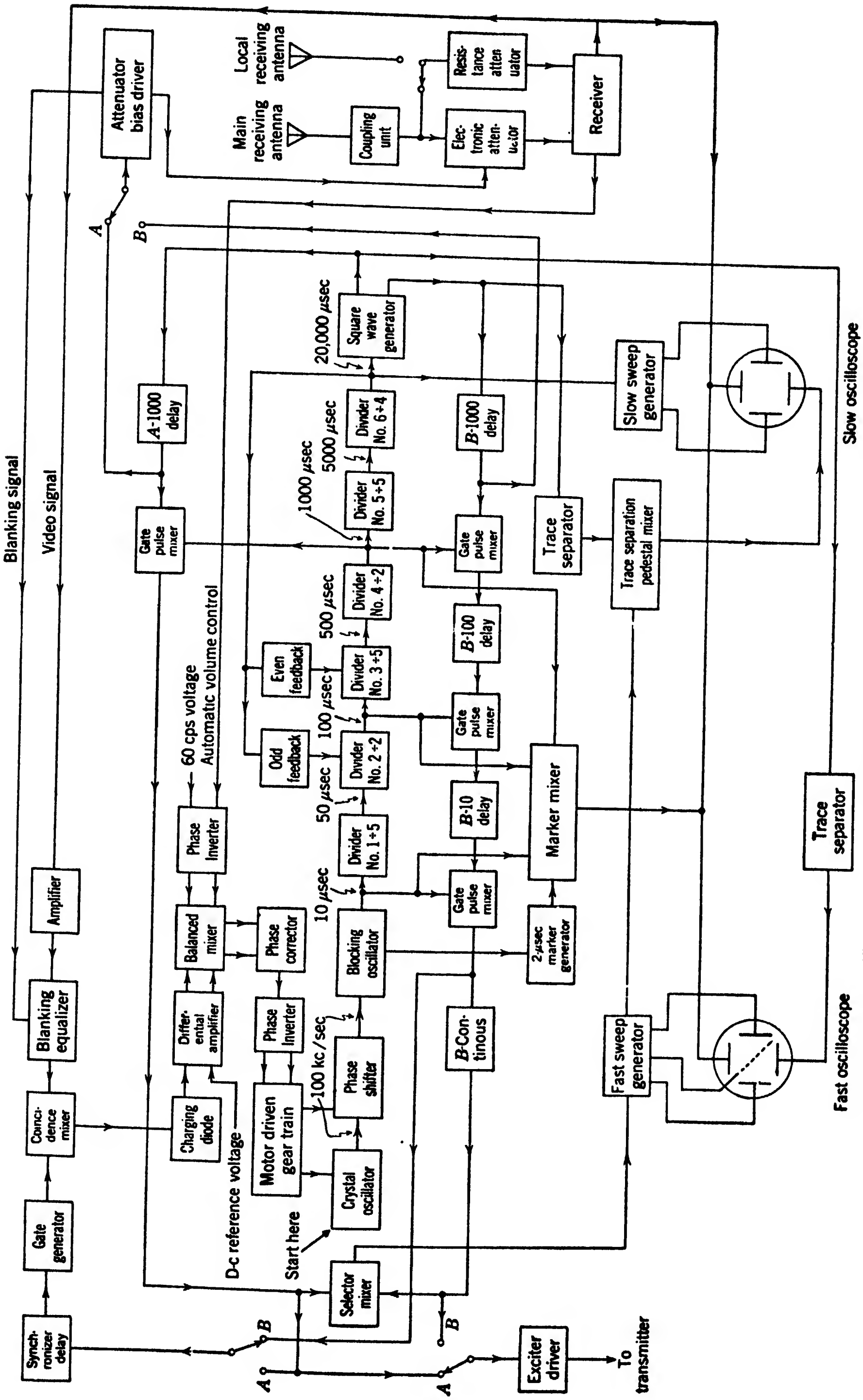


FIG. 7·12.—Block diagram of Model UE-1 timer.

vibrator and gate-pulse mixer in the *B*-selector provides complete and continuous coverage of the required time-difference range and eliminates the requirement for a fine delay multivibrator in the *A*-selector.

The 100-kc/sec oscillator (Meacham) circuit consists of a two-stage amplifier and a bridge containing the crystal. It is described in Sec. 7·10.

The automatic synchronizer maintains synchronism by controlling the rotation of a motor that is geared to the phase-shift capacitor and to the fine frequency control. The operation of the phase-control unit is described in Sec. 7·11.

The receiver can be tuned to any frequency between 1700 and 2100 kc/sec. The over-all 6-db bandwidth is approximately 70 kc/sec, and the sensitivity is such that a 2-μv signal gives full deflection of the oscilloscope trace. It is described in Sec. 7·12.

Since the operation of the Model UE-1 synchronizer differs considerably from that of the Model C-1, it is discussed in detail in Sec. 7·13.

Divider.—The divider circuits are similar to those of the Model C-1 timer. The divider chassis contains a 10-μsec blocking oscillator, six dividers with feedback, a square-wave generator, a 2-μsec marker generator and marker mixer, slow- and fast-trace separators, and separator-pedestal marker mixers. There are six dividers which divide by 5, 2, 5, 2, 5, 4 (or 3), respectively. The 2-μsec marker generator consists of a triode amplifier which is driven by the 10-μsec blocking oscillator and is transformer-coupled to a resistance amplifier. Both the primary and secondary of the transformer are tuned to 500 kc/sec. The resistance amplifier is cathode-biased so that it conducts for only a fraction of each cycle and generates sharp marker pulses that are capacitance-coupled to the output of the marker mixer. The marker mixer is a triple-coincidence mixer similar to that shown in Fig. 7·8. On the slow-sweep oscilloscope only 1000-μsec markers are displayed, whereas 2-, 10-, 100-, and 1000-μsec markers are displayed on the fast-sweep oscilloscope. Selector switches and cathode followers provide outputs for synchronizing the traces of the test oscilloscope and for testing the operation of the dividers.

Selector.—The selector circuits differ from those of the Model C-1 timer chiefly in the time-difference ranges of the delay multivibrators. There is only one delay multivibrator in the *A*-selector. It selects 1000-μsec pulses and can be varied from 1000 to 15,000 μsec. Unlike that of the Model C-1 timer, the *B*-selector can be varied continuously over the full range from slightly more than 1000 μsec to more than 15,000 μsec. The 1000 *B*-delay multivibrator, which selects 1000-μsec pulses, can be varied from 1000 to 15,000 μsec; the 100 *B*-delay multivibrator, which selects 100-μsec pulses, can be varied from 100 to 1100 μsec; the 10 *B*-delay multivibrator, which selects 10-μsec pulses, can be varied from 20 to 130 μsec; and the continuous *B*-delay multivibrator can be varied continuously from 10 to 21 μsec. The selector chassis also contains the bias generator for the electronic attenuator, the transmitter-exciter driver, sweep generators, and a selector switch and cathode follower for testing.

Test Oscilloscope.—The test oscilloscope is similar in function to that of the Model C-1 timer. A system of internal cabling and selector switches provides a convenient means of observing the signals at a number of test points in several chassis. The vertical-amplifier input circuit can be connected to the oscillator, the dividers, selectors, or an external probe. The sweep-synchronizing input circuit can be connected to the dividers or to an external probe.

The vertical deflecting circuits consist of an attenuator that can be switched in or out, a cathode follower with a gain control, a video amplifier, a phase inverter, and a push-pull amplifier that is capacitance-coupled to the vertical deflecting plates and the centering circuits.

Either of two sets of pulses from the square-wave generator, differing in time by 20,000 μsec and recurring every 40,000 μsec, can be selected to synchronize the sweep generator. The purpose of the sweep-synchronizing circuits is to permit the observation on a fast trace of signals recurring during any portion of the main recurrence period of 40,000 μsec. This is accomplished by introducing an adjustable time difference between the input synchronizing pulse and the initiation of the fast trace. To provide complete coverage of the whole recurrence period the time difference must be adjustable from a little more than 1000 μsec to a little more than 21,000 μsec. The synchronizing circuits consist of a pulse amplifier, a coarse delay multivibrator, and a fine delay multivibrator. To maintain the required stability over its wide range, the coarse delay multivibrator is locked on 1000-μsec pulses. It can be varied from 1000 to 20,000 μsec. The fine delay multivibrator is unlocked and can be varied continuously from 300 to 1500 μsec.

The sweep generator, which is triggered by the fine delay multivibrator, generates traces of any one of three speeds which is selected by a switch on the panel. The three trace speeds correspond to durations of 25,000, 3000, and 160 μsec.

7·10. Model UE-1 Oscillator.—The most stable oscillator that has ever been built in quantity is the Model UE-1. The crystal is a GT-cut quartz plate with a low temperature coefficient (approximately 1 part in 10^7 per degree centigrade). It is mounted in an evacuated glass bulb on wire supports that are soldered to its two silver-coated surfaces. This support is rugged and enables the crystal to withstand severe mechanical shocks without injury.

The crystal unit is contained in a heavy copper tube that is closed at both ends to ensure uniformity of temperature distribution. The fine heater consists of four heating elements of the bridge which are associated

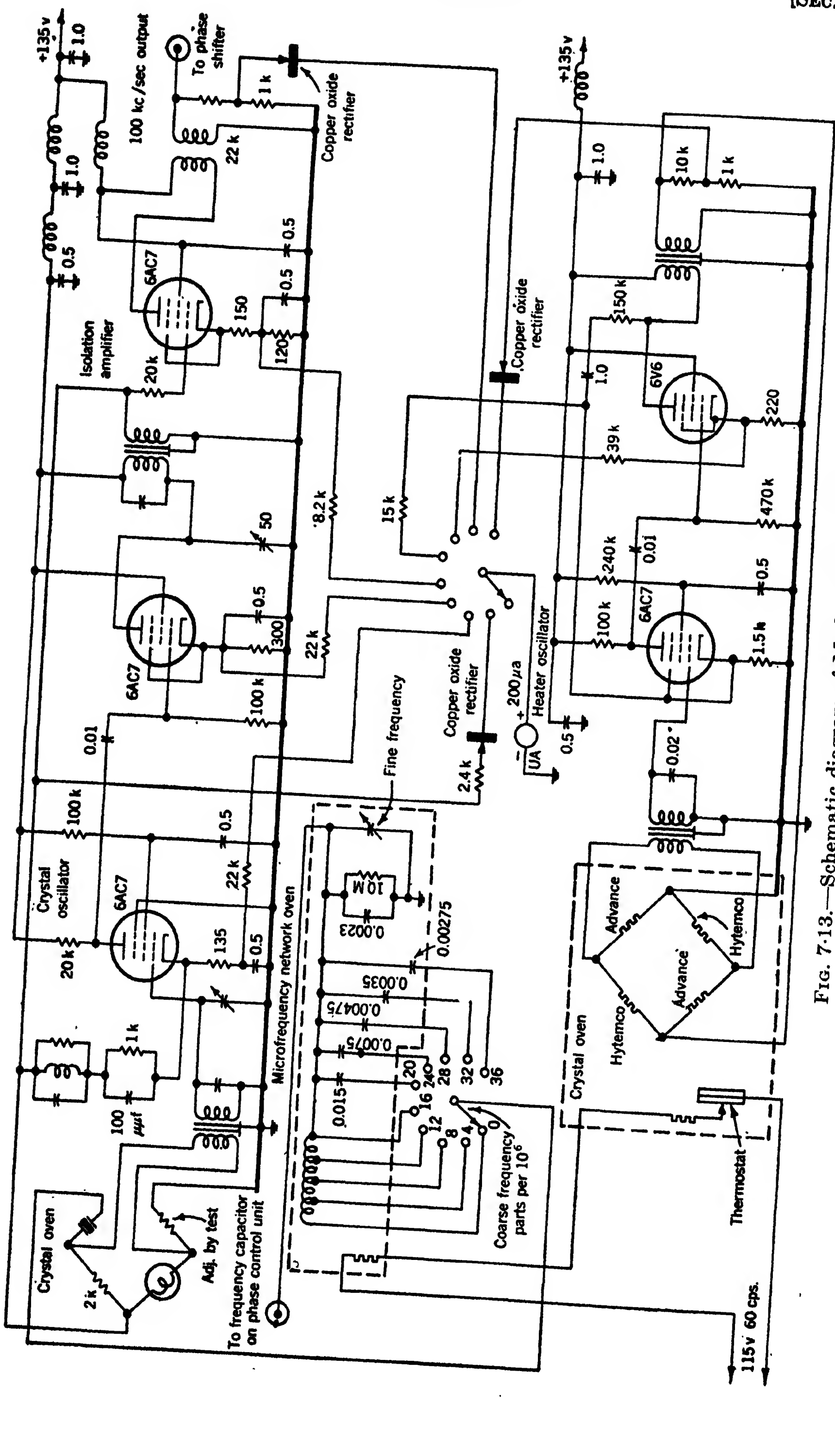


FIG. 7·13.—Schematic diagram of Model UE-1 oscillator.

with the heater oscillator shown in Fig. 7·13 and are wrapped around the copper tube. Although the resistances of two of them vary with temperature, the resistances of the other two are independent of temperature. The power supplied to these heating elements by the heater oscillator is controlled by the unbalance of the bridge, which in turn depends on the temperature of the heating elements. Thus the heating power is a continuously variable function of the temperature of the copper tube that encloses the crystal and varies in such a way that it tends to maintain the temperature at a constant value.

Surrounding the fine heater tube is a glass thermos cylinder closed at both ends by glass thermos plugs. This insulation minimizes the loss of heat from the fine heater. The thermos cylinder is enclosed in a copper tube with two end plates around which are wrapped the windings of the coarse heater. The power supplied to the coarse heater is controlled by a thermal switch mounted on one of the end plates. To minimize loss of heat and to provide uniform thermal distribution, the coarse heater is wrapped in alternating layers of felt and aluminum foil. The outer housing is a large chromium-plate brass cylinder.

The 100-kc/sec crystal-oscillator circuit (Fig. 7·13) consists of a two-stage amplifier and a bridge containing the crystal. The first stage is a resistance amplifier of moderately high gain. It is capacitance-coupled to the second stage which is transformer-coupled to the bridge circuit. The primary of the transformer is tuned to 100 kc/sec. Negative feedback is applied from the secondary of the transformer through a filter and through a parallel combination of a resistor and a capacitor to the cathode of the first amplifier tube. The filter is a damped antiresonant circuit tuned to 100 kc/sec. This negative feedback reduces any tendency of the oscillator to oscillate at undesired frequencies.

The output of the amplifier is applied to one terminal of a bridge, the opposite terminal being grounded. The voltage between the other two terminals is applied through a tuned transformer to the grid of the first amplifier tube. Two opposite arms of the bridge are resistors whose resistances are fixed and independent of temperature. Another arm is a lamp whose resistance varies with temperature and therefore depends on the amplitude of oscillation. The fourth arm contains the crystal in series with a network whose reactance can be adjusted to control the frequency of oscillation. Any reactance unbalance of the bridge causes the voltage impressed successively on the amplifier, on the bridge, and on the crystal to be phased in such a way that the frequency tends to increase or decrease so that the reactance unbalance is reduced. Thus the reactance introduced in series with the crystal controls the frequency of oscillation. Some of the power from the amplifier passes through the lamp and thereby heats it and controls its resistance. The resistance unbalance of the bridge determines the fraction of the voltage impressed on the bridge which is transferred to the grid of the first amplifier tube. This resistance unbalance controls the amplitude of oscillation and acts as an automatic volume control without the phase instability of the more conventional types of automatic volume control. Thus the bridge controls both the frequency and the amplitude of oscillation.

The coarse frequency control is a selector switch that permits the introduction of various fixed values of capacitive or inductive reactance in series with the crystal in one arm of the bridge. The switch has ten positions, each introducing a change in frequency of approximately 4 parts per million, and gives a total range of approximately 36 parts per million. The fine frequency control is a variable capacitor in series with the crystal and fixed reactor. It provides continuous control of the frequency over a range of 5 parts per million. In parallel with the fine frequency capacitor is another variable capacitor located in the phase-control chassis and geared to the phase-shift capacitor. The latter variable capacitor is capable of controlling the frequency over a range of nearly 5 parts per million.

An isolation amplifier and a transformer provide a low-impedance output and prevent any change in the output load from affecting the operation of the oscillator. The output is approximately 14 volts rms.

A microammeter with a selector switch and appropriate resistors and rectifiers provides a convenient means of checking the operation at several test points in the oscillator and oven-heater circuits.

The stability of the oscillator is such that the rate of aging does not exceed 1 part in 10^9 per hour, and the average short time variation does not exceed 3 parts in 10^9 for a 10-min period. Provision is made for checking the oscillator frequency against the signals received from radio station WWV, operated by the National Bureau of Standards.

7·11. Model UE-1 Phase-control Unit.—The phase-control chassis contains an amplifier, phasing circuits, a phase-shift capacitor, and an output amplifier similar to those in the Model C-1 timer. It also contains an a-c shunt motor which through a gear train drives the phase-shift capacitor and the variable capacitor that controls the oscillator frequency. Clutches that are operated by solenoids permit the decoupling of the phase-shift capacitor and the frequency capacitor from the gear train so that they can be operated manually and so that the phase-shift capacitor can be rotated without affecting the frequency of the oscillator. A functional diagram of the motor-drive system for the phase and frequency capacitors is shown in Fig. 7·14.

The motor can be controlled by either the automatic synchronizer or a manual LEFT-RIGHT switch that causes the motor to rotate the phase-shift capacitor so that the remote signal moves to the left or to the right.

When this switch is in the neutral position, the motor is controlled by the automatic synchronizer. The clutches that couple the phase-shift capacitor and the frequency capacitor to the gear train are disengaged when the solenoids are energized. When the automatic-synchronizer switch, located on the panel of the dual oscilloscope, is turned to the OFF position, it disengages the phase-shift capacitor clutch and grounds the output of the automatic synchronizer; consequently the motor does not turn, and the phase-shift capacitor can be rotated manually. The fre-

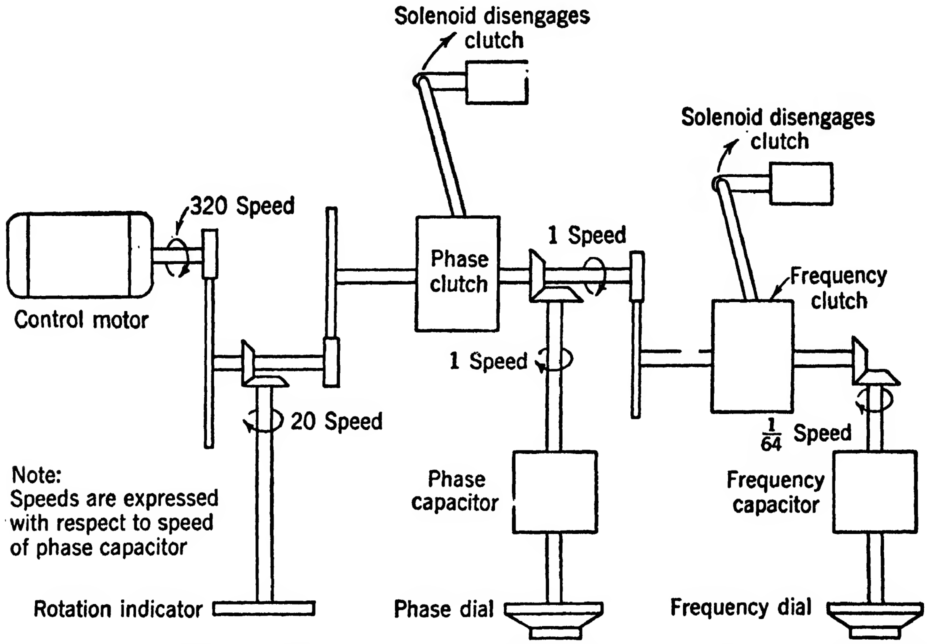


FIG. 7·14.—Functional diagram of phase- and frequency-control system of Model UE-1 timer.

quency-capacitor clutch is disengaged in the left and right positions (not in neutral) of the manual LEFT-RIGHT switch. It can also be disengaged by a frequency-reset push-button switch on the phase-control panel so that the frequency capacitor and fine frequency control in the oscillator may be reset when the frequency capacitor reaches the end of its range. Although no provision is made for it in the Model UE-1 timer, it would be desirable to have the phase-shift capacitor clutch disengaged when the signals are out of synchronism and the automatic synchronizer blinks the local signal.

The vacuum-tube circuits shown in Fig. 7·15 control the amplitude and phase of the voltages impressed on the field coils of the motor. A 60-cps signal from the heater supply is impressed on the grid of a phase inverter to provide two output voltages that are 180° out of phase. Either one of these can be selected by the LEFT-RIGHT switch to drive the motor in one direction or the other. A potentiometer in the grid circuit controls the speed of the motor for manual control with the LEFT-RIGHT switch. The phase-corrector circuit provides for the proper adjustment of the phase of the field current with respect to the phase of the armature current. For manual control with the switch the output of the phase-corrector circuit is applied to the grid of the amplifier; for automatic control (with the switch in the neutral position) the output from the automatic

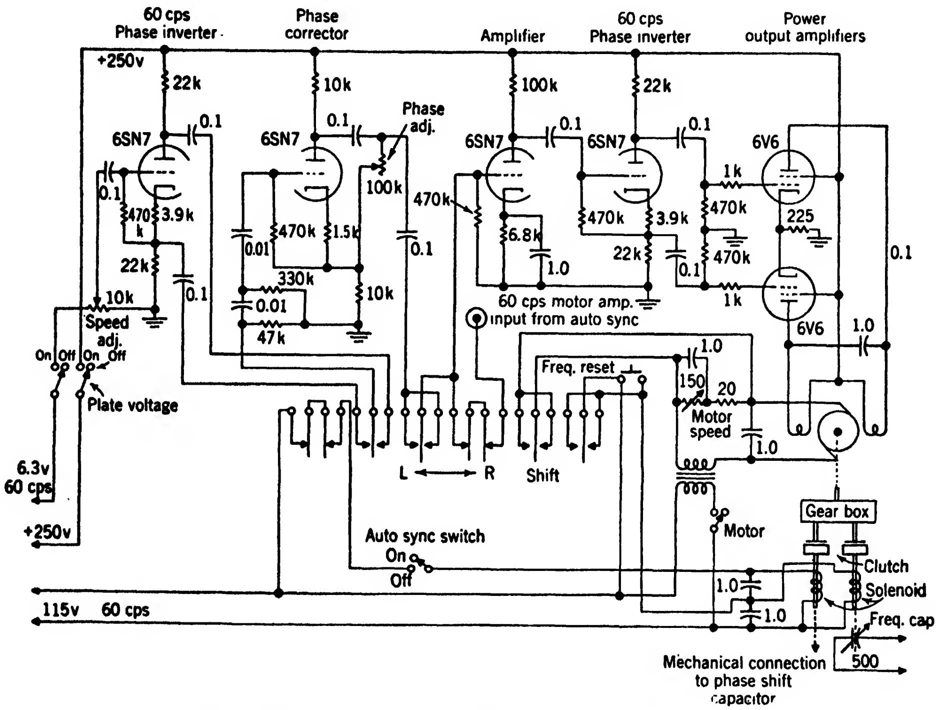


FIG. 7·15.—Schematic diagram of Model UE-1 phase-control unit.

synchronizer is applied to the grid of the amplifier. The amplifier drives a phase inverter and two power amplifiers operating in push-pull. The field coils of the motor are the plate loads of the power amplifiers.

Power at 60 cps is supplied through a transformer and a rheostat to the armature of the motor. The rheostat regulates the maximum speed at which the motor can rotate when it is controlled by the automatic synchronizer. When the switch is turned to the left or right position, the rheostat is short-circuited and consequently the speed is increased. In normal operation the maximum speed is reduced by means of the rheostat to the lowest value at which synchronization is possible in order to minimize the false corrections due to noise or interference on the incoming signal. When synchronization is first attempted, the difference between the frequencies of the master and slave oscillators usually necessitates operation at a relatively high maximum speed. After a few minutes of operation the maximum speed can be reduced. In this way the advantages of the automatic synchronizer and also the high precision of the crystal oscillator are retained.

7·12. Model UE-1 Receiver.—The receiver, which is of the superheterodyne type, is designed to operate at a single frequency. By means of screwdriver controls, however, the tuning can be adjusted to any frequency between 1700 and 2100 kc/sec. The tuning dial provides front-panel adjustment of the tuning over a range of ± 80 kc/sec. The over-all bandwidth is approximately 70 kc/sec as measured at 6 db below peak response. The sensitivity is such that a 2-μv signal gives full deflection of the trace on the cathode-ray tube.

As shown in the schematic diagram (Fig. 7·16) there are four tuned stages of preselection before the converter, providing an i-f and image-rejection ratio of more than 60 db and four stages of i-f amplification operating at 1100 kc/sec.

The remote signal (along with other signals) from the electronic attenuator of the switching equipment (Sec. 8·4) is impressed on the grid of the final stage of electronic attenuation, which functions as an amplifier except for a short period of time during which the local signal is transmitted. The local signal from the resistance attenuator of the switching equipment is passed through a resistance attenuator in the receiver and mixed with the signal from the electronic attenuator. The potentiometer in the resistance attenuator controls the amplitude of the local signal and is used to equalize the local and remote signals as they appear on the fast and slow oscilloscopes.

There are several devices for reducing the effect of interference caused by enemy jamming, undesired signals, and random noise. A wave trap of the infinite-rejection type in the plate circuit of the r-f amplifier introduces an attenuation of 50 db or more over a narrow band of frequencies. A control mounted on the front panel permits the tuning of the wave trap to any frequency between 1700 and 2100 kc/sec. It is effective in reducing interference produced by jamming or by radio signals of frequencies close to the frequency of the Loran signals. The rejected band is so narrow that the wave trap can be tuned to the Loran frequency without distorting the shape of the signal beyond usability. A wave trap in the plate circuit of the first i-f amplifier serves a similar function in reducing interference from signals of the intermediate frequency.

The r-f gain potentiometer controls the positive bias of the cathodes of the r-f amplifier and the first and second i-f amplifiers. The grids of the third and fourth i-f amplifiers are maintained at a positive potential of approximately 120 volts, and the cathodes are connected to the plate of a pentode that serves as a gain control and as an automatic volume con-

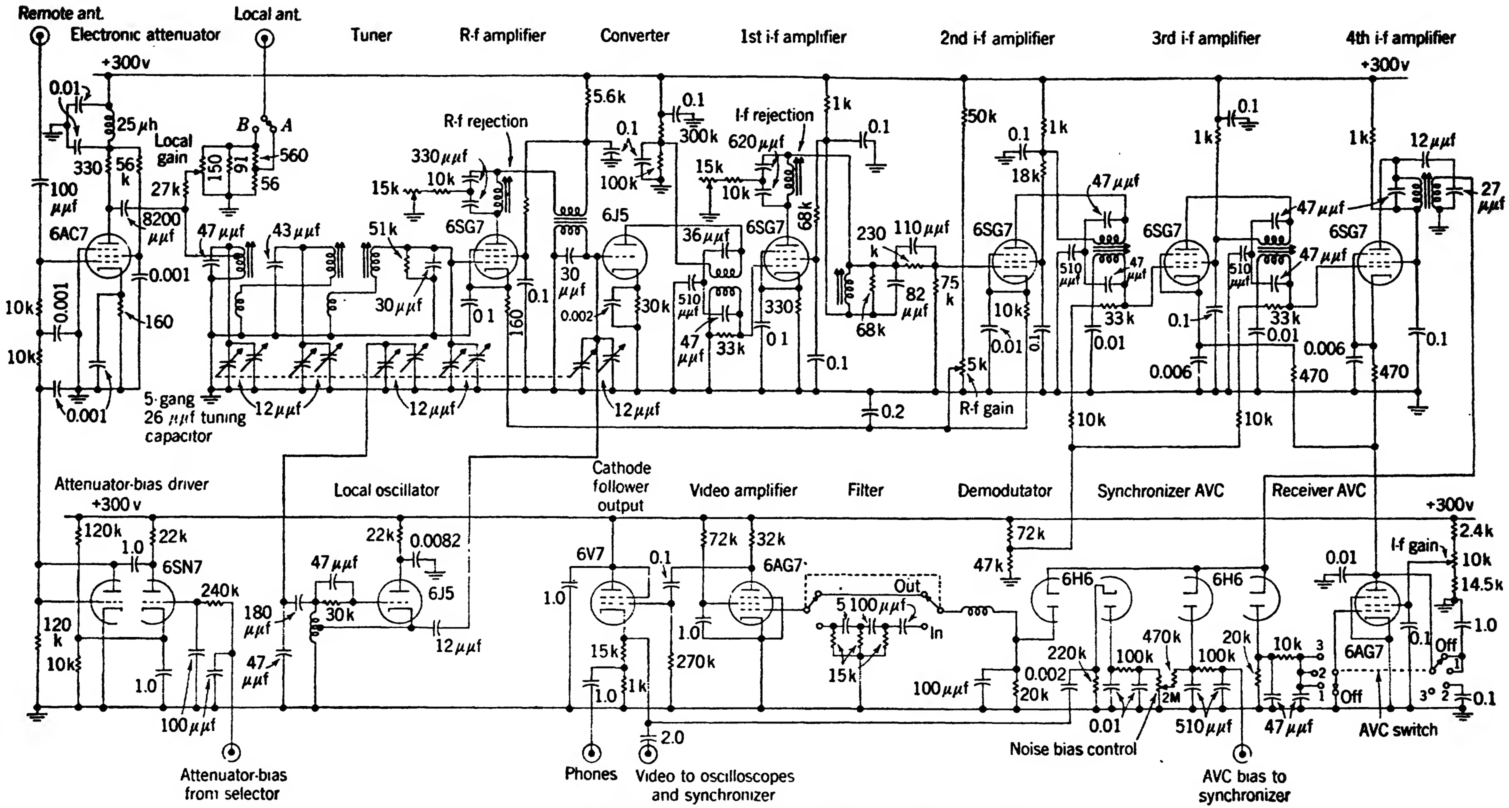


FIG. 7·16.—Schematic diagram of Model UE-1 receiver.

trol. The cathode of the AVC pentode is grounded, and the potential of the screen grid is controlled by the i-f gain potentiometer. The AVC selector switch has four positions. In the OFF position the grid of the AVC pentode is grounded; in the other three positions negative signals, resulting from the rectification of the output of the final i-f amplifier, are applied to the grid of the AVC pentode, and various capacitors are introduced in the plate circuit to provide three different AVC time constants.

When, in normal operation, the AVC switch is in the OFF position, it grounds the grid of the AVC pentode, and the cathodes of the i-f amplifiers tend to follow the grids. The cathode-biasing resistance is dependent upon the d-c plate resistance of the AVC pentode that is controlled by the i-f gain potentiometer. With the AVC switch on one of the other positions, the d-c plate resistance of the AVC pentode is determined by the negative rectified signal. The plate resistance is low except during bursts of noise, when the pentode current is cut off. The cathodes of the i-f amplifier then rise to the peak grid voltages and remain at a positive potential with respect to the grids until the AVC pentode again conducts and discharges the plate capacitor.

The video amplifier passes signals of frequencies between 500 cps and 40 kc/sec. A high-pass filter, which attenuates video signals of frequencies below 2 kc/sec, is helpful in reducing some types of interference.

A portion of the video signal is rectified and mixed with the normal AVC voltage and is applied to the grids of the balanced mixer in the automatic synchronizer to paralyze the automatic synchronizer during bursts of noise.

7·13. Model UE-1 Synchronizer.—At the slave station the remote signal on the *A*-trace precedes the local signal on the *B*-trace by a predetermined time difference (ordinarily 1000 μsec) plus half the recurrence period. The operator adjusts the *A*- and *B*-selectors to give the predetermined time difference between the initiations of the fast *A*- and *B*-traces and verifies the adjustment by means of calibration markers. Although the pulse that drives the local transmitter exciter occurs at the start of the fast *B*-trace, the local signal as it appears on the fast *B*-trace is displaced to the right because of the time delays in the transmission and receiving circuits. The remote signal on the *A*-trace is also delayed by the receiving circuits. When on the fast traces the remote signal is superimposed on the local signal, the time difference between the initiation of the *A*-trace and the rise of the remote signal equals and cancels the time difference between the initiation of the *B*-trace and the rise of the local signal. Thus the measured time difference between the initiations of the fast *A*- and *B*-traces accurately represents the time difference between the reception of the signal from the remote transmitter and the reception (not the initiation) of the signal from the local transmitter.

Although the *A*- and *B*-selectors are sufficiently stable to maintain for several hours the proper time difference between initiations of the two fast traces, an infinitesimal difference in the frequencies of the local and remote crystal oscillators causes the remote signal on the *A*-trace to drift to the right or to the left of the local signal on the *B*-trace. The purpose of the automatic synchronizer at the slave station is to hold the remote signal in a position directly above the local signal.

As shown in the block diagram (Fig. 7·12) a delay multivibrator controls the position of a gate on the *A*-trace. The gate is mixed with the video signal from the receiver, and the output charges a capacitor through a diode. The charge delivered once every recurrence period to the capacitor is proportional to the average amplitude of the remote signal for the duration of the gate. The resulting sawtooth voltage is applied to the control grid of one pentode of the differential amplifier; a d-c voltage is applied to the grid of the other pentode. The two outputs of the differential amplifier supply the screen voltages of the two pentodes that form the balanced mixer. Two 60-cps out-of-phase signals from a phase inverter are applied to the control grids of the balanced mixer. The output is applied through a phase corrector and through a phase inverter to the field coils of the a-c motor in the phase-control chassis. The motor drives the phase-shift capacitor in such a way that the remote signal appears to seek that position on the *A*-trace at which the gate lies a third of the way up the leading edge. More accurately, the timing of the fast traces and the transmission of the local signal with respect to the remote signal are so controlled by the automatic synchronizer that the gate seeks a position a third of the way up the leading edge of the remote signal.

A milliammeter located on the panel of the dual oscilloscope indicates the degree of unbalance of the differential amplifier. When the unbalance corresponding to the error in synchronism exceeds a certain limit, an alarm buzzer sounds and the local transmission is blinked to indicate to users of the signals that the signals are improperly synchronized.

At the master station, the local signal on the *A*-trace precedes the remote signal on the *B*-trace by a predetermined time difference of half the recurrence period plus the coding delay plus twice the time required for a radio signal to travel from one station to the other. The delay circuit of the automatic synchronizer is initiated at the start of the fast *B*-trace and is so adjusted that the gate lies a third of the way up the leading edge of the remote signal when on the fast traces the local signal is superimposed on the remote signal. The automatic-synchronizer switch is turned off; this grounds the synchronizer output and disengages the clutch between the motor and the phase-shift capacitor. In this condition, the automatic synchronizer sounds the warning buzzer and

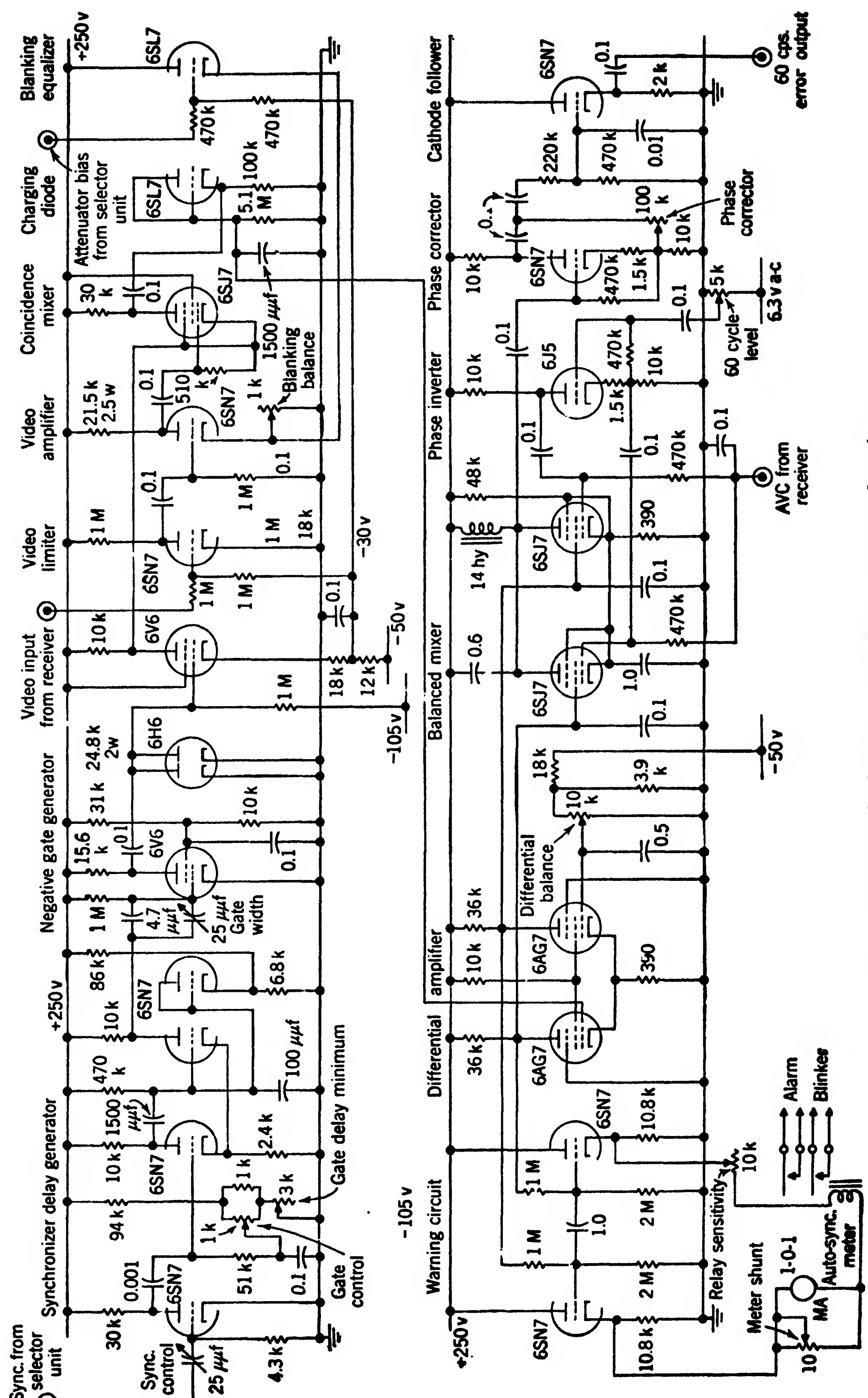


FIG. 7·17.—Schematic diagram of Model UE-1 synchronizer.

blinks the local transmission when the signals are incorrectly synchronized, but it does not directly control the synchronization.

The schematic diagram of the automatic synchronizer is shown in Fig. 7·17. At the slave station the synchronizer delay multivibrator is initiated by the pulse from the gate-pulse mixer of the *A*-selector; at the master station it is initiated by the pulse from the final gate-pulse mixer of the *B*-selector (because the pulse from the gate-pulse mixer is more stable than that from the continuous *B*-delay multivibrator). The trailing edge of the pulse from the delay multivibrator is differentiated to cut off the current through an amplifier and produce a positive flat-topped pulse, or gate, of approximately 10-μsec duration. This pulse is inverted in another amplifier whose plate is connected to the cathode of the gate-video coincidence mixer. Thus, the cathode of the coincidence mixer, which is normally at the potential of the *B*-supply, is driven to approximately ground potential for the duration of the gate. The video signal is impressed on the control grid of the mixer. The plate of the video mixer, which is normally at the potential of the *B*-supply, is driven toward ground potential by the action of the gate on the cathode and by the action of the video signal on the grid. The change of plate potential depends on the amplitude of the video signal.

To reduce the noise and increase the rate of rise, the lower third of the video signal is eliminated and the top is flattened in a negatively biased amplifier that is driven to saturation. In normal operation the gate is located on the steep leading edge of the amplified and limited remote signal. This signal is mixed in the blanking equalizer with a signal derived from the attenuator bias and is applied to the control grid of the gate-video coincidence mixer. At a double-pulsed station the attenuator is controlled by two timers operating at two recurrence rates. Consequently the remote signal as observed at either recurrence rate (on the oscilloscope of either timer) is periodically eliminated. Since the difference in recurrence periods is 100 μsec and at the low basic recurrence rate the recurrence period is approximately 40,000 μsec, the difference in the timing of the two signals is repeated every 400 periods, or every 16 sec. As an observer watches the slow-trace pattern, he sees a section of the trace from which the video signals have been eliminated move around the slow-trace pattern and then complete the circuit and eliminate the remote signal once every 16 sec. A signal of adjustable amplitude derived from the attenuator bias is introduced during the blanking period to compensate for the elimination of the remote signal and in this way to maintain proper synchronism.

The negative output pulse from the coincidence mixer charges a capacitor through a diode. The charge leaks off with a time constant of 7500 μsec, considerably less than the recurrence period of the remote pulse, and the voltage resulting from the charge on the capacitor is applied to the control grid of one pentode of the differential amplifier. The control grid of the other pentode of the differential amplifier is maintained at an adjustable d-c negative potential. When the local and remote timers are in proper synchronism with no difference in the oscillator frequencies, the gate lies approximately a third of the way up the leading edge of the remote pulse. The average potential on the charged capacitor and one control grid then equals the d-c potential on the other control grid, and the differential amplifier is balanced. A slight difference in the oscillator frequencies causes the remote signal to drift to the left or right with respect to the gate. Consequently the output of the coincidence mixer rises or falls with a corresponding change in the average potential of the charged capacitor and with a corresponding unbalance of the differential amplifier.

The two outputs of the differential amplifier supply the screen voltages for the two pentodes of the balanced mixer. Two equal 60-cps out-of-phase voltages from a phase inverter are impressed on the control grids of the balanced mixer. The plates are connected in parallel to an antiresonant plate load so that the phase and amplitude of the 60-cps output signal is controlled by the relative balance or nbalance of the screen voltages of the balanced mixer. The screen voltages depend on the potentials of the control grids of the differential amplifier. During bursts of noise the output of the balanced mixer is reduced by the action of the receiver automatic volume control on the bias of the balanced mixer.

By means of the phase corrector, the phase of the 60-cps output signal can be adjusted in relation to the phase of the current in the armature of the synchronizing motor to give maximum torque. As described in Sec. 7·11, the 60-cps output signal is applied to the field coils of the synchronizing motor and therefore controls the rotation of the phase-shift capacitor and the frequency capacitor.

LOW FREQUENCY TIMER

7·14. General Requirements.—As explained in Chaps. 3 and 5, a Low Frequency Loran system operating at 180 kc/sec has several advantages as compared with Standard Loran. The ground-wave ranges over both land and sea are greatly increased, and the factor of geometrical precision w is better because of the greater length of the baseline over which it is possible to synchronize the ground stations.

Simultaneous Fixing.—As explained in Sec. 3·8, the importance of simultaneous fixing (the measurement of two time differences simultaneously) for air navigation, for homing to an airport, and especially for aerial bombing has been clearly demonstrated. Because of the rapid motion of an airplane it is imperative that the navigator be able to obtain a fix as rapidly as possible. In bombing by Loran it should be possible for the navigator or bombardier to set the delay controls to the predetermined time differences of the target, fly along one line of position, and release the bombs when the signals corresponding to the other line of position move into coincidence. In homing to an airport, especially in congested areas, it should be possible for the navigator to apply the same technique. This cannot easily be done with pairs at two recurrence rates because the indicator would be too complex. Simultaneous fixing becomes practical when three ground stations, a master and its two slaves, operate at a single recurrence rate and the signals from any one station are everywhere distinguishable from the signals from any other station.

The LF stations are now operated in accordance with these requirements. The master station transmits signals at double the normal recurrence rate. One slave station (operating at the normal recurrence rate) is synchronized with one series of alternate pulses from the master station, whereas the other slave station is synchronized with the other series of alternate pulses. The sequence of pulses as observed at the master and slave stations is shown in Fig. 7·18. One series of alternate pulses X transmitted at the master station is distinguished from the other series of pulses Z by an identifying "ghost" series of pulses X' which is shifted in phase by 1000 μsec and appears fainter than the normal series of pulses because its recurrence rate is only a third of the normal recurrence rate. The other two series of pulses W and Y are transmitted by the two slave stations at the normal recurrence rate and are therefore normal in appearance.

This system provides three families of time-difference readings and three corresponding families of lines of position. With Standard Loran indicators, time differences can be measured between signals Z and Y, signals X and W, and signals W and Y. The intersection of any two of the corresponding lines of position establishes a fix.

Although the operation of the three ground stations on a single recurrence rate necessitates little modification of the timers at the slave stations, it requires several modifications of the timers and operational procedure at the master station. Since the Z-pulse is required to follow the X-pulse by precisely one-half of the normal recurrence period, one timer, the master timer, is used to trigger the transmitter at double the normal recurrence rate and also to monitor the timing of the signal from one of the slave stations. Another timer, the monitor timer, is used to monitor the timing of the signal from the other slave station. The oscillator of the master timer provides the 50-kc/sec signal for the monitor timer; consequently both operate at the same frequency, and the locally transmitted signals observed on the monitor timer do not drift.

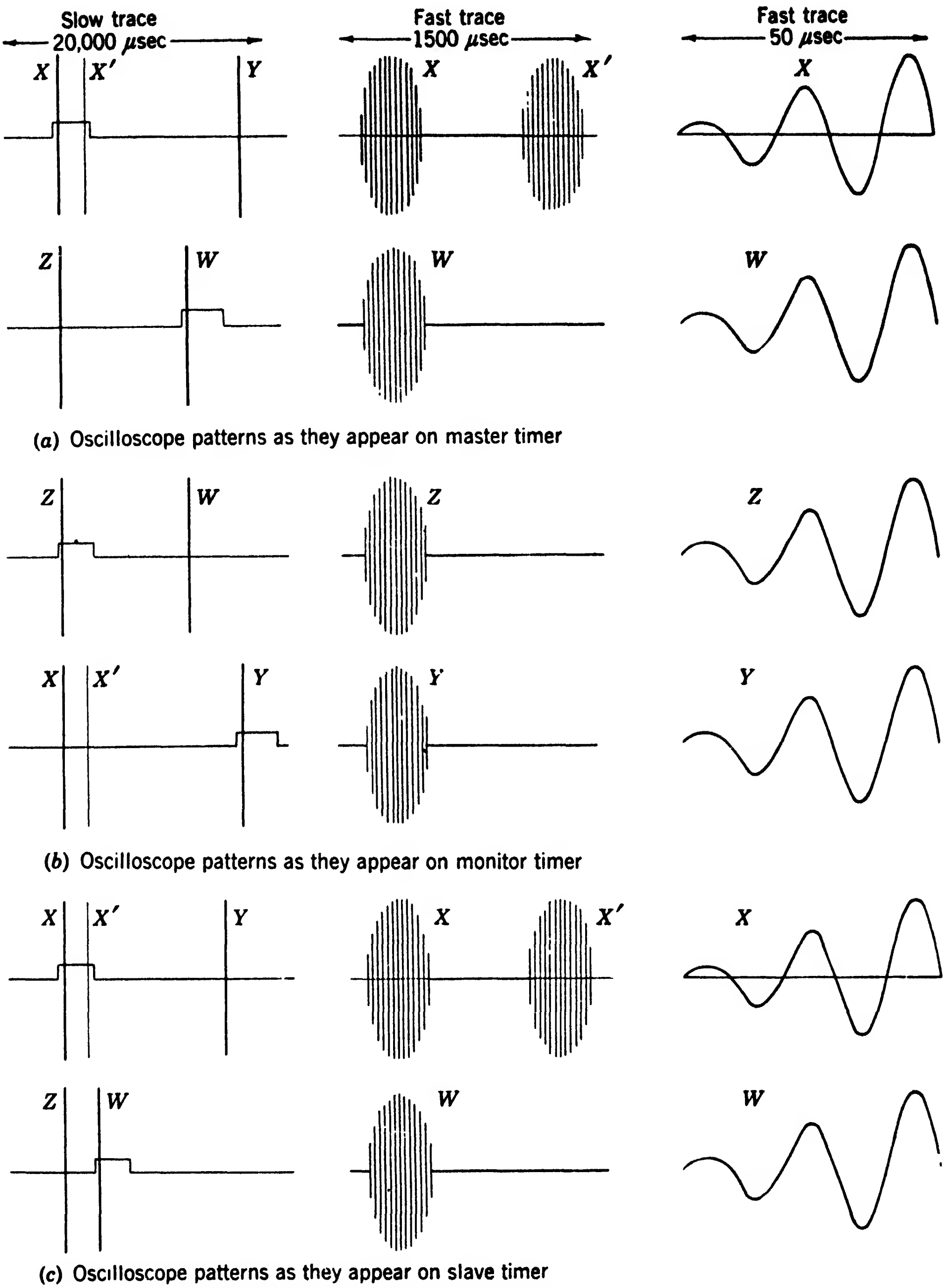


FIG. 7·18.—Basic oscilloscope patterns for Low Frequency Loran.

Because of the low frequency and the relatively narrow bandwidths of the transmitting and receiving equipment, there is a delay of 150 μsec or so between the triggering of the transmitter and the rise of the received locally transmitted signal. This delay necessitates the introduction of a time delay between the triggering of the transmitter and the initiation of the two fast traces. For the same reasons the received pulse rises slowly. This makes the accurate measurement of time differences difficult. In an effort to improve the accuracy of time-difference measurements, the technique of matching i-f cycles of the remote and local signals has been adopted.

Cycle-matching Technique.—The unrectified i-f (50-kc/sec) signal from the receiver is impressed on the vertical deflecting plate of the cathode-ray tube so that the individual cycles of the local signal can be superimposed on those of the remote signal. Although there is some difficulty in determining with certainty the proper cycle of one signal to be matched with a particular cycle of the other signal, the cycle-matching technique is capable of extremely accurate measurement of time differences when the proper correspondence of cycles has been established. With reasonable values of signal-to-noise ratio the cycle-matching technique seems to be capable of time-difference measurements with probable errors of approximately $\frac{1}{10}$ μsec. The cycle-matching receiver is discussed in detail in Sec. 12·2. One-microsecond markers have been added to the timers in order to take advantage of the improved timing accuracy offered by the cycle-matching technique.

Communication by Blinking.—Because of the difficulty of establishing the proper correspondence between the i-f cycles of the local and remote signals, communication between the master and slave operators is required. In addition to the motor-operated blinking that is used to indicate incorrect synchronism, manual control of the blinking is provided for communication between the master and slave operators. A simple blinking code permits the master operator to instruct the slave operator to advance or retard the timing of the slave transmissions by the required interval of time and also permits the slave operator to acknowledge the message.

At the slave station the operator superimposes the cycles of the remote signal on those of the local signal, selecting with some uncertainty the appropriate correspondence between cycles. As explained in Sec. 12·2, because of the irregular time difference $(2\beta + \delta + L/2)$ between local and remote signals, the operator at the master station cannot match cycles of the local and remote signals. Instead, he matches the envelopes. But, knowing the correct value of $2\beta + \delta + L/2$ and comparing it with the measured time difference between the local and remote signals, he can judge whether or not the synchronism is correct.

If necessary he advises the slave operator to advance or retard the timing at the slave station by 5.5 μsec (one cycle at the radio frequency of 180 kc/sec). For the purpose of adjusting the synchronism at the slave station and of adjusting the timing of the transmitter-trigger pulse in relation to the r-f cycles, a variable time delay is introduced between the selector output pulse (which normally triggers the transmitter) and the output pulse from the exciter driver. At the master station this time delay is maintained at a fixed value.

Because the phase of the i-f cycles of the receiver depends on the phase of the signal from the local oscillator as well as the phase of the received r-f signal, a highly stable local oscillator is required. For this purpose a 50-kc/sec signal from the crystal oscillator of the timer is converted in the receiver to produce a 130-kc/sec heterodyne signal. This beats with the r-f signal to produce an i-f signal of 50 kc/sec.

Since the stability required for the cycle-matching technique cannot be achieved with the type of pulsed transmitter used for Standard Loran, an oscillator-amplifier type of transmitter is used for LF Loran. A 50-kc/sec c-w signal from the timer is required to control the phase and frequency of the locally transmitted signal. It is converted in the transmitter to the pulsed r-f signal.

The automatic synchronizer is not sufficiently stable for maintaining synchronism in the LF Loran system. All synchronizing and monitoring operations are, therefore, manually controlled.

7·15. Block Diagram of Low Frequency Timer.—A block diagram of the Model C-1 timer as modified for service at an LF Loran ground station is shown in Fig. 7·19. The modified timer can be used at either a master or a slave station. At a master station it can function as a master timer to trigger the transmitter at double the normal recurrence rate and to monitor the timing of the signals from one of the slave stations, or it can function as the monitor timer to monitor the timing of the signals from the other slave station. The function of the slave timer is to trigger the local transmitter at the normal recurrence rate and in proper synchronism with the appropriate signal from the master station.

Crystal Oscillator.—The monitor timer does not control the transmission of either of the two local signals X and Z. To prevent the drifting of the master and slave signals as they appear on the oscilloscope of the monitor timer, the master and monitor timers are driven by a single oscillator, and therefore the phase shifter of the monitor timer, instead of being connected to its oscillator, is connected through a switch to the 50-kc/sec driver of the master timer.

50-kc/Sec Driver.—The phase-shifted 50-kc/sec signal from the timer oscillator must be supplied to the cycle-matching receiver in which it is converted to the 130–kc/sec heterodyning signal. When the timer

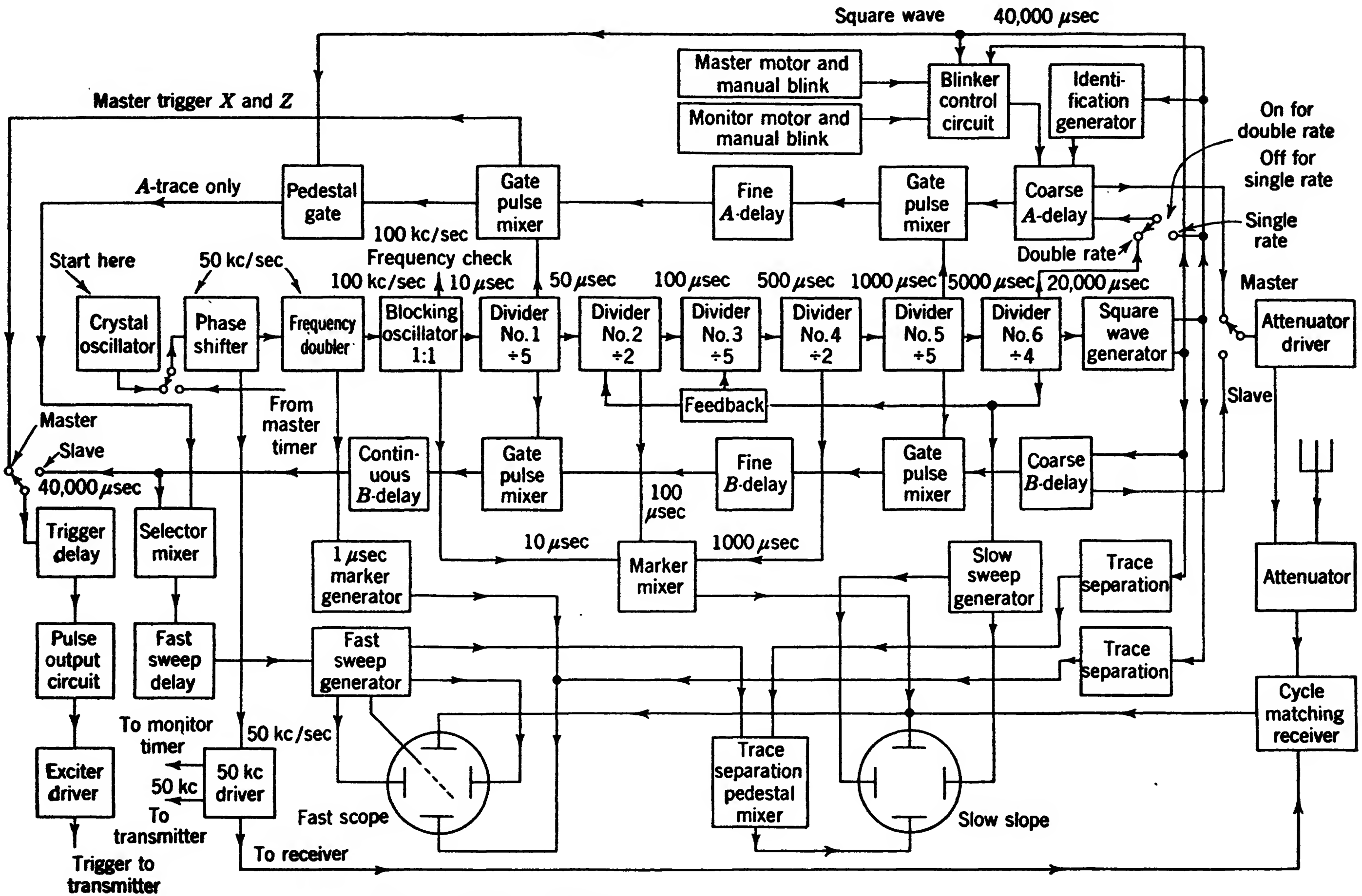


FIG. 7·19.—Block diagram of Model C-1 timer modified for Low Frequency Loran.

operates as a master or a slave, the 50-kc/sec signal is also supplied to the transmitter in which it is converted to the pulsed 180-kc/sec r-f signal. When the timer operates as a master, the 50-kc/sec signal is supplied to the phase shifter of the monitor timer. A driver consisting of a tuned amplifier with a low-impedance output supplies the 50-kc/sec signal for these three purposes.

Because of the increased precision offered by the cycle-matching technique, 1-μsec markers have been added to the calibration system. They provide a calibration scale with which it is possible to estimate time differences with a probable error of approximately 0.1 μsec.

Transmitter Trigger.—When the timer functions as a master, the output pulse from the A-selector triggers the transmitter. Consequently the A-selector of the master timer is triggered at double the normal recurrence rate by the pulse from the last divider. The A-selector of the monitor timer is triggered at the normal recurrence rate by the pulse from the square-wave generator.

When the timer functions as a slave, the output pulse from the B-selector triggers the transmitter, and both the A- and B-selectors are triggered at the normal rate by the pulse from the square-wave generator.

The master operator monitors the timing of the slave signal and, as necessary, instructs the slave operator to advance or retard by one r-f cycle the timing of the slave signal. On the slave oscilloscope the i-f cycles of the remote signal are superimposed on those of the local signal. Therefore the slave operator must be able to shift as instructed the timing of the transmitter-trigger pulse. For this purpose a calibrated delay multivibrator is inserted ahead of the exciter driver. The slave operator normally adjusts it to give a delay of 10 μsec. On instruction from the master operator, the slave operator can advance or retard the slave signal one r-f cycle with respect to the normal timing. At the master station the multivibrator is set and maintained at a fixed minimum delay. The calibrated delay multivibrator can also be used to adjust the timing of the transmitter-trigger pulse with respect to the r-f cycles.

Triggering of Fast-sweep Generator.—When the timer functions as a master timer, the A-selector is triggered at double the normal recurrence rate and the B-selector is triggered at the normal recurrence rate. However a single fast A-trace and a single fast B-trace are required. The output pulse from the A-selector (corresponding to the Z-signal) on the lower trace is therefore suppressed. This is accomplished by a pentode amplifier (the pedestal-gate circuit) which passes the output pulse from the A-selector to the selector mixer. The suppressor grid of the pentode amplifier is controlled by a signal from the square-wave generator, and hence the pentode amplifier is nonconducting for the duration of the lower slow trace.

Since there is a delay of approximately 150 μsec between the triggering of the transmitter and the rise of the local signal as it appears on the timer oscilloscope, a corresponding delay must be introduced between the triggering of the transmitter and the initiation of the fast *A*- or *B*-trace upon which the local signal appears. It is convenient to delay equally the initiation of both the fast *A*- and *B*-traces with respect to the output pulses of the *A*- and *B*-selectors. For this purpose the circuits have been modified by the addition of a delay multivibrator between the mixer and the fast-sweep generator. The delay multivibrator is continuously variable from 50 to 300 μsec.

Identification Blinker.—As explained in Sec. 7·14, one series of alternate signals *X* transmitted by the master station must be distinguishable from the other series of alternate pulses *Z*. The distinguishing feature is an identifying ghost signal which is displaced slightly to the right of and is less bright than the *X*-signal.

In order that this identification be achieved, every third *X*-pulse is delayed by 1000 μsec and appears on the slow trace in position X' of Fig. 7·18. The identification is recognizable on the fast trace by the horizontal line that passes through the base of the *X*-pulse (because every third *X*-pulse is missing).

The identifying shift of timing is accomplished by means of a multivibrator that has a division ratio of 3/1 and a long cycle of operation (approximately 120,000 μsec). The multivibrator is triggered by every third positive pulse from the square-wave generator. The output signal is applied through a pentode amplifier to the bias of the coarse *A*-delay multivibrator and is adjusted in amplitude to shift the delay by 1000 μsec once with every third recurrence of the *X*- (or X'-) pulse.

The identifying shift of timing is required only for the *X*- (and X'-) pulse on the upper trace, not for the *Z*-pulse on the lower trace. Therefore the signal from the square-wave generator is applied to the suppressor grid of the pentode amplifier so that the phase-shifting signal is eliminated for the duration of the lower trace.

Communication Blinker.—Provision must be made for two different blinker functions. At the master station independent controls of the motor blinker (indicating incorrect synchronism) for both the master *X*- and *Z*-pulses must be provided. Also, independent controls of the manual blinker (for communication between master and slave operators) for both master pulses are required. At the slave station the two blinker functions are simpler (because only one pulse must be blinked) and the same circuits are applicable.

The motor blinker shifts the timing of the local signal by 2000 μsec for approximately ½ sec every second. A cam, rotated by a synchronous motor, operates a switch with a period of 1 sec. The switch controls the bias potential of the coarse *A*-delay multivibrator and by means of this controls the timing of the *X*- and *Z*-pulses. The switched bias potential is applied to the delay multivibrator through two pentode amplifiers acting in parallel. One of the two signals (which are 180° out of phase) from the square-wave generator is applied to the suppressor grid of one of the pentode amplifiers to permit the blinking of the *X*-pulses only. The other square-wave signal is applied to the suppressor grid of the other amplifier to permit the blinking of the *Z*-pulse only.

The manual blinker permits the independent keying of either of the local signals (by a shift in timing of 2000 μsec) for the transmission of simple dot-dash messages to the slave operator. Two push-button switches control the bias of the coarse *A*-delay multivibrator. The same two pentode amplifiers that control the motor-switched blinker bias also control the manual blinker bias. These manual push-button controls are independent of each other and independent of the motor-blinker controls.

CHAPTER 8

SWITCHING EQUIPMENT

By R. H. Woodward

8·1. General Requirements.—The Loran technique of measuring the time difference between the arrivals of two pulsed signals requires an oscilloscope presentation in which a fast trace showing one pulsed signal appears directly above a similar fast trace showing the other pulsed signal. It must be possible to time the fast traces so as to make one signal appear directly below the other. Both signals as they appear on the oscilloscope must be of the same amplitude. These requirements are simple in principle, but it is difficult to comply with them at a Loran ground station because the signals to be compared differ so greatly in strength. The local transmitter produces signals in the receiving antenna that may be some 140 db greater than the signals from the remote station. It is necessary, therefore, to attenuate the local signal and to amplify (or pass unattenuated) the remote signal so that the local and remote signals as they are impressed on the inputs of the receiver are approximately equal; the final exact equalization is accomplished in a variable resistance network in the first stage of the receiver. Since the purpose of comparing the two signals is to measure their time difference accurately, the attenuator must not produce any appreciable delay or distortion of the local signal.

The local and remote signals that are induced on the receiving antenna pass through a coupling unit and a transmission line to the attenuator and receiver. The signals are delayed and their shapes are slightly altered by the action of the antenna, the coupling unit, and the transmission cable. The delay and distortion of the signals depend on the Q of these circuits. A local signal is also induced on the interconnecting cables and on the power lines. This local signal and the remote signal are induced at different locations and (as they appear at the attenuator input) are delayed and distorted in different amounts. If the local signal induced on the cables and power lines reaches the receiver input in sufficient strength to cause a deflection of the oscilloscope trace, it causes an error in the time-difference measurement, and, therefore, it must be eliminated.

The easiest way of providing adequate shielding is to enclose the attenuator and the timers in a doubly shielded room. Power is supplied to the equipment in this room through an isolation transformer that eliminates any r-f signals picked up by the power lines. All cables that enter the room pass through a metal box which serves as a common ground for both the inner and the outer shields of the room and for the shields of all the cables that enter the room.

It would be difficult to design an attenuator that would pass or amplify the remote signal and attenuate the local signal from the receiving antenna by a large constant ratio without causing delay and distortion. It is easier to attenuate the local signal from the main antenna so thoroughly that the receiver's output is negligible and simultaneously to introduce a weak local signal of suitable strength from another local source. This can be a short inefficient antenna or a dividing network of resistances that bypasses the attenuator and allows a suitable fraction of the local signal to reach the receiver.

The receiver has two inputs, one for the remote signal and one for the local signal, and these signals travel through different channels to the receiver. The remote signal is induced in the receiving antenna and passes through the coupling unit, the transmission cable, and the attenuator to the remote-signal input of the receiver. If the local signal is induced on a short antenna, it passes through a transmission cable to the local-signal input of the receiver. If the local signal is obtained from the receiving antenna, the strong local signal induced on the receiving antenna passes through the coupling unit, the transmission cable, and a passive attenuating network to the local-signal input of the receiver.

If the receiving antenna is not used as the source of the local signal, it is convenient to limit the positive and negative r-f peaks of the local signal at the receiving antenna by means of two gas-filled tubes associated with the coupling unit. When the local transmitter sends out a pulse, a discharge takes place in these gas-filled tubes that results in attenuation of the local signal from the receiving antenna. Because such limiting tubes distort the local signal, a local signal from another source must be provided for the measurement of the time difference. The use of two separate antennas for the remote and local signals, however, is a source of possible error in timing because of the different locations of the antennas and because of possible differences in the delays and distortions introduced by the circuits of the two channels. The timing uncertainty is especially serious when a Beverage wave antenna (Sec. 10·4) is used to receive the remote signal since a separate antenna must be used to receive the local signal. The use of a single vertical receiving antenna and a passive attenuating network to provide both the remote and local signals is preferred, therefore, when possible, even though the problem of attenuating an unlimited local signal is more difficult.

The attenuator is controlled by the timer and switches the remote-signal input of the receiver alternately to the receiving antenna and to ground. In the early models the attenuator consists of two relays. In the later models it consists of two or more stages of amplification. The bias of the amplifiers is driven to a large negative potential during the transmission of the local signal.

At a station transmitting at a single recurrence rate, there are two timers and two transmitters. The duplication assures continuous service and facilitates maintenance of equipment. At a double-pulsed station there are four timers and two transmitters. Each transmitter has two exciter units and a pulse mixer, so that it can be controlled by two timers and transmit at two recurrence rates at the same time. To take full advantage of the duplication of equipment, provision must be made for switching connections between the different transmitters and timers. This additional switching equipment is also housed in the shielded room.

The switching equipment used with timer Models A, B, and B-1 is primitive. The switching is accomplished by disconnecting cables from one set of terminals and connecting them to another. The attenuator consists of two relays connected in series between the receiving antenna and the receiver and controlled by the timer. For attenuation the circuit between the receiving antenna and the receiver is opened at each relay and the conductor is grounded. During the part of the recurrence period when there is no attenuation, the receiving antenna is connected directly to the receiver through the relay contacts. The attenuation provided by this method is ample, but the operation of the relays is unreliable.

The switching equipment Models C, C-1, and UK provide two selector switches for connecting each of two transmitter exciters with the exciter-driver circuits of any one of four timers. A two-stage low-gain amplifier, whose grids are driven below cutoff during a portion of the recurrence period, attenuates the local signal.

The Model UM switching equipment for use with the Model UE-1 timer provides complete switching between four transmitter exciters and four timers. Three discriminators, each consisting of an electronic attenuator with a bypassing resistance attenuator are provided. Each of two timers may be connected through an independent discriminator to a different antenna, and there is a third discriminator that may be taken out of service for maintenance. The use of a single antenna for the reception of both the local and remote signals is possible because of the resistance attenuators that bypass the electronic attenuators to provide undistorted local signals of the desired amplitude derived from the main receiving antenna. No gas-filled tubes are required to limit the local pulse.

A laboratory model of a Low Frequency discriminator has been constructed and tested. It consists of a four-stage triode electronic attenuator and a bypassing resistance attenuator. Special attention has been given to the shielding, the reduction of tube noise, and the elimination of distortion and unequal phase shifts, with the result that local and remote signals differing by 160 db or more can be handled with negligible errors in timing.

8·2. The Switching Equipment Used with Model A, B, and B-1 Timers.—All of these timers are enclosed in a shielded room. Limiting gas-filled tubes are used in the antenna coupling unit, and the weak local signals are supplied by a special inefficient antenna. The attenuator consists of two relays between the antenna and receiver that are open at the time of the local transmission. These relays are enclosed in individual insulated metal boxes, and the interconnecting leads pass through copper tubing, which serves both to shield the leads and to ground the boxes. The signals from the two antennas are both fed into a variable resistance network in the input of the receiver, where the final equalization of the remote and local signals is accomplished.

The attenuation of the relays is sufficient, but their operation is too unreliable for ordinary service. Furthermore, since the time of the attenuated portion of the recurrence period cannot be accurately controlled, it must be made relatively long. At a double-pulsed station the two timers operating at different recurrence rates control a single set of attenuator relays. The relative phasing of the two sets of transmitted pulses runs through a complete cycle in about 15 sec. The signal from each of the two remote stations disappears for the part of the cycle in which it arrives simultaneously with the interval of attenuation corresponding to the transmission from the other remote station. The length of this time of disappearance is proportional to the length of the individual interval of attenuation. It is, therefore, desirable to make this interval of attenuation as short as possible. For these reasons the pair of relays of the early model are replaced by an electronic attenuator in the later models of the switching equipment.

8·3. Model C-1 Switching Equipment.—Because the switching equipments designed for use with the Model C, C-1, and UJ timers are similar, only the Model C-1 switching equipment (Fig. 8·1) is discussed in this section. It provides greater flexibility in switching than do the earlier models. It uses an electronic attenuator that is more reliable than the relays of the earlier models and operates with shorter intervals of attenuation. This type of switching equipment is used for Sky-wave Synchronized Loran as well as for Standard Loran. The block diagram of transmitting, timing, and Model C-1 switching equipment at a typical Loran station is shown in Fig. 8·2. Provision is made for switching the exciter

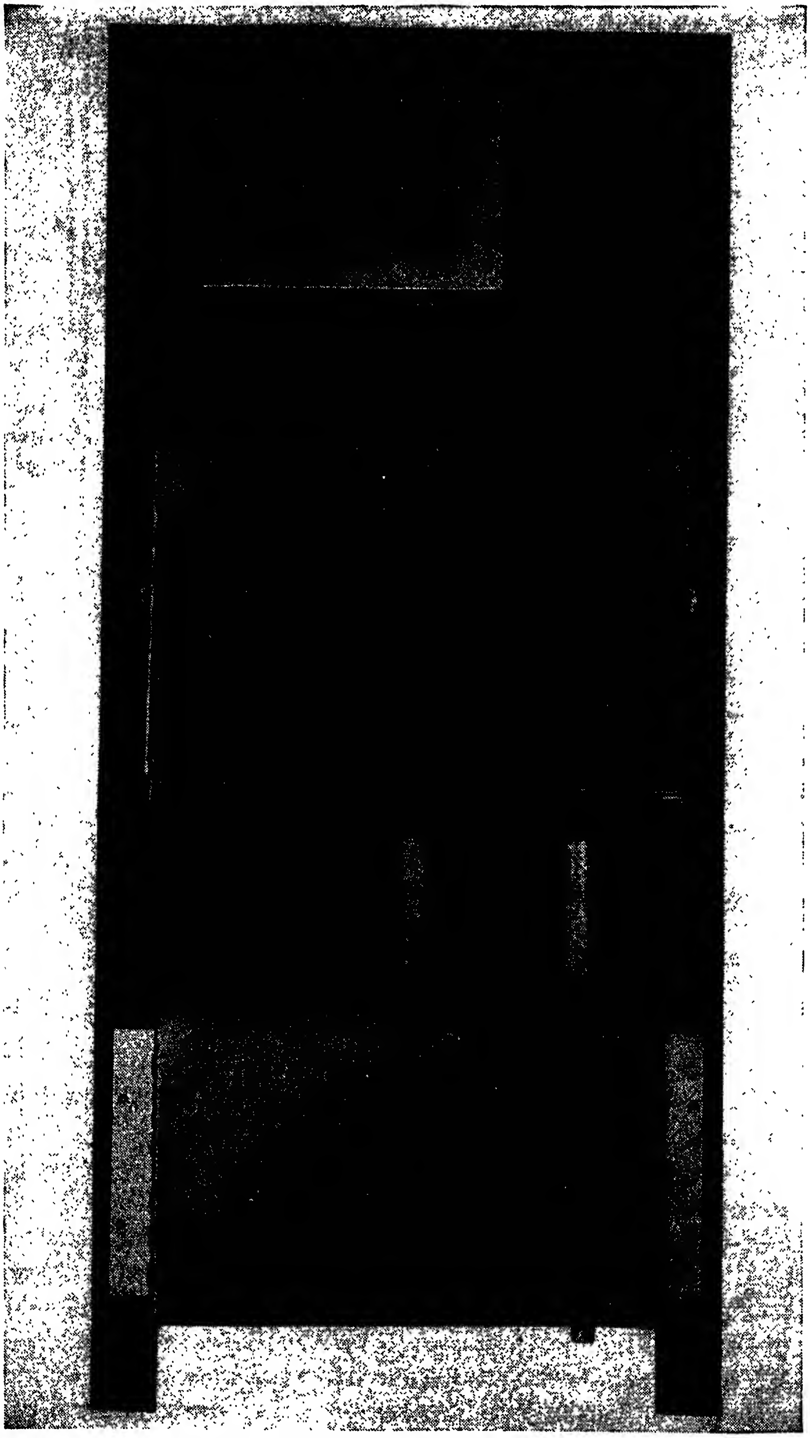


FIG. 8·1.—Model C-1 switching equipment.

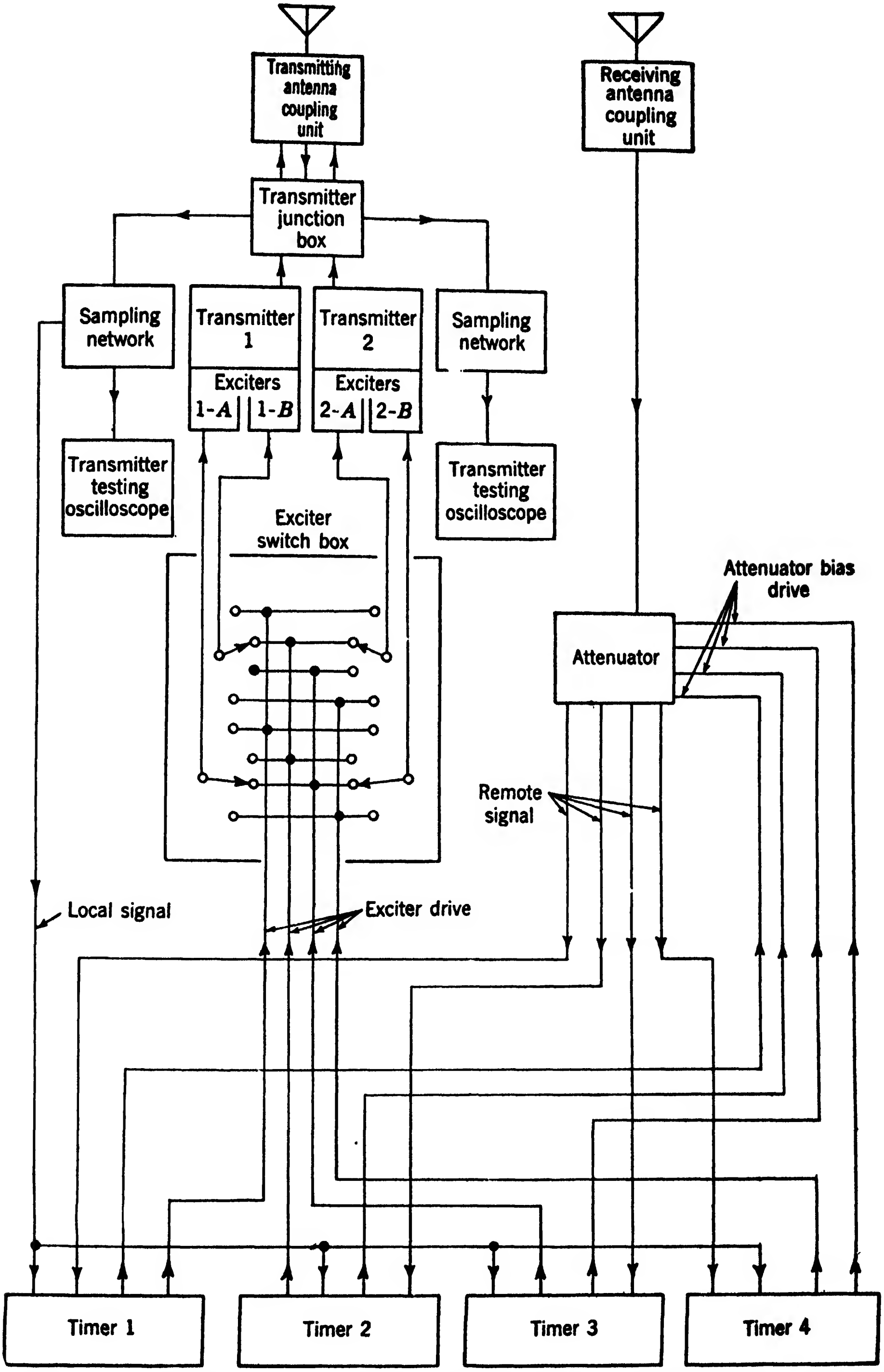


FIG. 8·2.—Block diagram of transmitting, timing, and Model C-1 switching equipment in a typical double-pulsed ground station.

driver from any two of the four timers to the two exciters of either one of two transmitters. The switches are enclosed in a metal box mounted on the inner wall of the shielded room.

The isolating transformer is located outside the shielded room just below the metal entrance box, which extends through the wall of the shielded room and serves as the common ground for the cable shields and for the inner and outer screens of the shielded room. The entrance box also encloses the first stage of the electronic attenuator, shown in Fig. 8·3.

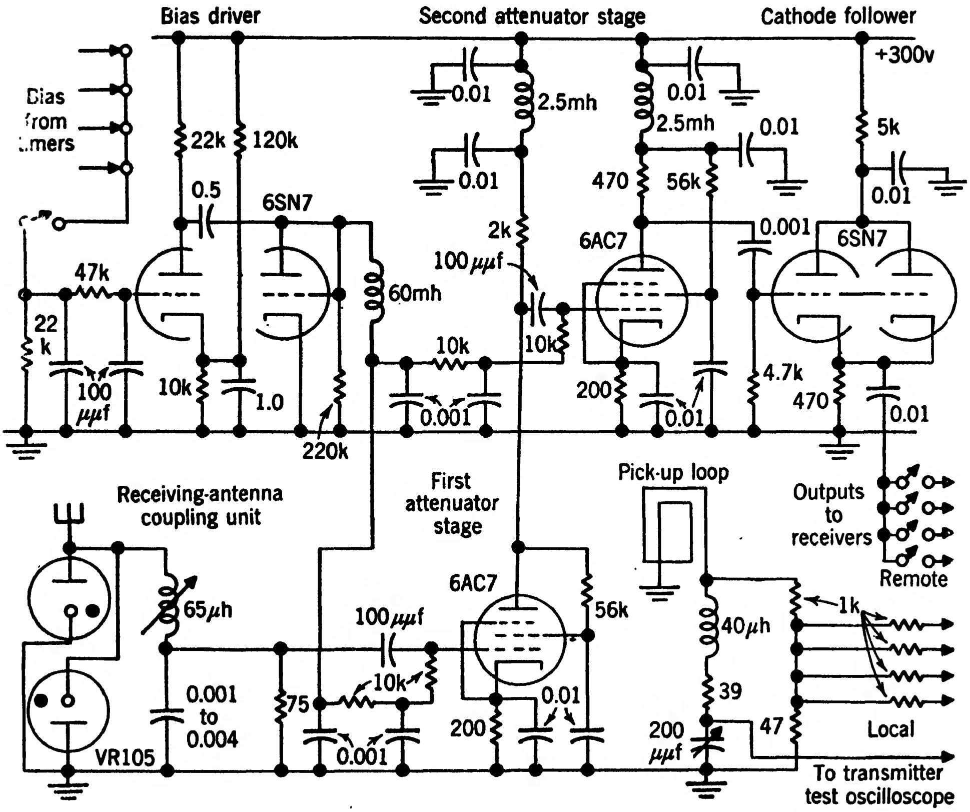


FIG. 8·3.—Schematic diagram of Model C-1 switching equipment.

The local signal is induced on a loop consisting of a single turn of sheet copper which is located near the coupling unit of the transmitting antenna. This signal is introduced into a signal-sampling network (mounted on the side of the transmitter) that has two outputs of local signal. A series-resonant circuit yields one signal of high voltage that is impressed directly on the vertical plate of the test oscilloscope of the transmitter. A second channel through a resistor supplies a local signal of suitable amplitude for the timers. Series resistors in the leads to the four timer receivers provide isolation between the receivers and so prevent changes of load with local-gain adjustments from changing the amplitude of the signal. As in the Model B-1 timer the final equalizing of the local and remote signals is accomplished in a variable resistance network in the input of the receiver where the local and remote signals are mixed.

The gas-filled tubes mentioned in Sec. 8·1 are used to help in the attenuation of the large local signal induced in the main receiving antenna. The coupling unit of the receiving antenna transforms the resistance of the antenna to that of the transmission line and neutralizes the antenna's reactance at the required frequency. The remote signal induced on the receiving antenna passes through the coupling unit, transmission line, and attenuator to the receiver. The attenuator acts as an amplifier during the time of reception of the remote signal. It consists of two 6AC7 tubes connected as amplifiers in cascade.

In the interval of attenuation of about 1800 μsec, the control grids of the attenuator tubes are driven far enough beyond cutoff so that no signals pass to the receiver. Since the local signal from the receiving antenna is then distorted by the limiting action of the gas-filled tubes, it must be completely eliminated from the input of the receiver. The maximum possible attenuation per stage is determined by the ratio between the grid-to-plate impedance and the plate-to-ground impedance. In practice this limit is not attained; the actual attenuation is limited by circulating ground currents and by pickup between the grid and plate circuits. To reduce these effects, the two stages are enclosed in separate boxes connected by coaxial cable and the grid and plate circuits are filtered.

The bias-driver circuits of the timers are all connected at the input of the bias driver of the attenuator so that any one, two, or more timers can control the attenuator. A single attenuator can serve a double-pulsed station operating at two recurrence rates. An attenuator for each of two antennas is required, however, at the double-pulsed stations where long baselines and severe noise conditions necessitate the use of Beverage antennas (see Sec. 10·4).

8·4. Model UM Switching Equipment.—The use of two different antennas and coupling units for the reception of the local and remote signals is a source of possible error in timing. Consequently, in the discriminator of the Model UM switching equipment (Fig. 8·4) provision is made for the use of a single antenna for the reception of both signals. The discriminator consists of an electronic attenuator and bypassing resistance attenuator. No gas-filled limiting tubes are used. The electronic attenuator is designed to handle the high voltages encountered during the transmission of the local signal.

Experience has shown that in operation over a long baseline or over land, a Beverage or wave antenna at the ground station gives a higher ratio of signal to atmospheric noise than does the standard vertical

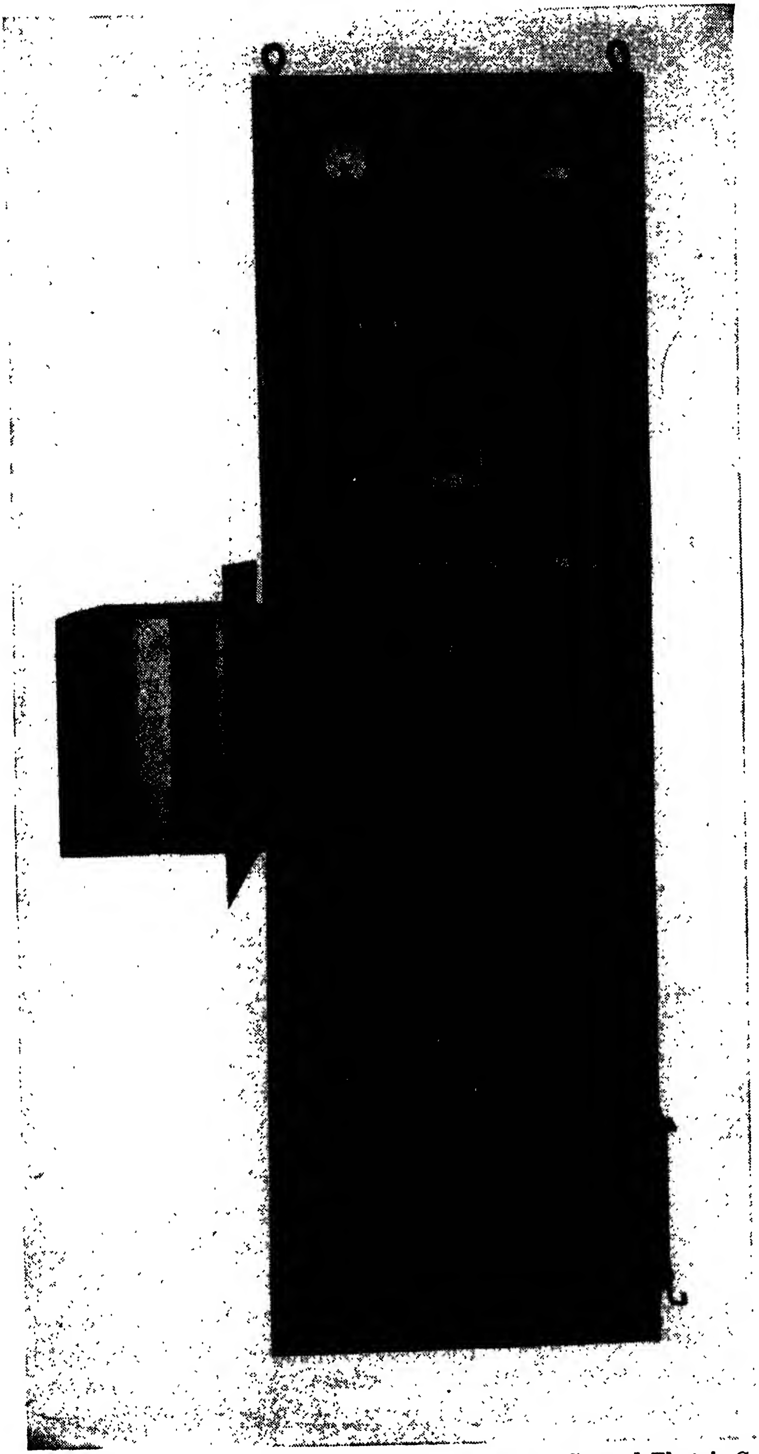


FIG. 8·4.—Model UM switching equipment. *(Courtesy of General Electric Company.)*

antenna and accordingly facilitates the maintenance of synchronism. Although the use of the Beverage antenna is not recommended, because of the resulting uncertainty of timing of the remote signal with respect to the local signal, it is sometimes necessary in maintaining synchronism over unusually long baselines. Since the Beverage antenna is directional, a separate antenna is required at a double-pulsed station for reception of signals from each of the two remote stations, and an individual discriminator must be used with each antenna. Consequently, three independent discriminators are incorporated in the Model UM switching equipment, the third serving as a stand-by.

Normally in a single-pulsed station there are two timers and two transmitters (four exciters); in a double-pulsed station there are four timers and two transmitters (see Fig. 8·5).

The Model UM switching equipment is constructed in a single cabinet equipped with space heaters and a ventilating blower. The cabinet is installed in the shielded room near one wall. All leads entering the shielded room pass through the entrance box, which protrudes through the wall and is bolted to it. The uppermost chassis contains (1) a selector switch for connecting a line from the standard frequency receiver (for checking the crystal oscillators against the Bureau of Standards time signals from station WWV) to the 100-kc/sec output of any one of four timers, (2) four selector switches for connecting from one to four transmitter exciters to any of four timers, (3) a line-frequency meter, and (4) a line-voltage meter. The second chassis contains (1) four selector switches for connecting the local- and remote-signal inputs of one to four timers to the local and remote outputs of any of three discriminators and (2) a toggle switch for connecting the ventilating blower of the cabinet to either of two power lines. The lowest panel contains circuit breakers, fuses, and switches for distributing power from either of two transformer-isolated sources to three discriminators in the cabinet and to the timers and lighting circuits in the shielded room.

Figure 8·6 is a block diagram of the Model UM switching equipment. In each of three discriminators two channels are provided. One is the electronic attenuator whose output is connected to the remote input of the timer receiver; the other is an adjustable resistance attenuator whose output is connected to the local input of the timer receiver. Provision is made for connecting a single antenna to the inputs of both channels or for connecting individual antennas to the two inputs. A bandpass antenna filter is provided for the reduction of cross modulation caused by strong signals of frequencies outside the pass band. Its introduction in both channels causes no timing error because it delays and distorts both remote and local signals equally. A ganged selector switch with three positions makes it easy to change connections. The three com-

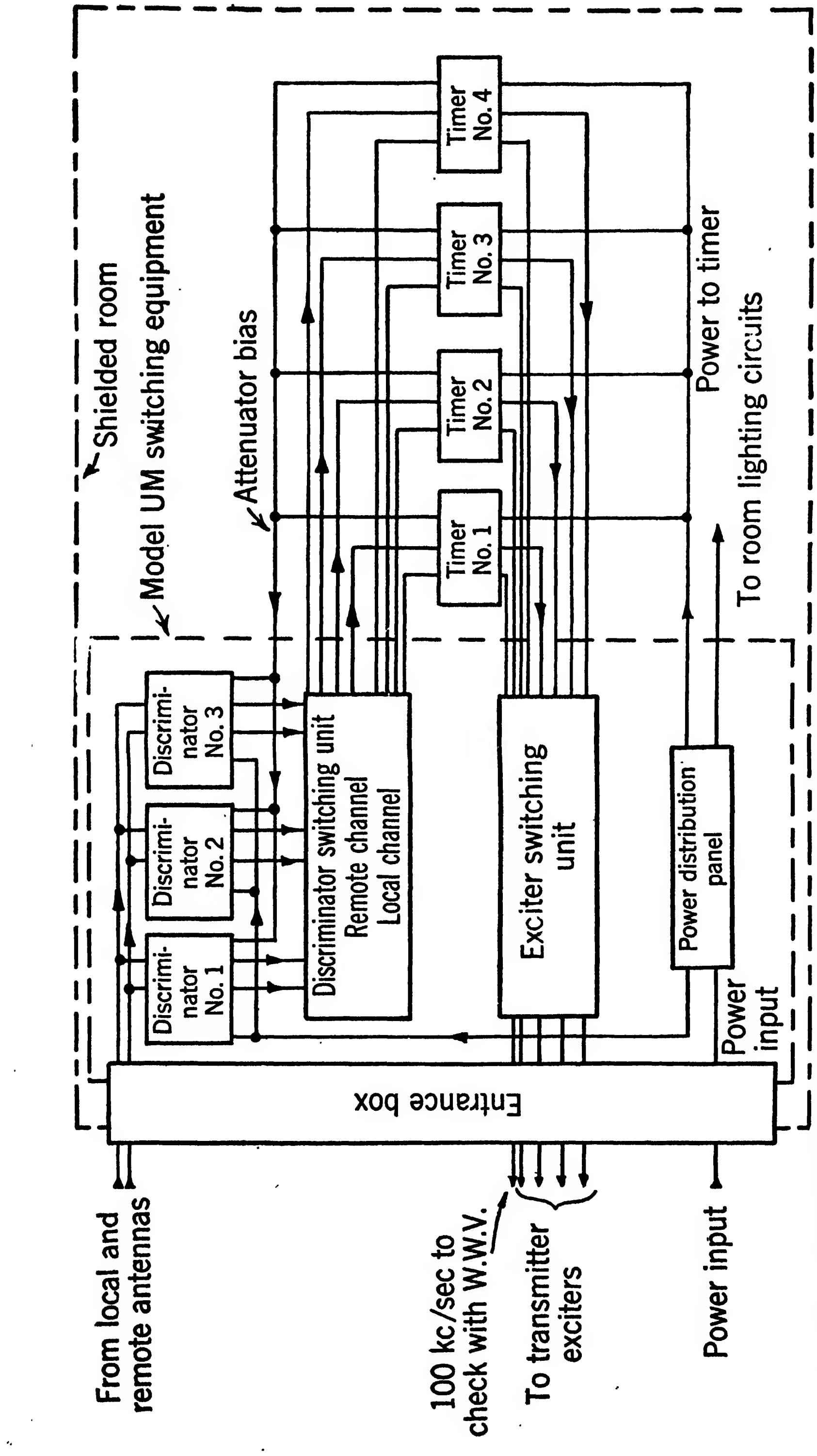


FIG. 8·5.—Block diagram of transmitting, timing, and Model UM switching equipment in a typical double-pulsed ground station.

binations are (1) single antenna with filter in, (2) single antenna with filter out, and (3) two antennas with filter out.

The schematic diagram of the discriminator is shown in Fig. 8·7. The resistance attenuator forms a continuously open channel between the antenna and the receiver. There is no need to interrupt this channel as the electronic channel is interrupted, because, with the exception of the local transmission, all signals reaching the receiver through this channel are negligibly small. The resistance attenuator, which is

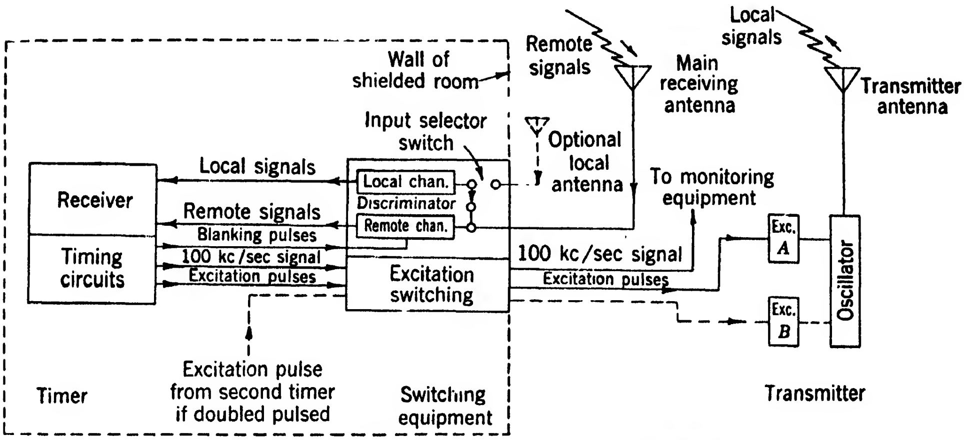


FIG. 8·6.—Block diagram of Model UM switching equipment.

adjustable in steps of 10 db from 20 to 130 db, can be set to compensate for the different signal strengths found at different stations. In normal operation the input voltage may be as high as 500 volts peak to peak. This is attenuated to approximately 150 μv at the 130-db tap. If the local signal is weaker or the remote signal stronger, a tap giving less attenuation can be used.

The electronic attenuator consists of three attenuator stages and a cathode-follower output. (There is a fourth attenuator stage in the receiver of the Model UE-1 timer.) The attenuator stages are conventional low-gain amplifiers that are periodically cut off by the action of the bias amplifier. The first stage, a triode, is designed to handle the high voltage of the local transmission. The grid is driven 300 volts below ground potential. The attenuation and gain are approximately 15 db and unity, respectively. The attenuating bias applied to the grids of the second and third stages, which are pentodes, is 90 volts. In each of these stages the attenuation and gain are approximately 60 and 4 db, respectively. There is a loss of approximately 4 db in the low-impedance cathode-follower output stage.

To reduce leakage of the r-f signal from the grid to the plate circuits, the components of the plate circuit of one stage are mounted in the shield that encloses the succeeding stage. The plate and screen voltage

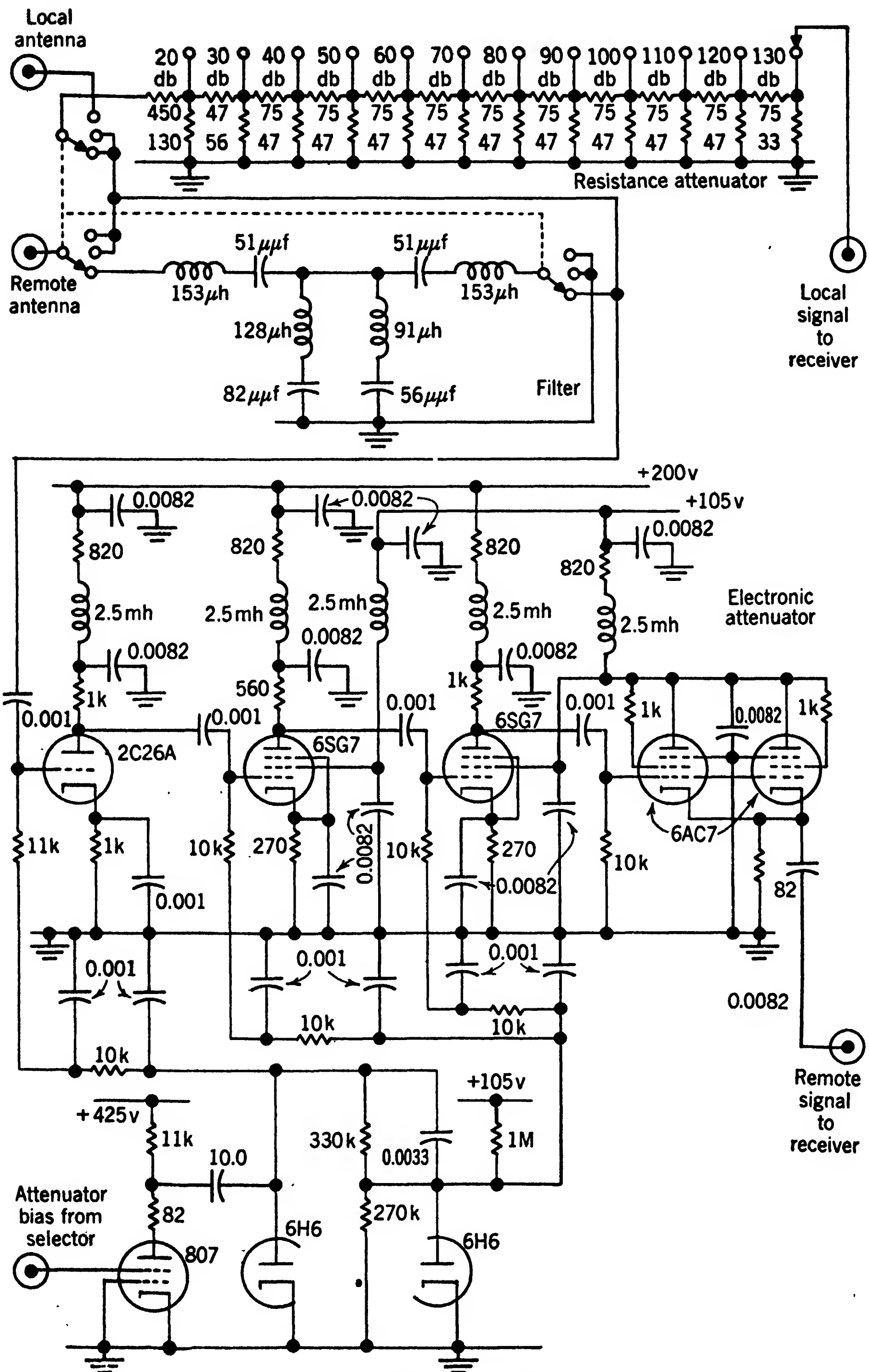


Fig. 8·7.—Schematic diagram of Model UM discriminator.

and bias leads are filtered by single π-sections that are critically damped to prevent oscillations. The filament transformers and plate-supply transformers are provided with electrostatic shields. Each attenuator stage, each section of the input selector switch, the bandpass antenna filter, and the resistance attenuator are enclosed in separate aluminum castings insulated from the chassis.

The bias for cutting off the attenuator stages is obtained from a bias amplifier. The timing and duration of the attenuating bias are controlled by the timers. The duration is approximately 1800 μsec. It must be long enough to provide adequate attenuation for the entire period during which local transmission may occur. This period depends upon the adjustment of the timer.

The bias circuits of all the timers are connected to a common resistance and to the bias-amplifier inputs of all the discriminators. Consequently, each operating timer controls all operating electronic attenuators unless its bias circuit is switched off. At a double-pulsed station all signals except the local transmissions are eliminated from two short sections of the slow-trace pattern. As observed on either of the two operating timers, one section remains stationary while the other moves around the slow-trace pattern, periodically eliminating the remote signal. The direction of motion is opposite for the two timers.

8·5. Low Frequency Switching Equipment.—The experimental LF Loran stations have been operated with slightly modified Model C-1 switching equipment. Since the requirements for switching equipment at an LF Loran ground station are more severe than those for Standard or Sky-wave Synchronized Loran, an experimental model of the proposed equipment has been built and tested at the Radiation Laboratory.

Experiments in this country and experience with the European SS ground stations that do not have shielded rooms have shown that under normal conditions it is possible to design an attenuator capable of satisfactory operation without the protection of a shielded room. The advantages of elimination of the shielded room are increased convenience and simplification of operation and more space in the timer building. The problem of providing sufficient attenuation without a shielded room is greatly simplified if the electronic attenuator is incorporated in the timer, closely associated with the r-f stage of the receiver. This, of course, would call for a complete redesign of the timer, which has not been feasible. The laboratory model of the LF switching equipment has, however, been designed keeping in mind the possibility of eventual elimination of the shielded room.

The requirements for the attenuator for the permanent LF system are more severe than those for the Standard and SS attenuator because the anticipated output power is 1 megawatt instead of 100 kw, and because of the continuous output of the 90-kc/sec c-w driver of the transmitter. This is about 20 watts and is present even during reception of the remote signal. To avoid difficulty expected from the radiation of the second harmonic from the 90-kc/sec driver and to alleviate the problem of attenuating the local signal, it is planned that the transmitter building shall be located 1000 ft or so from the timer building and that the receiving antenna shall be 1000 ft or more from the transmitting antenna. Furthermore, because the cycle-matching technique offers the possibility of measuring time differences with an error of only about $\frac{1}{10}$ μsec, the difference in phase shift (or distortion) introduced in the local-signal channel (resistance attenuator) and the remote-signal channel (electronic attenuator) must be less than 6°. If it proves to be necessary, an amplifier can be used in the local-signal channel that is a duplicate of the electronic attenuator when it is amplifying the remote signal.

As with the Model UM switching equipment a single receiving antenna and a resistance attenuator supply both the remote and local signals. With the exception of an additional switch for the 50-kc/sec signal to the transmitter, the switching is similar to that of the Model UM. However, in the design of the LF attenuator, considerable effort has been expended in reducing the thermal and "shot" noise in the electronic attenuator. The maximum over-all attenuation factor is determined by the negative grid bias of the first stage, which limits the maximum local signal that the attenuator can handle, and the thermal and shot noise of the attenuator (when acting as an amplifier), which limits the minimum remote signal that the attenuator can handle. In the design of the attenuator, the amplification when the attenuator is acting as an amplifier is limited by the cross modulation produced in the wide-bandpass amplifier by strong signals of unwanted frequencies. In an effort to reduce the noise, low-noise triodes are substituted for the pentodes of the earlier models. Although the maximum theoretical attenuation factor per stage of a pentode is greater than that of a triode, the attenuation factor attained in practice is limited by the coupling between the grid and plate circuits rather than by the ratio of the grid-to-plate and plate-to-ground impedances. The triode has the advantages that the circuit is simpler, microphonics and internal tube noise are lower, and cross modulation is less. Four low-noise triode stages of attenuation are used, instead of the two or three pentode stages of the earlier models.

Figure 8·8 is a schematic diagram of the LF attenuator. The four stages of attenuation are enclosed in a long copper box, each stage being separated from the succeeding stage by a copper partition. As with the Model UM switching equipment, the plate circuit of one stage is mounted

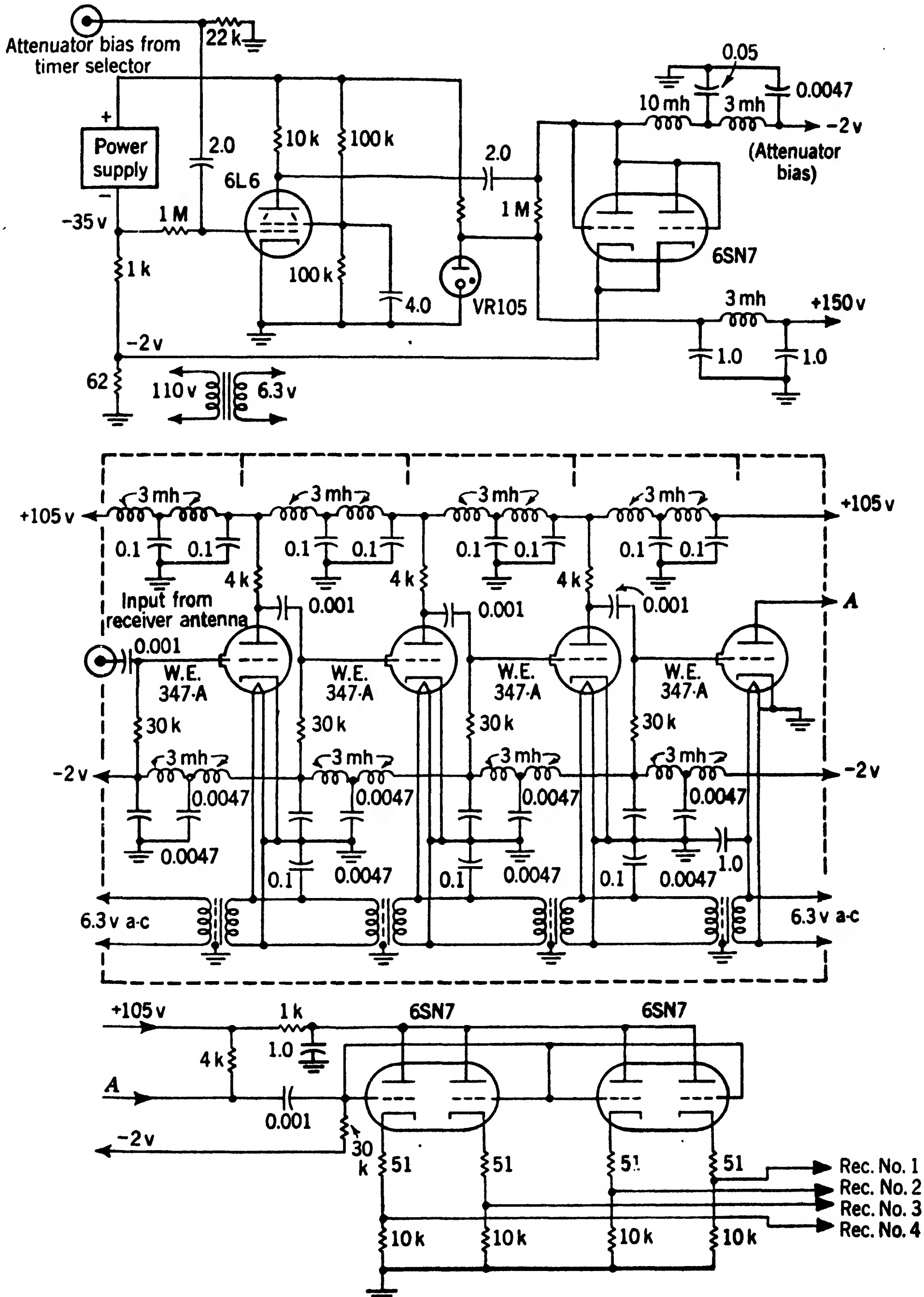


FIG. 8·8.—Schematic diagram of Low Frequency attenuator.

inside the compartment of the succeeding stage to minimize the coupling between the grid and the plate circuits. The routing of the leads is designed to minimize the coupling between the grid and plate circuits, and all bias and power leads are shielded and filtered. A separate electrostatically shielded filament transformer supplies power to the filament of each triode.

In an effort to reduce the phase shift through the attenuator, it is designed to pass all frequencies up to 10 Mc/sec. It is estimated that it produces a phase shift not exceeding 6°.

Each stage of attenuation is capable of an attenuation factor of 40 to 50 db. The over-all measured attenuation factor is greater than 165 db; the over-all measured gain is 45 db. The noise level is $\frac{1}{4}$ μv as compared with 10 μv for the Model C-1 attenuator.

CHAPTER 9

TRANSMITTERS

By A. J. Poté, R. B. Lawrance, and G. C. Trembly

9·1. General Requirements.—The design characteristics of the transmitter are based on the requirements of the system and on the accuracy with which time differences can be measured with the navigator's receiver-indicator. The navigator's instrument is designed to be capable of yielding readings to within 1 μsec of the true value. With a short baseline and normal signal-to-noise ratio, an average error in the synchronism between two transmitters is approximately 0.5 μsec. Since the period of a carrier cycle at the operating frequency is approximately 0.5 μsec, the maximum error assignable to the transmitter is a small fraction of a cycle. Once started, the output pulse from the transmitter must rise smoothly and steadily to its maximum to prevent "flutter" of the received pulse from impairing the accuracy of the navigator's time-difference reading.

To facilitate the accurate measurement of the time difference between pairs of received pulse signals, the leading edges of the signals should rise steeply. The reception of such pulses, however, necessitates wide-band receivers, with attendant increase in interference from noise and other signals. An experimental study has been made to determine optimum conditions consistent with the desired reading accuracy. The results of this study have led to the adoption of an effective receiver bandwidth of about 75 kc/sec. Under the stimulus of a trapezoidal transmitted pulse rising in approximately 10 μsec, such a receiver yields an output pulse requiring 35 μsec to reach its maximum. The transmitted pulse must therefore be at least 35 μsec long. An upper limit to the pulse length is set by the desirability of resolving sky-wave components which may follow at intervals as short as 65 μsec. A transmitted pulse length of approximately 45 μsec has been adopted.

The rise time of the transmitted pulse is only broadly defined by the required end result on the navigator's instrument. From the standpoint of apparatus the rise time is more strictly determined by such interrelated factors as the antenna Q, the Q of the transmitter tank circuits, and the requirement that the oscillations start consistently. In a trapezoidal pulse the sideband distribution is determined primarily by the pulse width and secondarily by the rise time; since 10-μsec rise time is easily achieved, this value has been adopted. The standard pulse has a rise time of 10 μsec, flat top of 35 μsec, and decay of 10 μsec, making the width at half amplitude 45 μsec.

The technique of matching the envelope amplitudes and leading edges of two pulses yields its highest precision when the shapes of the two transmitted pulses are exactly the same. If the two transmitters differ in frequency, the two pulse shapes are distorted differently in the receiver, and an error is introduced in the time-difference measurement. It is therefore necessary that the Loran transmitters have inherent frequency stability and that provision be made for simple and positive means of monitoring and maintaining frequency.

To conserve space in the limited frequency spectrum, pairs of Loran stations are identified by different recurrence rates rather than by different radio frequencies. This scheme also simplifies the receiver, although it requires a circuit complication in the indicator. Loran transmitters are accordingly designed in such a way as to be capable of emitting pulses at two recurrence rates concurrently.

Pulsing the transmitter at two recurrence rates results in doubling the duty cycle, increasing the average power output from 100 to 200 watts. These are reasonable values and present no problem; the real difficulties arise from the variable time interval between successive pulses. The starting and stopping characteristics of the transmitters and therefore the stability and shape of the emitted pulses are functions not only of the circuit constants but of the various voltages as well. Of practical necessity, these voltages perform some excursion during and immediately following each pulse. The conditions that determine the characteristics of a pulse, therefore, change with time; they depend on the variable time interval between successive pulses. The transmitters must perform so that the variation of pulse shape and amplitude and the variation in timing, caused by the fluctuations of the voltages, are restricted to tolerable limits.

Originally the power capabilities of the transmitter were dictated chiefly by existing tube types and their availability. Propagation studies have predicted and experience has shown that a daytime ground-wave range of 700 nautical miles can be expected from a radiated power of 100 kw. At the Loran frequency of 2 Mc/sec, a further increase in range of 100 miles would require nearly ten times the power, an increase that is not often worth while. A power of 100 kw gives ground-wave fields of about 500 μv/m at normal baseline distances over water, which is adequate for synchronization in most latitudes.

In addition to the system requirements for the transmitters, other important operating characteristics are required by the nature of the service to be rendered. The equipment must be capable of continuous operation for long periods of time, in any climate from the Arctic to the equator. It must be tolerant of power-source variations as well as being rugged, simple to operate, and easy to maintain.

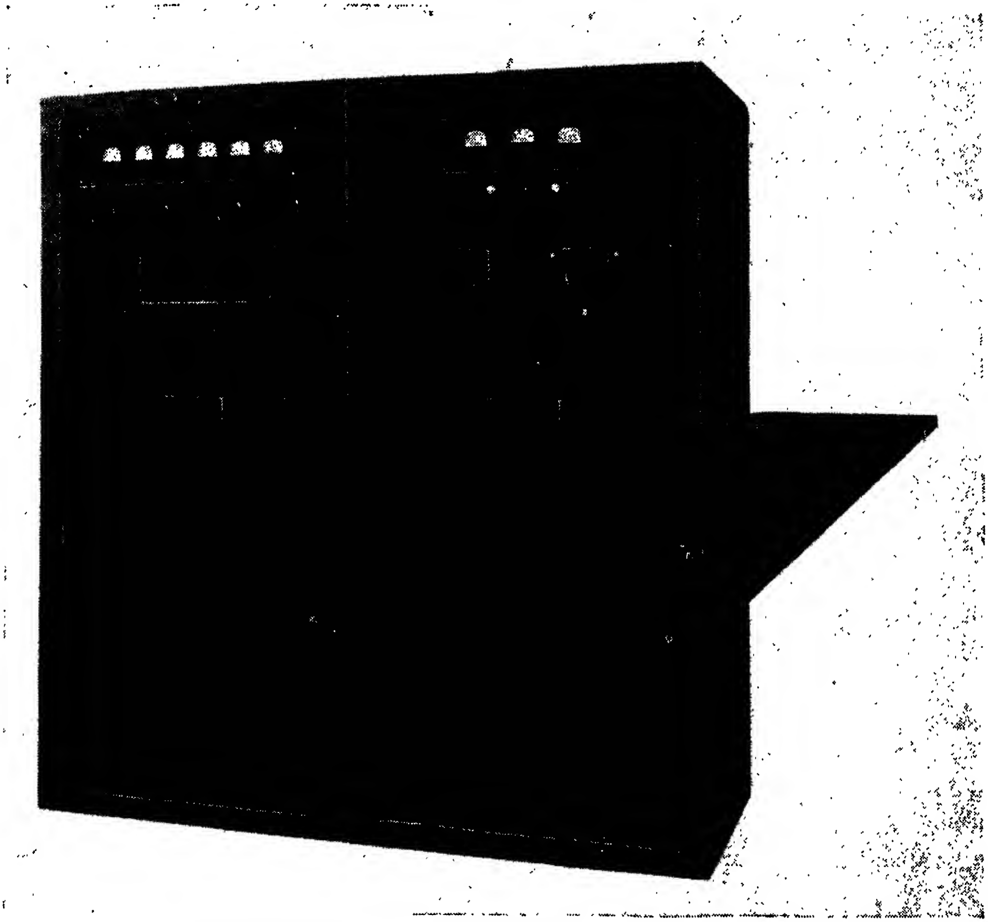


FIG. 9·1.—Model TDP transmitter. (*Courtesy of Radio Engineering Laboratories Inc.*)

9·2. Standard Loran Transmitters.—The major requirements of the transmitter to be used in the 2-Mc/sec Loran system may be briefly recapitulated as follows:

1. Starting time variation less than 0.1 μsec.
2. Smooth, steady rise of output pulse.
3. Pulse length of 45 μsec at half amplitude.
4. Consistent pulse rise time of 10 μsec.
5. Frequency stability and means for monitoring the frequency.
6. Ability to transmit two trains of pulses at different rates.
7. Peak power output of 100 kw.
8. Continuous operation in all climates.
9. Low harmonic radiation.
10. Simple operation and maintenance.

Several transmitter models, differing in physical construction but similar in electrical design, have been produced. A total of 18 units of the early Model 108T have been manufactured by Harvey Radio Laboratories, Inc. The same manufacturer has produced 10 Model 125T and 12 Model 170T transmitters. The Radio Engineering Laboratories, Inc., have constructed 36 Model 575 transmitters and 70 Model TDP (Fig. 9·1) transmitters. The General Electric Company has designed the Model TDP-1 (Fig. 9·2) transmitter to meet Navy specifications and has manufactured 66 units.

Model TDP Transmitter.—Electrically, Model TDP transmitter is a push-pull, tuned-plate, tuned-grid, self-excited oscillator with a modified form of cathode keying. Physically, it consists of two metal cabinets about 32 in. wide, 28 in. deep, and 72 in. high. One cabinet contains the power oscillator, modulator bias and screen supplies, output coupling circuits, and a dummy load. The second cabinet contains the control circuits, the high-voltage power supply, and the two exciter ("pulser") units.

In order to achieve timing stability each exciter is fed with recurrent trigger pulses from one timer only. For double-pulsed operation the equipment is set up as shown in the diagram of Fig. 9·3, the two sequences of pulses being mixed just before the modulator. For single-pulsed operation one exciter is entirely disconnected and the other feeds the "bias-and-pulse" modulator input line without first going through the mixer.

The trigger pulses are short and have a steeply rising front edge. After voltage amplification they trigger a gas-filled tetrode in a pulse-forming stage, the output of which feeds a beam power output stage. Each positive-going output pulse is roughly rectangular, approximately 45 μsec long, and several hundred volts in amplitude. One sequence of these pulses, together with a bias voltage, is fed from each exciter to the mixer, which in turn feeds the combined output and a resultant bias voltage to the grid of the modulator. The modulator is a normally off tube which is turned on by these high-voltage, positive-going pulses and is so connected that it keys the high-power oscillator on and off. The pulses of r-f energy are sent down a coaxial line to a tuning and matching unit at the base of the Loran antenna and thence to the antenna itself.

Exciter Operation.—The operation of the exciter can best be understood by study of the simplified diagram (Fig. 9·4). The synchronizing trigger from the timer is a positive pulse of either 3 or 20 volts' amplitude, depending on the type of timer. This pulse is fed into a video preamplifier which increases its amplitude to approximately 60 volts. The amplified pulse is then fed through the diode to the grid of the gas tetrode. In some of the later models the preamplifier is replaced by a pulse transformer. Before it is triggered, the gas-filled tube is in the nonconducting condition, with its plate voltage at the level indicated as $+LV$. The 0.008-μf capacitor has been fully charged through the 1-megohm resistor

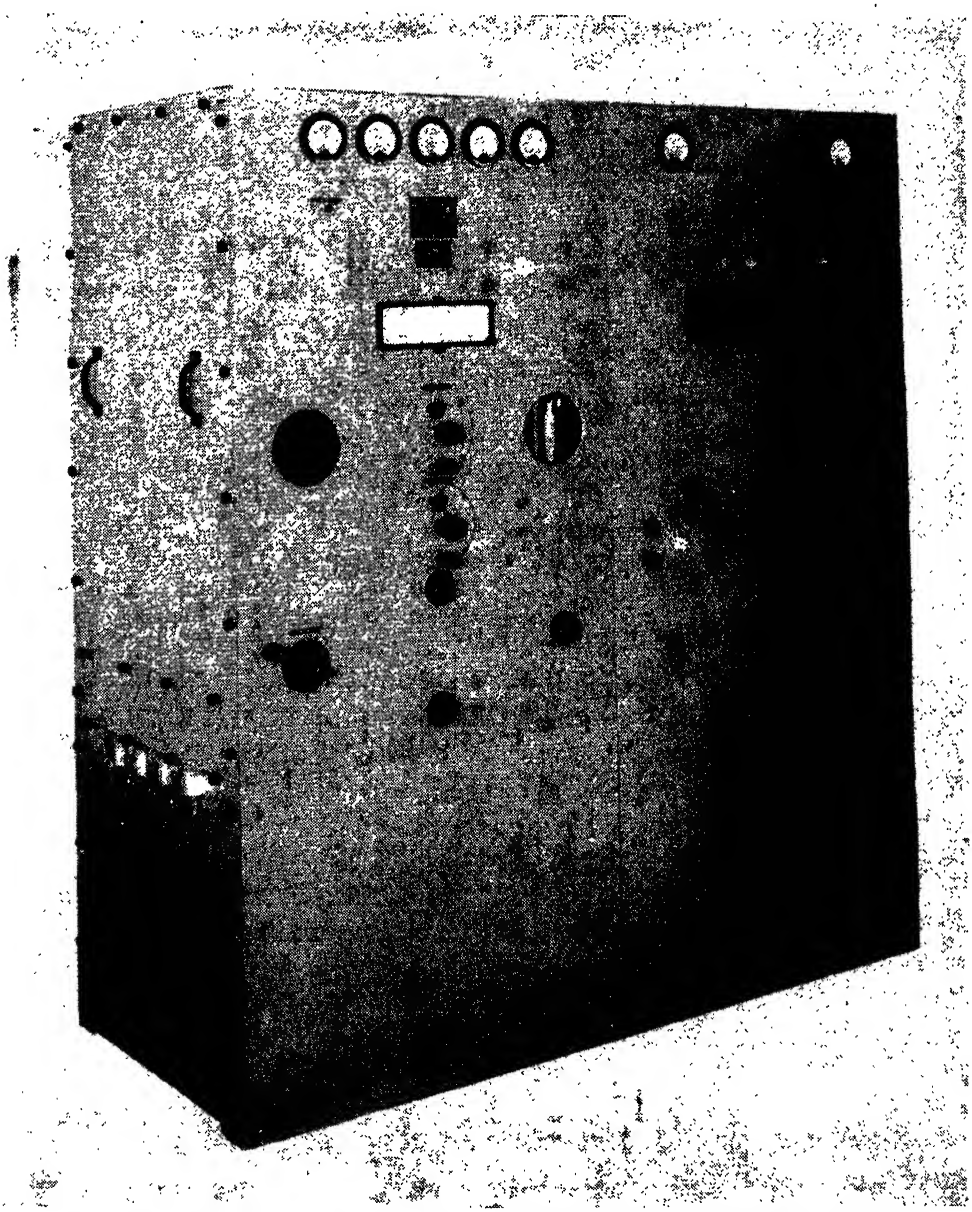


FIG. 9·2.—Model TDP-1 transmitter. (*Courtesy of General Electric Company.*)

which, during the pulse, isolates the circuits from the power supply. Upon being triggered the gas tube becomes conducting; the capacitor begins to discharge through the 40-mh inductor, the gas tube, and the 15-k cathode resistor. The increasing voltage across this resistor is

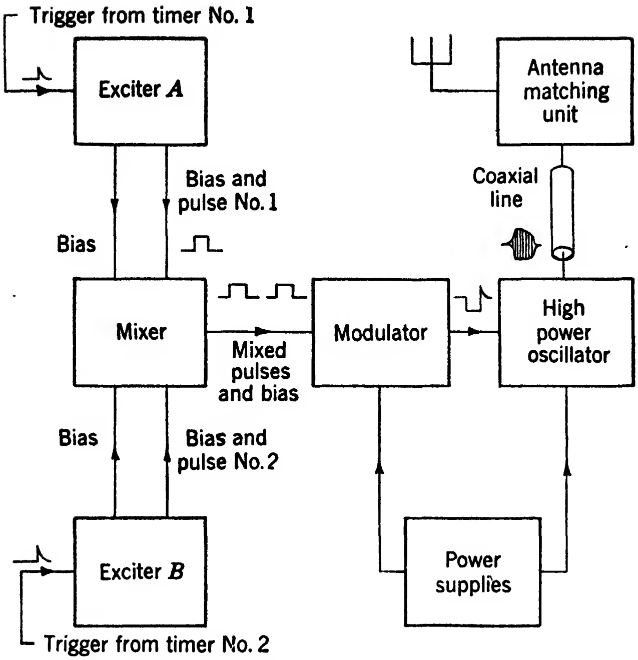


FIG. 9·3.—Block diagram of Model TDP transmitter.

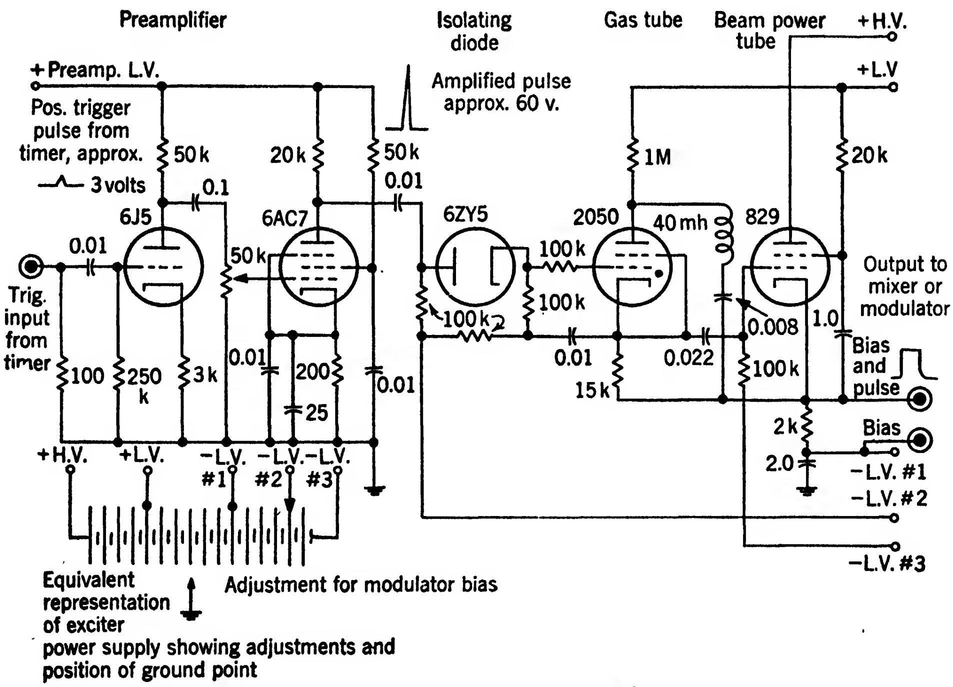


FIG. 9·4.—Simple diagram of exciter.

applied between the cathode and grid of the beam power tube and brings its bias rapidly from beyond cutoff to a slightly positive voltage. The plate current in the beam power tube and the output pulse voltage build up rapidly until the grid starts to draw current from the gas tube circuit.

After this time the inductor, the two capacitors in series, and the grid-cathode resistance of the beam power tube behave as an under-damped series circuit that executes a single half-cycle oscillation. During the first 20 μsec of this oscillation the grid swings slightly more positive and an even larger grid current flows; after 45 μsec, however, the grid voltage becomes negative and grid current ceases. The circuits are proportioned in such a way that at precisely this time the 0.008-μf capac-

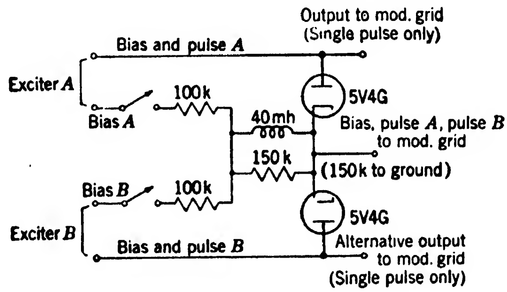


FIG. 9·5.—Simple diagram of mixer circuit.

itor is completely discharged; the gas tube again becomes nonconducting, and the output pulse is terminated.

The output point carries direct bias voltage as well as the positive pulse and is thus suitable for direct coupling to the modulator grid. Both the gas tube and the beam power tube are connected as cathode followers, and the "bootstrap" circuit allows a very large voltage output to be obtained. The function of the isolating diode is to disconnect the grid of the gas tetrode from its bias source during the pulse, thereby preventing positive-ion grid bombardment as the cathode potential is carried toward $+HV$ by the bootstrap action.

For double-pulsed operation the two exciters are used in conjunction with the diode mixer shown in the simplified diagram of Fig. 9·5. The function of the mixer is to transmit the output pulses of the exciters to the common modulator while isolating them from each other; it also provides a connection for the modulator tube bias. Means are provided, by the 100-k resistors, to accommodate a small amount of unbalance between bias voltages furnished from the two supplies in the exciters. A 40-mh inductance and shunting 150-k resistor are used to present a considerable impedance to the pulse output from the mixer, so that full voltage is applied to the modulator grid.

All transmitters are equipped with two exciters and a mixer. Simple switching operations permit either single-pulsed or double-pulsed operation.

Operation of Modulator and Power Oscillator.—The power oscillator has an essentially conventional tuned-plate, tuned-grid, push-pull circuit. The modulator is connected between cathode and ground and is designed to provide a cathode bias considerably greater than cutoff,

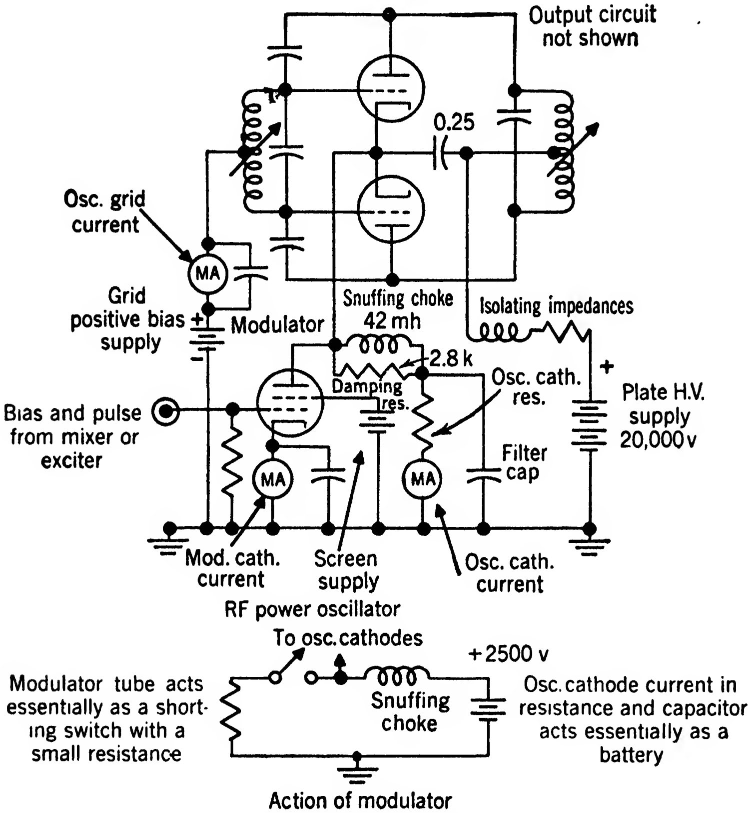


FIG. 9·6.—Simple diagram of modulator and oscillator.

so that no oscillations occur between pulses. At the instant when modulation is applied, the cathode bias is reduced to a low value and oscillations are started and sustained until the bias is again returned to a high value. Thus the modulator may be regarded as a shorting switch in series with a small resistance, as is shown at the bottom of the simplified diagram (Fig. 9·6).

A better understanding of the action may be had if some figures are assigned to the various voltages. The tubes used are VT98's. The cutoff bias at 25-kv plate voltage is −1000 volts. Most of the Loran transmitters are operated at a plate voltage of 17.5 kv, and the cathode voltage above ground, sustained by the filter capacitor and oscillator cathode resistance, is 2500 volts. This circuit has a long time constant, so that to all intents and purposes the voltage is constant. At the instant when the modulator is turned on, the oscillator cathode voltage drops to a value of about 500 volts and the remaining 2000 volts appear

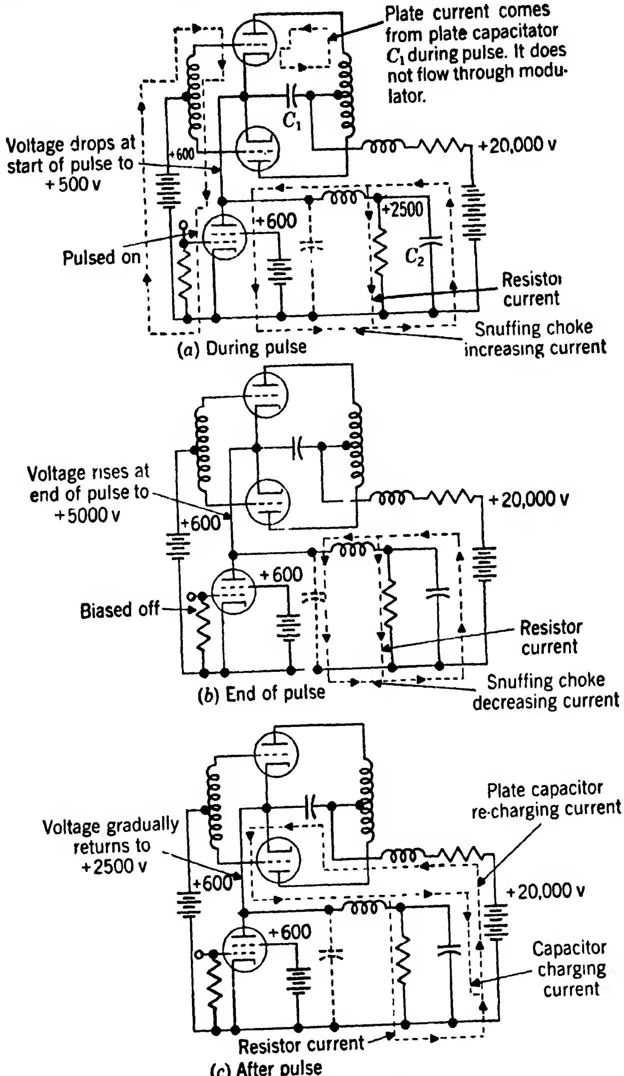


FIG. 9·7.—Current flow in transmitter. (a) During pulse; (b) end of pulse; (c) after pulse.

across the snuffing choke. The plate power for the oscillator is supplied from the large storage capacitor connected between the cathodes and the center tap of the plate tank circuit. This capacitor is permitted to make the same voltage excursion as the cathodes by the isolating impedances between the center tap and the plate high-voltage supply.

Figure 9·7a shows the various current paths during the pulse. The modulator grid has been driven positive by the exciter output. The oscillator grid current path is through the modulator tube and the positive bias supply, whereas the plate current path does not go through the modulator but is confined to the tubes, plate inductance, and storage capacitor. Another component of modulator plate current comes through the snuffing choke from the 2500-volt charged capacitor. This capacitor is also discharging slowly through the oscillator cathode resistor. The positive bias supply compensates for voltage drop in the modulator tube, making the initial flow of oscillator plate current large and greatly aiding the speedy and consistent start of oscillations.

Figure 9·7*b* shows the current paths at the end of the pulse. The modulator grid voltage has been returned to below cutoff. Both grid and plate current of the power oscillator have stopped, as well as the plate and screen current of the modulator. Current is still flowing from the filter capacitor through the snuffing choke and into the distributed capacitance of the oscillator cathode circuit (modulator plate current), and the filter capacitor is still discharging through the cathode resistor. At this instant the action of the snuffing choke has raised the oscillator cathode voltage to about 4500 volts, so that the oscillations are quickly quenched.

The currents flowing shortly after the pulse are shown in Fig. 9·7*c*. The storage capacitor which has lost charge by supplying energy to the oscillator plates is being recharged from the plate high-voltage supply, as is the filter capacitor and the distributed capacitance of the cathode circuit. This recharging cycle lasts for a few hundred microseconds, so that after that interval another pulse may be satisfactorily transmitted. It is apparent, however, that at times when the two pulses of different rates are nearly in coincidence, the circuit voltages do not have time to attain their steady value and the succeeding pulse is therefore of reduced amplitude. This is undesirable, but a more serious effect is a tendency to delay the starting time of the succeeding pulse for a few microseconds. This can happen if the operating voltages are not carefully maintained. In general, any condition that makes the device a poor oscillator results in a delay in starting time. The excursion of the cathode voltage immediately after the modulator is turned off is a critically damped oscillation of the circuit made up of the snuffing choke and the distributed capacitance of the cathode circuit.

The output circuit is shown schematically in Fig. 9·8. It is desired to present a load impedance of 4000 ohms between the plates of the oscillator tubes. The stepdown from this value to the 50 ohms required for proper termination of the coaxial cable is achieved in two steps. A capacitance divider reduces the 4000-ohm impedance to approximately 400 ohms, and the tuned transformer reduces that impedance to 50 ohms. Means are provided by taps and plug-in capacitors to tune the transmitter and coupling networks over the range from 1700 to 2000 kc/sec. As shown on the simplified diagram, the 0.002-μf capacitor across the primary of the coupling transformer is the resultant of the capacitance divider and the capacitance required to tune the primary. In practice the transformer tuning procedure consists of shorting the primary of the coupling transformer and series-resonating the secondary, any residual detuning on the primary being taken care of in the tuning of the plate tank of the oscillator.

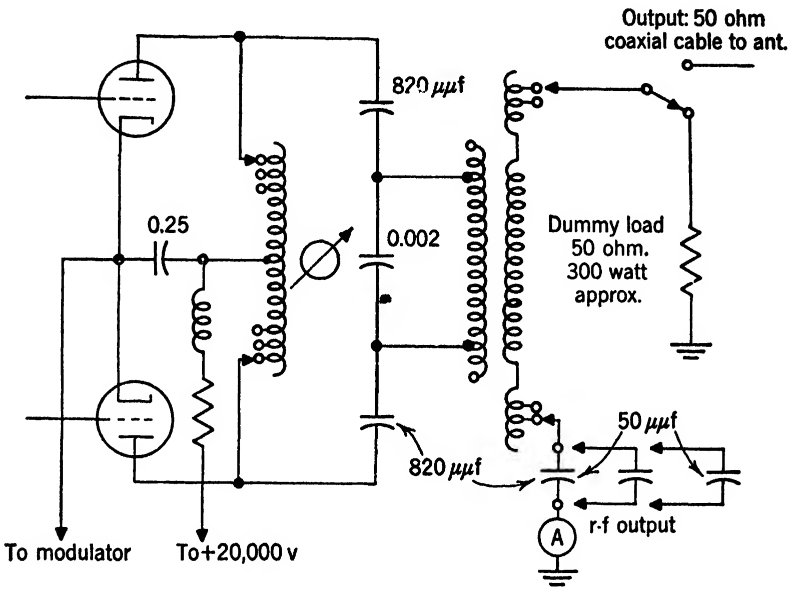


FIG. 9·8.—Simple diagram of output circuits.

9·3. Transmitter Test Oscilloscope.—Alignment, operation, and maintenance of the transmitter require special testing facilities that can most conveniently be made in the form of an oscilloscope. Such an oscilloscope is required to inspect the envelope of the transmitted r-f pulse and to inspect certain r-f waveforms for measuring the transmitter frequency. The oscillator cathodes, the oscillator grids, the output terminal of the pulser, and the input stages of the pulser are normal points of inspection. A crystal oscillator and appropriate circuits for comparing its frequency with that of the transmitter are included in the oscilloscope. The triggered sweep circuits are sufficiently stable to permit careful examination of the r-f cycles.

Several models of the transmitter test (or monitor) oscilloscopes have been produced. The Sylvania Electric Products, Inc., have manufactured 25 Model A-1 oscilloscopes (Fig. 9·9), and the Du Mont Laboratories, Inc., have produced 40 Model CDU, 110 Model OCA, and 70 Model OBN oscilloscopes.

The sweep is initiated by the same pulse from the timer that triggers the transmitter. Any one of three sweep speeds, giving full deflection in 20,000, 200 or 25 μsec, may be selected. Provision is made for displaying the r-f cycles or video signals from the transmitter directly on

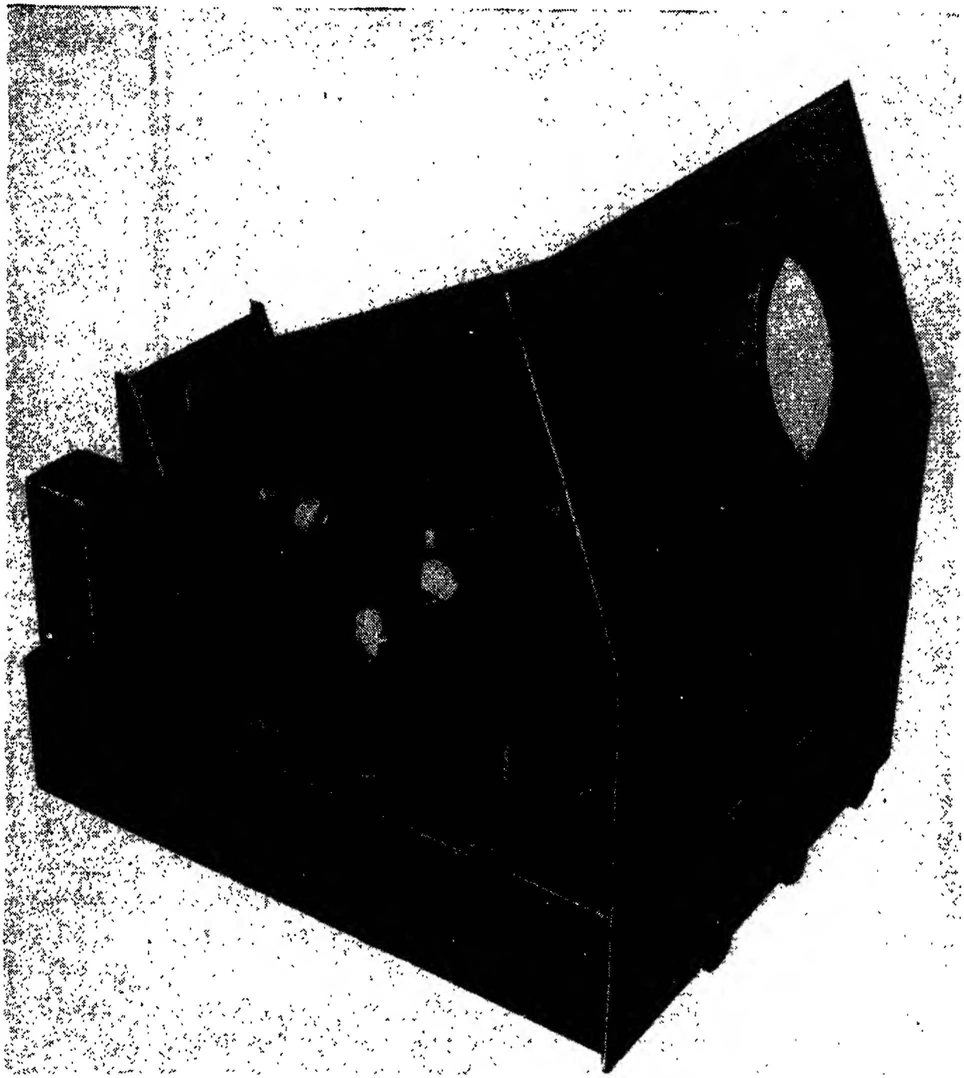
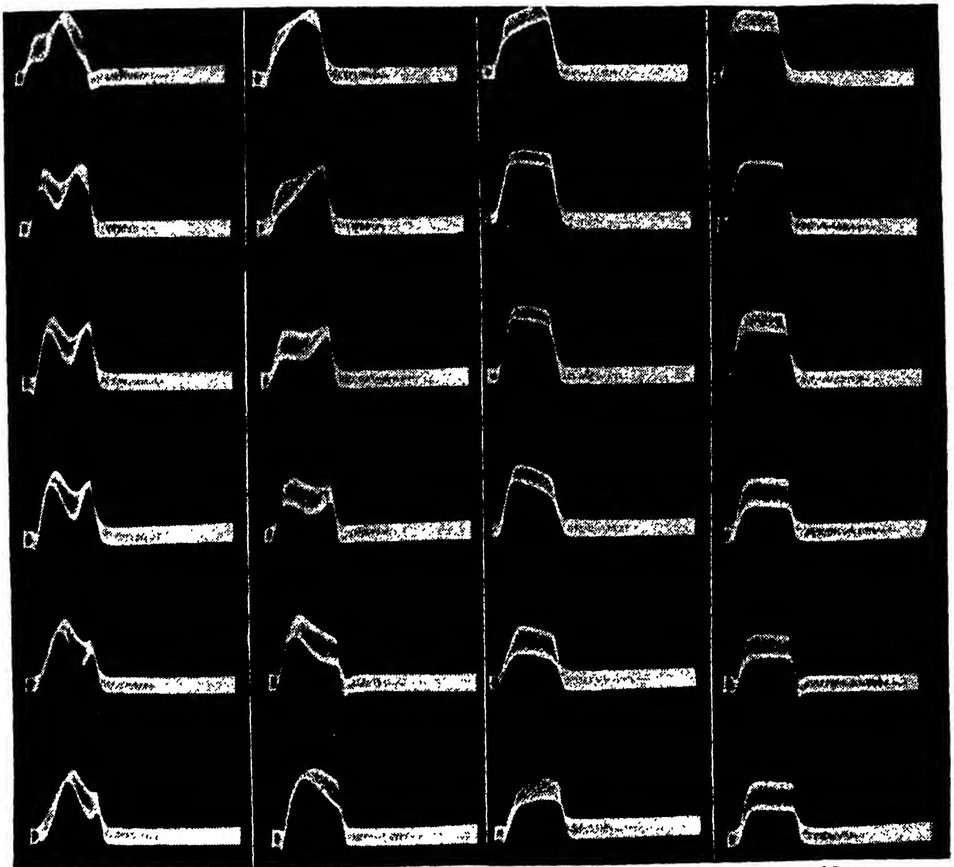


FIG. 9·9.—Model A-1 transmitter test oscilloscope.

the cathode-ray tube or for displaying the rectified cycles either alone or mixed with the rectified signals from the internal crystal oscillator. A high intensifying voltage (9000 volts) provides satisfactory intensity even at the highest trace speed and at the low repetition rate.

The frequency of the transmitter is measured by beating the pulse against a crystal oscillator. The mixing action is performed only when the detector is in use, so the pattern that is observed is always a modification of the envelope of the r-f pulse. When the transmitter is about 37 kc/sec off frequency, a pattern similar to that of Fig. 9·10*a*, which is a series of motion-picture frames, results. The beats appear as a sine-wave modulation of the top of the pulse, moving laterally across the pulse. The operator makes a preliminary adjustment of the transmitter



(*a*) (*b*) (*c*) (*d*)

FIG. 9·10.—Waveforms observed when the difference between the frequencies of the transmitter and of the crystal oscillator are (*a*) 37 kc/sec, (*b*) 20 kc/sec, (*c*) 4 kc/sec, (*d*) less than 1 kc/sec.

and then observes that the picture on the oscilloscope screen looks like Fig. 9·10*b*, which is another series of motion-picture frames with the transmitter 20 kc/sec off frequency. In this case, the beats are slower; thus the sine waves are longer, so that each cycle takes about the same time as the duration of the pulse and only one cycle can be seen at a time. The beats progress across the pulse as before but at a slower rate. When the operator makes a further correction of the transmitter frequency, the picture then resembles Fig. 9·10*c*. In this case the transmitter is about 4 kc/sec off frequency, so that only part of a beat can be seen at any one time. The top of the pulse displays a rocking motion, and the thickness of the trace at the top of the pulse varies at the same time. The progression of the beats continues, giving the series shown, and in this case is an aid to detection of the beat. In fact, if the progression is not taking place, the operator must switch the crystal oscillator on and off in order to obtain random samples of the sequence shown, "a frame at a time," and judge the transmitter setting from them by careful observation of the thickness of the trace at the top of the pulse. Finally, when the transmitter is as nearly on the desired frequency as the operator can set it, the picture is as shown in Fig. 9·10*d*. No rocking or changing in trace thickness from side to side can be seen, but only the bobbing of the top of the pulse and the uniform change in thickness of the trace. This setting is within 0.10 per cent of the frequency of the crystal oscillator, which is sufficiently accurate for the service required.

Assuming that the two signals are in phase at the beginning of each pulse, the phase near the end of the pulse depends upon the difference in frequency of the two signals. For example, if the difference in frequency is 25 kc, the phase will have changed 360° in 40 μsec. One complete cycle of beat action will have been completed so that the pulse will appear to have one cycle of sine wave superimposed on it. The ultimate accuracy then depends on the minimum amount of phase change that can be detected during the pulse.

LOW FREQUENCY LORAN TRANSMITTERS

9·4. Low Frequency Transmitter Requirements. *Introduction.*—An LF transmitter intended for Loran timing measurements must meet rather stringent requirements, since the period of one carrier-frequency cycle becomes comparable with or greater than the maximum tolerable timing error. At a carrier frequency of 180 kc/sec each cycle is 5.55 μsec long, and much refinement of conventional Loran practice is necessary in order to keep synchronization errors down to about 1 μsec. The principal requirements are the following:

1. The carrier frequency must be established in such a way that it is accurately the same at all stations. Any frequency difference in two received pulses would lead to different pulse shapes at the output of the receiver, which has a fairly narrow bandwidth. No such difference in pulse shapes can be tolerated when the sought-for timing accuracy is so high.
2. All stations must radiate pulses whose waveforms have precisely the same characteristics, namely, the shape of the envelope and the timing relationship between the envelope and the carrier-frequency cycles.

In addition to these two basic requirements it is desirable to incorporate precautions for reducing all spurious harmonic and adjacent-channel radiation to levels that will not cause excessive or unnecessary interference.

The transmitter to be described was developed as part of an emergency program. It represents a valuable first step in the effort to meet the requirements just stated, and many of the techniques employed have proved entirely satisfactory. All of the individual circuits described have been in use for several months in the stations of the East Coast experimental triplet.

The LF Station and Equipment.—As mentioned in Sec. 7·15, the timer is modified by the addition of a 50-kc/sec driver, one of whose functions is to provide the transmitter with crystal-controlled signals of this frequency. The act of holding the two stations of a pair in synchronism maintains their respective crystal oscillators at frequencies that differ by less than 1 part in 100 million. Their transmitted carrier frequencies can also be made equal, with this same accuracy, by designing the transmitter as an oscillator amplifier whose frequency-determining device is the continuously running crystal in the timer.

The carrier frequency of 180 kc/sec must be obtained from the 50-kc/sec crystal without dependence on any other frequency source; this is done by the use of circuits in which the crystal-controlled signal is heterodyned with other signals derived from it by frequency multiplication and division. The phase and frequency of the eventual 180-kc/sec output are thus rigidly determined by the phase and frequency of the crystal oscillator.

Both the design of the frequency-changing and amplifying stages and the layout of the station are influenced by the fact that the remote signal must be received during the interval between local pulses. Although the carrier frequency is to be derived from the 50-kc/sec crystal through frequency-changing stages that run continuously, the spurious signal picked up by the receiver from these stages must be much weaker than the remote signal. Two precautions have been adopted to avoid trouble from such interference. In planning the station layout the transmitter and the receiving equipment have been separated by about 1000 ft, the necessary interconnections being made with shielded cables.[1] More important, in designing the transmitter the carrier frequency of 180 kc/sec is made to appear only during the transmission of the local pulse; the low-power continuously running stage operates at a frequency of 90 kc/sec, and the following doubler stage is inactive except when intentionally pulsed. The stages following the pulsed doubler are used to

[1] Experience indicates that interference is not severe even with the transmitter and timer in the same building.

shape the 180-kc/sec pulse and amplify it to its final level of approximately 100 kw.

As shown in the block diagram of Fig. 9·11, the transmitter is supplied with two input waveforms: the usual trigger and the continuous 50-kc/sec wave. It is evident that the 50-kc/sec signal must be derived from a point *following* the capacitor phase-shift circuit in the timer oscillator; doing so allows the relative timing of the trigger and the 50-kc/sec wave to remain undisturbed when the timer phase shifter is manipu-

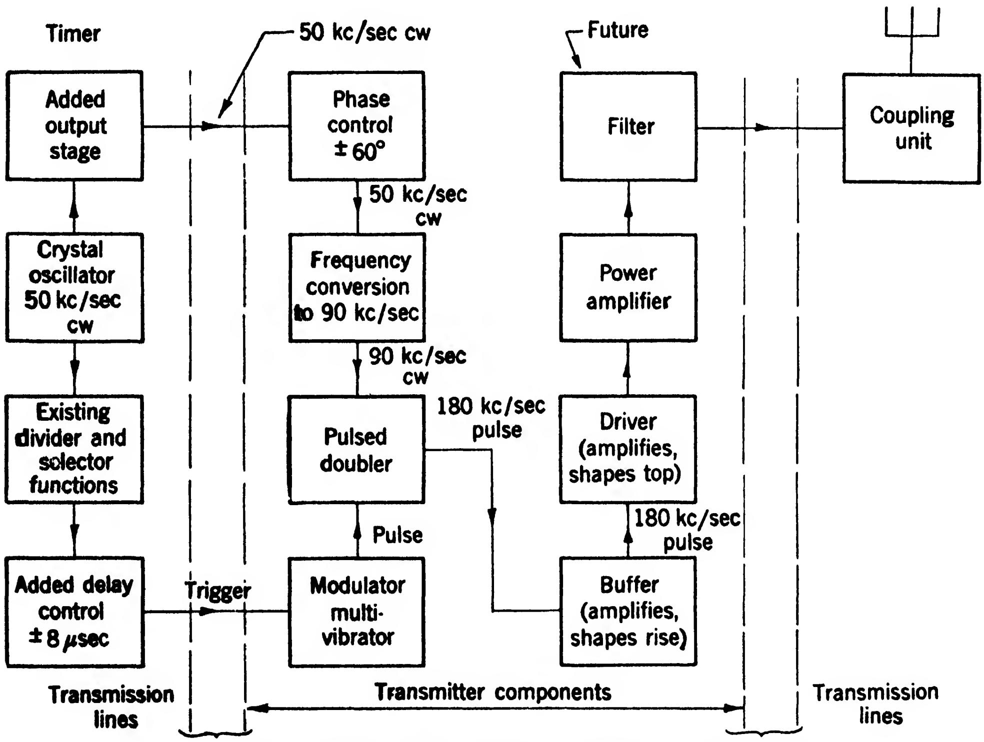


FIG. 9·11.—Block diagram of Low Frequency transmitter.

lated. The cycle-envelope timing relationship of the emitted pulse is hence independent of the setting of this control.

In Sec. 7.15 it was also mentioned that the trigger output of the timer is passed through a calibrated delay multivibrator whose total adjustment range is about 16 μsec, or 8 μsec each side of the normal center position. This trigger-delay control and the phase control in the transmitter are intended for use in obtaining and maintaining the proper relationship of the envelope and the carrier cycles. Once the envelope shape has been adjusted for proper rise rate and flat-top duration, the cycle-envelope relation may be adjusted by sliding the cycles relative to the envelope, using the phase control for the purpose; alternatively the envelope may be moved relative to the cycles by the trigger-delay control. In the ultimate version of the transmitter only one of these two nearly equivalent controls will be retained, but further operating experience is necessary before the selection can be made.

An oscilloscope is installed as one of the units of the transmitter. By manipulating selector switches the radiated pulse or the waveform at any one of 12 intermediate points in the transmitter may be observed on this test oscilloscope. The 12 test points have been chosen to provide maximum usefulness in initial tuning and adjusting, in detecting incipient failure of tubes or other components, and in quickly isolating the location and nature of any actual failure. The oscilloscope used is a close copy of the timer test oscilloscope, whose circuit is shown in Fig. 7·6.

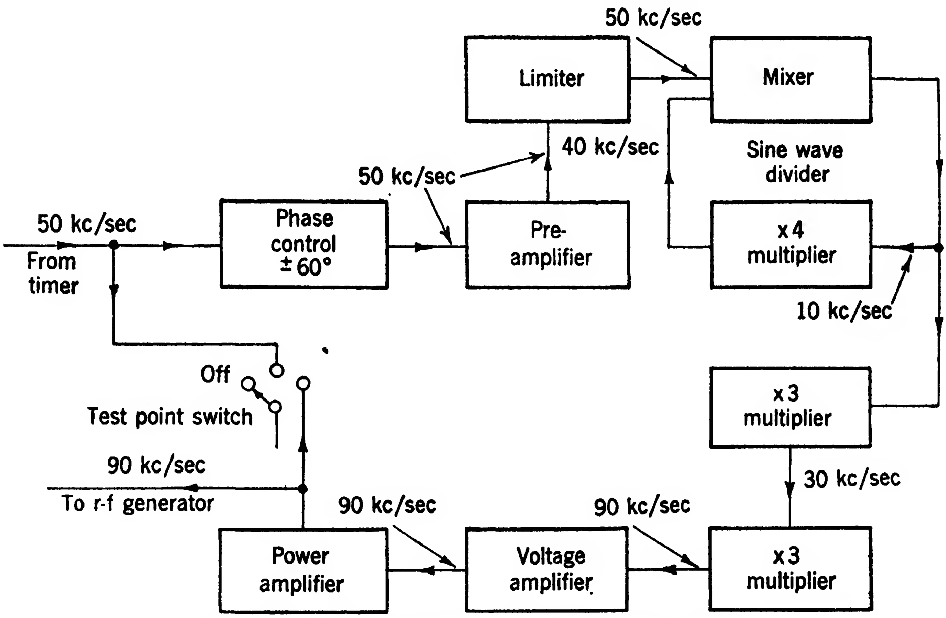


FIG. 9·12.—Block diagram of 90-kc/sec generator.

9·5. Low Frequency Transmitter. *90-kc/Sec Generator.*—The function of the 90-kc/sec generator is to take the low-power low-impedance 50-kc/sec c-w input signal and convert it to a 90-kc/sec c-w output signal at a power level (about 2 watts) sufficient to excite the c-w channel of the r-f generator. A phase control is included for adjusting the cycle-envelope relation of the transmitted pulse. Limiting amplifiers are included to make operation independent of input voltage and other factors over rather large ranges. All frequency-converting stages in the unit operate with sinusoidal input and output voltage waveforms, thereby minimizing the chances of producing and radiating harmonics at 180 kc/sec.

Figure 9·12 gives a block diagram of the unit, and the circuit diagram is given in Fig. 9·13. The incoming 50-kc/sec voltage is applied first to

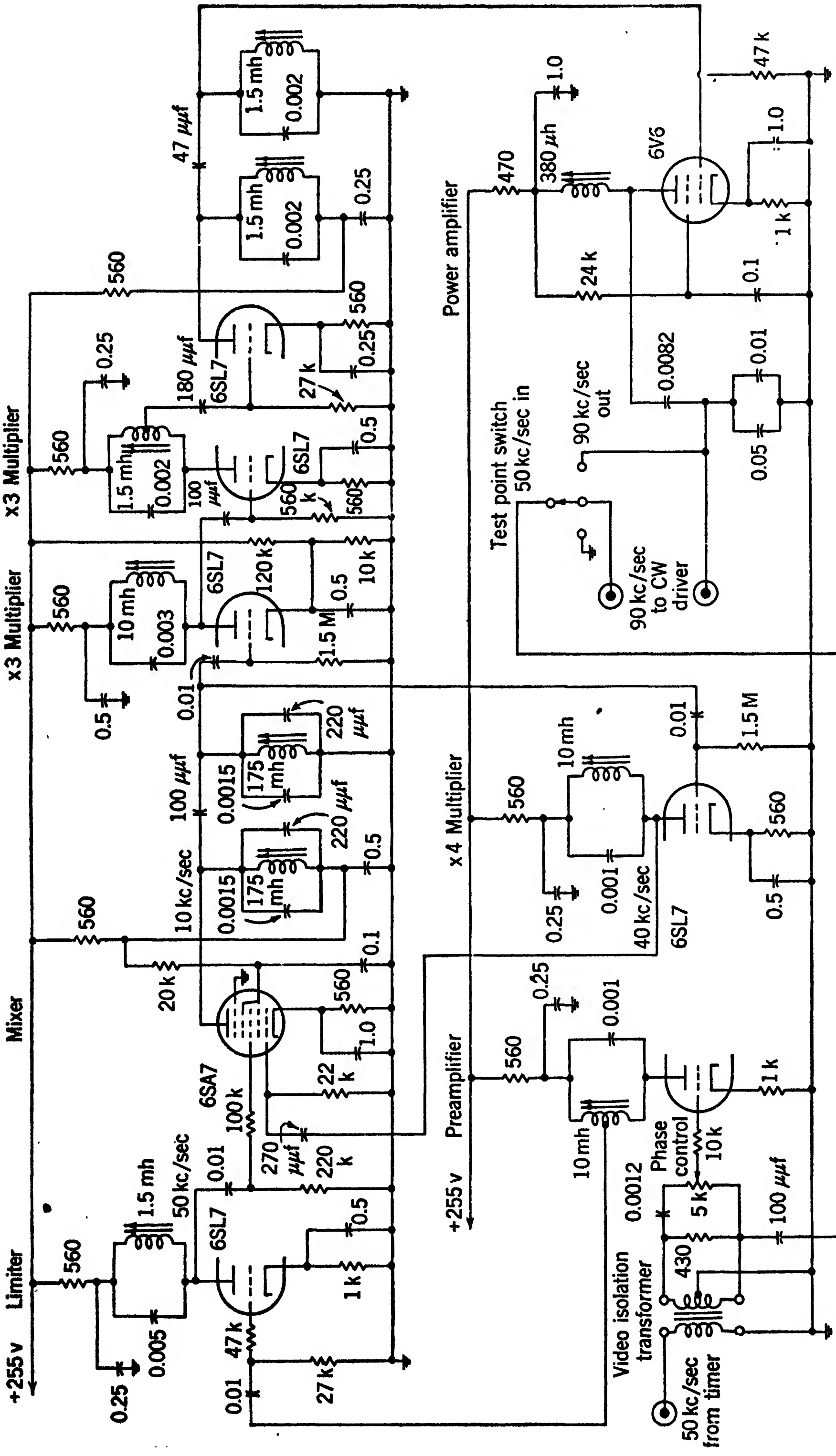


FIG. 9·13.—Circuit diagram of 90-kc/sec generator.

a passive network associated with the phase control; the phase difference between input and output voltages of this circuit depends upon the setting of the control. For adjusting the transmitter output cycle-envelope relationship it is necessary to be able to vary the phase of the 180-kc/sec carrier frequency through slightly more than one cycle. This frequency of 180 kc/sec is locked to that of the 50-kc/sec input to the generator, and the phase variation introduced at 50 kc/sec need therefore be but $\frac{50}{180}$ of that required at 180 kc/sec. By the same token, phase shift occurring at the 90-kc/sec output of the generator will be $\frac{90}{50}$ the amount provided at 50 kc/sec. The range of operation of the phase control has been made approximately 120°, providing 216° variation at 90 kc/sec and 432° at 180 kc/sec.

The output voltage of the phase-control stage is not sufficient to operate the sine-wave divider. Moreover, the voltage amplitude at the output of the phase-control circuit varies by 2 to 1 through the control range. The sine-wave divider, on the other hand, operates most satisfactorily when the 50-kc/sec input to the mixer tube is constant in amplitude and ceases to function entirely when this input fails to exceed a certain minimum. An adequate and constant signal level is obtained by the use of preamplifier and limiter stages, which have sufficient gain to permit satisfactory operation even with abnormally low 50-kc/sec input voltage.

The transition from 50 to 90 kc/sec is accomplished in three steps: (1) The input frequency of 50 kc/sec is divided by 5 to produce 10 kc/sec; (2) this is multiplied by 3 to obtain a frequency of 30 kc/sec; and (3) this in turn is multiplied again by 3, resulting in the final frequency of 90 kc/sec. The factors by which frequencies in the generator are multiplied and divided are small, leading to great stability of operation.

The sine-wave divider stage, which divides the 50-kc/sec input frequency by 5, consists of a pentagrid-mixer circuit and a conventional frequency-quadrupling stage. The two control grids of the mixer are driven with 50 and 40 kc/sec, respectively; the 10-kc/sec output frequency is multiplied by 4 in the quadrupler to provide the necessary driving voltage at 40 kc/sec. Frequency-dividing operation starts spontaneously within a few tenths of a second after the 50-kc/sec input signal is applied and continues as long as the input signal is present. Bias voltages and signal levels are arranged so that no output is obtained from the 90-kc/sec generator if the crystal-controlled 50-kc/sec input from the timer is missing; thus the transmitter operates at the correct crystal-controlled frequency or not at all.

R-F Generator. The r-f generator may be considered the heart of the transmitter. Its input voltages are the trigger from the timer, and the continuous 90-kc/sec sine wave from the 90-kc/sec generator. Its output is a completely shaped pulse at 180 kc/sec, requiring only further amplification before being fed to the antenna.

The unit is designed to fulfill the following specific requirements:

1. Negligible 180-kc/sec output except during transmission of local pulse.
2. Sufficient power output for driving following amplifiers.
3. Smooth and independent controls for adjusting the rise-time and the flat-top duration of the radiated pulse.
4. Ability to give smooth variation in output cycle-envelope relationship as phase control (90-kc/sec generator) or trigger delay (timer) are manipulated.

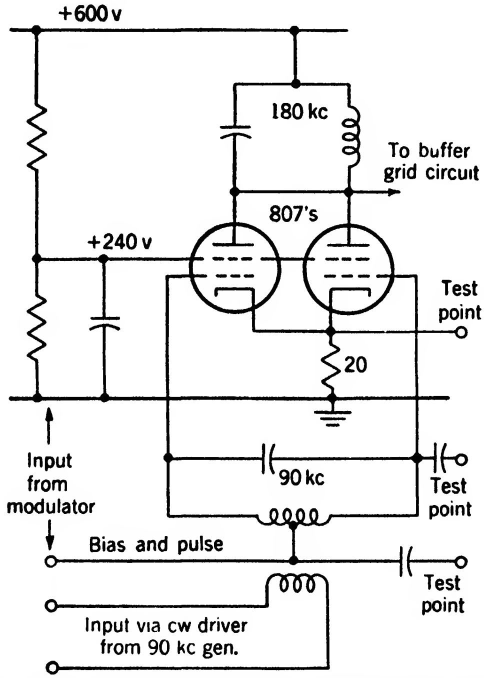


FIG. 9·14.—Simplified diagram of push-push doubler.

The pulsed doubler is located at the confluence of two types of signals —the amplified continuous sine wave from the 90-kc/sec generator and the modulating pulse generated by the modulator in response to a trigger from the timer.

The usefulness of push-push frequency doublers has been known for many years. In this type of circuit the control grids of two tubes are driven from opposite ends of a center-tapped tank circuit tuned to the input frequency. If, as is usual, the grid bias is greater than cutoff, then the out-of-phase drive results in the tubes conducting alternately. The plates are connected in parallel to a tank circuit that is tuned to a frequency twice that of the grid tank; the desired high second-harmonic output is produced by the equal and alternate surges of plate current drawn by the two tubes.

Figure 9·14 shows a simplified diagram of the push-push doubler used in the r-f generator. As can be seen from this figure the c-w excitation at 90 kc/sec is coupled inductively into the grid tank by a small link-type primary coil. The normal bias and the superimposed modulating pulse are applied to the center tap of the grid circuit; and since the 90-kc/sec coupling is inductive rather than capacitive, the speedy application and removal of the modulating pulse are not hindered by unwanted flow of modulator current in coupling impedances.

As used in the r-f generator the tube cutoff bias is approximately 60 volts and the alternating grid voltage is somewhat greater than 100-volt peak. The modulator pulse changes the bias to about 1.5 times cutoff, so that there are times when neither tube conducts. These operating conditions result in high efficiency and in adequate protection against unwanted continuous doubling.

The pulsed doubler, then, requires two inputs with the following characteristics:

1. An inductively coupled 90-kc/sec continuous wave, obtained from a source that can supply grid driving power without appreciable change in driving voltage.
2. A bias whose steady value of approximately −200 volts can be pulsed, in response to a trigger from the timer, to a voltage in the range between −150 and −50 volts. This pulsed value is to remain constant for a controllable time and thereafter return to the initial value of −200 volts.

The first requirement is met by the use of a c-w driver stage that amplifies the output of the 90-kc/sec generator to a level of about 20 watts, nearly all of which is intentionally dissipated in fixed resistors. During the pulse the grids of the pulsed doubler absorb energy at a rate of less than a watt, so the effect of their additional load is negligible. Figure 9·15 shows the complete circuit diagram of the r-f generator, including the c-w driver.

The modulator is simply a delay multivibrator whose flat-topped output pulse is passed through a cathode follower to the center tap of the doubler grid circuit. The need for a −250-volt bias supply for the doubler and the following buffer makes natural the use of this supply for the plate voltage of the multivibrator and cathode follower. Operating these circuits from this negative supply makes the power-supply problem simpler and, by permitting direct-coupling, gives a flat-topped modulating pulse without the use of a large coupling capacitor. The modulator output potentiometer is used to establish the operating condition of the pulsed doubler for maximum output and efficiency, and in so doing it is capable of compensating for a considerable variation in the amount of 90-kc/sec grid driving voltage.

Buffer and Driver Grid-tank Circuit.—The standard pulse envelope used in experimental LF work is a nonisosceles trapezoid, modified so that the rising and falling edges are approximately half-cycle sine curves rather than straight lines. The rise and flat top are obtained by impressing on the grid of an amplifier (the driver) an r-f voltage whose amplitude starts at zero and increases linearly with time. At first this input signal produces no output because the grid bias is greater than cutoff. When

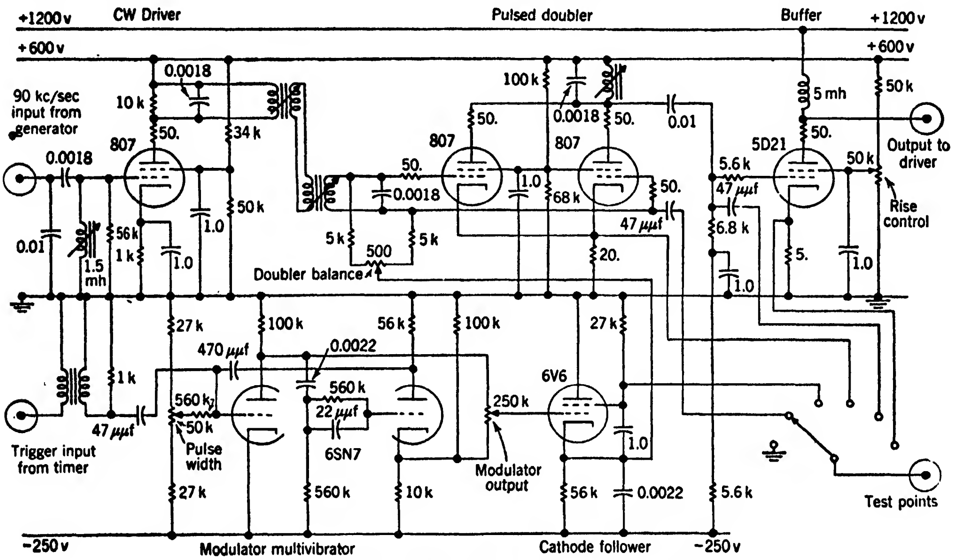


FIG. 9·15.—Schematic diagram of r-f generator.

the grid voltage starts to swing above cutoff, the plate-circuit output increases with time, first parabolically and then linearly. Finally, at the crest of some input cycle the grid attempts to swing to a higher potential than the cathode. At this time grid current through a series resistor causes the grid swing to be limited to a few volts positive. The larger input cycles that follow are limited in a similar way, with the result that a flat top is produced on the envelope of the plate-current alternating output voltage. The smoothness of the transition from the linear rise to the flat top may be controlled by choosing the proper size of series grid resistor.

The essentials of the pulse-shaping scheme outlined above are thus an amplifier whose grid is biased slightly past cutoff and an r-f driving voltage whose amplitude increases linearly with time. In the present transmitter the buffer tube, located in the r-f generator and driven by the pulsed doubler, produces the required linearly increasing oscillation in the driver grid tank. The circuit is shown in Fig. 9·16. The elements associated with the buffer plate and driver grid function as a single unified circuit, although for convenience some components are located in the exciter cabinet and some in the driver.

The grid of the buffer tube is operated Class C, with bias well past cutoff and with a large 180-kc/sec driving voltage from the pulsed doubler. The flow of grid current in a series resistor limits the positive excursion of the grid to a few volts above cathode potential, and plate

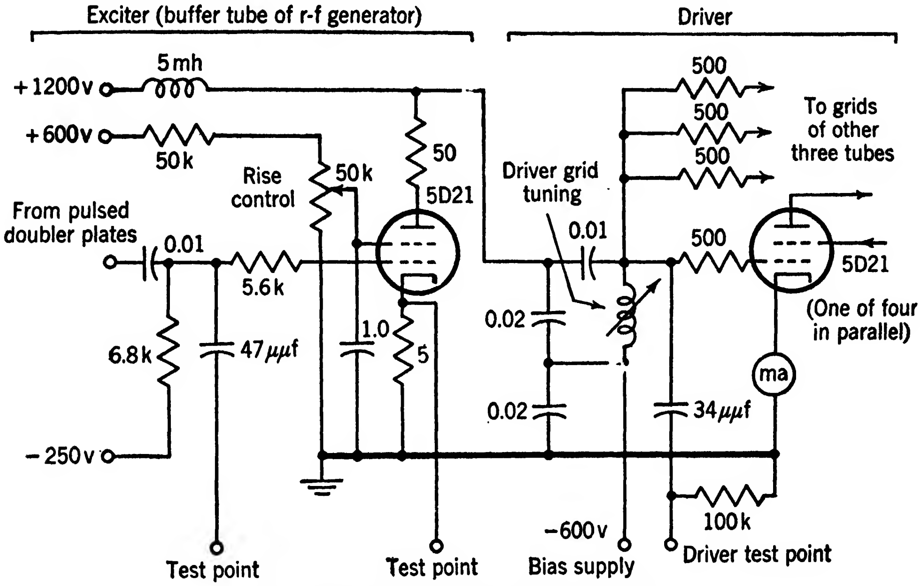


FIG. 9·16.—Simplified circuit of buffer.

current is accordingly drawn in definite-sized short pulses. The buffer plate tank circuit (driver grid tank) has unusually high capacitance, low inductance, and high Q. When the trigger, modulator, and pulsed doubler have impressed 180-kc/sec driving voltage on the buffer grid, therefore, many cycles elapse before the plate-circuit oscillations reach their full amplitude. The initial portion of this buildup is sufficiently long and linear to be useful in forming the desired leading edge.

The time to reach full amplitude (or the saturation that produces the flat top on the output pulse) is controlled by varying the screen voltage of the buffer tetrode, thus adjusting the amount of charge drawn from the tank circuit by each pulse of plate current. The correct setting of the rise control is easily arrived at by observing the final radiated pulse waveform on the test oscilloscope while the adjustment is made. As the rise control is varied, the slope of the leading edge changes smoothly and at an approximately uniform rate; the control exerted by the pulse-width adjustment is also inherently continuous and linear. Special circuit precautions are necessary, however, to ensure smooth cycle-envelope adjustment by the phase control and trigger-delay control. The normal buffer plate current pulses are of uniform size; it is necessary that at least the first of these pulses be made smaller than the others and capable of growing smoothly to full size or diminishing smoothly to zero as the phase control is manipulated. This is easily accomplished by the use of a high-capacitance plate tank circuit in the pulsed doubler, spreading the rise of buffer grid voltage over approximately 12 cycles.

The five r-f generator test points are shown in Fig. 9·15. The first test point is connected through a small capacitor to one of the pulsed-doubler grids, revealing quickly the presence of 90-kc/sec input, proper functioning of the c-w driver, the presence of pulse output from the modulator, and satisfactory operation of the −250- and 600-volt supplies. It is thus useful for a rapid comprehensive check at the point where the pulsed- and continuous-wave signals are united.

Test Point 2 is directly connected to the pulse-voltage output of the modulator and is intended for measurements that might be necessary in correcting a fault in the modulator circuit. Test Point 3 samples the cathode-current pulses of the pulsed doubler by observing the voltage across a small noninductive cathode resistor. It is used in observing and adjusting the balance between the doubler tubes. Test Point 4, which is connected through a small capacitor to the doubler plate tank circuit, is used for making nearly all the r-f generator tuning adjustments as well as for establishing the proper setting of the modulator-output control. Finally, test Point 5 is connected to the small cathode resistor of the buffer tube. It serves as a trouble-tracing point that gives information about the buffer tube; the presence of plate, screen, and bias voltages; the condition of the plate-circuit components in the r-f generator; and the proper connection and functioning of those tank circuit components located in the driver.

Driver and Power Amplifier.—Except for the driver grid tank, which is functionally part of the buffer stage of the r-f generator, the driver and power-amplifier stages are rather conventional Class B linear amplifiers. The chief reason for departures and refinements is that the major emphasis is placed on careful control of the pulse leading edge, even at the sacrifice of a large proportion of the output power obtainable from the tubes. Thus although more than 40 kw is available from the four-tube driver, the major part of this power is dissipated in the fixed-load resistors necessary to obtain adequate fidelity in the power amplifier; the net power gain obtained from the power amplifier is thus but a factor of 2 or 3, which is relatively inefficient.

A simplified diagram of the driver is shown in Fig. 9·17. Four 5D21 high-current tetrodes are used in parallel, with screen and plate-supply voltages of 1100 volts and 8 kv, respectively. The use of individual metering positions for reading the cathode current of each tube allows qualitative check on their parallel operation, and oscilloscope test points are provided on the grid and plate circuits.

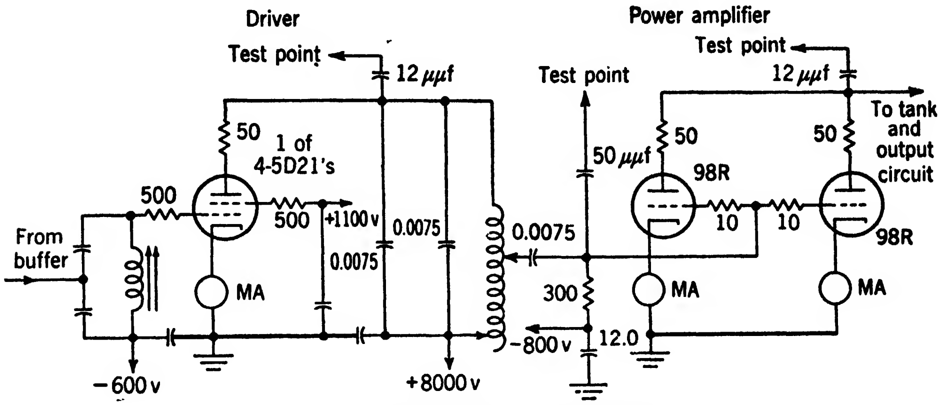


FIG. 9·17.—Simplified circuit of driver.

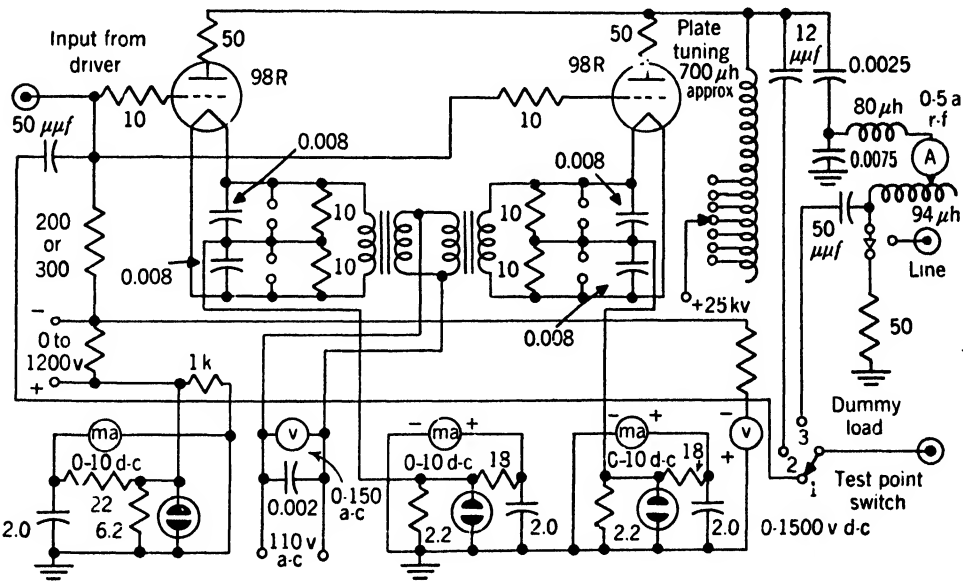


FIG. 9·18.—Simplified circuit of power amplifier.

The power amplifier (Fig. 9·18) is notable chiefly in that although two VT98 triodes are used in parallel, no neutralization is required. This is a consequence of the low operating frequency and of the heavy grid damping to ground by the noninductive linear-load resistors. The plate tank circuit is designed to work into a 50-ohm coaxial transmission line, and one of its two tuning adjustments is a continuously variable crank coil. Test points are provided so that grid, plate, and output waveforms may be viewed on the oscilloscope; the latter position is extremely valuable in that it allows the oscilloscope to be used as an accurate pulse voltmeter, for relative measurements.

Using the oscilloscope as a voltmeter makes it relatively simple to adjust the transmitting-antenna coupling unit without an r-f bridge or other measuring apparatus. This procedure recommends itself, since the adjustment for best transient performance, which can be obtained with the oscilloscope, is not necessarily identical with that for best c-w performance as obtained from single-frequency impedance measurements. The technique consists of first measuring the r-f output current and oscilloscope deflection when a 50-ohm noninductive resistor is used as a load for the transmitter. The transmission line, terminated with the coupling unit and antenna, is then connected in place of the resistor. Adjustments are systematically made to the coupling unit until the r-f line current and oscilloscope deflection regain their former values.

CHAPTER 10

ANTENNA SYSTEMS

By R. B. Lawrance

10·1. Requirements for Ground-station Antennas. *General Characteristics: Polarization.*—Transmitting and receiving antennas for Loran ground stations are designed for vertical polarization, since the horizontal field of a wave traveling along the earth's surface is rapidly attenuated. All Loran synchronizing paths depend on propagation either by ground waves that follow the curvature of the earth's surface or by sky waves that are emitted at low angles and are then reflected from the ionosphere to a distant receiving station. Efficient low-angle radiation and reception are obtained by the use of extensive radial ground systems that also minimize the variable effects of soil conductivity on transmission and reception.

Transmitting Antennas.—Four requirements determine the design of Loran transmitting antennas. (1) The Q of the antenna must be low enough to permit the radiation of a rapidly rising pulse. (2) The directive pattern must be such as to irradiate the intended service area effectively, without substantial loss of energy in other directions. (3) The input impedance must be stable and present a suitable load for the transmitter, so that the radiated pulse shapes are the same for all stations. (4) The antenna must be capable of handling the required peak and average power.

The widespread use of modulated oscillators (whose frequency depends on the impedance of the antenna) for the 2-Mc/sec ground-station transmitters has made the third requirement particularly important. It has been almost universal practice to use a single vertical transmitting antenna with no large potentially resonant metallic objects in its vicinity, thereby avoiding interaction which might distort the all-important leading edge of the radiated pulse. This construction gives an efficient and simple radiator with no inherent directivity in the horizontal plane. This lack of horizontal directivity is not often serious.

Since none of the energy radiated at angles higher than about 20° above the horizontal is useful for Loran purposes, it is necessary to conserve and if possible enhance the low-angle radiation. The use of an extensive radial ground system involving a half ton or more of copper wire has been found to give a worth-while increase in signal strength at extreme ranges, attributable to decreased loss of low-angle energy in the region near the antenna.

All short vertical antennas operated against such a ground system exhibit almost similar radiation patterns in elevation. As the antenna length is increased to a half wavelength or slightly more, however, the proportion of low-angle radiation increases significantly. A half-wavelength antenna at Standard Loran frequencies would be approximately 260 ft high; although an antenna of this size would be beneficial in a peacetime Loran system, the wartime requirements have been better met with a length of the order of 110 ft, slightly less than a quarter wavelength. This gives an antenna that is relatively easy to erect and that meets the electrical requirements satisfactorily. Both the full-length vertical and the "inverted-L" types have been used.

The Low Frequency Loran experiments have involved a carrier frequency of 180 kc/sec, for which a quarter wavelength is of the order of 1360 ft. A temporary solution of the mechanical and electrical problems has been the use of a thin wire 1300 ft long, supported by a helium-filled barrage balloon. A more permanent antenna has been designed but not yet erected; it consists of a 625-ft self-supporting top-loaded base-insulated steel tower.

Receiving Antennas.—The primary function of the receiving antenna at a ground station is to deliver to the receiving apparatus a remote-signal voltage considerably in excess of the internal-noise voltage. The form of the received pulse at the receiver-input terminals should not be appreciably distorted or delayed; hence the receiving-antenna system must have adequate bandwidth.

If the baseline is not too long, the received signal is at all times usefully stronger than the received atmospheric noise. Under these circumstances a simple vertical receiving antenna is adequate even though it lacks directivity in the horizontal plane. The length of the antenna is determined by the necessary bandwidth and is ordinarily between an eighth and a quarter wavelength. Such a nondirectional receiving antenna is particularly useful at a double station, where two remote signals must be received usually from quite different directions.

When circumstances force the use of long baselines or a poor receiving location, the remote signal may no longer predominate over atmospheric noise and other received interference. Since the interference generally arrives from all directions and the desired signal arrives from but one, a directive antenna is helpful. The simplest nonresonant directive antenna is the Beverage "wave" antenna, which has been used successfully for 2-Mc/sec Loran. This type of antenna is simple to construct and works best when the soil conductivity is poor, but it requires considerable ground space.

10·2. Antenna Coupling Units. *General Considerations.*—There are two common schemes for coupling energy from the transmitter to the transmitting antenna. In the simpler of these the transmitter is located near the input terminals of the antenna, and the connection is made without the use of a transmission line. The antenna input impedance is seldom suitable for use directly as a plate load, but an impedance match can be accomplished by the use of a reactive network. Such a network may or may not resemble a conventional tank circuit; its design requires fairly accurate knowledge of both the desired plate-load impedance and the antenna input impedance as well as of the nature of the signals to be transmitted. This type of coupling between transmitter and antenna has not been used in any Standard Loran equipment.

In the more complex scheme the transmitter is located at a convenient distance from the antenna and is connected to it by a transmission line. This gives more freedom in the layout of the transmitting station and, since the characteristic impedance of the transmission line is known in advance, makes it possible to design the transmitter for a single standard value of load impedance. The input impedance of the transmission line is a pure, constant resistance over the range of frequencies for which the terminating impedance equals the line characteristic impedance. Over the range of frequencies including the carrier and all significant sideband components, therefore, the coupling unit should be able to transform the frequency-varying resistance and reactance of the antenna into an impedance equal to that of the transmission line, primarily resistive and practically constant.

In Low Frequency Loran the shape of the transmitted pulses must be controlled with great care, and even with the faster-rising pulses of 2-Mc/sec Loran the antenna and coupling unit must not produce appreciable lengthening of the pulse rise time. This requirement may be stated in terms of input impedance, as in the preceding paragraph, or in equivalent and alternative terms of energy storage.

Consider an antenna that is radiating energy at a constant power level; stored in the electric and magnetic fields surrounding the antenna is an amount of energy several times as great as that radiated per cycle. This means that if the flow of energy to the antenna is suddenly stopped, the antenna will continue to radiate, with slowly decreasing amplitude, until this stored energy is exhausted. Conversely, if input power is suddenly applied to an antenna, several cycles will elapse before the stored energy builds up and the antenna radiates at full power.

The presence of some stored energy is unavoidable, but for pulse transmission the amount must be kept relatively low. For a given length of antenna, the stored energy may be reduced by increasing the effective diameter of the antenna conductor. From an impedance standpoint, this causes the input reactance to vary less rapidly with frequency; hence the bandwidth is increased. The effects of an antenna's dimensions on its input impedance and bandwidth are discussed in Sec. 10·3; in designing a coupling unit the bandwidth of the antenna is always the limiting factor.

Simple Reactance Networks.—In general the input resistance of a Loran transmitting antenna is different from the characteristic impedance of the transmission line, and the input reactance is not, except fortuitously, equal to zero. Although ideally the coupling unit should provide exact matching over a considerable range of frequencies, it has been found that under certain conditions it is sufficient to design the unit for exact matching at the carrier frequency only. If the Q of the antenna is not excessively high, and if the antenna input resistance is not too greatly different from the line impedance, simple ladder networks of two or three reactances can be used. In order to keep to a minimum the energy stored in the coupling unit, all series impedances (which carry high current) are made small whereas the shunt impedances are made as large as is feasible.

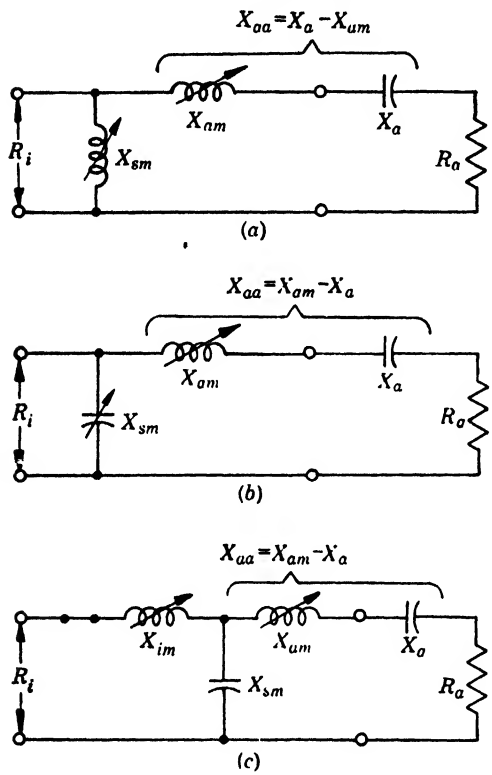


FIG. 10.1.—Simple L- and T-networks for matching impedances at carrier frequency.

The transmission line commonly used in Loran stations is a standard solid-dielectric coaxial cable with a nominal characteristic impedance of 52 ohms. Since the antenna input resistance is usually between 15 and 45 ohms, a small impedance transformation is required. Figure 10·1 shows three simple networks that are suitable for the purpose. In all three circuits the symbols are defined as follows, values being taken at the carrier frequency:

R_A = antenna input resistance,
X_A = antenna input reactance,
R_I = source resistance to be matched (usually the characteristic impedance of a transmission line: 52 ohms),
X_{AM} = reactance of antenna arm of matching unit,
X_{IM} = reactance of input arm of matching unit,

X_{SM} = reactance of shunt arm of matching unit,
X_{AA} = net reactance of antenna and antenna arm of matching unit.

For the T-network, which is the more general form, the relations between the quantities are given in the formulas below. In these formulas all reactances, capacitive and inductive, appear as positive numbers, their nature being indicated by the note at the side of the equation and by the symbols in the diagram.

$$X_{SM} \geqq \sqrt{R_A R_I} \qquad \text{(capacitive).} \tag{1a}$$

$$X_{AA} = X_{SM} - \sqrt{(X_{SM}^2 - R_A R_I)\frac{R_A}{R_I}} \qquad \text{(inductive).} \tag{1b}$$

$$X_{IM} = X_{SM} - \sqrt{(X_{SM}^2 - R_A R_I)\frac{R_I}{R_A}} \qquad \text{(inductive for } R_A \text{ large, capacitive for } R_A \text{ small).} \tag{1c}$$

$$X_{IM} \text{ changes sign when } R_A/R_I = X_{SM}^2/(X_{SM}^2 + R_I^2).$$

A slight change in R_A necessitates no readjustment of X_{AA} (but does require an adjustment in X_{IM}) when $X_{SM} = \sqrt{2R_A R_I}$.

The mathematical treatment yields two solutions each for X_{AA} and X_{IM}, one having a positive sign before the radical and the other having a negative sign. However, the choice of the positive sign yields values of reactances that are unnecessarily large (with excessive stored energy and consequent reduction of bandwidth). The fact that two sets of adjustments exist which give proper matching at the carrier frequency is, of course, a consequence of the fact that the coupling unit has three independent elements. This is one more than the minimum number necessary for independent adjustment of input resistance and reactance; if X_{SM} were continuously variable, there would be an infinite number of suitable settings.

As in all reactive impedance-transforming circuits, conditions at the carrier frequency remain unaltered if each inductive reactance is replaced by a corresponding capacitive reactance, and vice versa. Conditions at other frequencies are reversed; if for the original circuit a slightly higher frequency gives an increased resistance and a capacitive reactance component, then for the revised circuit a slightly *lower* frequency gives a similar increased resistance and a corresponding *inductive* reactance. This effect is discussed later, in connection with Fig. 10·4. In general the use of a capacitive shunt arm is preferable, since harmonic components are bypassed.

The T-network is most useful when R_A is greater than about one-half R_I, although it may be used for values as low as one-fourth R_I if X_{SM} is changed or if a capacitor is inserted at *a-a* in the input arm. A T-network is used, in the form shown in Fig. 10·1*c*, for matching the Wincharger antenna (see Sec. 10·4). It can also be used satisfactorily with a vertical wire antenna if the inductor X_{AM} is sufficiently large. In the LF application the T-network is used with both the balloon-supported wire antenna and the permanent umbrella-loaded tower (see Sec. 10·5); for use with the tower the reactance of X_{SM} is reduced and a series capacitor is inserted at *a-a*. With the balloon antenna, X_{SM} is proportioned so that changes in antenna resistance, produced by varying angle of inclination, cause relatively little error in coupling unit adjustment.

For the lower values of antenna resistance, as obtained with inverted-L and T-antennas, the L-network is satisfactory. The standard coupling unit, Navy type CG-47368, is normally used as a T-network but can be reconnected as an L-network; thus a single unit is adequate for use with all 2-Mc/sec Loran transmitting antennas. Since the step-up (looking from antenna into transmission line) L-network may be regarded as a T-network with series input reactance X_{IM} equal to zero, the formulas for its elements are the following:

$$X_{IM} = 0. \tag{2a}$$

$$X_{SM} = R_I \sqrt{\frac{R_A}{R_I - R_A}}. \tag{2b}$$

$$X_{AA} = \sqrt{(R_A)(R_I - R_A)}. \tag{2c}$$

Of the two forms of stepup L-network shown in Fig. 10·1 the first is the more useful, since at Loran frequencies variable inductors of appropriate reactance are simpler and less expensive than corresponding variable capacitors. In addition, since a low-resistance antenna usually has capacitive input reactance, a smaller inductor may be used at X_{AM}, making the over-all bandwidth appreciably greater than with the circuit of Fig. 10·1*b*. The suppression of harmonic radiation is the sole advantage of the latter circuit.

Finally, there is another form of the L-network that can be used to step down antenna resistances that are greater than twice the line characteristic impedance. This network may also be derived from the T-network formulas, by setting X_{AA} equal to zero. As yet, however, it has not been used as a Loran coupling unit.

Adjustment of T- and L-networks.—The adjustment of these coupling units may be facilitated by the use of r-f impedance-measuring equipment, but this is not essential. In the absence of measuring equipment the transmitter is first tuned into a 50-ohm resistance load, and the output current, pulse shape, and operating conditions are carefully noted. The output connection is then transferred to the transmission line and antenna circuit, and the two coupling-unit tuning controls are adjusted until the previous conditions are closely simulated. Careful use is made of the transmitter-testing oscilloscope during the tuning procedure, because the appearance and relative size of the pulse are valuable guides to proper adjustment.

In the LF transmitter the built-in oscilloscope can be connected in such a way that it serves as an accurate output voltmeter. This facilitates the tuning of the coupling unit, since with proper coupling-unit adjustment the input impedance of the transmission line is nearly 52 ohms, making the current and voltage at the transmitter output terminal the same as for the resistive load. Higher voltage and lower current indicate higher input impedance, whereas the reverse shows the input

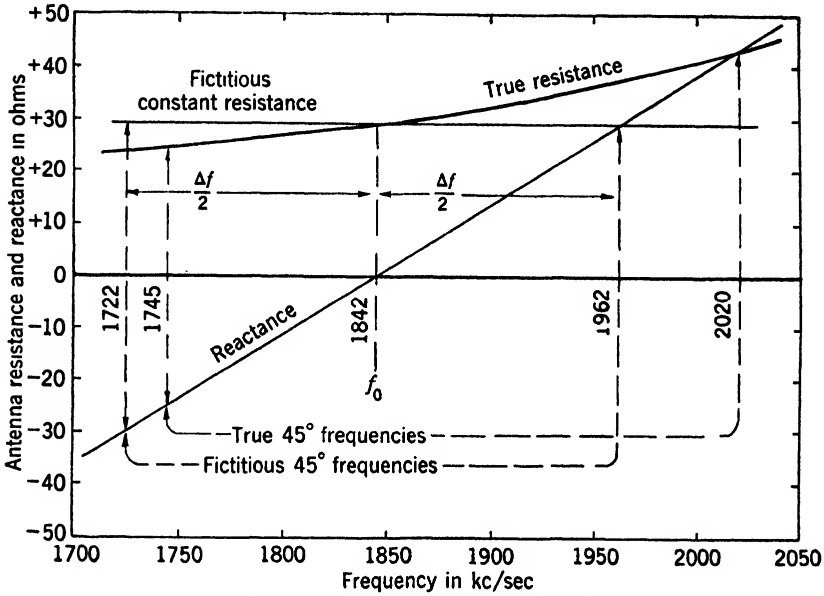


FIG. 10·2.—Illustrative bandwidth calculation for Wincharger antenna.

impedance to be too low. Large currents and voltages, together with low antenna current, indicate a severe mismatch, causing the transmission line and coupling unit to appear almost purely reactive. Simple rules indicate the proper sequence and nature of corrective adjustments.

Input Impedance over a Band of Frequencies.—As yet, relatively little has been said about the exact behavior of the L- and T-networks at sideband frequencies. The input impedance of the coupling unit would change but slowly with frequency if it were not for the rapidly changing reactance of the antenna. This changing reactance, together with the antenna input resistance, determines an important quantity Δf, which may be called the bandwidth of the antenna. Figure 10·2 illustrates the calculation of Δf for a Wincharger antenna.

At resonance the antenna resistance is approximately 29.5 ohms, and the reactance is zero but changes at the rate of 0.245-ohms per kc/sec shift in frequency. This rate of change, which is quite constant for frequencies near resonance, is termed the reactance slope; mathematically it is the derivative dX_A/df. Although the antenna resistance also changes appreciably with frequency, it may, for simplicity, be considered as constant, with its resonant value of 29.5 ohms. The bandwidth Δf is defined as the range of frequency over which the reactance is numerically less than this resonant resistance. For the resonant Wincharger antenna, calculation gives

$$\Delta f = \frac{2R_A}{\left(\frac{dX_A}{df}\right)} = \frac{(2)\ (29.5)}{(0.245)} = 240 \text{ kc/sec}. \tag{3}$$

The nature of the approximations involved is evident from Fig. 10·2; owing to the variation of antenna resistance the two frequencies of 45° phase angle actually lie approximately 275 kc/sec apart and are not centered on the resonant frequency. Fortunately, for antennas of lower resistance or larger reactance slope the approximation is much better, and the simplified description is useful in comparing the performance of various coupling units and antennas. An approximate value of the Q of a resonant antenna is given by the formula

$$Q = \frac{f_0}{\Delta f} = \frac{f_0\left(\frac{dX_A}{df}\right)}{2R}. \tag{4}$$

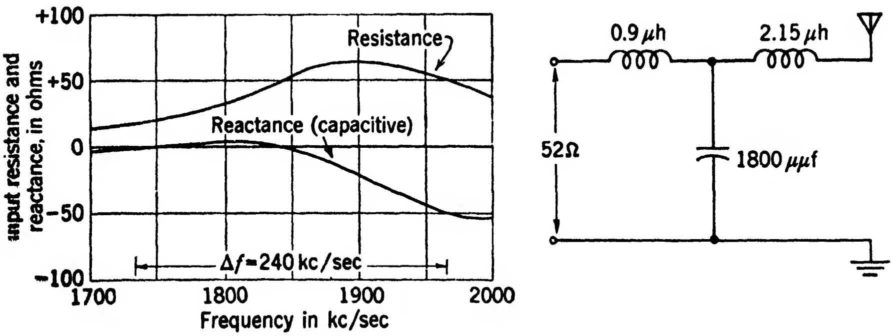


FIG. 10·3.—Input impedance of T-type coupling unit and Wincharger antenna, in the region of 1850 kc/sec.

For an antenna not operated at its resonant frequency a similar analysis may be made by adding to the reactance slope of the antenna the slope contributed by the loading coil or capacitor. This calculation is performed in Sec. 10·3, and the results are shown there in Figs. 10·13 and 10·14; for antennas operated below their resonant frequency Δf is smaller and Q is larger than for a similar resonant antenna.

Figure 10·3 shows the calculated input impedance of a Wincharger antenna operated at 1850 kc/sec and matched to a 52-ohm line by a standard T-network. At the carrier frequency the input reactance is zero, and it remains very small for all sideband frequencies below the carrier. For the upper sidebands the reactance increases capacitively at a nearly constant rate of 0.45 ohm per kc/sec, reaching a maximum capacitive reactance of slightly more than 50 ohms at approximately 1980 kc/sec. The input resistance has a value of 52 ohms at the carrier frequency, smaller values for lower frequencies, and larger values for higher frequencies. At approximately 1900 kc/sec a characteristic broad resistance maximum is reached, and it should be noted that, as is true in general, this maximum occurs at a frequency removed from the carrier

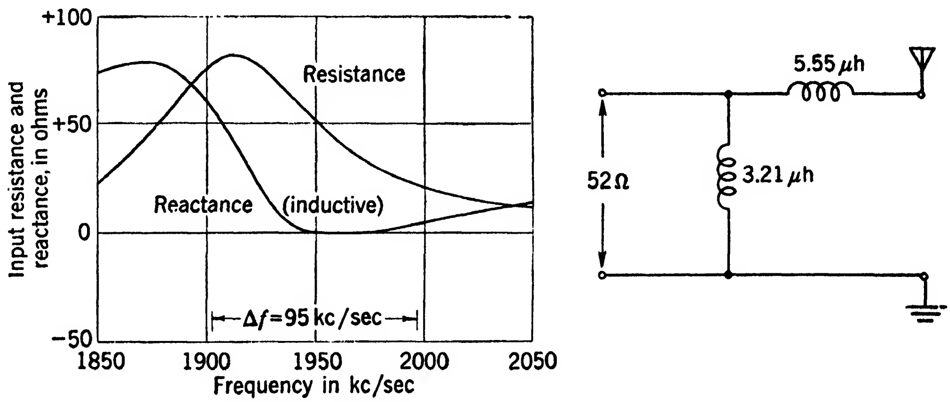


Fig. 10·4.—Input impedance of L-type coupling unit and inverted-L antenna, in the region of 1950 kc/sec.

by less than one-half Δf. At frequencies 50 kc/sec below and above the carrier frequency the input resistances are 33 and 63 ohms respectively, whereas the corresponding reactances are 5 ohms inductive and 23 ohms capacitive. Although this is not perfect, it is adequate, and the Wincharger antenna tuned in this manner has performed satisfactorily.

The corresponding curves for an inverted-L antenna tuned by a two-inductance L-network are shown in Fig. 10·4. The bandwidth of this antenna is only four-tenths that of the Wincharger antenna.

Figure 10·5 gives the data of Figs. 10·3 and 10·4, replotted in terms of antenna bandwidth. The total variations of resistance and reactance are somewhat smaller for the Wincharger antenna, but the general shapes of the two sets of curves are quite similar. The behavior of the input impedance may be summarized as follows:

1. A frequency shift in the direction that causes the shunt reactance X_{SM} to decrease produces an increase in the input resistance.
2. For this direction of frequency shift the input reactance increases rapidly; for shift of one-half Δf the reactance has a value approximately equal to the matched input resistance at the operating frequency.

3. For this direction of frequency shift the input reactance is of the same nature as the shunt reactance X_{SM}, for example, capacitive.
4. For the opposite direction of frequency shift the reactance remains small and the resistance decreases. For a shift of one-half Δf, the resistance is approximately 40 per cent of the matched value at the operating frequency.

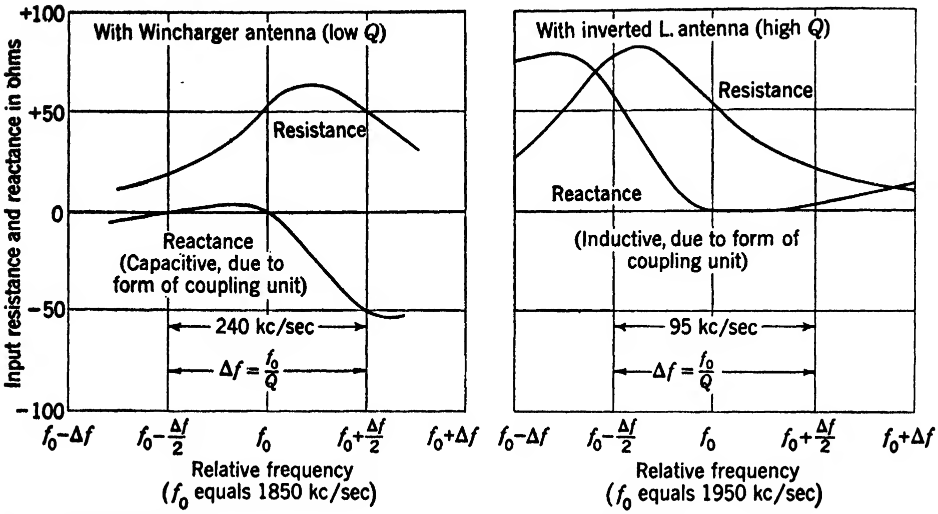


FIG. 10·5.—Coupling-unit input impedance for low- and high-Q antennas, in terms of antenna bandwidth.

Coupling Networks with Symmetrical Impedance Characteristic.—Spectrum measurements on signals from the present type of 2-Mc/sec Loran station have always showed asymmetrical sideband distribution and the presence of somewhat higher-order sideband energy than is desirable or necessary. With the end of the war it has become essential to re-examine the possibilities of reducing interference while retaining navigational usefulness. The larger part of the modernization program concerns the transmitters, which at present are modulated oscillators and which are to be changed to crystal-controlled multistage units. It is probable that with the transmitter-output circuits there will be associated a spectrum-control filter, used to reduce the amplitude of the high-order sidebands. Such a filter would presumably require that the transmission-line input impedance be very nearly a pure, constant resistance for all frequencies in the pass band of the filter. This would, in turn, require a more accurate impedance match by the coupling unit.

Some of the design factors for such a coupling unit are considered briefly in the following discussion. Although written in terms of antennas that are operated in the vicinity of the first resonance, the discussion can easily be applied to antennas operated at or near the second resonance. The process for doing this is familiar in network theory.

Impedance-changing circuits with symmetrical characteristics are most easily obtained by the use of a transformer. Since a physically realizable transformer has neither infinite inductance nor perfect coupling it can be represented in terms of an ideal transformer combined with finite impedances. A simple equivalent circuit of this type, valid when losses and distributed capacitances may be neglected, is shown in Fig. 10·6. The properties of the ideal transformer are that its open-circuit primary and secondary impedances are infinite, that its short-circuit impedances are zero, and that the primary voltage and current are *exactly* related to the secondary voltage and current by the turns ratio. Any

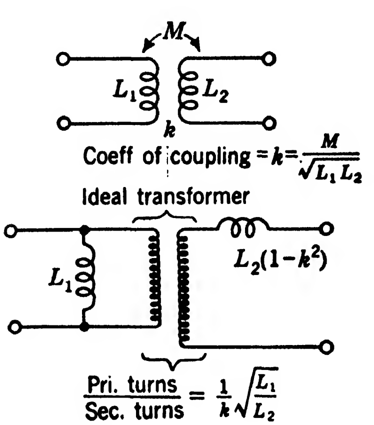


FIG. 10·6.—Equivalent circuit for practical transformer, in terms of ideal transformer.

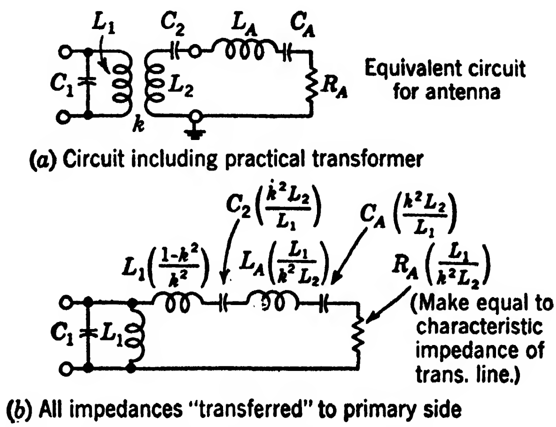


FIG. 10·7.—Use of transformer in matching antenna to transmission line.

impedance appearing at one side of the transformer may thus be "transferred" to the other side by simply multiplying by the square of the appropriate turns ratio.

The simplest use of a practical transformer for matching an antenna to a transmission line is shown in Fig. 10·7. Values of the equivalent series inductance and capacitance of the antenna may be calculated by the methods described in Sec. 10·3. If the antenna has a capacitive input reactance larger than the transformer leakage reactance, the capacitor C_2 is replaced by an inductor. Tuning of the circuits is simple both theoretically and practically: the primary circuit is tuned to resonance while the secondary is open-circuited, and the secondary is similarly tuned with the primary short-circuited.

The transformed antenna resistance can be made equal to the line impedance, but at the input terminals it appears in series with a series-resonant circuit, the combination being in parallel with the shunt-resonant primary circuit. The behavior at frequencies off resonance depends on the relationship that the values of the resonant-circuit reactances bear to the transformed resistance. Since the antenna con-

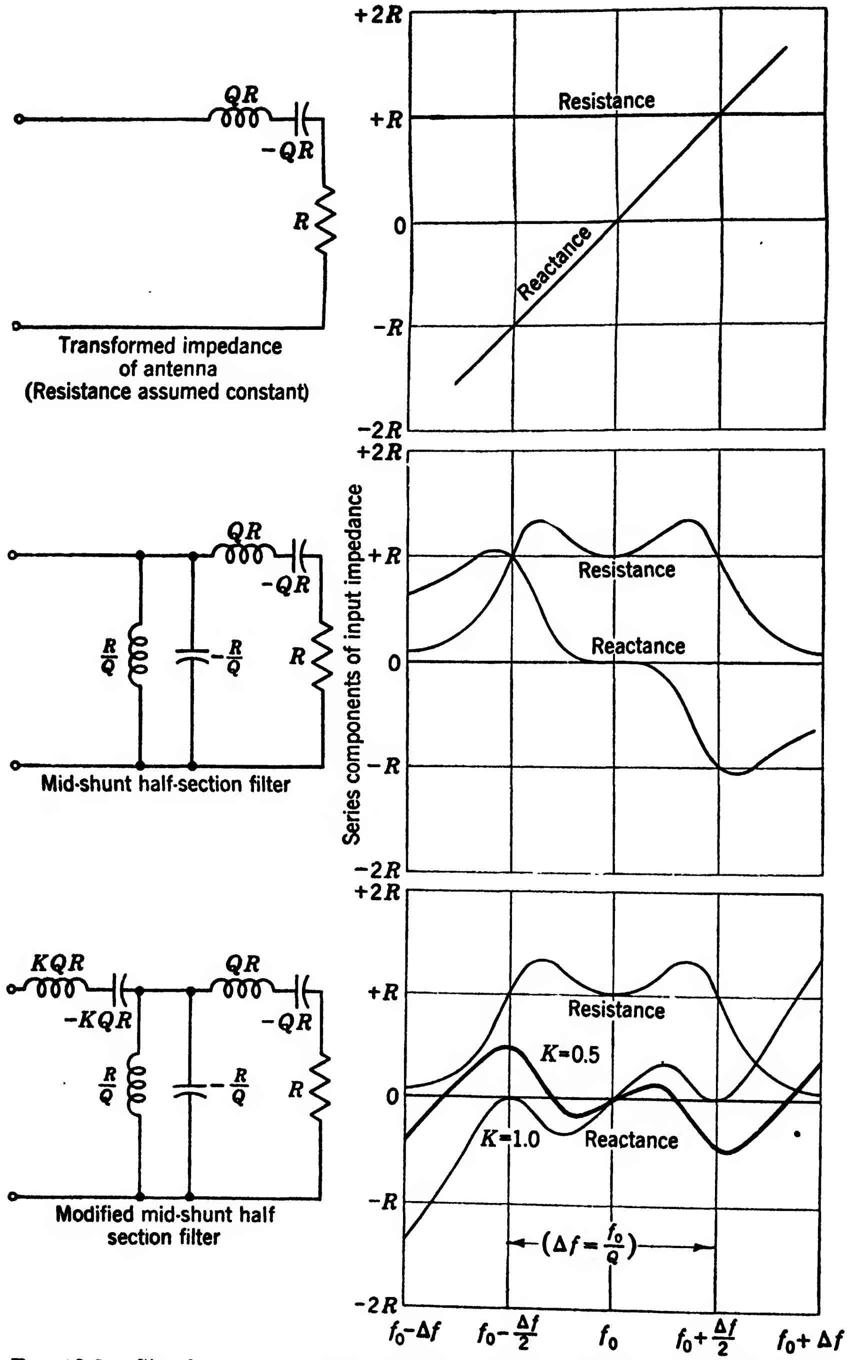


FIG. 10·8.—Simple coupling units with symmetrical impedance characteristics.

tributes large reactances to the series-resonant circuit, the Q of this circuit cannot be less than that of the antenna; if any tuning reactances are necessary, the circuit Q will be somewhat larger. Thus the antenna limits the bandwidth of a transformer-type coupling unit, exactly as with the T- and L-networks. As shown in Fig. 10·7 the coupling unit and

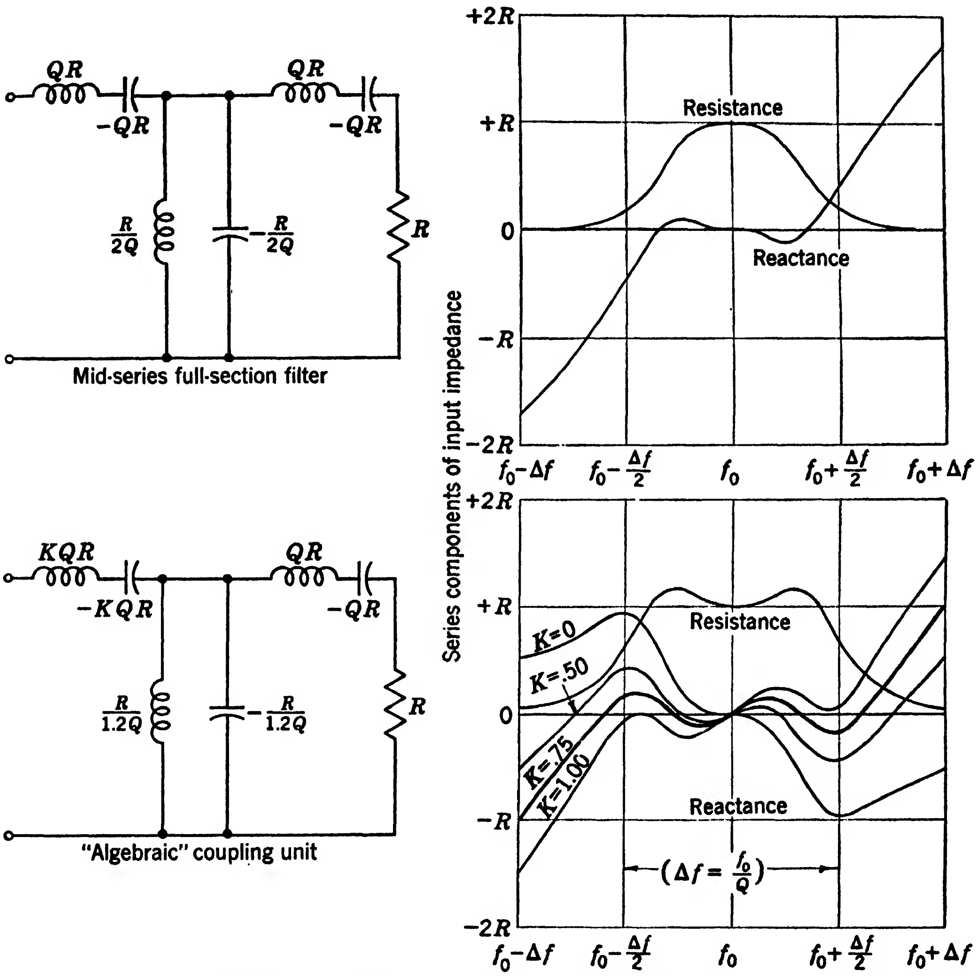


FIG. 10·9.—More elaborate coupling units with symmetrical impedance characteristics.

antenna form an embryonic bandpass filter, whose bandwidth cannot exceed the bandwidth Δf of the antenna.

The way in which the input impedance varies with frequency may be controlled by adjusting the impedance level of the shunt-resonant circuit, as shown in the second curve of Fig. 10·8. By making the resonant shunt reactances *smaller* than the transformed resistance, by a factor equal to the Q of the secondary circuit, the input reactance can be made to have zero slope at the operating frequency. This gives a desirable behavior for frequencies in the immediate region of the carrier, but for frequencies removed by one-half Δf the reactance and resistance are equal. The third set of curves in Fig. 10·8 shows a method of improving the input impedance at the higher sidebands, with some sacrifice of performance near the carrier frequency.

Figure 10·8 shows the curves for a coupling unit treated as a midshunt half-section filter; in Fig. 10·9 the characteristics of a midseries full-section filter are shown. The improved resemblance to the filter-theory behavior is evident, with the reactance very nearly zero throughout the pass band and with the resistance decreasing smoothly to a small value at the edge of the band. A modified circuit, with performance intermediate between the two filter circuits, is also shown in Fig. 10·8. It is thought that in the embodiment in which the factor K is equal to approximately 0.75 a circuit may be provided that will terminate the transmission line satisfactorily for all significant components transmitted through the filter at its input.

10·3. Prediction and Simulation of Antenna Characteristics.—In the design of Loran transmitting and receiving antennas it is obviously desirable to be able to predict the various characteristics in advance, with a fair degree of accuracy. Estimates of the bandwidth are necessary for reassurance that distortion of the pulse signals will not be excessive, and predictions of antenna impedance furnish the starting basis for coupling-unit design.

Furthermore, in experimental work with transmitters, it is desirable to have available dummy antennas that are capable of handling the full transmitter-output power and that simulate closely the steady-state and transient response of the antenna to be used ultimately. Both experimentation and the training of personnel are facilitated by the use of such dummy antennas.

In recent years the accurate calculation of antenna input impedance has been the subject of many published papers. The most comprehensive and apparently the most accurate methods are those of Schelkunoff, and the reader is referred to his papers.[1] The present section is concerned with calculations in which some accuracy is sacrificed for simplicity; in some cases results are taken from Schelkunoff directly, and in others approximations are made from his formulas. In a few cases original empirical results have been found useful and are given. The discussions are confined to vertical antennas of uniform cross section operated at or below the first resonant frequency.

[1] S. A. Schelkunoff, "Theory of Antennas of Arbitrary Size and Shape," *Proc. IRE*, **29**, No. 9, September 1941; "Concerning Hallen's Integral Equation for Cylindrical Antennas," *Proc. IRE*, **33**, No. 12, December 1945; "Principal and Complementary Waves in Antennas," *Proc. IRE*, **34**, No. 1, January 1946.

Characteristic Impedance and Electrical Length.—The concept of characteristic impedance, much used in discussing transmission lines, is also useful in antenna theory. Strictly speaking, a biconical antenna is the only type possessing uniform characteristic impedance, since its inductance and capacitance per unit length do not change with distance from the generator. The cylindrical antennas can, however, be considered as having an *average* characteristic impedance, which is useful in both the detailed and simplified theories. Schelkunoff gives a formula that, for a cylindrical antenna operated against a perfectly conducting ground plane, may be written as

$$Z_o = 138.2 \log_{10} \frac{l}{d} + 23.2, \tag{5}$$

where Z_o = average characteristic impedance, ohms,
l = length of antenna conductor, any units,
d = diameter of antenna conductor, same units as l.

It is interesting to note that this is exactly the characteristic impedance of a single-wire transmission line operated against ground, where the height is 1/2.718 times the length l of the antenna. Other authors have given other formulas, differing in the additive constant by as much as 40 ohms and sometimes including a term dependent on frequency.

The first, "quarter-wave," resonance occurs at a frequency lower than that giving a free-space quarter wavelength equal to the length of the antenna. One of the many alternative ways of representing this effect is by defining an electrical length θ, such that

$$\theta = K_\theta \frac{l}{\lambda}, \tag{6}$$

where θ = electrical length, degrees,
K_θ = a factor greater than 360°,
λ = free-space wavelength, same units as l.

Inserting the wavelength-frequency relation and expressing the quantities in convenient units, we obtain

$$\theta = (1.016)\,(K_\theta)\,(l_{\text{feet}})\,(f_{KC})\,(10^{-6}). \tag{7}$$

The factor K_θ is a function of the proportions of the antenna and is hence a function of Z_o; it is plotted in Fig. 10·10. The reason for expressing the electrical length in this manner is that in the region of the first resonance the input reactance varies approximately as a cotangent function. This relationship is not theoretically exact except for antennas of infinite characteristic impedance, but its simplicity is a great asset, and its accuracy is quite good for frequencies up to and slightly beyond the first resonance.[1] If subsequent discussions are confined to electrical lengths not exceeding 90°, then the reactive component of the antenna input impedance is given by the approximate formula

$$X_A = -Z_o \cot \theta, \tag{8}$$

where X_A = antenna input reactance, ohms.

The input resistance of an antenna is customarily analyzed into three components, one of which represents the useful radiation of a portion of

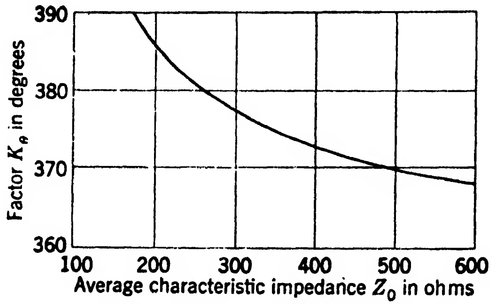


FIG. 10·10.—Effect of average characteristic impedance in lowering first resonant frequency of vertical cylindrical antennas. (*Data from Schelkunoff, Proc. IRE, September,* 1941.)

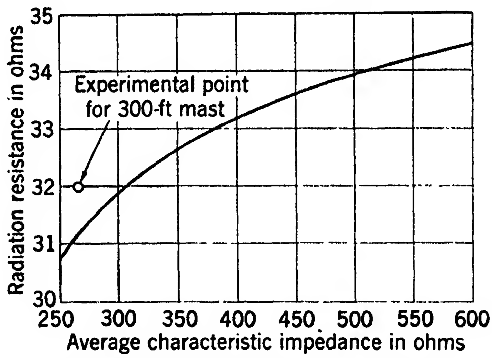


FIG. 10·11.—Radiation resistance at first resonance, as a function of characteristic impedance. (*Data from Schelkunoff, Proc. IRE, September,* 1941.)

the input power. The other two components represent dissipation in the imperfect conductors of the antenna and of the ground. For a good radial ground system and a reasonably efficient antenna conductor the latter two resistance components are usually of the order of 2 to 5 ohms; thus when the electrical length is greater than approximately 45°, the radiation resistance is the dominant component.

The radiation resistance may be represented as a function of the electrical length and of the characteristic impedance. For a given *length* of antenna the radiation resistance increases slightly as the diameter is

[1] For example, reactance measurements on a uniform 300-ft tower with Z_o = 264 gave points evenly scattered about a cotangent curve, the average deviation being 2 per cent. The measurements covered the region from θ = 16° to θ = 125°.

increased; the lowering of the resonant frequency and the consequent increase in electrical length are, however, more pronounced, with the result that the radiation resistance of a "fat" antenna *at resonance* is somewhat lower than that of a "thin" one. Figure 10·11, adapted from Schelkunoff, shows this effect; by adding an estimated value of loss resistance the total input resistance at resonance may be obtained.

For frequencies below the first resonance it has been found experimentally that a single curve well represents the variation of total input resistance with frequency, provided that ground losses are reasonably low. Experimental data from seven widely different antennas with uniform cross section[1] have been analyzed; these data follow a single curve within errors of approximately 5 per cent. Figure 10·12 shows this curve, whose empirical equation, valid for electrical lengths between 45° and 110°, is

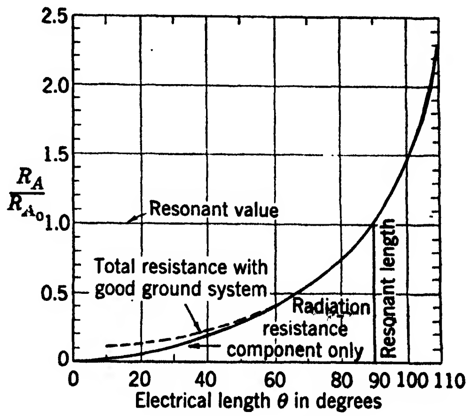


FIG. 10·12.—Empirical variation of input resistance of short vertical antennas.

$$R_A = R_{A_0}\left(\frac{\theta}{90}\right)^{2+\left(\frac{\theta}{90}\right)^4},$$

in which R_{A_0} = input resistance at resonance,
R_A = input resistance for electrical length θ.

With the aid of Figs. 10·10 to 10·12, therefore, approximate values of the input resistance and reactance of a vertical cylindrical antenna can be obtained simply and rapidly. The real usefulness of these simplifications lies in their adaptability to discussions of antenna bandwidth and of equivalent circuits.

Bandwidth Considerations.—The bandwidth of an antenna of electrical length θ depends on its input resistance and reactance and upon the rate with which the input reactance changes with frequency. When the electrical length is less than 90°, the input reactance is capacitive, and the necessary series loading coil may cause a significant increase in the net Q of the antenna circuit. In making comparisons it is convenient to calculate the effect of a series inductance just sufficient to reduce the net input reactance to zero. A coil with inductance L henrys has a reactance that changes with frequency at a rate of $2\pi L$ ohms per cycle per second; since the value of inductance is determined by the antenna reactance

[1] Three of the antennas were of the inverted-L type.

$Z_o \cot \theta$ we find that the coil contributes a "reactance slope" of value

$$\text{Slope } X_L = \frac{d}{df}(X_L) = \frac{2\pi f L}{f} = \frac{Z_o \cot \theta}{f}, \tag{9}$$

where $d/df\,(X_L)$ = rate of change of loading-coil reactance with frequency.

By a simple differentiation we find that for the input reactance of the antenna itself the rate of change is

$$\begin{aligned} \frac{d}{df}(X_A) &= \frac{d}{df}(-Z_o \cot \theta) \\ &= \frac{Z_o}{\sin^2 \theta}\frac{d}{df}(\theta \text{ radians}). \end{aligned}$$

But since θ radians $= (\pi/2)\,(f/f_o)$, we obtain

$$\text{Slope } X_A = \frac{d}{df}(X_A) = \frac{\pi Z_o}{2 f_o \sin^2 \theta}. \tag{10}$$

The net reactance slope is obtained by adding the components due to the antenna and to the loading coil. Since we are interested in comparing at the same operating frequency the performance of antennas with different electrical lengths, we express the net reactance slope in the following form:

$$\begin{aligned} \text{Slope } X_{\text{total}} &= \frac{d}{df}(X_{\text{total}}) = \frac{Z_o}{f}\left(\cot \theta + \frac{\pi f}{2 f_o \sin^2 \theta}\right) \\ &= \frac{Z_o}{f}\left(\cot \theta + \frac{\theta \text{ radians}}{\sin^2 \theta}\right). \end{aligned} \tag{11}$$

For an antenna of resonant length, θ is equal to 90° and the total reactance slope is equal to $\pi Z_o/2f$. By division we obtain the relations that are plotted in Fig. 10·13:

$$\frac{\text{Slope } X_{\text{total}}}{\text{Slope } X_{\text{comp. ant.}}} = \frac{2}{\pi}\left(\cot \theta + \frac{\theta \text{ radians}}{\sin^2 \theta}\right). \tag{12a}$$

$$\frac{\text{Slope } X_A}{\text{Slope } X_{\text{comp. ant.}}} = \frac{2}{\pi}\left(\frac{\theta \text{ radians}}{\sin^2 \theta}\right). \tag{12b}$$

$$\frac{\text{Slope } X_L}{\text{Slope } X_{\text{comp. ant.}}} = \frac{2}{\pi}\cot \theta. \tag{12c}$$

in which

Slope $X_A = \frac{d}{df}(X_A)$ = reactance slope of antenna at operating frequency f.

Slope $X_L = \frac{d}{df}(X_L)$ = reactance slope of series-loading coil required to resonate antenna at operating frequency f.

Slope $X_{\text{total}} = \frac{d}{df}(X_A + X_L)$ = reactance slope of combination at operating frequency f.

Slope $X_{\text{comp. ant.}} = \frac{\pi Z_o}{2f}$ = reactance slope of a similar, larger, antenna self-resonant at the operating frequency ("comparison antenna").

It will be seen that reducing the electrical length of an antenna does not produce extreme increases in reactance slope, since the net slope at 45° is only 64 per cent greater than that at 90°. Reduction in electrical length does, however, profoundly affect the input resistance and hence

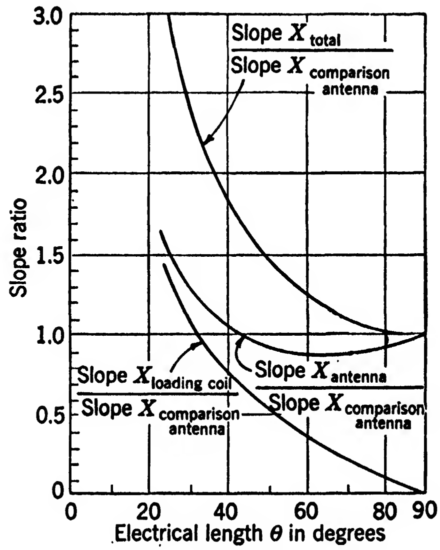


FIG. 10·13.—Reactance slopes with vertical antennas shorter than the length for first resonance.

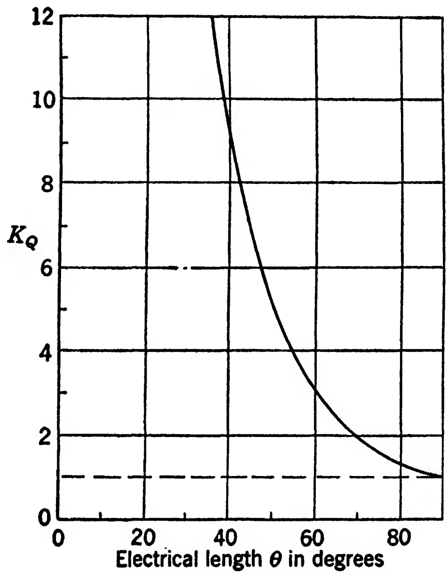


FIG. 10·14.—Increase of antenna circuit Q as length of vertical antenna is decreased.

the Q. If R_A is the antenna input resistance for an electrical length θ, then the Q of the antenna and loading coil, considered as a simple series circuit, may be expressed as

$$Q = \frac{f}{2R_A}\frac{d}{df}(X_{\text{total}})$$
$$= \frac{Z_o}{2R_A}\left(\cot\theta + \frac{\theta \text{ radians}}{\sin^2\theta}\right). \qquad (13)$$

This has a value Q_o for an antenna resonant at the operating frequency

$$Q_o = \frac{\pi}{4}\frac{Z_o}{R_{A_o}}.$$

From Figs. 10·12 and 10·13, it can be seen that both the decreasing input resistance and the increasing reactance slope cause the Q to rise rapidly as the electrical length is decreased; this result is shown in Fig. 10·14. The factor K_Q is defined as follows:

$$K_Q = \frac{2}{\pi}\frac{R_{A_0}}{R_A}\left(\cot\theta + \frac{\theta \text{ radians}}{\sin^2\theta}\right) \tag{14}$$

= ratio of net Q to Q of comparison antenna (both at operating frequency f)

= ratio of net Q to Q of the antenna at its resonant frequency.

The net Q of a particular antenna can be obtained from the expression

$$Q = \frac{\pi}{4}\frac{Z_o}{R_{A_0}} K_Q = 0.785\,\frac{Z_oK_Q}{R_{A_0}}. \tag{15}$$

It will be noted that the use of an antenna of electrical length 70° gives a Q that is double the resonant value whereas for an electrical length of 45° the factor is nearly 7. It is thus evident that for transmitting purposes the electrical length should not be much less than 90°.

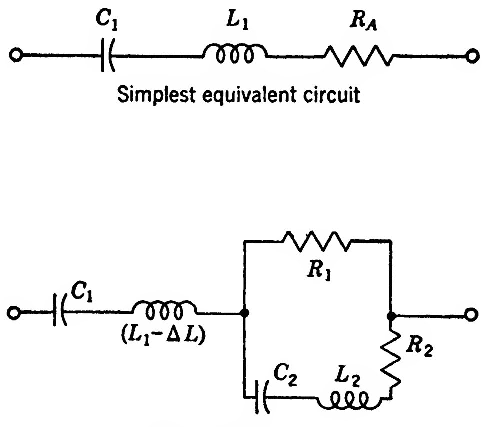


FIG. 10·15.—Equivalent circuits for input impedance of a short vertical antenna.

It should be mentioned that the above values of Q are calculated on the basis of negligible damping by the internal impedance of the source feeding the transmitting antenna (or by the load impedance fed by the receiving antenna.) If such a matched impedance is used and if the impedance is essentially a pure resistance, the resulting Q will have half of the value given. This is almost always true in the case of Loran ground-station receiving antennas, a fact that allows moderately short antennas to be used without trouble from inadequate antenna-circuit bandwidth. For transmitting antennas the situation is somewhat complicated, since the impedances of both the transmitter and the antenna may be considered to change during the different portions of the pulse. In general, however, the radiated pulse can be made to rise to 95 per cent of full amplitude in a number of cycles slightly less than the value of Q obtained from Eq. (15).

Design of Dummy Antennas.—The foregoing analysis may be used in designing dummy antennas for the simulation of actual load conditions during transmitter testing. Use is made of the expression for the antenna input reactance, $X_A = -Z_o \cot \theta$.

The way in which the input reactance varies with frequency leads to a simple lumped-parameter equivalent circuit consisting of an inductance and a capacitance in series. The input resistance is represented in series with these reactances, and the full circuit takes one of the forms shown in Fig. 10·15. In designing a network to simulate the input impedance of a particular antenna in the region of a preassigned operating frequency, series inductance and capacitance values may be chosen in such a way that their net reactance has both the proper value and the proper rate of change. The formulas are

$$L_1 = \frac{Z_o}{f} \frac{1}{720} \left(\frac{\theta_{\text{deg}}}{\sin^2 \theta} - \frac{180 \cot \theta}{\pi} \right) = \frac{Z_o}{f} K_L, \tag{16}$$

$$C_1 = \frac{1}{fZ_o} \frac{180}{\pi^2 \left(\frac{\theta_{\text{deg}}}{\sin^2 \theta} + \frac{180 \cot \theta}{\pi} \right)} = \frac{1}{fZ_o} K_C, \tag{17}$$

in which f = specified center frequency, cycles/sec,
Z_o = average characteristic impedance, ohms,
L_1 = equivalent series inductance, henrys,
C_1 = equivalent series capacitance, farads,
θ_{deg} = electrical length, degrees.

The labor of computing results from these formulas is reduced by taking the values of K_L and K_C from Figs. 10·16 and 10·17, respectively. For the simpler equivalent circuit the input resistance is regarded as being essentially constant over the range of frequencies in question and is simply represented by a fixed series resistor.

For antennas of low Q it may be desirable to make the input resistance of the dummy antenna vary with frequency in approximately the same manner as that of the real antenna. The second equivalent circuit of Fig. 10·15 is useful for this purpose; the values of the components that represent the frequency-varying input resistance are

$$L_2 = (0.82) \frac{R_A}{f} \quad \text{henrys}, \tag{18}$$

$$C_2 = \frac{(0.048)}{R_A f} \quad \text{farads}, \tag{19}$$

$$R_1 = 2R_A,$$

$$R_2 = 0.7R_A,$$

where f = specified center frequency, cycles/sec,
R_A = input resistance at this frequency, ohms.

An alternative way of expressing the relation of L_2 and C_2 is by the formulas

$$\text{Resonant frequency} = \frac{1}{2\pi\sqrt{L_2C_2}} = (0.8)f.$$

$$\text{Impedance level} = \sqrt{\frac{L_2}{C_2}} = (4.1)R_A.$$

The means by which the frequency variation is obtained are obvious. If the antenna is known to possess small loss resistance, the total input resistance can be included in R_A; but if the loss resistance is comparatively large, it should be represented separately as a fixed resistor in series with L_1 and C_1, the radiation resistance alone being simulated by the components R_1, R_2, L_2, and C_2.

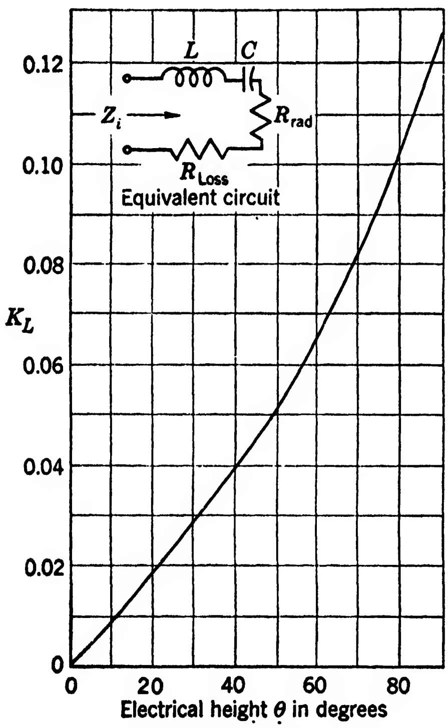


FIG. 10·16.—Factor for calculating equivalent series inductance of short antenna.

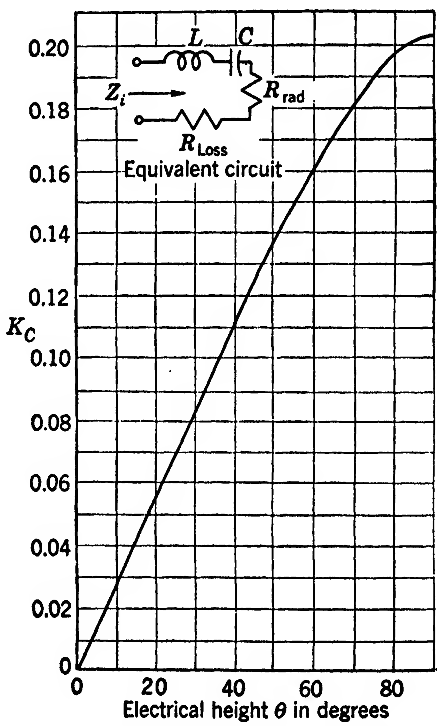


FIG. 10·17.—Factor for calculating equivalent series capacitance of short antenna.

The circuit for producing the frequency-varying resistance possesses at the operating frequency a small inductive reactance, approximately equal to R_A. The value of L_1 should thus be decreased by an appropriate small amount ΔL in order to restore the net series reactance to the proper value.

A measured or computed set of values for antenna input resistance and reactance can, with a little experimenting, be simulated with errors of less than 5 per cent over a band of frequencies extending 10 per cent each side of the operating frequency. A dummy antenna constructed for use with Loran transmitters should, of course, be capable of handling

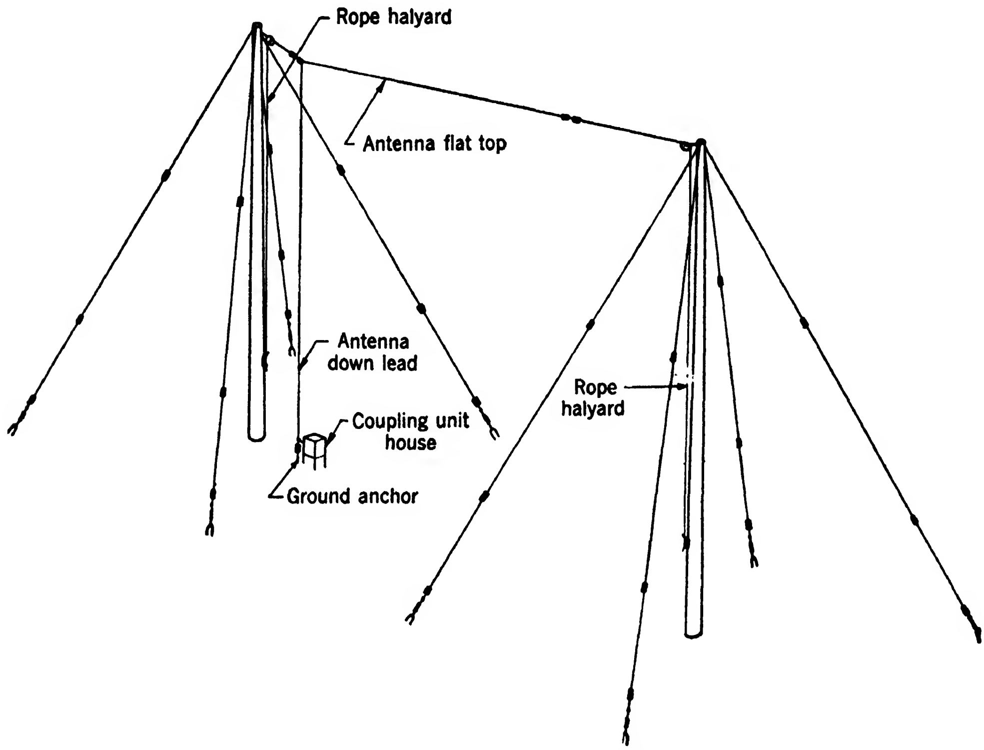


FIG. 10·18.—Standard "L" transmitting antenna.

the average power and peak voltages involved. The voltages across the components L_1 and C_1 are approximately equal to those at the top of the antenna, and comparable insulation is required.

10·4. Ground-station Antennas for 2-Mc/sec Loran. *Inverted-L Wire Transmitting Antennas.*—The earliest standard transmitting antenna used for 2-Mc/sec Loran was an inverted-L antenna suspended between two medium-sized telegraph poles. The appearance of a typical installation is shown in Fig. 10·18. The two 65-ft telegraph poles are installed with a distance between them of about 80 to 90 ft, and the four top guys on each pole are arranged in such a manner that the region between the poles is left clear. In the guy wires compression-type insulators spaced approximately 20 ft apart are used to reduce power loss and pattern distortion. Figure 10·19 shows the input impedance of such a transmitting antenna.

In antennas of this type, the radiation resistance is of the order of 15 ohms, or approximately half what it would be if the entire length of antenna wire were suspended vertically. Good efficiency and good low-angle radiation require an adequate and well-bonded ground system, keeping the ground-loss resistance to the order of 2 ohms.

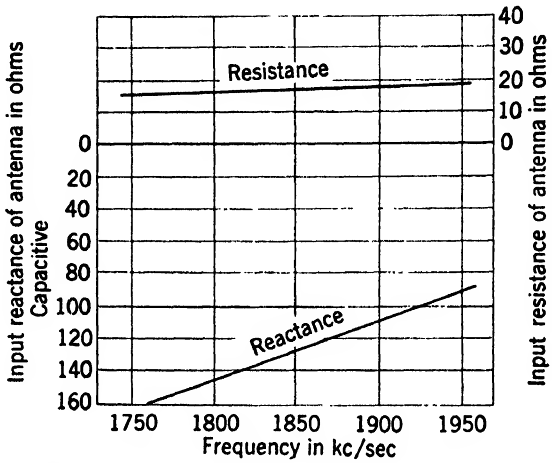


FIG. 10·19.—Input resistance and reactance of 107-ft inverted-L antenna bent at 53 ft.

A typical ground system that has been used with the inverted-L antenna consists of 120 AWG No. 10 copper wires converging toward a point beneath the antenna downlead. The radials have a minimum length of 150 ft and are usually simply laid on top of the soil rather than being plowed below its surface.

The weatherproof house containing the coupling unit is located within 2 or 3 ft of the ground-system center and the antenna downlead for short connections. An effort is made to reduce to a minimum both the resistance and the inductance of the connection from the coupling unit to the radial ground system and earth. The need for a low-inductance lead may be seen from the fact that with a pulse input of 100 kw the current in this connection has a value of more than 100 amp peak. Even with a ground-lead inductance of only half a microhenry, the potential difference between "ground" points, supposedly at the same potential, would reach 600 volts peak. The use of ground rods, 6-in.-wide copper strap, and careful bonding of the transmission-line sheath reduces such potential differences to a satisfactorily low value.

For a peak-power level of 100 kw, adequate insulation of the transmitting antenna is obtained with standard porcelain insulators having anticorona bell-shaped metal end pieces. At the upper end of the antenna a single insulator 12 in. in length and $1\frac{1}{2}$ in. in diameter is usually used. Where fog and salt air make leakage likely, two such insulators are connected in series.

Steel Mast Transmitting Antenna.—The Wincharger 110-ft steel mast has been almost universally used as the main transmitting antenna in Loran stations installed since the latter part of 1944. As shown in Fig.

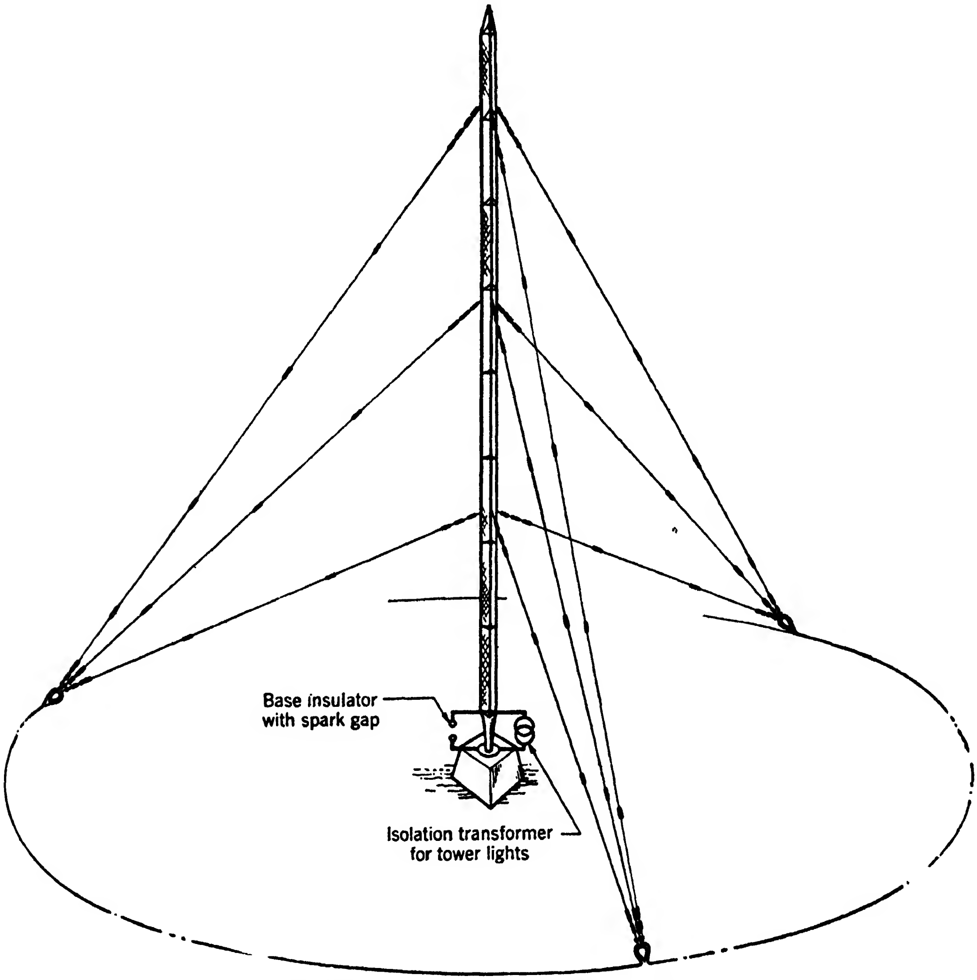


FIG. 10·20.—Elevation of Wincharger 110-ft transmitting antenna.

10·20, the antenna conductor extends 110 ft above the top of the base insulator. Ten feet of additional height is sometimes obtained with a piece of $1\frac{1}{4}$-in. pipe.

The cross section of the mast is an equilateral triangle 13 in. on a side and is uniform except for the tapering 5-ft top section. On each of the three sides three guys are used, spaced vertically at intervals of slightly more than 30 ft. These three guys are brought through turnbuckles to a common ground anchor at a distance of 75 ft from the tower base. At one ground anchor the turnbuckle assembly includes three individual spring-balance devices. By virtue of the 120° spacing of the guys around the mast, the three spring balances suffice for adjusting the tensions in all nine guy wires. All guys are insulated from the mast and from

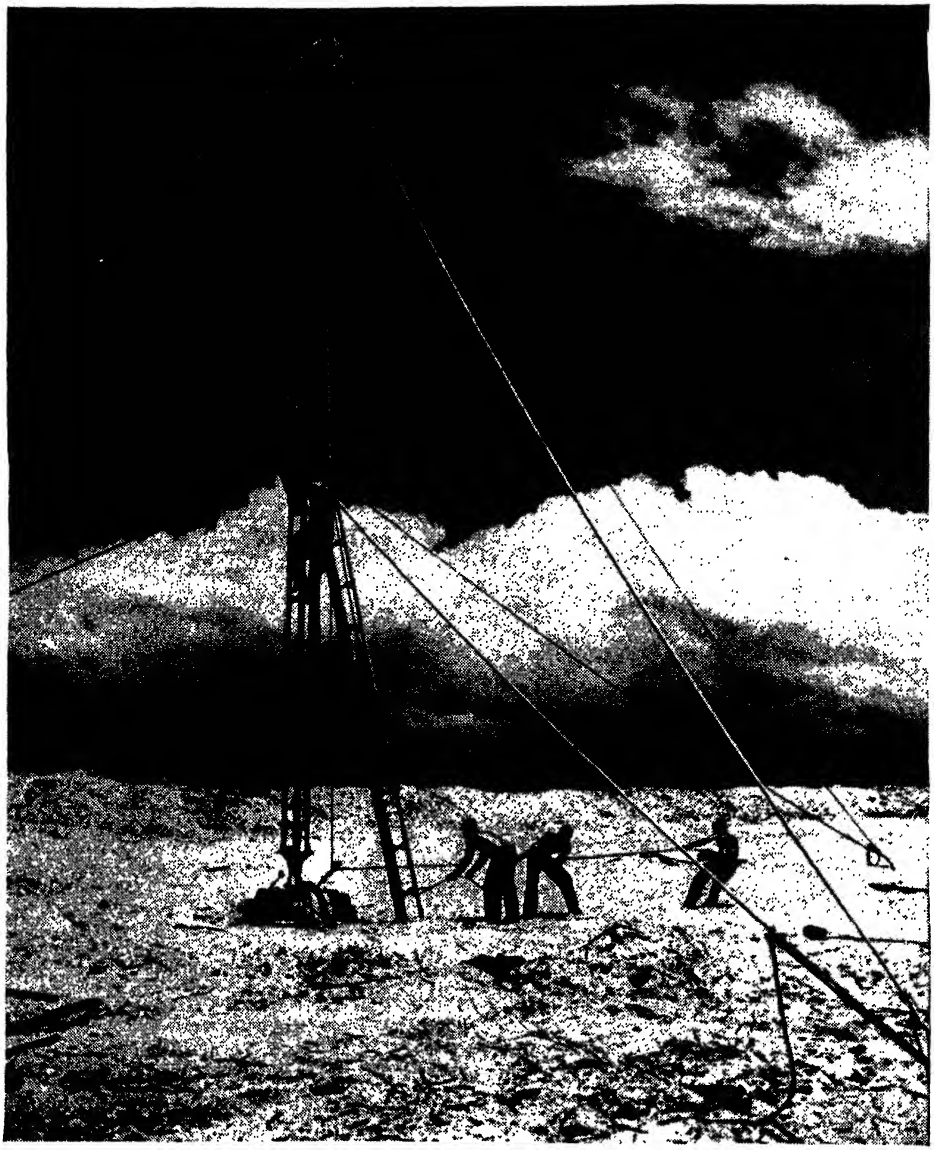


FIG. 10·21.—Crew erecting a Wincharger antenna on Lorainne Island, Majuro Atoll of the Marshall Islands group. (*Courtesy of U. S. Coast Guard.*)

ground and are in addition broken up with compression-type insulators every 25 ft to avoid resonance and power loss.

The mast is erected in 20-ft sections, each section being assembled on the ground from preformed parts. Figure 10·21 is a photograph showing the second section ready for hoisting into place. Bolts are used both for the section assemblies and for holding the sections together.

The standard radial ground system with which this antenna is used consists of 120 radials of AWG No. 10 copper wire, each 300 ft long. At their outer extremities these radials are bonded to a piece of AWG No. 8 copper wire formed in a circle of 600-ft diameter. Twenty ground rods are ordinarily used around this circle, spaced at 18° intervals. A 25-ft circle of wire near the center of the system is similarly bonded to the radials, and at the center heavy copper strap and wire cable are used for bonding and connection. Ground rods are used at the antenna base and around the 25-ft circle.

The input impedance of a Wincharger antenna in the 2-Mc/sec Loran range is shown in Fig. 10·22. These data, taken from a Navy instruc-

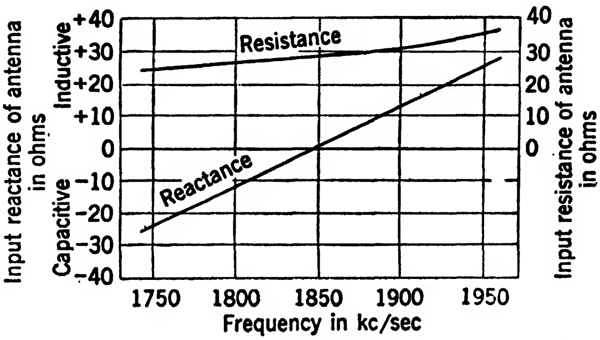


FIG. 10·22.—Input resistance and reactance of Wincharger 110-ft antenna. (*Data from U.S. Navy and General Electric Co.*)

tion book,[1] are of interest in that the input reactance is given as zero at 1842 kc/sec, corresponding to a free-space quarter wavelength of 133 ft. Since 110 ft is shorter than this value by 17 per cent, it is believed that in making the measurements either the additional 10-ft top section or a rather high-inductance connection was used.

Comparing the curves of Fig. 10·22 with those of Fig. 10·19, it can be observed that the input resistance of the Wincharger antenna at 1950 kc/sec is 31.5 ohms as compared with 19 ohms for the inverted-L antenna. In the region of this frequency, the input reactance of the former changes at the rate of 0.25 ohm per kc/sec, whereas that of the latter has a slope of 0.35 ohm per kc/sec. Although the difference in resistances is primarily a matter of vertical extension, the relatively large equivalent diameter of the Wincharger mast makes its reactance vary less rapidly with frequency. In both of these respects the Wincharger antenna is a less frequency-selective device and consequently more suitable for the radiation of pulses. Some slight additional benefit is

[1] "Instruction Book for Antenna Coupling Unit Navy Type CG-47368," *Navships* 900, 751, June 9, 1945.

derived from the fact that the coupling unit for the Wincharger antennas may be made of greater bandwidth, since smaller impedance transformation is required to match the 52-ohm transmission line.

Vertical Receiving Antennas.—The receiving antenna consists of a vertical wire, No. 10 enameled copper, about 55 ft long suspended from a telephone pole with crossarm at the top. The lower end of the wire is secured by a deadman anchor. A ground system of 60 radials of No. 10 copper wire approximately 125 ft long, placed on the ground, ensures a low resistance and, probably more important in this case, a more constant real component of antenna impedance under varying weather conditions.

The impedance of the antenna is about $10 - j550$ ohms in the vicinity of 2.0 Mc/sec, and for a bandwidth of 100 kc/sec the equivalent circuit is approximated by a series 10-ohm resistor and 150-$\mu\mu$f capacitor.

Beverage Receiving Antenna.—Because of its inherently circular pattern in the horizontal plane the vertical antenna may not provide a sufficiently high signal-to-atmospheric-noise ratio when the remote station is unusually far away. Under these conditions, it is desirable to use an antenna that provides some directivity in order to raise the signal-to-noise ratio.

The Beverage or wave antenna has been used at some Loran stations in order to raise the ratio of signal to atmospheric noise. This antenna has a marked directional characteristic and little sensitivity for horizontally polarized waves. A great reduction in precipitation static has been reported at stations that experienced much trouble from this source when using the vertical antenna for reception.

The Beverage antenna as used in typical Loran installations consists of a straight horizontal wire (No. 10 or No. 12 enameled copper) from one to two wavelengths (500 to 1000 ft) long, supported 6 to 10 ft above the earth. The wire is located so that one end of it is several hundred feet from the timer building, the far end pointing toward the station to be received.

This far end is terminated in a noninductive resistance to ground equal to the characteristic resistance of the antenna (usually of the order of 500 to 1000 ohms). The other end is terminated in a coupling unit that transfers the energy from the antenna to the 50-ohm coaxial line leading to the attenuator.

The antenna functions best over soil of poor conductivity. The voltage in the antenna is induced by a horizontal component whose direction is the same as that of the wave propagation. This horizontal component is the result of the forward tilt of the vertically polarized wave that suffers progressive attenuation as it travels over the earth's surface (Fig. 10·23). The effect of the earth's conductivity and dielectric constant on the tilt angle are shown in Table 10·1. If the antenna is terminated at each end by an impedance equal to the characteristic impedance of the line, no reflections occur, the energy from waves traveling toward the receiving end is transferred to the receiver, and energy from waves traveling toward the far end is dissipated in the terminating resistance.

TABLE 10·1.—PENETRATION DEPTHS AND TILT ANGLES* FOR VARIOUS GROUNDS AT 2.0 MC/SEC

Character	Conductivity, σ (emu)	Dielectric constant, ϵ	Penetration depth d, ft	Tilt angle, θ
Sea water	5×10^{-11}	80	2.5	0°
Salt marsh	4×10^{-12}	30	9.0	0.7°
Dry ground	2×10^{-13}	10	41.5	2.3°
Average land	5×10^{-14}	15	86.0	7.0°
Rocky ground	2×10^{-14}	4	131.0	10.2°
Very dry ground	1×10^{-15}	4	1575.0	23.0°

* Depth given is that at which the current density is one-quarter of the surface current density. Tilt angle is the angle between normal to the surface and the wavefront.

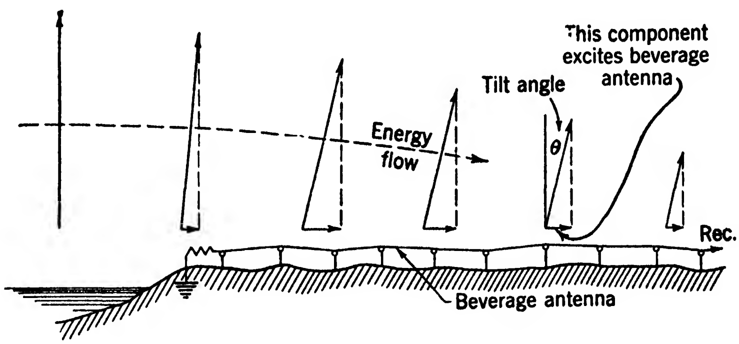


FIG. 10·23.—Beverage antenna. The poor conductivity of the soil attenuates the vertically polarized signal and produces a forward tilt of the electric vector. The resulting horizontal component induces a voltage in the Beverage antenna.

Signal-to-noise improvements of the order of 3 to 10 over the vertical antenna (and larger increases in the ratio of signal to precipitation static) have been reported.

Owing to the fact that the internal resistance of the Beverage antenna is about fifty times greater than that of the vertical antenna, the Beverage antenna delivers less energy to the receiver than does the vertical antenna.

10·5. Ground-station Antennas for 180-kc/sec Loran: Balloon-supported Transmitting Antenna.—Reconciliation of the mechanical and electrical requirements of an antenna suitable for the transmission of high-power Loran pulses is somewhat more difficult at a carrier frequency of 180 kc/sec than at the higher frequencies of Standard Loran. In the Low Frequency application the shapes of the pulses actually radiated from all ground stations must be precisely the same in order to preserve matching accuracy with the long rise times and pulse lengths. This implies that the antenna structures must behave identically or else that their pulse-shaping effect must be made negligible compared with that of other controllable variables. Thus it is desirable for the bandwidths of the antenna and coupling unit to be at least as broad, relative to the frequency, as those of the Wincharger antenna and coupling unit in the 2-Mc/sec Loran band.

A scale model of the Wincharger antenna would be a base-insulated tower approximately 1120 ft high, having a uniform cross section of approximately 10-ft equivalent diameter. Even with considerable sacrifice in electrical requirements the engineering and construction of a

FIG. 10·24.—Barrage balloon used to support the experimental Low Frequency transmitting antenna.

permanent antenna structure would, it is clear, require considerable time and effort. Since the LF Loran program aimed at a speedy test and demonstration of the effectiveness of Loran techniques at 180 kc/sec, a cruder antenna was acceptable. The transmitting antenna used in the tests was a long thin wire supported by a lighter-than-air balloon.

The Copperweld antenna wire is 1300 ft in length and $\frac{1}{10}$ in. in diameter. Its d-c conductivity is 30 per cent of that for a pure copper wire of the same diameter, because of the steel core. At 180 kc/sec, however, the effective conductivity is only a few per cent less than for pure copper, since the skin depth for copper at this frequency is only approximately 0.006 in. The weight of the antenna wire is approximately 38 lb; the insulators and other hardware weigh about 10 lb.

A small barrage balloon is used to lift the antenna. The type used in the tests has a fully dilated volume of 3000 cu ft; its length is approximately 36 ft, and it is 14 ft in diameter. The balloon has three wooden-braced, cloth-covered stabilizing fins which give kiting action in the presence of wind. When used with helium the lifting force is 58 lb, or 15 lb less than would be obtained with hydrogen. A photograph of the balloon is shown in Fig. 10·24.

Although soil is a much better conductor for 180 kc/sec than for the higher frequencies of Standard Loran, an adequate ground connection is still necessary. A ground system with 120 AWG No. 10 copper radials

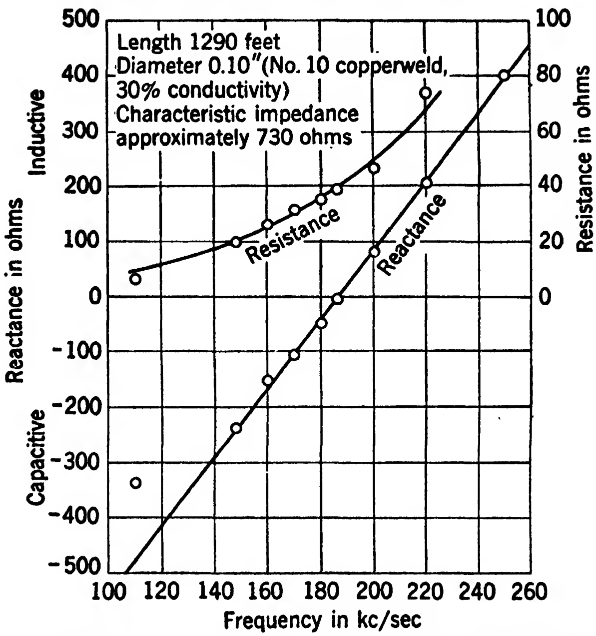


FIG. 10·25.—Input resistance and reactance of balloon-supported Low Frequency transmitting antenna.

each 400 ft long has been used successfully, but ground rods at the center and around the circumference are relatively more important than at 2 Mc/sec. In later installations 1000-ft radials of No. 10 Copperweld wire have been used; although no measurements are available, an improvement in efficiency is to be expected.

The input impedance of a typical balloon-supported antenna is shown in Fig. 10·25. The resistance of the antenna wire is about 4.5 ohms per thousand feet, indicating that 2 or 3 ohms of the input resistance are attributable to this factor. The ground loss also contributes a resistance component of the same order of magnitude, leading to an estimated radiation efficiency of approximately 80 to 85 per cent at 180 kc/sec.

The input reactance of this antenna changes rapidly with frequency, and the input impedance has a phase angle of 45° at about 7 kc/sec either side of the operating frequency. Thus the apparent Q of the antenna, considered as a series combination of inductance, capacitance, and resistance, is approximately 13, about twice that for the Wincharger antenna. The reason for the high reactive slope is that the antenna is extremely thin compared with its length. This gives an unusually high characteristic impedance, of the order of 720 to 740 ohms.

The balloon-supported antenna has several disadvantages, some of which significantly affect its usefulness for Loran purposes. Most of these stem from the varying position of the balloon with changing winds and temperatures. It is not abnormal for the balloon to drift laterally as much as 450 ft from its ideal location directly over the base of the antenna; in this condition the antenna wire makes an angle of about 45° with the ground.

In maintaining synchronism it is desirable that several quantities remain constant, notably the radiated power, the cycle-and-envelope structure of the radiated pulse, the amplitude and phase of the received local signal, and the amplitude and phase of the received remote signal. Changes in the attitude of the balloon-supported transmitting antenna cause variations in each of these quantities.

As a vertical antenna is inclined, its radiation resistance decreases, changing both the radiation efficiency and the power delivered by the transmitter. With some sacrifice in output power these changes can be made to cancel; partial compensation is achieved if the coupling unit is initially adjusted to match an inclined antenna. Another objectionable result of variable antenna resistance is that the Q and bandwidth of the antenna are affected, with some effect on the shape of the radiated pulse. Compensation for this effect requires vigilance on the part of the transmitter operator.

In addition to influencing the radiated signals, changes in the attitude of the transmitting antenna can affect both the remote and local signals, as obtained from the receiving antenna. This antenna, located about 1000 ft from the transmitting antenna, is in a region where the induction field contributes as much to the local-signal pickup as does the radiation field. If the effective distance to the transmitting antenna decreases by 100 ft (a conservative estimate), then the amplitude of the local signal will increase by about 15 per cent, giving a total range of variation of 30 per cent. Under some circumstances this causes operational error. Even without this amplitude change a timing error is introduced that, although small, is greatest for the otherwise optimum orientation of transmitting and receiving antennas. Finally there is the possibility that the rather closely coupled transmitting antenna may, by acting as a tuned parasitic element, affect the directive pattern of the receiving antenna. Movement of the transmitting antenna can thus affect remote-signal reception.

Tower Transmitting Antenna.—In designing the permanent transmitting antenna for an LF Loran station the problem of reconciling electrical requirements with mechanical limitations of strength, weight, and size becomes acute. It is vital for the antenna input impedance to have sufficient bandwidth so that the fast-rising pulses can be radiated with negligible shaping. During each cycle the antenna must thus radiate a fairly large percentage of the reactively stored energy present, in its fields and in the coupling unit, at the beginning of the cycle. In other words, the antenna and coupling unit must have a suitably low value of Q.

As previously mentioned, satisfactory electrical characteristics could be obtained with a base-insulated tower of approximately 10-ft diameter

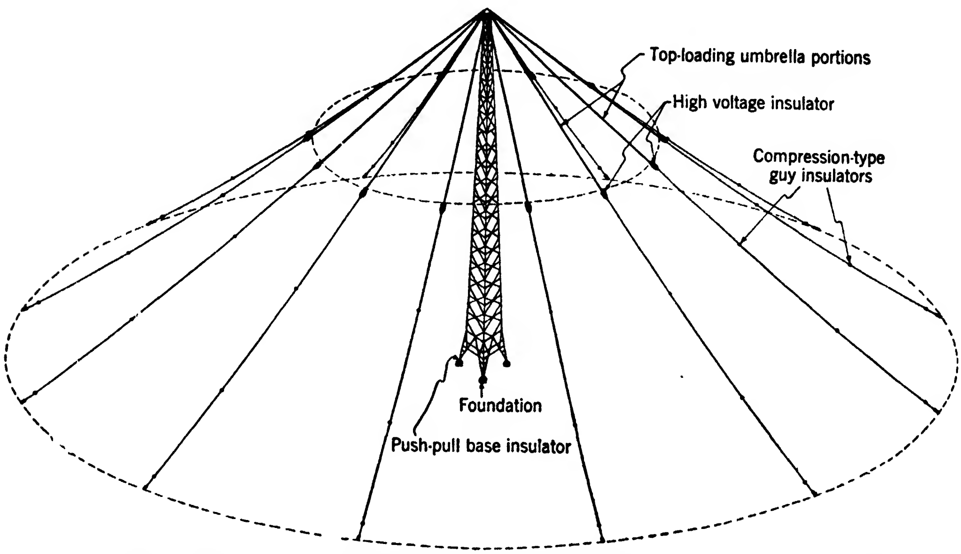


FIG. 10·26.—625-ft top-loaded tower antenna designed for Low Frequency Loran.

and 1120-ft height. Such a tower not only would be difficult and expensive to erect but would also require elaborate guying and an extremely strong insulator at its base. Extensive tests made with model structures have led to the design of a more practicable antenna whose main component is a self-supporting tapered steel tower 625 ft high. The cross section of the tower is a square whose side tapers from 59 ft at the base to 5 ft at the top. The four legs are supported on push-pull porcelain insulators with a 10-in. leakage path and an over-all height of nearly 5 ft. Since the insulators can withstand both tension and compression, the tower requires no guying.

The distinctive feature of the antenna is its top-loading by 12 conductors arranged like the ribs of an umbrella. As shown in Fig. 10·26 these elements are held away from the tower by insulated guy wires which are anchored 850 ft from the tower base; because of sag the angle between the tower and the umbrella elements is approximately 45°. The small tensions required in the umbrella-supporting guy wires and the symmetrical nature of their mechanical load make the umbrella lighter, simpler, and safer than a comparable inverted-L or T-antenna. If certain proportions are assumed for the central tower, much can be learned by studying the effects of varying the number, length, and angle of inclination of the umbrella elements. Such a study yields values for the optimum sizes of the tower and umbrella structure and also gives estimates of the bandwidth, insulation requirements, and efficiency.

Comprehensive measurements have been made with a 50-ft model tower constructed of copper wire and suspended over an extensive radial ground system. Input impedance has been measured over a large range of frequencies in the vicinity of the first resonance, and field-strength measurements have been made for the evaluation of efficiency. A portion of the impedance data is presented in Figs. 10·27 to 10·29. In these figures the frequencies have been divided by 12.5 in order to convert the data for application to a 625-ft tower. The values of reactance and resistance are unchanged.

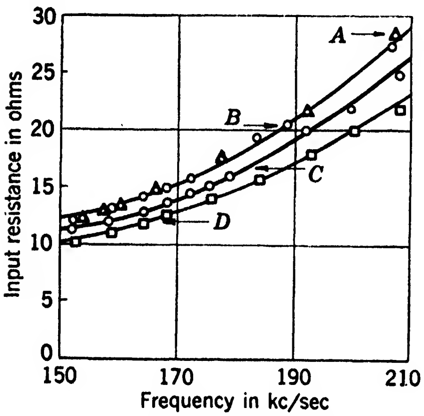


FIG. 10·27.—Input resistance of 625-ft tower antenna for various top-loading conditions. (*A*) Twelve elements, length 469 ft, anchored at 835 ft; (*B*) twelve elements, length 512 ft, anchored at 1250 ft; (*C*) twelve elements, length 312 ft, anchored at 835 ft; (*D*) eight elements, length 312 ft, anchored at 835 ft. (All data from measurements on 50-ft scale model.)

Figure 10·27 shows how the input resistance is affected by changing the number of umbrella elements from 12 to 8, by changing their length from 312 ft to 469 ft, and by moving their anchor points from 835 to 1250 ft from the tower base. The significant fact to be noted is that the input resistance at 180 kc/sec remains within 10 per cent of 16 ohms for all the top-loading conditions shown.

As shown by Figs. 10·28 and 10·29, however, the input reactance at 180 kc/sec can be varied over a large range with different top-loading conditions. Figure 10·28 shows results for eight umbrella elements; as the length is increased from 312 to 469 ft, the input reactance increases positively from −23 ohms (capacitive) to +44 ohms (inductive). An example of the effect of holding the umbrella elements out at a slightly greater angle, obtained by moving the anchor points from 835 to 1250 ft, is also shown in Fig. 10·28.

Figure 10·29 shows similar effects when 12 umbrella elements are used. By comparison with the 8-element curves of Fig. 10·28 it will be noted that in all cases 12 elements give the more inductive reactances. Average values of the various effects are given below in Table 10·2.

It is worthy of note that all the reactance curves in Figs. 10·28 and 10·29 display very nearly the same slope at 180 kc/sec, the values ranging

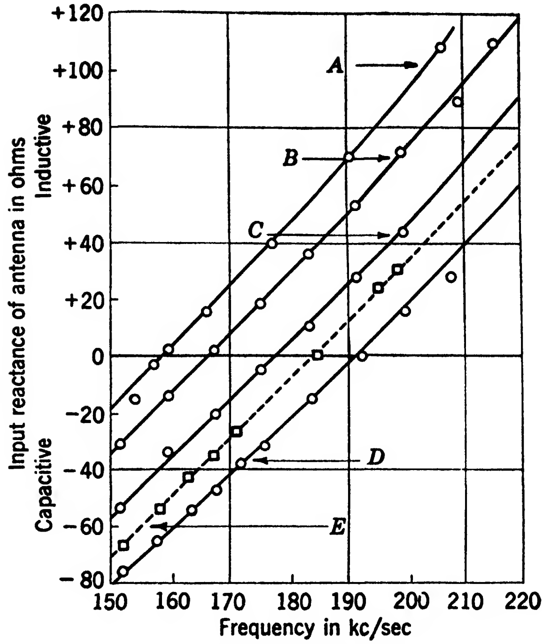


FIG. 10·28.—Input reactance of 625-ft top-loaded tower antenna with eight umbrella elements. (*A*) Length 469 ft, anchored at 835 ft; (*B*) length 416 ft, anchored at 835 ft; (*C*) length 365 ft, anchored at 835 ft; (*D*) length 312 ft, anchored at 835 ft; (*E*) length 312 ft, anchored at 1250 ft. (All data from measurements on 50-ft scale model.)

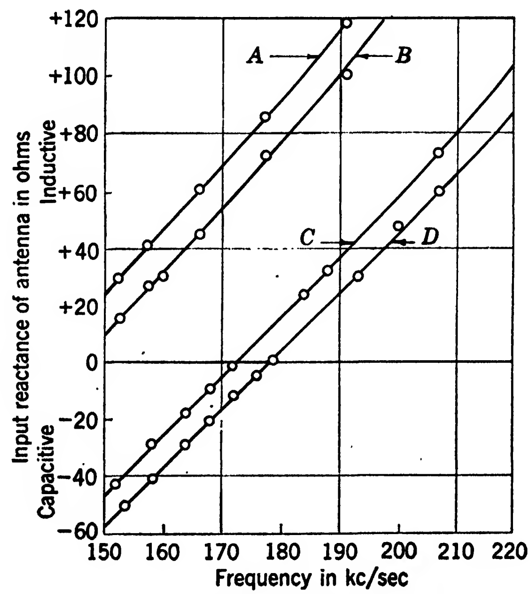


FIG. 10·29.—Input reactance of 625-ft top-loaded tower antenna with twelve umbrella elements. (*A*) Length 469 ft, anchored at 1250 ft; (*B*) length 469 ft, anchored at 835 ft; (*C*) length 312 ft, anchored at 1250 ft; (*D*) length 312 ft, anchored at 835 ft. (All data from measurements on 50-ft scale model.)

from 2.0 ohms per kc/sec for the more capacitive arrangements to 2.2 ohms per kc/sec for those with the higher inductive reactances. For comparison, the tower without top loading has at 180 kc/sec an estimated capacitive reactance of −180 ohms and an estimated reactance slope of 1.6 ohms per kc/sec. These values are used in estimating the antenna Q, as given in a later table.

TABLE 10·2.—AVERAGE CHANGES IN 180-KC/SEC REACTANCE FOR VARIOUS UMBRELLA CHANGES

By increasing	Reactance is increased inductively, ohms	Resonant frequency is lowered, kc/sec
Number of elements from 8 to 12....	27	13
Length from 312 to 469 ft...........	72 (46 ohms/100 ft)	33
Anchor distance from 835 to 1250 ft..	13.5	6.5

Specifications of the physical structure must start with the dimensions of the tower. As previously mentioned the preceding data have been presented in terms of a 625-ft tower; Fig. 10·30 gives the data upon which this choice of height was based. Although, as shown in Fig. 10·27, the input resistance of a given tower of fixed dimensions does not vary greatly as the top loading is changed, it is not true that the input resistance is independent of tower height. In plotting Fig. 10·30 the data have been treated somewhat differently, the model height of 50 ft being multiplied by the ratio of the observed resonant frequency to 180 kc/sec. Thus Fig. 10·30 represents the input resistance of towers of various heights, the top loading in each case being adjusted to produce resonance (zero input reactance) at 180 kc/sec. The required length of umbrella elements is given for each measured point; it is estimated that a tower approximately 1250 ft high would be self-resonant at 180 kc/sec and hence would require zero length of umbrella elements.

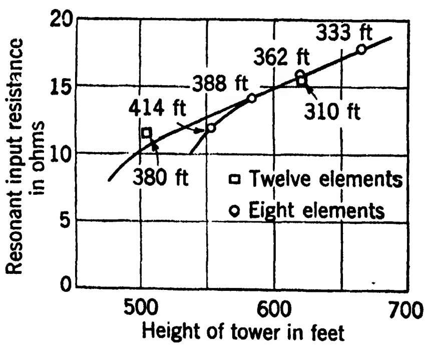


FIG. 10·30.—Effect of tower height on resonant input resistance. Numbers are lengths of elements at 180 kc/sec. Elements are anchored at distances of (1.33) × (tower height).

Figure 10·30 shows that the resonant value of input resistance increases rapidly with increasing tower height, being relatively unaffected by the exact top-loading arrangement except for the smaller tower heights. With the shorter towers a considerable length of umbrella elements is required to resonate the antenna; when this length exceeds approximately seven-tenths of the tower height, the umbrella produces a shielding effect that reduces the external field and severely decreases the radiation resistance. In order to make an effective radiator with a tower height of, say, 500 ft, it would be necessary to use the maximum feasible number of umbrella elements and hold them away from the tower at the greatest practicable angle, both factors tending to reduce the required length and consequent shielding effect of the umbrella. Even so, the input resistance

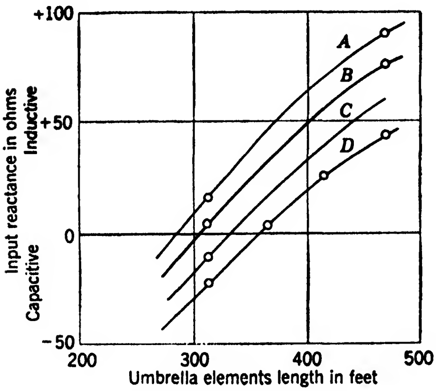


FIG. 10·31.—Input reactance at 180 kc/sec of 625-ft top-loaded antenna vs. length of loading elements. (*A*) Twelve elements anchored at 1250 ft; (*B*) twelve elements anchored at 835 ft; (*C*) eight elements anchored at 1250 ft; (*D*) eight elements anchored at 835 ft. (All data from measurements on 50-ft scale model.)

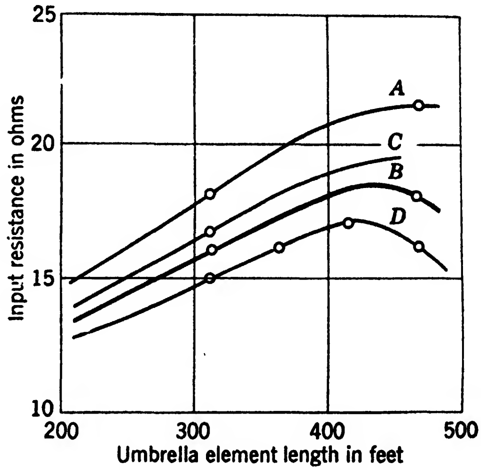


FIG. 10·32.—Input resistance at 180 kc/sec of 625-ft top-loaded antenna vs. length of loading elements. (*A*) Twelve elements anchored at 1250 ft; (*B*) twelve elements anchored at 835 ft; (*C*) eight elements anchored at 1250 ft; (*D*) eight elements anchored at 835 ft. (All data from measurement on 50-ft scale model.)

and radiation efficiency would be lower than desirable, and the use of many umbrella elements in high mechanical tension would be disadvantageous.

Twelve is a desirable number of elements electrically, and is not too elaborate mechanically; an angle of 45° for the umbrella elements is about the maximum that can be obtained with reasonably light guy tension. These values have accordingly been chosen for the final design. A height of 625 ft requires approximately 310 ft of umbrella length, which gives little shielding and a good measured efficiency. This height has therefore been chosen as being both mechanically practicable and electrically suitable.

Figures 10·31 and 10·32 show, in somewhat condensed form, the 180-kc/sec reactance and resistance for various top-loading conditions including that of the final design. In Fig. 10·31 the four reactance curves converge, as the umbrella-element length is decreased, to a value estimated as -180 ohms. It should be mentioned that all reactance data were measured with umbrella elements simulating six-wire cages 6 in. in diameter. Other measurements indicate that a reduction of umbrella-element diameter to 0.2 in. would make the reactances on the average 15 ohms more capacitive and the resonant frequencies 6 kc/sec higher.

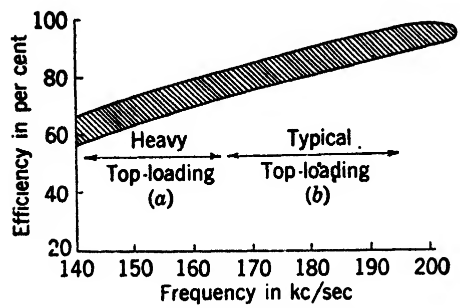


Fig. 10·33.—Estimated efficiency of 625-ft tower antenna with twelve umbrella elements. Top-loading varied to control resonant frequency. (a) Length 450 ft, anchored at 850 ft; (b) length 325 ft, anchored at 850 ft. (All data from measurements on 50-ft scale model.)

The effect of shielding by the umbrella is clearly shown in the lower curve of Fig. 10·32 wherein the input resistance reaches a definite maximum for an umbrella length of the order of 420 ft. Finally, Fig. 10·33 gives a rough estimate of the efficiency to be expected from a properly top-loaded 625-ft tower antenna. At 180 kc/sec the expected efficiency is of the order of 80 per cent or better.

Table 10·3 summarizes the characteristics of various LF transmitting antennas.

Table 10·3.—Comparison of 180-kc/Sec Transmitting Antennas

	"Wincharger"†	"Balloon"‡	"Tower"§	"Umbrella"‖
Vertical length, ft	1120 (est.)	1340	625	625
Equivalent diameter	9.6 ft (est.)	0.1 in.	40 ft (est.)	...
180-kc reactance, ohms	0	0	-180 (est.)	0
React. slope, ohms per kc/sec	2.5	6.5	1.6 (est.)	2.0
180-kc/sec resistance, ohms	29	39	10 (est.)	16
Q* with loading coil	8	15	23 (est.)	11

* In calculating Q the effects of generator resistance and of coupling-unit reactances other than that of the loading coil have been neglected. The effective bandwidth is in general greater than indicated by this value of Q.

† Scale model of Wincharger antenna, enlarged by a factor of approximately 10.2 for resonance at 180 kc/sec.

‡ Balloon-supported wire antenna, lengthened 4 per cent for resonance at 180 kc/sec.

§ Tower antenna with square cross section tapering from 59- to 5-ft side. Resonant at approximately 360 kc/sec.

‖ Same tower top-loaded with 12 umbrella elements approximately 310 ft long, anchored 835 ft from base. Resonant at 180 kc/sec.

It will be noted that because of its extreme thinness, the balloon-supported wire has a reactance slope of 6.5 ohms per kc/sec. At the other extreme, the 625-ft tower without top-loading has a reactance slope estimated as 1.6 ohms per kc/sec. The capacitive input reactance, however, is estimated to be −180 ohms or even somewhat more negative; the necessary loading coil will hence contribute an additional slope of at least 1.0 ohm per kc/sec. The net Q of the tower without top loading is therefore approximately 23. By the use of top loading the Q of the tower antenna is made to approach that of the desirable but impracticable Wincharger scale model. With a balloon-supported antenna, pulses rising in 10 or 12 cycles can be radiated satisfactorily; the umbrella-topped tower antenna should be capable of radiating pulses rising in 8 cycles.

Experimental LF Loran stations have used pulse powers of the order of 100 kw, but in order to allow eventual increases in transmitter power the tower antenna has been designed to handle pulses of 1 megawatt. With this power the input current will have a value of approximately 250 amp rms, and the question of adequate insulation arises. Since the antenna is operated in the vicinity of resonance, the voltage across the base insulators will not be excessive, having a value of about 5.7-kv peak if the antenna is resonant and 8-kv peak if the antenna's input reactance is allowed to equal its input resistance.

The insulation of the guy wires has received much attention. At the ends of the umbrella elements, in particular, the voltage to ground is expected to be of the order of 50-kv peak. The qualitative arguments leading to this conclusion are based on the concept, recently set forth by Schelkunoff,[1] that it is valid to consider a straight vertical antenna of reasonably uniform longitudinal cross section as a dissipationless transmission line, with radiation represented as a terminal impedance.

Consider that the 625-ft tower represents a portion of a transmission line with characteristic impedance of the order of 200 ohms. We know that 625 ft is about one-eighth wavelength, and we know furthermore that the addition of top-loading reduces the input reactance to zero. The umbrella can be considered as shunting the top of the tower to ground with a lumped capacitive reactance, which must be of the order of 200 ohms. The 1-megawatt input current is estimated as 250 amp rms; this will be reduced to 175 amp rms at the top of the tower. By the flow of this current through a capacitive reactance of 200 ohms a potential to ground of 35 kv rms (50-kv peak) will be produced. Since the umbrella elements are each but 6 per cent of a wavelength long, little resonant increase of this voltage is to be expected, and the potential to ground of the umbrella elements will be substantially that of the top of the tower.

As a check of this argument it is worth while calculating approximately the capacitance of the umbrella. A single element has a capacitance to ground of approximately 750 $\mu\mu$f, and it appears reasonable for a com-

[1] S. A. Schelkunoff, "Theory of Antennas of Arbitrary Size and Shape," *Proc. IRE*, **29**, No. 9, 493–521, September 1941.

bination of 12 such elements to have the 4400 $\mu\mu$f required for a reactance of 200 ohms.

Another cruder estimate is based on the fact that for a quarter-wave resonant vertical antenna the voltage at the top is greater than that at the base by a factor which is approximately the ratio of characteristic impedance to input resistance. We should expect this relation to hold within perhaps a factor of 2 when we apply the criterion to our very different antenna structure. The characteristic impedance is of the order of 200 ohms, and the input resistance is 16 ohms; this indicates that the base voltage of 4 kv rms will be stepped up to 50 kv rms, which is of the same order of magnitude as the preceding estimate.

Only a small fraction of this total voltage to ground appears across the insulator separating an umbrella element from its supporting guy wire. As pointed out by Brown,[1] estimates of the voltage ratings required for guy insulators are frequently too conservative. In his paper are published results of insulator-voltage measurements on a thin steel mast guyed at three levels. The topmost guys were attached about two-thirds of the way up the mast, a total of four equally spaced insulators being used in each guy. His measurements and calculations show that at a frequency making the mast 0.1425 wavelength long, a power input of 500 kw would produce across the insulators voltages of 3.38, 1.83, 1.21, and 1.14 kv rms respectively, the highest voltage occurring at the top.

This evidence, together with the preceding qualitative arguments, indicates that moderate-sized insulators will be adequate. The principal concern is the prevention of corona by carefully maintaining suitably large radii of curvature for the metallic surfaces of the umbrella elements and tower top.

The physical size of the antenna may be judged from the fact that the weight of the tower itself is approximately 170 tons. The radial ground system planned for permanent installation is 2000 ft in diameter and involves 46 miles of No. 8 Copperweld wire.

Receiving Antenna.—The receiving antenna is a 59-ft Lingo pole that is constructed of sectionalized steel tubing tapering from a diameter of 3½ in. in the center to 2½ in. at each end (Fig. 10·34). It is mounted vertically on a compression-type insulator at the base and is guyed at four levels. Each level is guyed every 90°, and the four ground anchors are spaced symmetrically around the pole, each being 33 ft 6 in. from the center of the base insulator. A boom section, built into the assembly, enables two men to erect the pole in a short time.

Because of its large diameter, the reactance of the Lingo pole at 2.0

[1] G. H. Brown, "A Consideration of the Radio-frequency Voltages Encountered by the Insulating Material of Broadcast Tower Antennas," *Proc. IRE*, **27**, No. 9, 566–578, September 1929.

Mc/sec is lower than that of the 55-ft vertical wire antenna. The impedance of the antenna is about $10 - j350$ ohms at that frequency. At 180 kc/sec the impedance as measured with a rather poor ground system is $45 - j3700$ ohms.

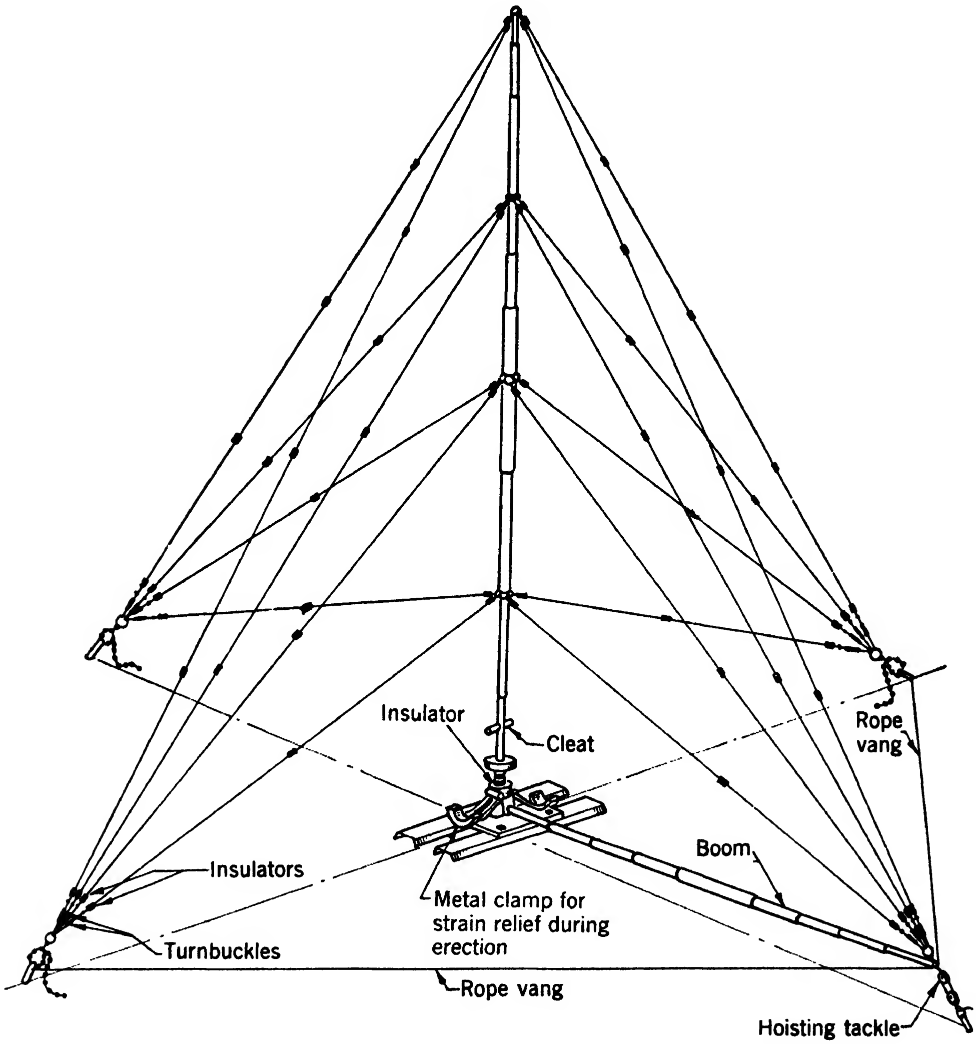


FIG. 10·34.—Perspective view of Lingo 59-ft mast.

The ground system consists of 60 radials 100 ft in length. There is little point in striving to attain an extremely low resistance, as the Q of the antenna must be held below 10 to prevent undue shaping of the pulses. The reason for specifying an extensive ground system is to ensure a resistance independent of the soil conditions.

The coupling unit (Fig. 10·35) is designed to meet the low-Q requirements and to transfer sufficient voltage to the input of the attenuator. The 3.5-mh inductance resonates with the antenna capacitance, and the

560-ohm resistance determines the Q of the circuit. The center parallel-resonant circuit is tuned to 180 kc/sec and presents a high resistance to ground at and near this frequency. The capacitance of the 50-ohm transmission line is part of the total 0.02 μf. The 1.5-mh inductance and the 600-μf capacitance are series-resonant, and the grid voltage at the first attenuator tube is that produced across the 600-μf capacitor. The 10,000-ohm resistor damps this circuit.

The over-all gain should be such that every microvolt per meter of field strength produces about 10 μv at the input of the attenuator.

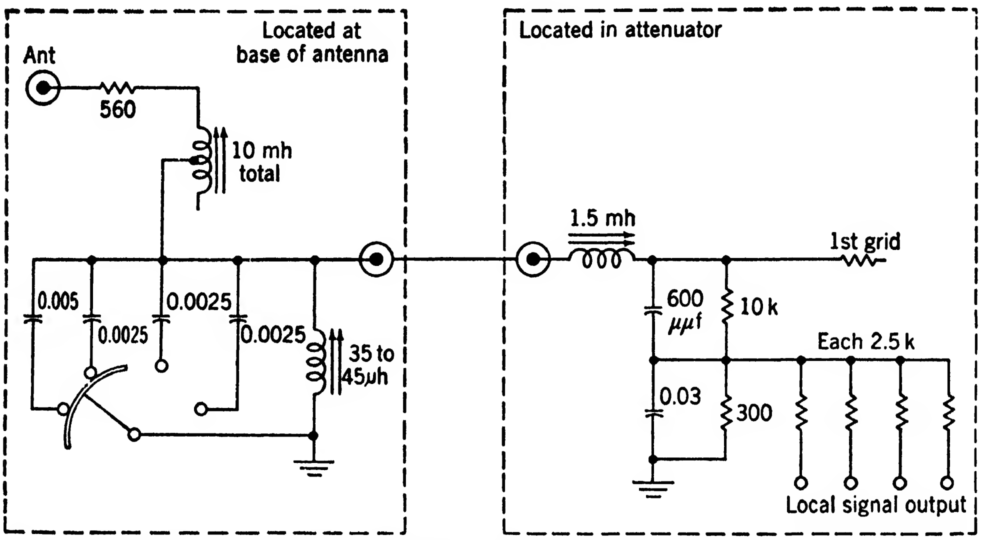


FIG. 10·35.—Network for coupling Low Frequency receiving antenna to input of attenuator.

Because of atmospheric noise a field strength of at least 200 μv/meter is required for reliable synchronization. This would produce 2000 μv at the attenuator input, which is ample in comparison with internal attenuator and receiver noise and simplifies the problem of attenuating the local signal. During summer months, particularly in the lower latitudes, field strengths of 500 to 1000 μv/meter are desirable.

10·6. Receiver-indicator Antennas. *Shipboard Antennas.*—The shipboard receiving antenna usually consists of a fairly long (50 to 125 ft) vertical wire, strung between two strain insulators, one connected to the end of a yardarm and the other to a brace on the side of the cabin or compartment housing the receiver-indicator.

The coupling unit, which is merely a loading coil with appropriate connectors, is located near the lead-through insulator either inside or outside the cabin. A lead-in wire connects the lower end of the antenna to the input of the loading coil, and a shielded cable connects the output of the loading coil to the receiver. The input impedance of the receiver matches the characteristic impedance of the cable. The purpose of the cable is to shield the receiver from noise generated in the cabin housing the receiver-indicator.

The loading coil is adjusted approximately to balance the capacitive reactance of the antenna. Since the antenna is long enough to give strong signals, the reception (signal-to-noise ratio) is limited by atmospheric noise rather than by internal noise in the receiver. Therefore the tuning of the coupling unit is not critical.

Airborne Trailing Antenna.—All airborne Loran equipment now in service has been designed with the expectation that it is to be used with a trailing antenna. Because of the noise generated inside the aircraft, the lead from the antenna reel must be shielded, and the receiver input impedance is designed to match the impedance of the shielded cable. The wire cable with a weight of several pounds on the end is reeled out to a length of 120 ft or so (approximately a quarter wavelength), although satisfactory results are obtained with considerably shorter lengths. Because of the length of the antenna, the received signals are so strong that no coupling unit is required. The reel for the British trailing antenna is manually operated and is usually mounted in the belly of the plane; the American reel is electrically operated and is usually mounted near the tail of the plane.

There are several serious objections to the use of a trailing antenna. There is danger, especially in fast planes, that the weight or the complete antenna may be broken off by the strong wind. Both the British and American types of reel occasionally jam (this is especially serious in icing conditions), and the reeling of the antenna in and out are two more inconvenient operations for the navigator. The trailing antenna is an intolerable hazard in flying in tight formation and during evasive action.

Fixed Airborne Antenna.—Toward the end of the war an intensive effort was made to substitute a fixed antenna for the trailing antenna. In a fighter or light bomber it is usually possible to install a 30-ft fixed antenna; in a heavy bomber it may be possible to install a 60-ft antenna, although usually a length of only 30 ft or so is available for Loran. It is estimated that the capacitance of the antenna lies between 50 and 300 $\mu\mu$f. Without the use of a coupling unit, the signal induced on such a short antenna is too small for satisfactory reception; the signal-to-noise ratio is limited by the internal noise of the receiver.

Coupling units of several types have been tested. It has been found that the results obtained with a loading coil are as good as those obtained with coupling units that match the impedance of the antenna to the impedance of the cable. The gain of the coupling unit (the ratio of the signal with the coupling unit to the signal with direct connection to the cable and receiver) is practically independent of the type of coupling unit provided the antenna is tuned. The gain is between 6 and 10, depending on the untuned impedance of the antenna. It has also been found that the effective capacitance of the antenna decreases when the plane is airborne. Therefore the coupling unit and the first r-f transformer should be adjusted in the air.

The physical location of the coupling unit between the antenna and the cable or between the cable and the receiver is of no consequence electrically. However, since it must be tuned in the air, a convenient location is near the receiver. The tuning of the coupling unit (since the Q is necessarily rather high) must be readjusted for each change of the r-f channel (a different loading coil is required for the Low Frequency channel). Therefore, in the design of future equipment, individual loading coils should be incorporated in the receiver so that they are selected by the r-f channel selector switch.

Precipitation Static.—Loran reception like that of all airborne radio systems, is seriously affected by precipitation static. No completely satisfactory equipment for eliminating such static was available at the end of the war. However the findings of the scientists of the Army-Navy Precipitation Static Project are reasonably promising.[1]

[1] "Precipitation Static," *Air Forces Manual No.* 40, December 1944; R. Gunn, W. C. Hall, and G. D. Kinzer, "Precipitation-static Interference Problem and Methods for Its Investigation," *Proc. IRE*, **34,** 156–160, April 1946; R. C. Waddel, R. C. Drutowski, and W. N. Blatt, "Aircraft Instrumentation for Precipitation-static Research," *Proc. IRE*, **34,** 161–166, April 1946; R. G. Stimmel, E. H. Rogers, F. E. Waterfall, and R. Gunn, "Electrification of Aircraft Flying in Precipitation Areas," *Proc. IRE*, **34,** 167–177, April 1946; G. D. Kinzer and J. W. McGee, "Investigations of Methods of Reducing Precipitation-static Radio Interference," *Proc. IRE*, **34,** 234–240, May 1946; R. Gunn and J. P. Parker, "The High-voltage Characteristics of Aircraft in Flight," *Proc. IRE*, **34,** 241–246, May 1946; M. Newman and A. O. Kemppainen, "High-voltage Installation of the Precipitation-static Project," *Proc. IRE*, **34,** 247–253, May 1946.

CHAPTER 11

RECEIVER-INDICATORS

By R. H. Woodward

SHIPBOARD RECEIVER-INDICATORS

11·1. Requirements and General Description.—The receiver-indicator is the instrument with which the Loran navigator measures the difference in the times of arrival of pulsed signals. The navigator takes measurements of signals from two pairs of ground stations. Each measurement determines a line of position, and the intersect on of two such lines establishes a fix, the navigator's position.

Time-difference Measurement.—As explained in Sec. 3·3, the method of measurement of the time difference is similar to that used at the ground stations (see Chap. 7). The signals of a particular recurrence rate from two ground stations are displayed on an oscilloscope pattern of the same recurrence rate. The pattern consists of two horizontal traces, one above the other and each having a duration of half the recurrence period. Since the recurrence rates of the signals and of the oscilloscope patterns are the same, the signals remain stationary on the pattern (whereas signals of other recurrence rates drift to the right or to the left). If one pulse appears on the upper trace and the other on the lower trace, the pulse that appears to the left of the other is by definition the A-pulse and the one to the right is the B-pulse. The A- and B-pedestals are small rectangular deflections of the traces that indicate those portions of the total recurrence period to be examined later in detail. The A-pedestal is fixed in position near the beginning of the upper trace, whereas the B-pedestal can be continuously adjusted to any position on the lower trace to the right of the A-pedestal. By momentarily increasing or decreasing the recurrence rate of the oscilloscope pattern, the pulses can be moved to the left or to the right on the traces and from one trace to the other. In this way the navigator causes the A-pulse to move onto the upper trace if originally on the lower one and then onto the A-pedestal (see Fig. 11·1a); the B-pulse then appears on the lower trace to the right of the A-pulse. The initiation (which determines the position) of the B-pedestal with respect to the slow-oscilloscope pattern is adjustable, and the navigator so adjusts the initiation that the B-pedestal appears under the B-pulse.

The time difference is taken as the horizontal distance from a point

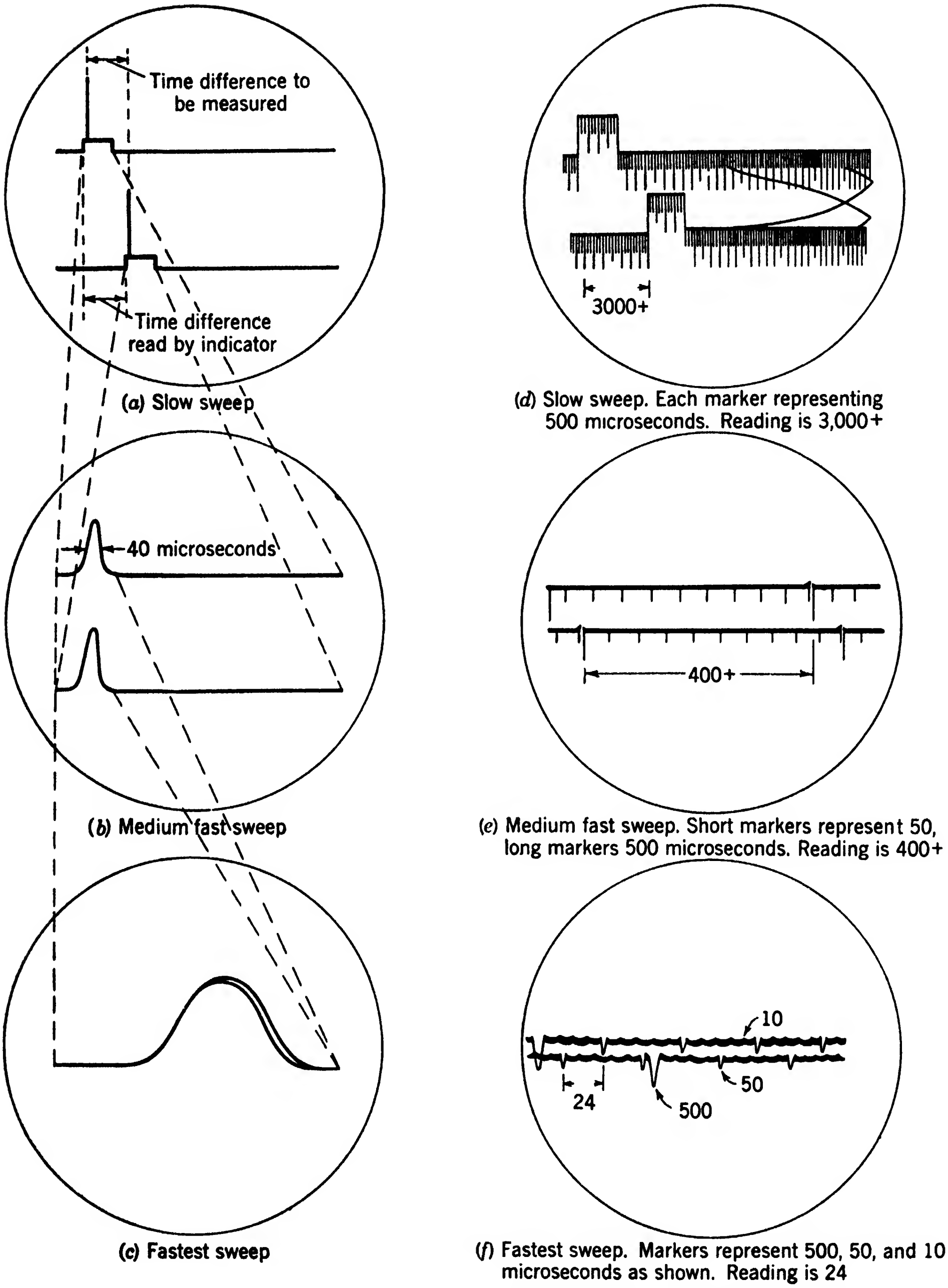


FIG. 11·1.—Oscilloscope patterns of Model DAS-1 receiver-indicator. (*a*) Slow-trace pattern with signals; (*b*) medium-trace pattern with signals; (*c*) fast-trace pattern with signals; (*d*) slow-trace pattern with 50- and 500-μsec markers, showing time difference of 3000 μsec plus approximately 500 μsec; (*e*) medium-trace pattern with 50- and 500-μsec markers, showing additional time difference of 400 μsec plus approximately 30 μsec; (*f*) fast-trace pattern with 10-, 50-, and 500-μsec markers, showing time difference of 24 μsec. Total time difference is 3424 μsec.

on the lower trace, directly below the *A*-pulse to the *B*-pulse. This convention cancels out one half of the recurrence period. The time difference can be estimated approximately by means of calibration markers. A method of greater precision is required, however. The upper and lower pedestals of Fig. 11·1*a* are expanded and displayed as two full-length traces (Fig. 11·1*b*,) one above the other. The amplitudes of the *A*- and *B*-pulses are equalized by means of the balance control. The recurrence rate of the oscilloscope pattern is altered slightly to move the *A*-pulse to a position near the left end of the trace, and the initiation of the *B*-pedestal (lower trace) is adjusted to move the *B*-pulse into position directly below the *A*-pulse. On a third oscilloscope pattern (Fig. 11·1*c*) consisting of a faster pair of traces between which the vertical separation is eliminated, the amplitudes are more accurately equalized, and the leading edge of one pulse is superimposed on that of the other.

When the signals have been so matched, the time difference between them is exactly the same as that between the initiations of the pedestals. This time difference is estimated to the nearest 500 μsec by calibration markers on the slow-trace pattern (Fig. 11·1*d*). The displacement between a 500-μsec marker on the lower fast trace and one on the upper fast trace gives the time difference to the nearest 50 μsec (Fig. 11·1*e*). Similarly, the displacement between 50-μsec markers on two faster traces gives the time difference to the nearest microsecond (Fig. 11·1*f*).

This method of presentation for measurement of time differences is employed in all shipboard Loran receiver-indicators except the direct-reading receiver-indicator, Model DBE, described in Sec. 11·4. The method of presentation and the receiver-indicators described in this chapter can be used for all Loran systems—Standard, Sky-wave Synchronized, and Air Transportable—with the exception of Low Frequency. For LF Loran, a small low-frequency converter is required in conjunction with the receiver-indicator.

Requirements.—The transmissions from Loran ground stations are identified by their radio frequencies and their pulse recurrence rates. The receiver-indicator must be capable, therefore, of receiving signals and measuring their time differences at several radio frequencies and at several recurrence rates. Four r-f channels have been assigned for Loran transmission in various parts of the world: Channel 1, 1950 kc/sec; Channel 2, 1850 kc/sec; Channel 3, 1900 kc/sec; Channel 4, 1750 kc/sec. These signal frequencies are easily identified by a four-position switch that selects any one of four fixed-tuned channels in the receiver. Each channel should be tunable from 1700 to 2000 kc/sec.

Pairs of stations operating in a particular region on a single radio frequency are distinguished by their pulse recurrence rates. Signals from all Loran stations operating at a single frequency and within receiving range are displayed on the cathode-ray tube and drift across the screen at various speeds. The recurrence rate of the oscilloscope pattern of the indicator is adjustable. Only the signals from that pair of stations operating at the same recurrence rate as the indicator remain stationary. Ground stations are operating at two basic recurrence rates, approximately 25 and $33\frac{1}{3}$ pps, designated as low, L, and high, H, respectively. If necessary, a slow, *S*, basic recurrence rate of approximately 20 pps

TABLE 11·1.—PULSE RECURRENCE RATES

Designation	Approx. No. of pps	Recurrence period, μsec
L0	25	40,000
L1	$25\frac{1}{16}$	39,900
L2	$25\frac{2}{16}$	39,800
L3	$25\frac{3}{16}$	39,700
L4	$25\frac{4}{16}$	39,600
L5	$25\frac{5}{16}$	39,500
L6	$25\frac{6}{16}$	39,400
L7	$25\frac{7}{16}$	39,300
H0	$33\frac{1}{3}$	30,000
H1	$33\frac{4}{9}$	29,900
H2	$33\frac{5}{9}$	29,800
H3	$33\frac{6}{9}$	29,700
H4	$33\frac{7}{9}$	29,600
H5	$33\frac{8}{9}$	29,500
H6	34	29,400
H7	$34\frac{1}{9}$	29,300

may be used in the future. As shown in Table 11·1, eight specific recurrence rates, numbered from 0 through 7 for each basic recurrence rate, are in general use. The indicator should be provided with a switch for selecting either the high or low basic recurrence rate and with another switch for selecting any one of the eight specific recurrence rates.

In addition to the r-f channel switch and the basic PRR and specific recurrence-rate (station) selector switch, the receiver-indicator must be provided with the following front-panel controls: the receiver-gain control, the amplitude-balance control for equalizing the oscilloscope deflections of the two signals from a pair of stations, coarse and fine framing or phase-shift controls for placing the *A*-signal on the *A*-pedestal, and coarse and fine delay controls for placing the *B*-pedestal under the *B*-signal. A fine control of the trace recurrence rate (oscillator frequency) allows it to be made exactly equal to the recurrence rate of the received signals, thus causing the signals to remain stationary. A trace-speed switch, a receive-calibrate switch for selecting the display of received signals or calibration markers, and a control of the trace separation are also required. In some models several of these controls are combined in a single switch.

General Description.—As indicated in Table 11·2, all models of the shipboard receiver-indicator are similar, with the exception of the Model DBE. There has been a steady trend toward standardization of the r-f channels in the range of frequencies between 1700 and 2000 kc/sec, and many of the early models have been modified to provide four channels in this frequency range. Models LRN-1 and LRN-1A, constructed for NDRC, are copies of an experimental receiver-indicator designed at the Radiation Laboratory. Models DAS-1, DAS-3, and DAS-4 (see Sec. 11·2), constructed for the Navy, are practically identical with Model LRN-1A electrically but show a steady improvement in mechanical construction and in the quality of components. Models DAS and DAS-2 (see Sec. 11·3) are designed to meet Navy specifications and are therefore heavier and more rugged. The operation of these models is simplified by combining the coarse and fine framing controls and by combining the trace-separation and sweep-speed controls in a five-position switch. There are also several improvements in the electrical design.

TABLE 11·2.—REFERENCE DATA FOR SHIPBOARD RECEIVER-INDICATORS

Model	Manufacturer	Approx. prod. to Aug. 1945	Width, in.	Height, in.	Depth, in.	Weight, lb	Power consump., watts	R-f channel No. 1, kc/sec	R-f channel No. 2, kc/sec	R-f channel No. 3, kc/sec	R-f channel No. 4, kc/sec	I-f, kc/sec	Bandwidth, kc/sec at 6 db	PRR switch	Vacuum-tube complement
LRN-1...	Fada	77	23	17	21	130	240	1800 3400	3600 5600	5800 8700	8200 11600	1050	80	No	43
LRN-1A..	Fada	177	23	17	21	130	240	1800 3400	3600 5600	5800 8700	8200 11600	1050	80	No	43
DAS	GE	200	28¼	17½	22¼	210	240	1700 2075	1700 2075	9900 12100	9900 12100	1100	80	No	43
DAS-1	Fada	640	23	17	21	130	240	1700 3200	1700 3200	8850 11900	8850 11900	1050	80	No	43
DAS-2	GE	960	28¼	17½	22¼	210	240	1700 2075	1700 2075	9900 12100	9900 12100	1100	80	Yes	43
DAS-3	Fada	1801	23	17	21	130	240	1700 2000	1700 2000	1700 2000	1700 2000	1050	80	Yes	43
DAS-4	Fada	705	23	17	21	130	240	1700 2000	1700 2000	1700 2000	1700 2000	1050	80	Yes	43
DBE	Sperry	6	15	40	15	230	300	1700 2000	1700 2000	1700 2000	1700 2000	550	50	Yes	44

Trends in Design.—For service aboard ship, the size, weight, and power consumption are minor considerations. The chief requirement is that the equipment give reliable service under abnormally severe conditions of temperature, humidity, salt-water spray, and shock. Furthermore, the operation should be simple and as free as possible from sources of error. Probably the chief source of error is the counting of calibration markers; and, as a consequence, considerable effort has been spent in designing an indicator with which it is possible to read the time difference directly on calibrated scales or on a mechanical counter.

Such an indicator was designed at the Radiation Laboratory in 1942. It consisted of two divider chains, one of which was driven by a 100-kc/sec

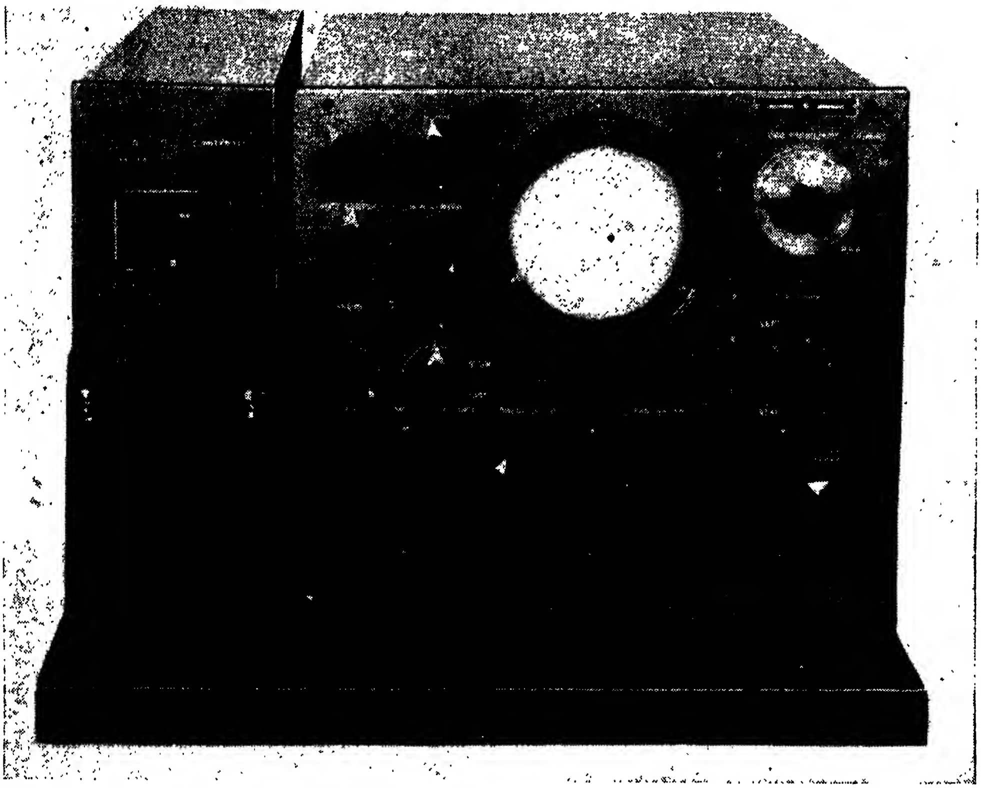


FIG. 11·2.—Model DAS-1 receiver-indicator used on ships. (*Courtesy of Fada Radio and Electric Co., Inc.*)

oscillator and the other by the 100-kc/sec output signal from a phase-shift capacitor. The number of rotations of the phase-shift capacitor (multiplied by 10) gave the time difference in microseconds. A later version was similar in operation but somewhat simpler, because the oscillator operated at 10 kc/sec. Both designs were rather complicated electrically and mechanically. Another direct-reading indicator, built of miniature components, is described in Vol. 20 of this series. The Model DBE, the only direct-reading receiver-indicator to be produced commercially, is described in Sec. 11·4.

11·2. Model DAS-1 Receiver-indicator.—The Model DAS-1 receiver-indicator has been used extensively by the U.S. Navy, the Royal Navy and the Royal Canadian Navy for convoy duty in the North Atlantic. A photograph of this equipment is shown in Fig. 11·2.

Functional Description.—As indicated in Fig. 11·3, the necessary accuracy and stability for the timing of the sweeps and for the generation of the calibration markers are derived from a 100-kc/sec crystal oscillator. The oscillator is capable of adjustment to a frequency that is a few parts per million above or below the nominal frequency to permit synchronization with signals whose recurrence rates are not precisely accurate. Furthermore, a momentary change in the oscillator frequency permits a fine adjustment of the timing of the sweeps with respect to the received signals for the proper positioning of the signals on the traces.

The pulse generator is an amplifier that is driven between saturation and cutoff by a 100-kc/sec sine-wave signal from the oscillator. The output is roughly a square wave that on differentiation yields positive and negative pulses of short duration for driving and precisely controlling the divider circuits.

By means of the divider circuits, output pulses of a recurrence rate corresponding to that of the sweeps and to twice that of signals from each ground station are derived from the crystal oscillator. The four divider circuits are adjusted to divide by 5, 10, 5, and 8 or 6. The adjustment of the last divider to divide by 8 yields the low basic recurrence rate; for the high basic recurrence rate the last divider is adjusted to divide by 6. A six-position selector switch permits the adjustment of the feedback of pulses from the last divider to the second divider for the control of the specific recurrence rate. A momentary change of the feedback provides a coarse adjustment of the timing of the oscilloscope sweeps with respect to the received signals for positioning the signals on the slow-trace pattern. The output pulse from the last divider initiates the square-wave generator and the slow-sweep generator.

The output pulses from the first and second dividers are mixed and impressed on one vertical plate to provide 50- and 500-μsec markers. A 100-kc/sec sine-wave signal from the oscillator is shifted in phase, peaked, and applied to the other vertical plate to form 10-μsec markers. The phase of the 10-μsec markers is adjusted to coincide with that of the 50-μsec markers.

The square-wave generator, an Eccles-Jordan circuit, produces two square-wave outputs identical in form but opposite in phase. The polarity of each output is reversed with each triggering pulse from the last divider. Voltages of variable amplitude and derived from the square-wave amplifier are impressed on the vertical plate of the oscilloscope to raise or lower alternate horizontal traces. These voltages produce the upper and lower traces of the slow and fast oscilloscope patterns.

The *A*-delay multivibrator is triggered by one output of the square-

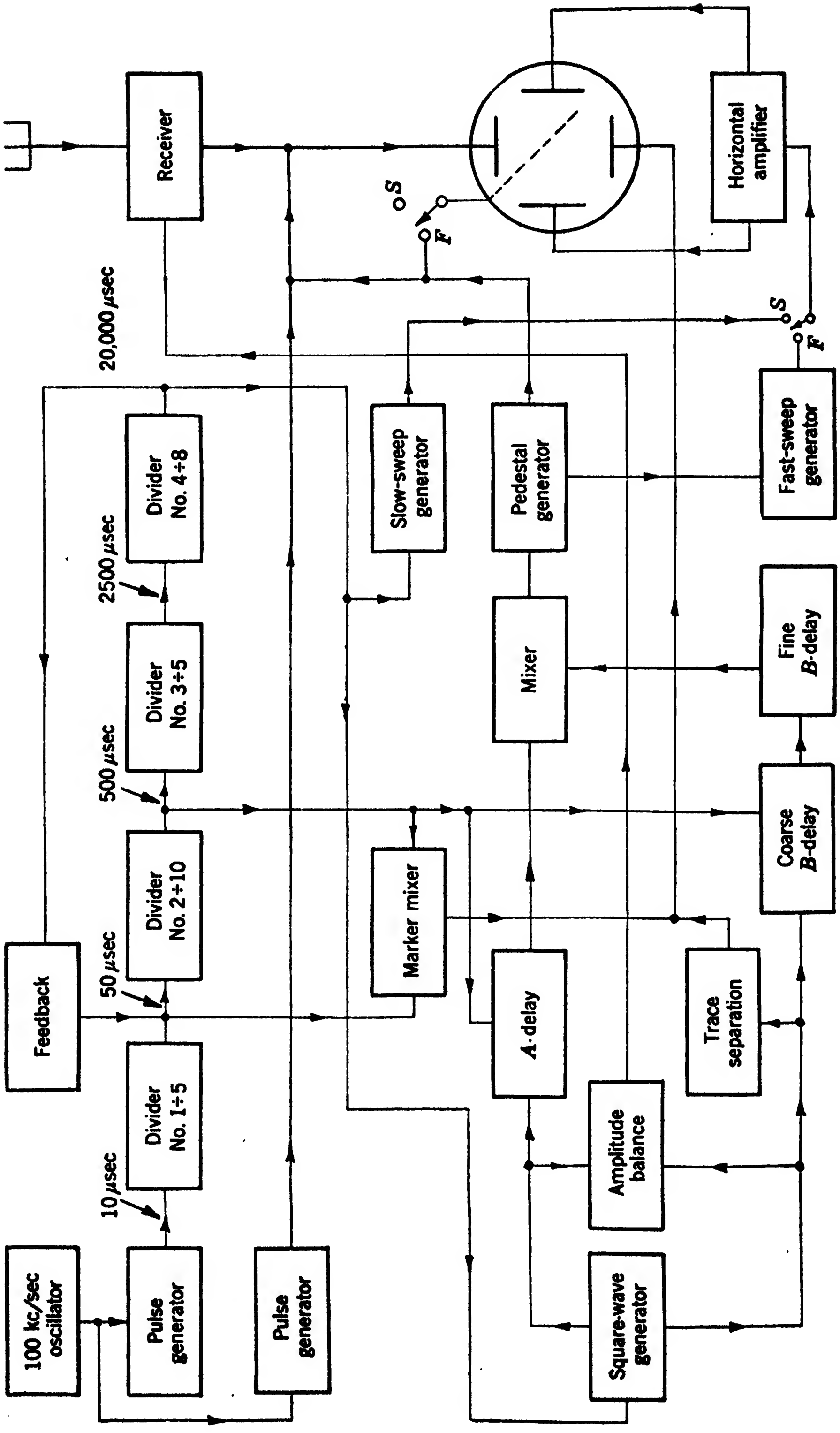


FIG. 11·3.—Block diagram of Model DAS-1 receiver indicator.

wave generator at the beginning of the upper slow trace. It introduces a fixed time delay of approximately 1000 μsec. The coarse *B*-delay multivibrator is triggered by the other output of the square-wave generator at the beginning of the lower slow trace. It introduces a time delay that is variable in increments of 500 μsec from approximately 1000 to approximately 11,000 μsec. Both the *A*-delay and the coarse *B*-delay multivibrators are stabilized by the introduction of 500-μsec locking pulses derived from the second divider. The coarse *B*-delay multivibrator initiates the fine *B*-delay multivibrator which introduces an additional time delay that is continuously variable from 200 to 700 μsec. The delayed outputs of the *A*-delay and the fine *B*-delay multivibrators are mixed and used to trigger the pedestal generator.

The pedestal generator produces identical square-wave outputs which are impressed on the vertical plate of the oscilloscope to produce the *A*- and *B*-pedestals of the slow trace pattern. Any one of three values of the pedestal length can be selected by means of the fast-sweep switch.

The fast-sweep generator is triggered by the pedestal generator and produces a sweep voltage whose amplitude varies linearly with the time represented by the pedestal. When the horizontal plates of the oscilloscope are switched from the slow to the fast sweeps, only that fraction of the recurrence interval represented by the tops of the pedestals is shown on the oscilloscope screen. The traces are expanded to the full width of the screen, and the trace of the *A*-pedestal appears directly above the trace of the *B*-pedestal.

The transmitted pulses are received and amplified in a superheterodyne receiver and are impressed on the vertical plate of the oscilloscope. The receiver consists of one stage of r-f preselection, a pentagrid converter, three i-f stages operating at 1050 kc/sec, a diode detector, and one stage of video amplification. The bandwidth is approximately 80 kc/sec at 6 db, and the sensitivity is such that a signal of less than 10 μv gives full-scale deflection of the oscilloscope. Any one of four fixed-tuned r-f channels can be selected by a switch. The frequency ranges of the channels are given in Table 11·2. The pulses as displayed on the oscilloscope are of approximately 75-μsec duration.

The amplitude-balance circuit, driven by the square-wave generator, applies adjustable voltages of either polarity to one stage of i-f amplification. This provides a control of the relative gain of the receiver on alternate oscilloscope traces and permits the equalization of the amplitudes of the *A*- and *B*-pulses. Such equalization is required for the accurate measurement of time differences.

Manipulation.—In carrying out the time-difference measurement as outlined in Sec. 11·1, the operator of the Model DAS-1 receiver-indicator must manipulate the following controls:

1. Radio-frequency channel switch. This is a four-position switch for selecting any one of four preadjusted channels corresponding to the frequency of the transmitted signals.
2. Station selector. A six-position switch varies the divider feedback and the trace recurrence rate to correspond with the specific recurrence rate of the signals. By means of the phase-shift switch the number of specific recurrence rates can be extended to eight. The last divider is adjusted by screwdriver to control the basic recurrence rate.
3. Receiver gain. The gain control varies the cathode bias of the r-f stage, the converter, and first and second i-f stages of the receiver. There is no automatic gain control.
4. Phase shift. The feedback in the divider chain is controlled by a three-position switch that is used for momentarily changing the trace recurrence rate to position the *A*-pulse on the *A*-pedestal of the slow-trace pattern.
5. Coarse *B*-delay. By means of the coarse *B*-delay control the *B*-pedestal can be moved in increments corresponding to 500 μsec from a position below the *A*-pedestal to a position halfway across the lower slow trace.
6. Fine *B*-delay. By means of the fine *B*-delay control the *B*-pedestal can be moved continuously over the 500-μsec increments of the coarse *B*-delay. On the fast trace pattern the *B*-pulse can be placed precisely below the *A*-pulse.
7. Sweep speed. A two-position sweep-speed switch provides the selection of the slow-trace pattern or one of the fast-trace patterns.
8. Fast-sweep switch. A three-position switch selects any one of three fast-sweep speeds. The three speeds give full-scale deflection in 2000, 700, and 150 μsec.
9. Framing or left-right switch. A three-position switch, controlling the frequency of the crystal oscillator, momentarily changes the trace recurrence rate by a small amount for positioning the *A*-pulse on the fast *A*-trace.
10. Oscillator frequency control. The frequency of the crystal oscillator is continuously variable over a range of ± 30 parts per million for accurately synchronizing the trace recurrence rate with that of the signals. When the traces are properly synchronized the signals remain stationary.
11. Amplitude balance. A continuously adjustable potentiometer controls the relative gain of the receiver throughout the *A*- and *B*-traces for equalizing the amplitude of the *A*- and *B*-pulses.
12. Trace separation. A potentiometer provides a continuous control of the vertical spacing between the *A*- and *B*-traces.

13. Receiver switch. A two-position receiver switch permits the selection of receiver signals or calibration markers for display on the oscilloscope.
14. Filter. A toggle switch permits the insertion of a high-pass filter in the receiver video circuit for reducing certain types of interference.

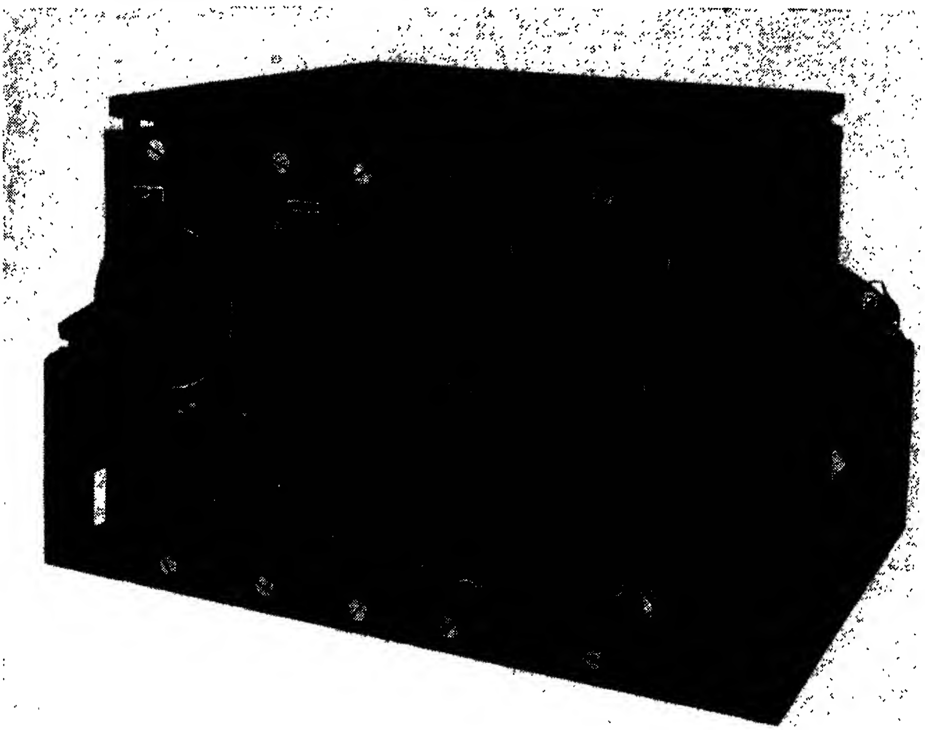


FIG. 11·4.—Model DAS-2 receiver-indicator used on ships. (*Courtesy of General Electric Company.*)

There are also several oscilloscope and divider controls, but these do not require frequent manipulation. In the designs of later models an attempt has been made to reduce the number of controls and to simplify the procedure for time-difference measurements.

11·3. Model DAS-2 Receiver-indicator.—The Model DAS-2 receiver-indicator (Fig. 11·4) is heavier and more rugged than the Model DAS-1. It is constructed of Navy-approved components and is designed to meet Navy specifications.

Functional Description.—As indicated in Fig. 11·5 the calibration markers and the trace recurrence rates are derived from a 100-kc/sec crystal oscillator and four dividers similar to those of the Model DAS-1. The introduction of the time corrector, however, is an improvement. The interval of time between the initiation of the A-delay (or the coarse

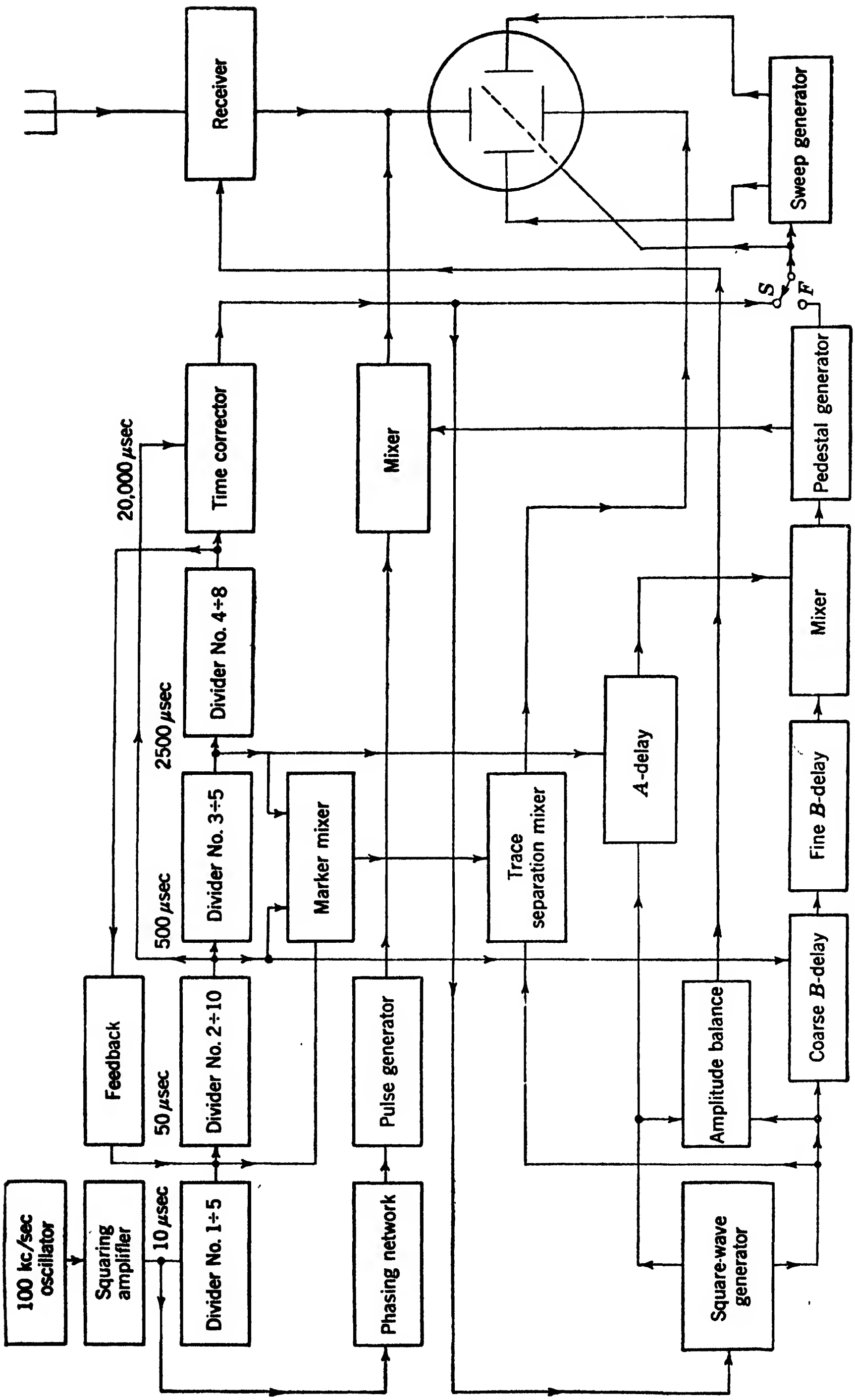


FIG. 11·5.—Block diagram of Model DAS-2 receiver-indicator.

B-delay) multivibrator and the succeeding 500-μsec locking pulse from the second divider varies with the position of the station selector switch that controls the feedback. This interval of time is equal to 500 μsec minus 50*N* μsec, where *N* is the feedback number and may be any integer from 0 to 7. Because of the variation of this interval of time, the design of the Model DAS-1 *A*- and coarse *B*-delay multivibrator is more complicated than would otherwise be necessary. The purpose of the time corrector is to eliminate the variable time interval between the initiation of the *A*-delay (or coarse *B*-delay) multivibrator and the succeeding 500-μsec locking pulse. The time corrector is a derivative of the Eccles-Jordan circuit that has two inputs. It generates a flat-topped signal that is initiated by the pulse from the last divider and is terminated by the first succeeding 500-μsec pulse from the second divider. The duration of the flat-topped signal is 500 μsec minus 50*N* μsec. The square-wave generator and the *A*- and coarse *B*-delay multivibrators are initiated at the termination of the flat-topped signal. The time corrector also simplifies and improves the operation of the slow-sweep generator and suppresses the retrace of the slow-trace pattern.

The *A*-delay multivibrator is locked by 2500-μsec pulses from the third divider and is adjusted to introduce a fixed time delay of 2000 μsec after the initiation of the upper slow trace (2500 μsec minus 50*N* μsec after the pulses from the last divider). The *B*-delay multivibrators, pedestal generator, sweep generator, and receiver are similar in function to those of the Model DAS-1 receiver-indicator.

Manipulation.—The manipulation of the Model DAS-2 receiver-indicator is somewhat simpler than that of the Model DAS-1. A PRR toggle switch provides a convenient selection of the two basic recurrence rates. The trace-separation control and the fast-sweep switch are eliminated, and their functions are performed by the sweep-speed switch. A single LEFT-RIGHT switch shifts the positions of the *A*- and *B*-signals on both the slow and fast traces.

To measure a time difference, the operator must manipulate the following controls:

1. R-f channel switch. A four-position switch selects any one of the preadjusted channels listed for the Model DAS-2 receiver-indicator in Table 11·2.
2. PRR switch. A toggle switch with *L* (low) and *H* (high) positions selects one of two adjustments of the last divider to provide the required basic recurrence rate.
3. Station selector. An eight-position switch controls the specific pulse recurrence rate.
4. Gain control. This varies the amplitude of the received signals as they appear on the oscilloscope.

5. LEFT-RIGHT switch. By means of the LEFT-RIGHT switch the operator can adjust the positions of the signals on the traces. On the first (slow trace) position of the sweep-speed switch, the timing of the traces is shifted rapidly with respect to the timing of the signals by the introduction of pulses of either polarity from the A-delay multivibrator to the first divider. On the other positions of the sweep-speed switch a slight change in the oscillator frequency provides an appropriate change of the recurrence rate.
6. Coarse delay. By means of a potentiometer control the interval of time between the start of the lower slow trace and the initiation of the B-pedestal can be varied in increments of 500 μsec.
7. Fine delay. The fine B-delay control enables the operator to vary continuously the total B-delay time over the required range.
8. Sweep speed. A five-position switch provides selection of the slow-trace pattern with wide trace separation, fast traces of 2300-μsec duration with medium separation, fast traces of 650-μsec duration with medium separation, fast traces of 160-μsec duration with small separation, or fast traces of 160-μsec duration with no separation.
9. Frequency control. A fine control of the frequency of the crystal oscillator permits precise synchronization of the oscilloscope traces with the received signals.
10. Amplitude balance. A potentiometer controls the relative amplitudes of the A- and B-pulses as they appear on the oscilloscope.
11. Receiver switch. By means of a four-position switch any one of four types of signals can be selected for display on the oscilloscope. In the OFF position, calibration markers alone are displayed. In the ON position, calibration markers are displayed with signals from the receiver. In the CAL. 1 position, the stair-step pattern of the second divider is displayed for checking the adjustment of the second divider and the feedback. In the CAL. 2 position, the stairstep pattern of the third divider is displayed for checking the adjustment of the third and fourth dividers. The first divider is checked by means of the 10- and 50-μsec calibration markers. For checking feedback on position CAL. 1 and on the third position of the sweep-speed switch, the sweeps are initiated at the start of the flat-topped time-corrector signal instead of at its termination.
12. Filter. A toggle switch permits the introduction of a filter for reducing certain types of interference.

11·4. Model DBE Receiver-indicator.—The direct-reading Model DBE receiver-indicator (Fig. 11·6) stands upright on the deck and is secured to the deck and bulkhead by S-shaped steel springs that serve as shock mounts. The oscilloscope screen and operating controls are on

FIG. 11·6.—Model DBE direct-reading receiver-indicator for use on ships. (*Courtesy of Sperry Gyroscope Co., Inc.*)

the top panel. The front cover is removable for routine adjustment of the dividers, multivibrators, oscilloscope, and receiver. The entire chassis assembly can be rolled forward out of the cabinet on rails for servicing.

The oscilloscope presentation and the procedure for positioning and matching the pulses are similar to those described in Sec. 11·1. The

FIG. 11·7.—Front panel of Model DBE receiver-indicator showing slow-trace presentation without signals. (*Courtesy of Sperry Gyroscope Co., Inc.*)

counting of calibration markers, however, is eliminated. When the pulses have been matched, the time difference is indicated on a Veeder-Root counter (see Fig. 11·7).

Functional Description.—As indicated in Fig. 11·8 the crystal oscillator, divider, feedback circuits, square-wave generator, pedestal generator, sweep generator, and receiver are similar in their function to those of Models DAS-1 and DAS-2. There are five dividers, each one of which

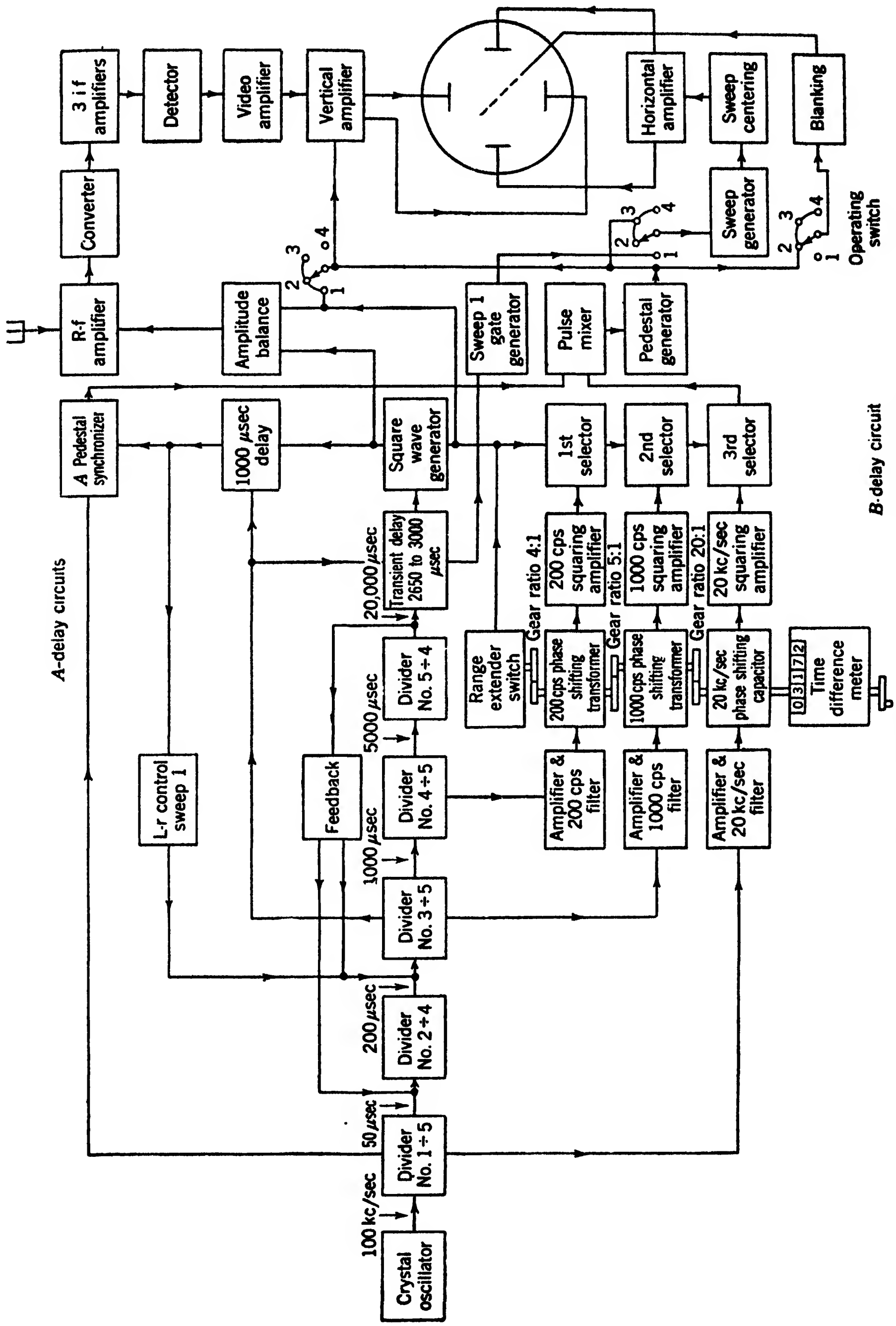


FIG. 11·8.—Block diagram of Model DBE receiver indicator.

divides the pulse recurrence rate by a ratio of 5/1 or less. Because of the lower dividing ratios the over-all operation is more reliable than that of earlier models. The transient delay circuit is a locked delay multivibrator that serves the same purpose as the time corrector of Model DAS-2. It also reduces the effect of the distortion of the phase-shifting sine waves caused by feedback.

The rotations of the 200- and 1000-cps phase-shifting transformers and of the 20-kc/sec phase-shifting capacitor control the position of the *B*-pedestal and determine the measured time difference when the received signals are matched. The sine waves of the three phase-shifted frequencies are derived through amplifiers and low-pass filters from the dividers of the appropriate recurrence rates. The three phase shifters are coupled through a gear train to the time-difference counter and to the coarse and fine delay controls. Since the gear ratios between the phase shifters are equal to the ratios of their frequencies, a rotation of the fine delay control produces the same change in time difference in all three frequencies. The three phase-shifted sine waves are squared and differentiated to yield the pulses that terminate the flat-topped output signals of three selector circuits. Each selector circuit is a multivibrator of the Eccles-Jordan type with two inputs similar to the time-corrector circuit of Model DAS-2. The first selector circuit is initiated at the start of the lower slow trace by a pulse from the square-wave generator. The output signal is terminated, depending on the bias selected by the extender switch, by the first, second, or third 5000-μsec pulse derived from the 200-cps phase-shifting transformer. By means of the fine delay control the time delay introduced by the first selector may be varied continuously from less than 1000 to more than 18,000 μsec. The time delay so introduced, however, is not itself sufficiently accurate for the time-difference measurement. To obtain the precision required for the time-difference measurement, the selecting process is repeated in two succeeding selectors of greater precision whose output signals are terminated by pulses derived from the phase-shifted 1000-cps and 20-kc/sec signals. The second selector is triggered at the termination of the first selector output signal, and its output signal is terminated by a pulse derived from the phase-shifted 1000-cps sine wave. The third selector is triggered at the termination of the second selector signal. Its output signal is terminated by a pulse derived from the phase-shifted 20-kc/sec sine wave and having the precision required for the time-difference measurement. The pedestal generator and fast-sweep generator are triggered at the termination of the third selector output signal.

By means of the coarse delay control the *B*-pedestal can be moved rapidly by increments of 1000 μsec. The coarse delay control through the range-extender switch varies the bias of the first selector and shifts the phase of the terminating pulse. Also, through a differential gearing and detent system, it rotates the thousands and ten-thousands dials of the time-difference counter.

Similarly the *A*-delay is obtained from the combination of a fixed coarse selector (1000-μsec delay) and a fixed fine selector (*A*-pedestal synchronizer). The output signal of the 1000-μsec delay is terminated by a 1000-μsec pulse from the third divider, and the output signal of the *A*-pedestal synchronizer is terminated by a 50-μsec pulse from the first divider. The pedestal generator is triggered at the termination of the output signal from the *A*-pedestal synchronizer.

Manipulation.—As shown in Fig. 11·7 the manipulation is simplified by the arrangement of the controls. The three station-selecting switches, r-f channel, basic PRR, and specific PRR, are grouped in a row. The coarse and fine delay controls are concentric, as are the gain and amplitude balance controls. The LEFT-RIGHT switch and drift (oscillator frequency) control are a concentric lever and disk. The four-position operations switch provides selection of the normal slow-trace pattern, a pair of vertically spaced 1300-μsec traces, a pair of spaced 175-μsec traces, and a pair of 175-μsec traces with no trace separation.

AIRBORNE RECEIVER-INDICATORS

11·5. General Description and Trends in Design.—The methods of measurement, the oscilloscope presentation, the r-f channels, and recurrence rates of the airborne receiver-indicator are similar to those of the shipboard instrument. For airborne equipment the requirements of light weight and small size are severe. As indicated in Table 11·3, these requirements are recognized, and an effort has been made to reduce the weight, size, and power consumption as far as practical. All airborne receiver-indicator models have been designed for operation in both American and British aircraft, and most of them are physically interchangeable with Gee sets. They can be operated on input power of either 80 or 115 volts and of any frequency between 400 and 2400 cps.

General Description.—The Models SCR-722 and SCR-722A are lightweight modifications of the Model DAS-1 receiver-indicator with a power supply designed for operation at 400 to 2400 cps instead of 60 cps. They are awkward for operation in the air but have been used for training purposes.

The Model AN/APN-4 receiver-indicator, of which there are five modifications, was used most extensively during World War II. Modifications I and II could not be used in normal service because of divider instability and high-voltage arcing at high altitudes. Modification III has been used extensively and has performed well. There has been no large production of Modification IV, and Modification V reached the

TABLE 11·3.—REFERENCE DATA IOR AIRBORNE RECEIVER-INDICATORS

Model	Manufacturer	Approximate production to Aug. 1945	Indicator			Receiver				Power consumption, watts	R-f channel No. 1, kc/sec	R-f channel No. 2, kc/sec	R-f channel No. 3, kc/sec	R-f channel No. 4, kc/sec	I-f, kc/sec	Bandwidth, kc/sec at 6 db	Basic PRR switch	Vacuum-tube complement
			Width, in.	Height, in.	Depth, in.	Width, in.	Height, in.	Depth, in.	Weight, lb									
SCR-722	Fada	250 (SCR-722 and SCR-722A)	12	15½	19½	5	7½	19½	65	265	1800 3400	3600 5600	5,800 8,700	8,200 11,600	1050	80	No	43
SCR-722A	Fada		12	15½	19½	5	7½	19½	65	265	1800 3400	3600 5600	5,800 8,700	8,200 11,600	1050	80	No	43
AN/APN-4 I	Philco Emerson Delco	......	9	11¾	19½	9	8	19½	70	240	1600 3300	1600 3300	7,600 11,700	7,600 11,700	1050	80	No	42
AN/APN-4 II	Philco Emerson Delco	......	9	11¾	19½	9	8	19½	70	240	1600 3300	1600 3300	7,600 11,700	7,600 11,700	1050	80	No	42
AN/APN-4 III	Philco Emerson Delco	45,348 (AN/APN-4 I–V)	9	11¾	19½	9	8	19½	70	240	1600 3300	1600 3300	1,600 3,300	7,600 11,700	1050	80	No	42
AN/APN-4 IV	Philco Emerson Delco	......	9	11¾	19½	9	8	19½	70	240	1600 3300	1600 3300	1,600 3,300	1,600 3,300	1050	60	No	42
AN/APN-4 V	Philco Emerson Delco		9	11¾	19½	9	8	19½	70	240	1600 3300	1600 3300	1,600 3,300	1,600 3,300	1050	60	Yes	45
AN/APN-9	RCA Philco	24,088	9	12	18	..	..	...	40	190	1900 2000	1800 1950	1,800 1,950	1,700 1,850	1100	60	Yes	35

European Theater too late for service. Modification V has a basic PRR switch and six dividers instead of four; it is described in Sec. 11·6.

All the components of Model AN/APN-9 receiver-indicator (described in Sec. 11·7) are contained in a single case that fits the same shock-mounted frame as the AN/APN-4 and Gee indicator. The set weighs only 40 lb, and its power consumption is only 190 watts. Although it arrived too late for service in the European Theater, it was used in the Pacific. Its notable features are a 3-in. cathode-ray tube with a magnifying glass, nonlinear sweeps, and a rather complicated system of calibration markers.

Trends in Design.—Because of the rapid motion of an aircraft, the time required to make two readings and plot a fix is a most important quantity, and, indeed, the reduction of this time should be the prime consideration in the future development of the Loran system and equipment. For example, a plane may travel at a speed of 5 miles per minute, and the navigator may require 1 min for the measurement of each time difference and another minute for plotting the lines of position. Since the plane travels 5 miles while he makes the second measurement and 5 miles while he plots the lines of position, the intersection of the two lines does not represent the navigator's true position. There are two methods for overcoming this difficulty, both of them awkward. The navigator may calculate the distance that the plane has traveled in the interval between the two measurements and advance the first line of position by the appropriate distance. The intersection of the advanced first line of position with the second line is the true position at the time of the second measurement. As an alternative method, the navigator may make three measurements (with equal intervals of time between the first and second measurements and between the second and third measurements) and compute the mean of the first and third measurements. The intersection of the second line of position with the line corresponding to the mean of the first and third measurements determines his position at the time of the second measurement.

To reduce the time required to make a reading, the airborne receiver-indicators are designed so that the operator can control the sweep speed, the trace separation, and the selection of received signals or calibration markers by means of a single selector switch. This unification of the controls simplifies the operation slightly but leaves much to be desired. The Gee indicator, for instance (see Sec. 1·4), is much simpler to operate than the Loran indicator because it permits the measurement of two time differences simultaneously and thus eliminates the necessity of advancing a line of position or of making three readings to determine a fix. For this reason the Gee system is admirably adapted to a simple and useful type of navigation, called the homing technique, that is described in Sec. 1·6.

This technique cannot easily be applied to navigation by Loran in its present form.

As mentioned in Secs. 3·8 and 7·7 the requirements for instantaneous fixing over a particular area are that it shall be possible to receive signals from two pairs of ground stations transmitting at a single recurrence rate and that the navigator shall be able to adjust two sets of controls to measure the appropriate time differences simultaneously. The simplest system of synchronization of the ground stations is that used for the Low Frequency trials and described in Sec. 7·8. The same system can be applied to Standard Loran with practically no modification of the ground-station equipment now in service, but long trains of sky waves may at times make the presentation confusing.

The simplest type of receiver-indicator for instantaneous fixing is one similar to AN/APN-4, but it is provided with a second set of delay controls and a switch for simultaneously selecting either pair of *B*-delay controls, either of two gain-balance adjustments, and either of the outputs from the square-wave generator for initiation of the *A*- and *B*-delay multivibrators and for the trace separation. Such a receiver-indicator would be little more complex than AN/APN-4. The only duplication would be in the potentiometers that control the biases of the delay multivibrators and the relative amplitudes of the signals.

A decimal system of calibration markers similar to that of the Gee indicator seems preferable to the common Loran display of 10-, 50-, 500-, and 2500-μsec markers on the slow, medium, and fast traces. The display of 1000-μsec markers on the slow traces, 1000- and 100-μsec markers on the medium traces, and 100- and 10-μsec (and possibly 1- or 2-μsec) markers on the fast traces seems satisfactory. Furthermore, the 100-μsec markers should coincide in time with the corresponding 10-μsec markers as do the markers displayed on the oscilloscope of the timer.

A much simplified form of the synchronizer (Sec. 7·3) has been designed to control the frequency of the crystal oscillator in such a way that the signal from the master station remains stationary on the upper pedestal. This feature, called "top locking," is believed to be a worthwhile convenience for the operator of the receiver-indicator.

By the addition of a third delay multivibrator the advantage of the direct-reading indicator can be incorporated in the instantaneous-fixing receiver-indicator. In such a receiver-indicator, the first delay multivibrator would be variable in increments of 1000 μsec and the second delay multivibrator would be variable in increments of 100 μsec. Calibrated selector switches would indicate the numbers of thousands and hundreds of microseconds of time difference. The third delay multivibrator would be variable continuously from 20 to 120 μsec, and a calibrated dial on the potentiometer would indicate the number of units of time difference.

The two switches and one potentiometer would be duplicated, but the delay multivibrators would not be duplicated.

As suggested in Sec. 10·6, individual loading coils should be built in the receiver and should be selected by the r-f channel switch.

Low Frequency Converter.—No receiver-indicator designed for the reception of LF signals has been manufactured. However, an LF converter in conjunction with a standard receiver-indicator permits the

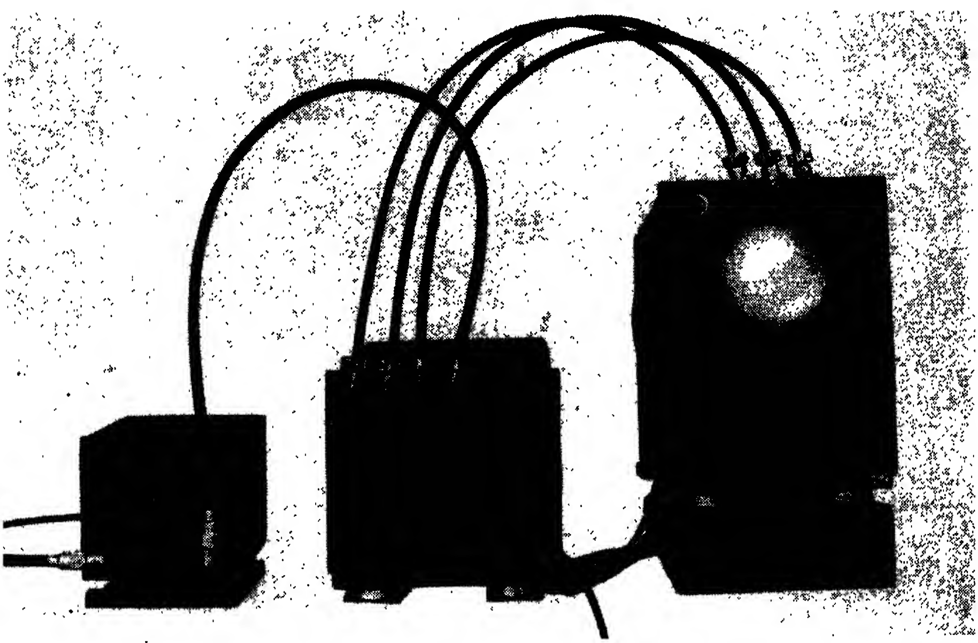


FIG. 11·9.—Converter attached to a standard receiver-indicator (AN/APN-4) to permit either Standard or Low Frequency signals to be observed.

reception and measurement of signals of either Low or Standard Loran frequencies. The converter, shown in Fig. 11·9 with a Model AN/APN-4 receiver-indicator, has been produced on a rather large scale. It converts the LF signal to a Standard frequency of 1950 kc/sec. The schematic diagram is shown in Fig. 11·10.

11·6. Model AN/APN-4 Receiver-indicator.—The Model AN/APN-4 airborne receiver-indicator (Fig. 11·9) has been produced in greater quantity and was more extensively used during World War II than any other Loran or radar equipment. The smaller unit contains the receiver and power supply; the indicator, consisting of the crystal oscillator, dividers, delay and deflecting circuits for the 5-in. cathode-ray tube, is enclosed in the larger unit. Of the five modifications of the Model AN/APN-4 receiver-indicator, the latest and most satisfactory is described in this section.

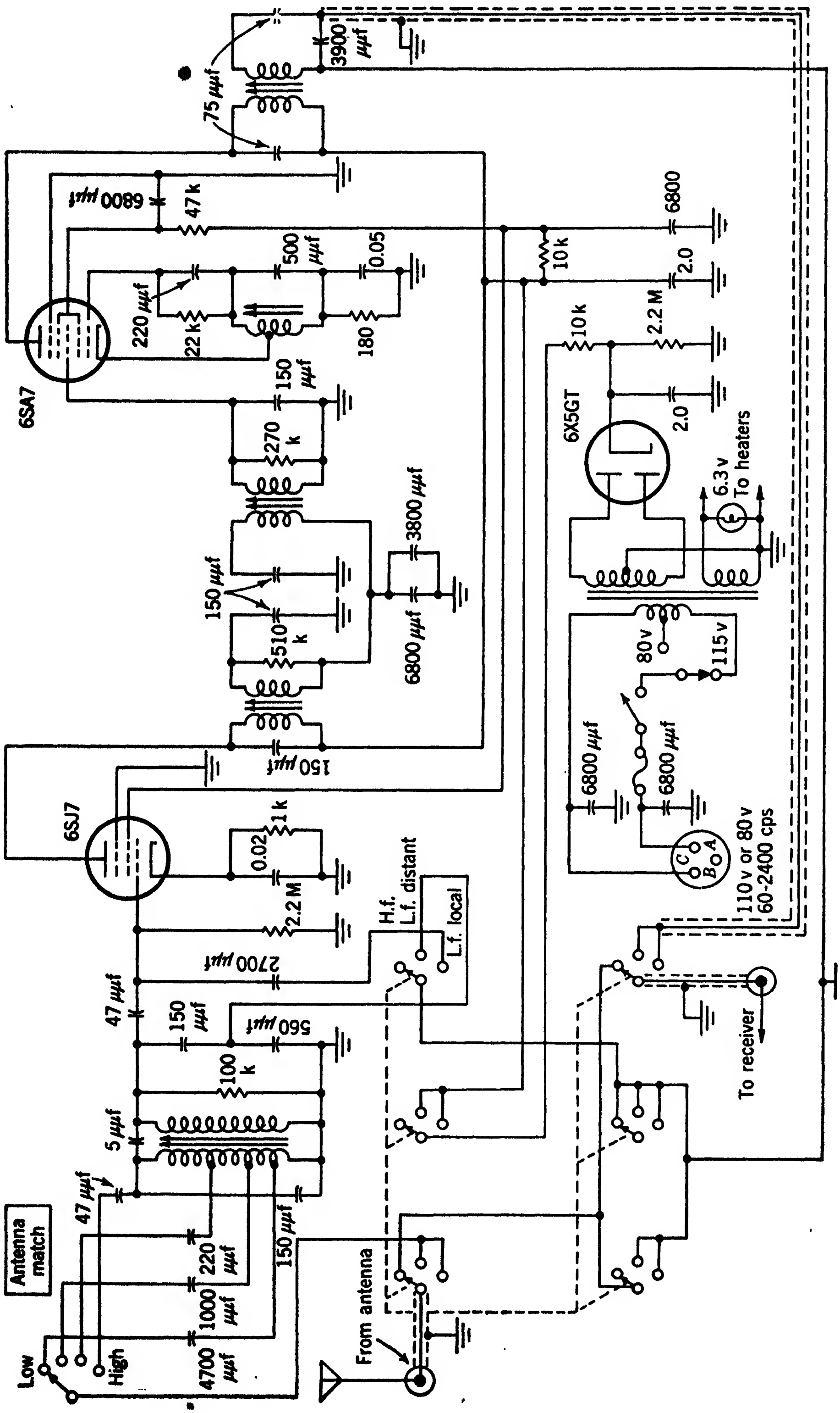


FIG. 11·10.—Schematic diagram of Low Frequency converter.

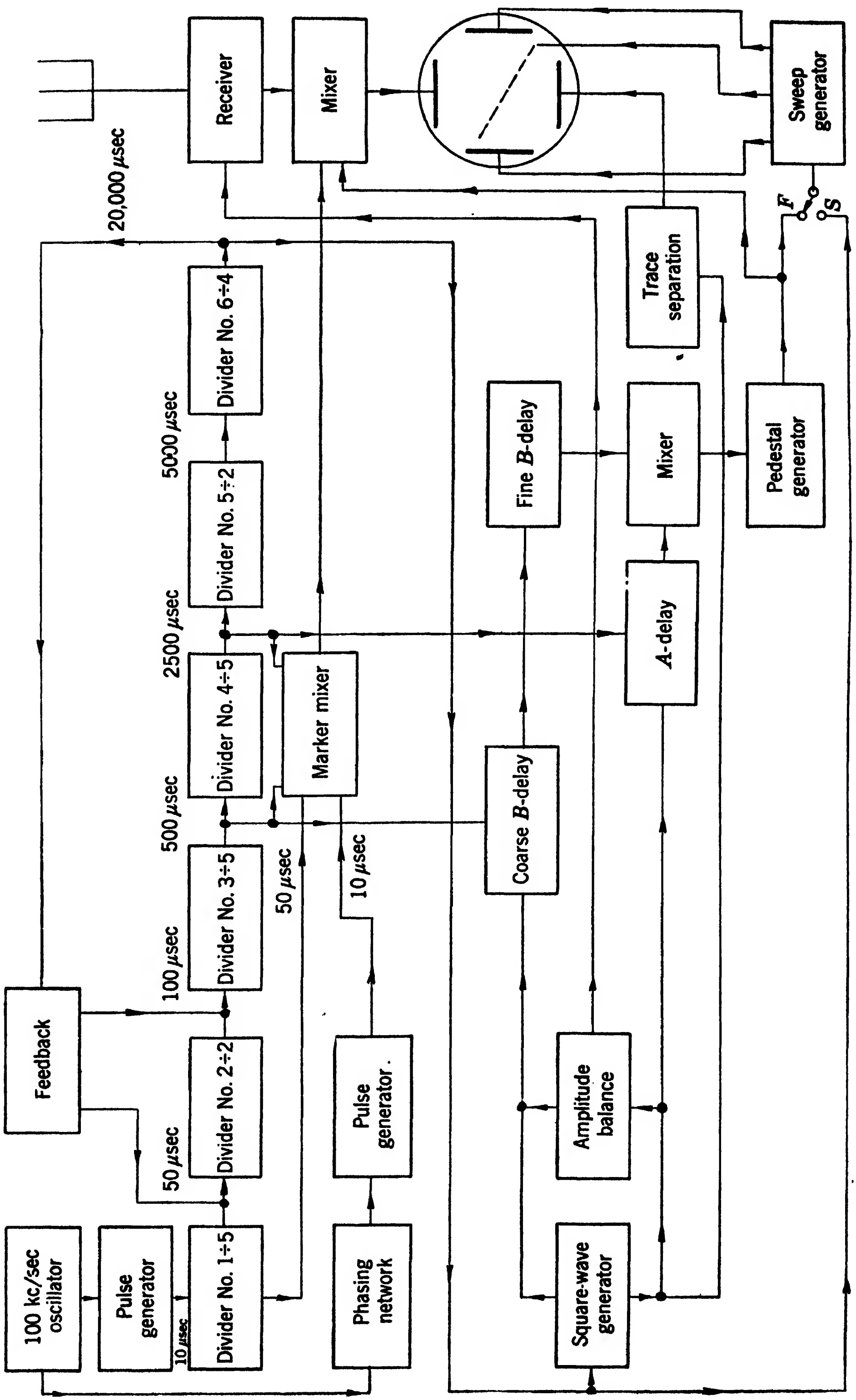


FIG. 11·11.—Block diagram of Model AN/APN-4 receiver-indicator.

Functional Description.—The block diagram of the Modification V Model AN/APN-4 receiver-indicator, shown in Fig. 11·11, is similar to that of the Model DAS-1 receiver-indicator (Fig. 11·3). Since there are six dividers instead of four, the maximum dividing ratio is 5/1 instead of 10/1, and the operation is therefore more reliable. The output pulse from the last divider is fed back to the second and third dividers to control the specific recurrence rate.

Pulses derived from the crystal oscillator and from the first, third, and fourth dividers are mixed and applied to the vertical plate (along with the trace separation and pedestals) of the cathode-ray tube as calibration markers, at time intervals of 10, 50, 500, and 2500 μsec.

The complete schematic diagrams of the receiver and the indicator are shown in Figs. 11·12 and 11·13. Circuits of these types are described in some detail in Chap. 7 and in other volumes of this series.

Manipulation.—In making a time-difference measurement, the operator must manipulate the r-f channel; basic PRR and station selector switches; the gain, amplitude-balance and frequency controls; the LEFT-RIGHT and sweep-speed switches; and the coarse and fine *B*-delay controls, as well as the usual oscilloscope controls. These controls are simpler to operate than those of the Model DAS-1 receiver-indicator and are similar to those of Model DAS-2.

When the slow-trace oscilloscope pattern is displayed, the LEFT-RIGHT switch moves the signals rapidly along the trace by momentarily changing the feedback; when one of the fast-trace patterns is displayed, the switch moves the signals slowly by changing the oscillator frequency.

The eight-position sweep-speed switch is so designed that in making a time-difference measurement the operator rotates the switch in numerical sequence from Position 1 to Position 7. The first four positions show the received signals and are used for positioning and matching the signals. On the first position the normal slow-trace pattern is displayed. The patterns of the second and third positions are fast traces of 750 μsec and 200-μsec respectively. For the final matching of the pulses, the separation of the 200-μsec traces is eliminated in Position 4. Positions 5, 6, and 7 are used for measuring the time difference between the initiations of the fast traces corresponding to the time difference between the received signals. For this purpose 10-, 50-, 500-, and 2500-μsec calibration markers are displayed on these three positions. The pattern on Position 5 is two 200-μsec traces with markers; on Position 6 it is two 750-μsec traces with markers; and on Position 7 it is two slow traces with pedestals and markers. On Position 8 two 200-μsec traces with the stair-step pattern of the third divider are presented for checking the adjustment of the feedback.

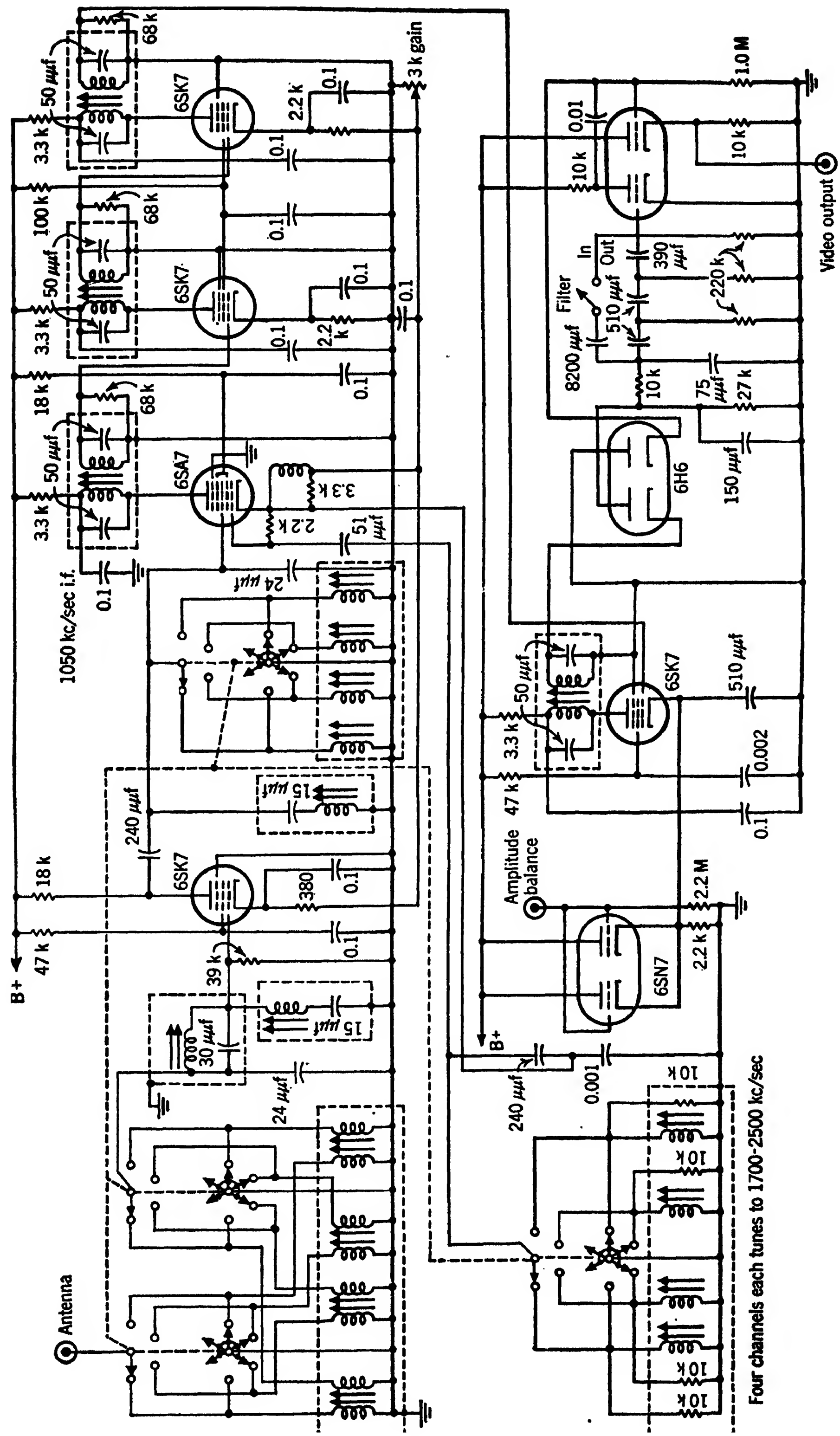


FIG. 11·12.—Schematic diagram of Model AN/APN-4 receiver.

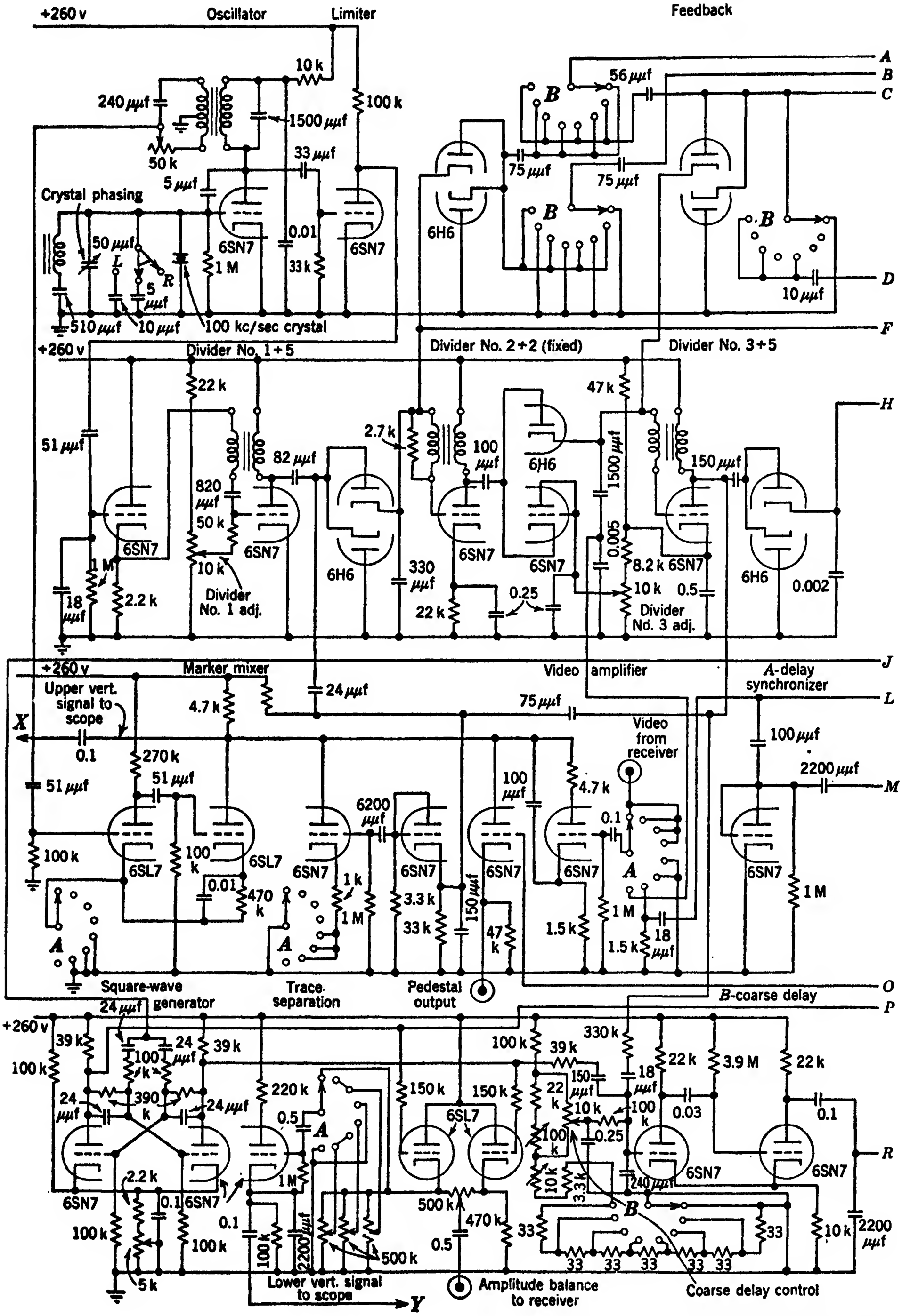
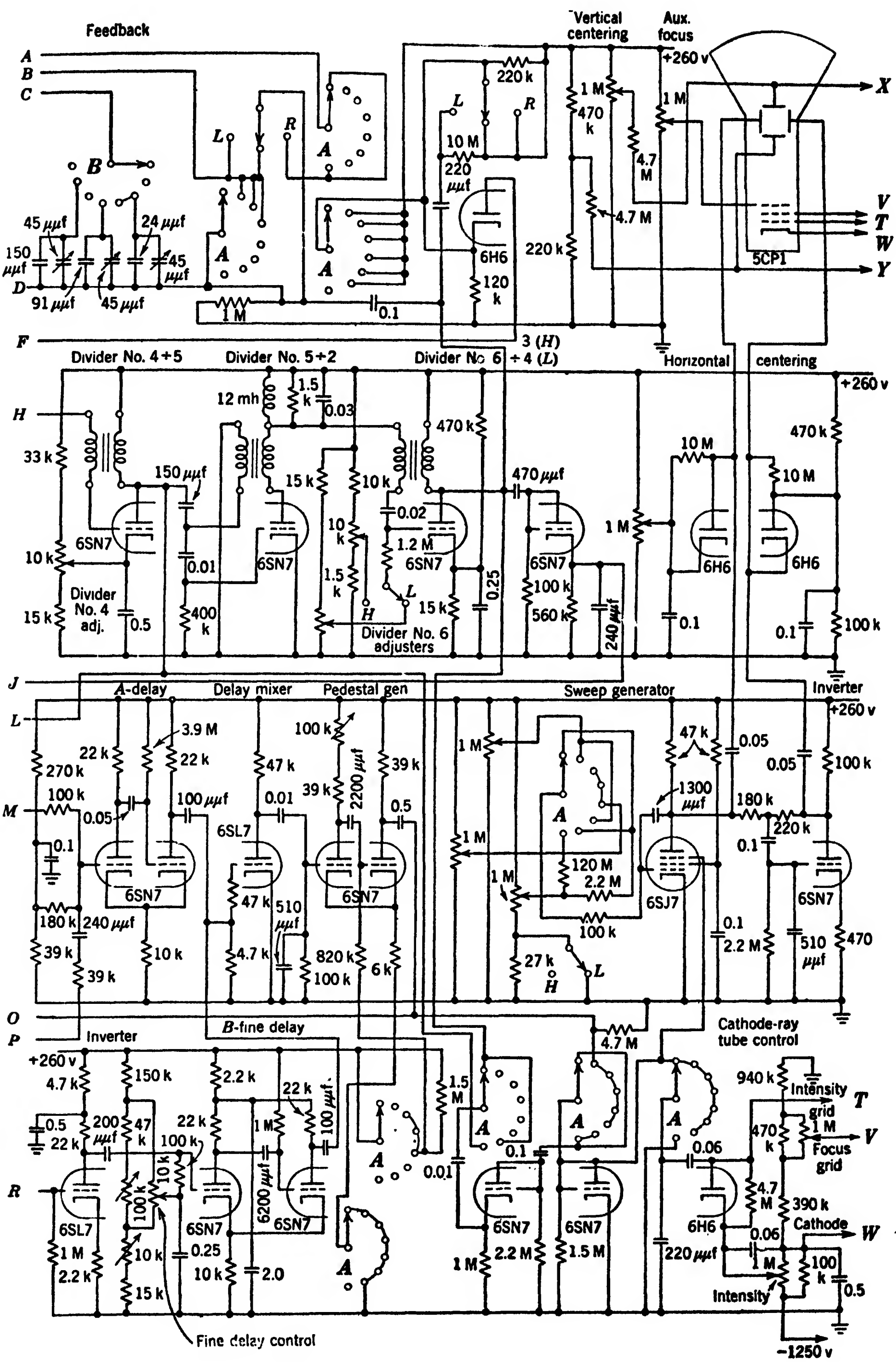


FIG. 11·13.—Schematic diagram



of Model AN/APN-4 indicator.

11·7. The Model AN/APN-9 Receiver-indicator.—The Model AN/APN-9 airborne receiver-indicator, shown in Fig. 11·14, is constructed in a single unit weighing only 40 lb and consuming 190 watts of power. It employs a 3-in. cathode-ray tube and is equipped with a magnifying glass and detachable visor.

Oscilloscope Presentation.—As indicated in Fig. 11·15, the oscilloscope patterns differ radically from those of the earlier models. The slow-trace pattern with received signals (Fig. 11·15*a*) consists of two slow linear traces. The slow-trace pattern with 1000- and 5000-μsec calibration markers (Fig. 11·15*f*) is a single slow linear trace, the lower trace of Fig. 11·15*a*. The relative timing of the two fast traces is represented on the slow trace by two differentiated negative markers instead of the *A*- and *B*-pedestals of other models. One differentiated marker (corresponding to the *B*-pedestal) is stationary at the left end of the lower trace; the position of the other (corresponding to the *A*-pedestal) can be varied from the right end of the lower trace to approximately the center of the lower trace. In earlier models of the receiver-indicator the time difference is measured from a point on the lower trace directly below the start of the *A*-pedestal to the start of the *B*-pedestal. In Model AN/APN-9 the time difference is measured from the right end of the lower trace, which is the same in time as the point on the upper trace directly above the start of the *B*-marker, to the start of the *A*-marker.

The fast-trace pattern consists of two nonlinear fast traces with received signals (Fig. 11·15*b*, *c*, *d*, and *e*) or with calibration markers (Fig. 11·15*g*). The nonlinear trace is derived from a sweep waveform having a double slope and a duration of 1400 μsec. During the first 100 μsec of the trace the slope is steep; the cathode-ray beam moves rapidly to the right. During the remaining 1300 μsec the slope is less steep, and the beam moves more slowly to the right. Because of the nonlinearity of the fast trace, the received signals are distorted. As the signals move from left to right along the fast trace, they decrease in width. Similarly, the spacing between calibration markers decreases along the fast trace from left to right. The calibration markers on the upper fast trace, spaced at intervals of 10, 100, and 1000 μsec, are used for measuring the time difference in the initiations of the fast traces. Calibration markers spaced at 10-, 50-, and 500-μsec intervals are displayed on the lower trace, but in measuring the time difference the operator uses only the second 50-μsec marker as a cross hair. He measures the distance in microseconds from a point on the upper trace directly above the cross hair to the 10-μsec marker immediately preceding the first 1000-μsec marker to the right. Since the sweep waveform for the upper trace is similar to that for the lower trace, the time difference between the initiations of the fast traces is equal to the time difference measured from a point above any 1000-μsec marker to the first 1000-μsec marker to the right on the upper fast trace (plus the appropriate number of thousands of microseconds). However, to attain the required precision, the estimation of the units and tens of microseconds must be made on the expanded portion of the trace. If there were no time delay in the divider circuits and the square-wave and sweep generators, a 1000-μsec marker would appear at the start of the lower trace and it would coincide

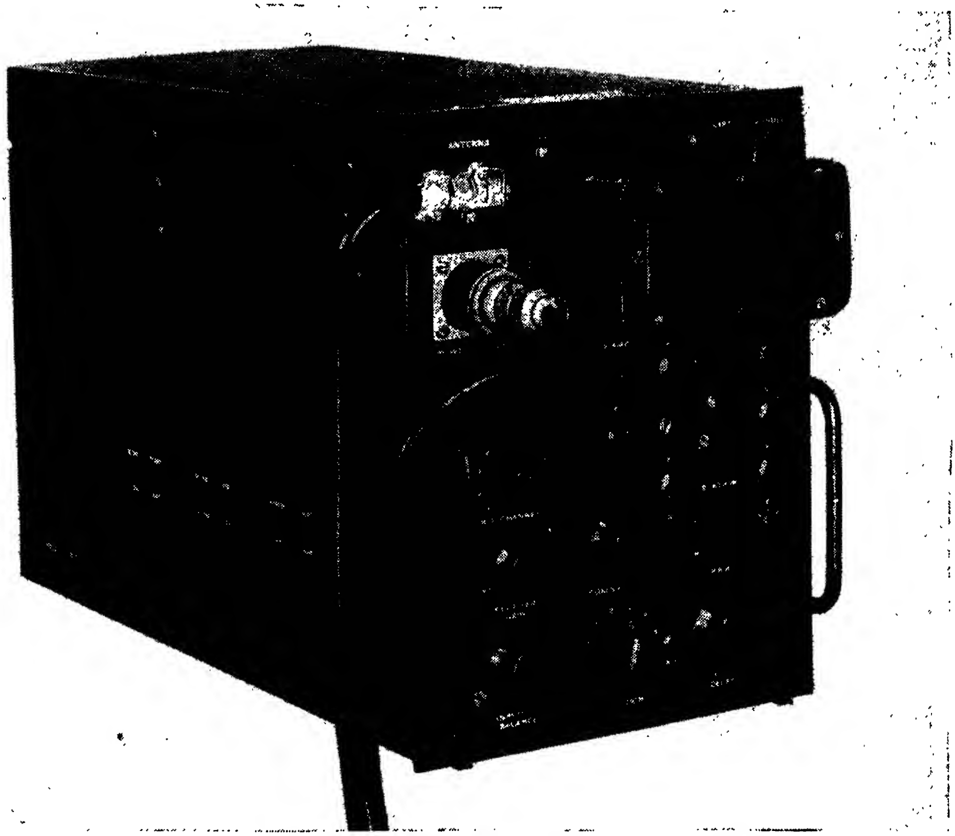


FIG. 11·14.—Model AN/APN-9 airborne receiver-indicator.

in time with the corresponding 10-μsec marker. Since the total time delay introduced by these circuits is slightly less than 50 μsec, the first 50-μsec marker following the 1000-μsec marker appears at the start of the lower fast trace. It is convenient to make the measurement from the second 50-μsec marker, which serves as a cross hair, to the 10-μsec marker on the upper trace that precedes the first 1000-μsec marker to the right of the cross hair. The true time difference between the received signals (and the initiations of the fast traces) is equal to the number of thousands of microseconds (observed on the slow trace) plus the time difference between 1000-μsec markers (estimated on the fast-trace pattern). Since the cross hair follows the invisible 1000-μsec marker that initiates the

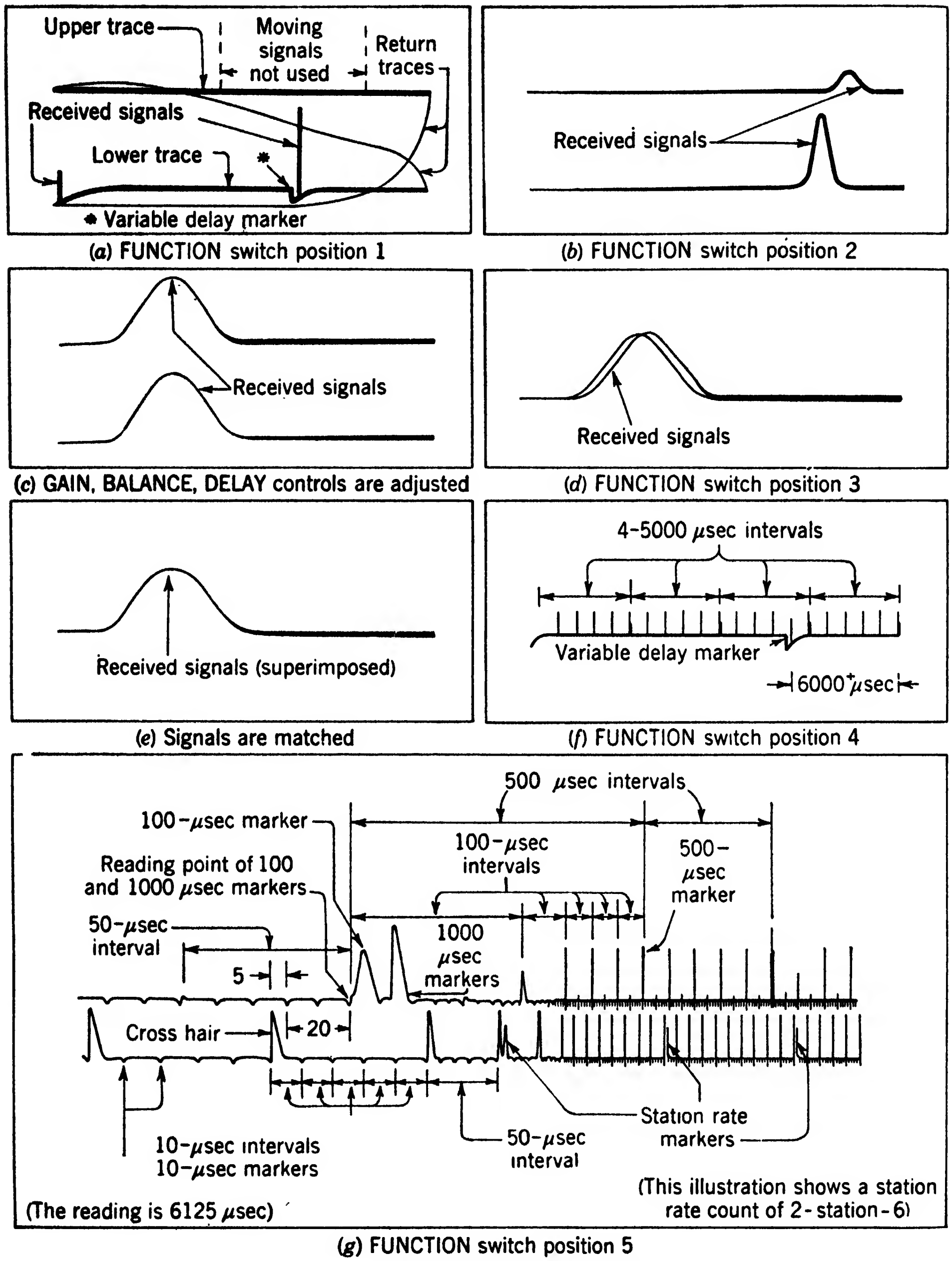


FIG. 11·15.—Oscilloscope patterns of Model AN/APN-9 airborne receiver-indicator. (*a*) Function switch on Position 1; (*b*) function switch on Position 2; (*c*) gain balance, delay controls adjusted; (*d*) function switch on Position 3; (*e*) signals matched; (*f*) function switch on Position 4; (*g*) function switch on Position 5.

lower trace by 100 μsec, this period must be added to the time difference measured from the cross hair.

Operational Procedure.—On Position 1 of the function switch both received signals are placed on the lower trace by means of the left-right switch and the signal at the left is moved to the extreme left end of the lower trace. The operator adjusts the coarse delay control to place the variable delay marker under the signal appearing to the right (Fig. 11·15*a*).

The received signals appearing on the fast traces of Position 2 (Fig. 11·15*b*) are balanced in amplitude, and the lower signal is moved to the left, expanded portion of the trace. The fine-delay control is adjusted to move the upper signal to a position directly above the lower signal (Fig. 11·15*c*).

On Position 3 (Fig. 11·15*d*) the separation between the two traces is eliminated. The operator adjusts the amplitude-balance and the fine-delay controls so that one signal is superimposed on the other (Fig. 11·15*e*). In this condition the time difference between the received signals is equal to the time difference between the initiations of the fast traces.

On Position 4 of the function switch (Fig. 11·15*f*) the time difference between the initiations of the fast traces (less half the recurrence period) is measured from the right extremity of the trace to the start of the variable delay marker. The operator counts the number of whole 1000-μsec intervals in this distance. In the example shown there are six such intervals, indicating that the time-difference reading is 6000 μsec plus a small time difference to be measured on the fast-trace pattern.

With the function switch turned to Position 5, the time interval from a point directly above the cross hair to the 10-μsec marker preceding the first 1000-μsec marker is estimated to the nearest microsecond. In the example shown (Fig. 11·15*g*) the interval is 25 μsec, and the total time-difference reading is 6000 plus 25 plus 100 μsec, or 6125 μsec.

The oscilloscope pattern displayed on Position 6 is similar to that on Position 2 and is used in that method of navigation called "homing" (Sec. 1·6). The operator preadjusts the coarse and fine delay controls to the time difference corresponding to his destination. Then, observing the received signals, he flies such a course that one signal approaches a position directly above the other. If he has two receiver-indicators, he may fly such a course that the two time-difference values approach the destination values simultaneously. Otherwise, it is common practice to bring one time difference to the destination value and then, flying along the corresponding line of position, to observe the time difference between the other pair of received signals as it approaches the destination value.

Functional Description.—The block diagram of the Model AN/APN-9 receiver-indicator as arranged for generating the slow-trace pattern (on Positions 1 and 4 of the function switch) is shown in Fig. 11·16. The

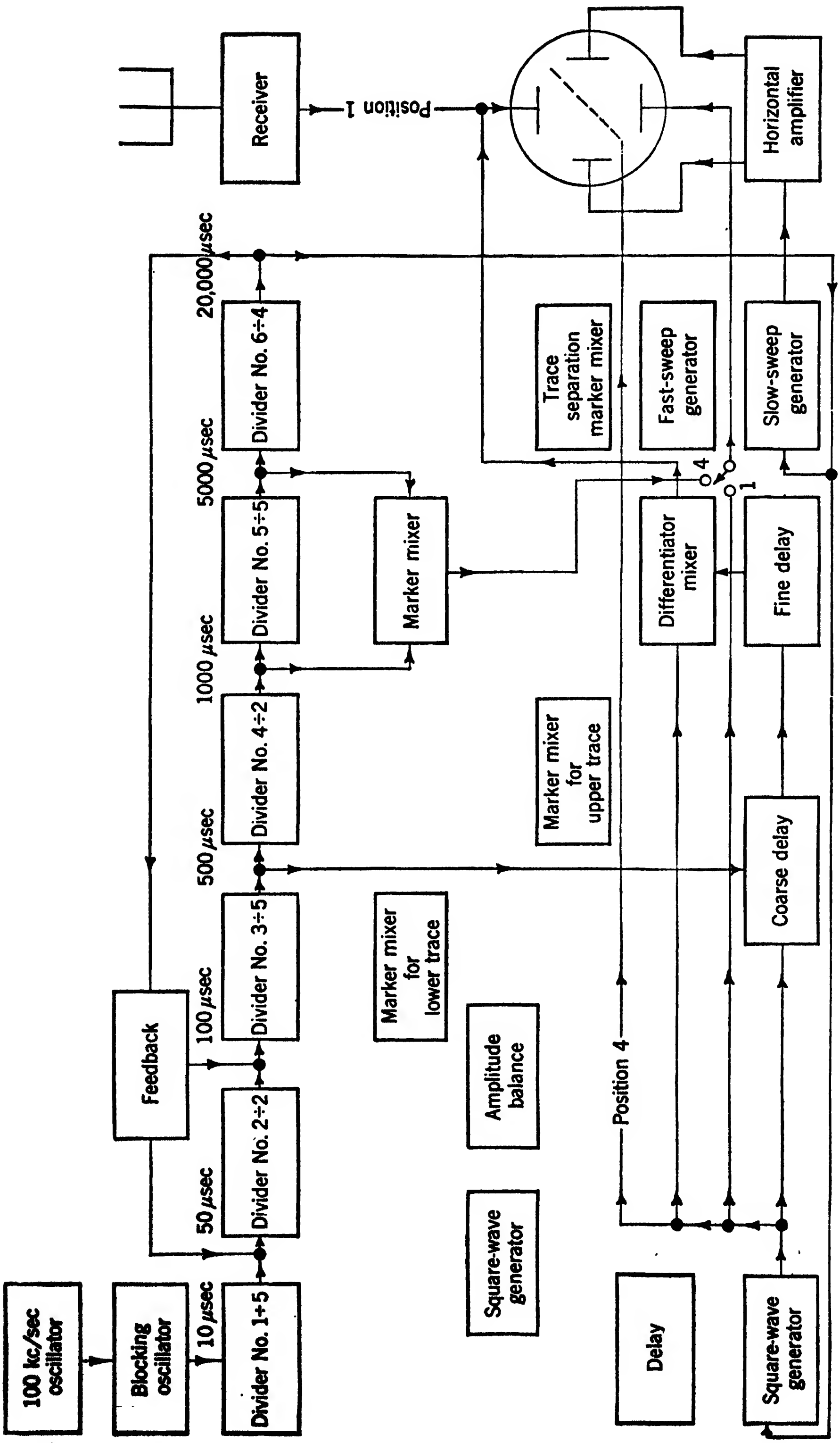


FIG. 11·16.—Block diagram of Model AN/APN-9 receiver-indicator on Positions 1 and 4 of the function switch.

oscillator, dividers, feedback circuits, and square-wave generator are similar to those of Model AN/APN-4.

The coarse delay multivibrator, triggered by positive pulses from the square-wave generator, is locked by 500-μsec pulses from the third divider. The delay introduced by this multivibrator can be varied in increments of 500 μsec from approximately 3000 μsec (to the right of the left extremity of the lower trace) to 15,000 μsec (the right extremity of the lower trace) on the high recurrence rate and from 6000 to 20,000 μsec on the low recurrence rate. Thus the time difference as measured from the right extremity of the lower trace can be varied from zero to 12,000 μsec on the high recurrence rate and from zero to 14,000 μsec on the low recurrence rate. The fine delay multivibrator, which is tripped by the coarse delay multivibrator, is continuously variable from approximately 400 to 1400 μsec. The positive output pulses from the fine delay multivibrator and from the square-wave generator are differentiated, mixed, and displayed on the cathode-ray tube to indicate the relative timing of the fast trace.

The slow-sweep generator is triggered by the output pulses from the last divider and provides linear sweeps each of which has a duration equal to half the recurrence period. On Position 4 the upper trace is eliminated by the action of a square wave on the grid of the cathode-ray tube, and calibration markers are displayed on the lower trace at 1000- and 5000-μsec intervals.

When the function switch is turned to Position 2, 3, 5, or 6 to display one of the fast-trace patterns, the circuits are arranged as indicated in the block diagram shown in Fig. 11·17. On the slow trace both markers indicating the initiations of the fast traces appear on the same level, whereas for the accurate matching of signals, one fast trace must appear directly above the other. For the fast-trace presentation, therefore, the square wave that provides the trace separation (and the amplitude-balance) is delayed approximately 3000 μsec with respect to the original square wave that initiates the stationary fast trace. To accomplish this the original square wave is passed through a delay network and the resulting differentiated waveform is applied at the appropriate level to the grid of a squaring amplifier.

In Position 5, output pulses from the first and third dividers are mixed in a circuit that is activated by the square wave. The output of this circuit is applied to one vertical deflection plate of the cathode-ray tube to provide 50- and 500-μsec calibration markers on the lower trace only. Similarly, 100- and 1000-μsec markers from the second and fourth dividers are displayed on the upper trace. Pulses from the blocking oscillator are applied to the other vertical deflecting plate to provide 10-μsec markers on both traces.

The fast-sweep generator, when triggered, produces a waveform that

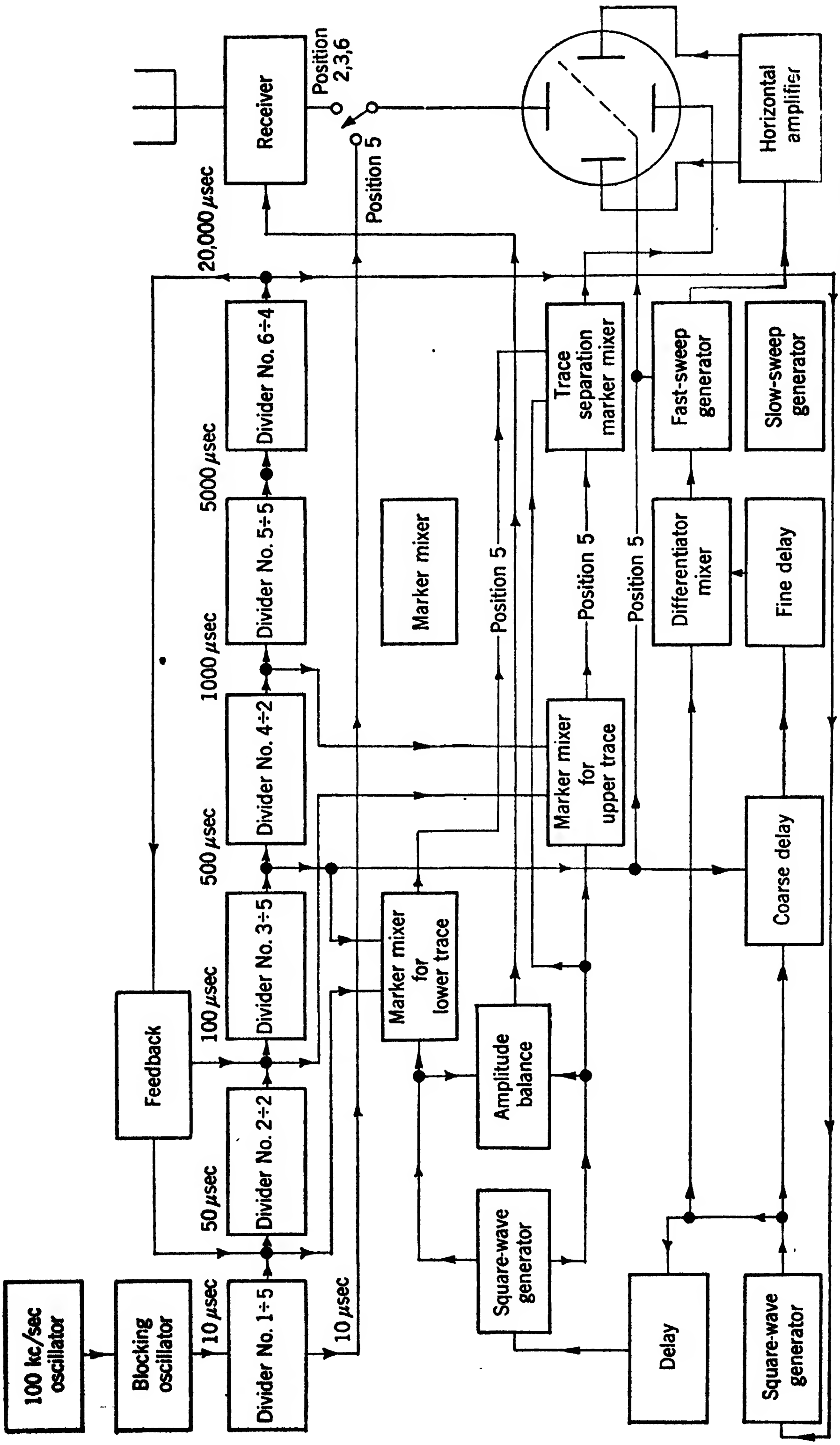


FIG. 11·17.—Block diagram of Model AN/APN-9 receiver-indicator on Positions 2, 3, 5, and 6 of function switch.

varies rapidly with time during the first 100 μsec and varies more slowly during the remaining 1300 μsec of the sweep. Two networks, one having a long time constant and the other having a short time constant, are connected in series between ground and the cathode of a triode. The junction between the two networks is connected to the cathode of another triode. The triodes, which are normally conducting, are cut off for the duration of the fast sweep. The cathodes, which are normally at high potential, are allowed to approach ground potential at rates that are determined by the characteristics of the networks. The combination of the two rates produces the desired waveform for the nonlinear traces.

TEST AND TRAINING EQUIPMENT

11·8. Pulse-signal Generators.—A low-power pulse-signal generator capable of simulating Loran signals of various radio frequencies, various

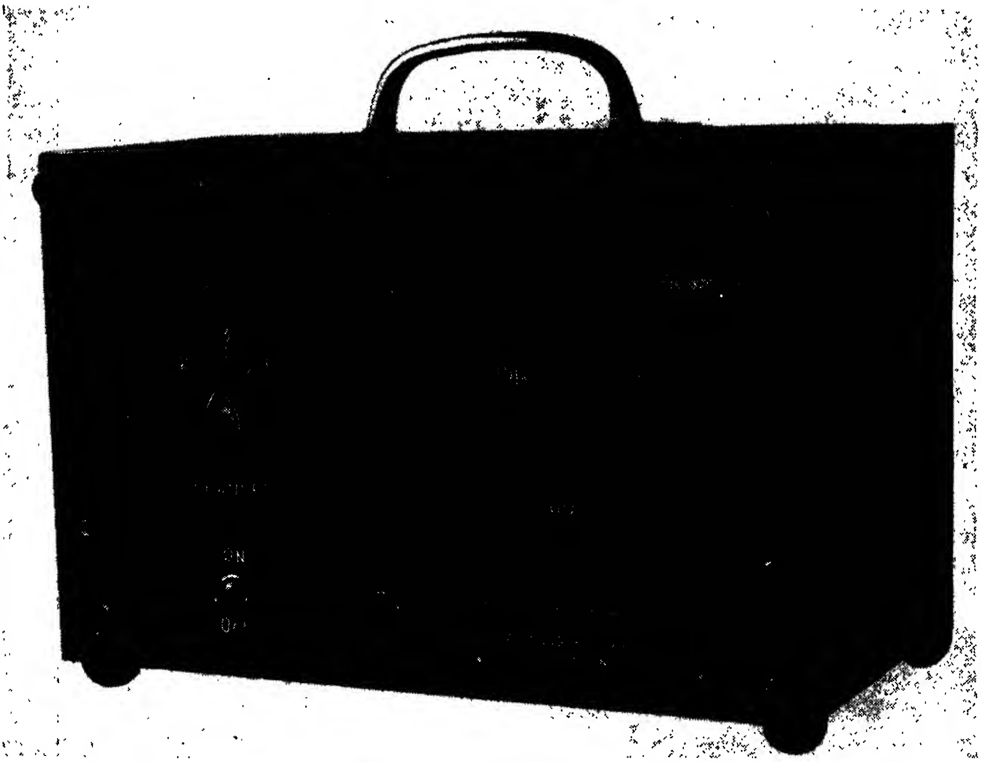


FIG. 11·18.—Pulse-signal generator for testing receiver-indicator.

pulse recurrence rates, and various time differences is a convenient device for training Loran operators and for testing Loran receiver-indicators. The Model I-204-A pulse-signal generator is designed for operation with shipboard indicators. The radio frequency can be varied from 1700 to 2000 kc/sec; and since the pulse generator is triggered by a standard indicator, the recurrence rate and time difference can be adjusted to any values encountered in standard Loran operations.

The Model I-194-A pulse-signal generator is designed for operation with airborne indicators. The circuit is similar to that of the Model I-204-A, but it is designed for operation on power of 80 or 115 volts and of a frequency from 400 to 2500 cps. The pulse generator is triggered by the indicator at the start of each pedestal. The differentiated positive pulse is amplified in two stages and impressed through a cathode follower on the screen grid of a pentode that serves as a pulsed Hartley oscillator operating at an adjustable radio frequency. The r-f pulse is amplified by two untuned pentode amplifiers and a tuned beam power amplifier. The amplitude and relative amplitudes of the output signals can be varied by means of the indicator gain and amplitude-balance controls.

The Model TS 251/UP test set (Fig. 11·18) has been developed as a portable pulse-signal generator for servicing Loran receiver-indicators. It produces signals at any one of three radio frequencies (1850, 1900, and 1950 kc/sec) and at any one of three amplitudes (15 μv, 1 mv, and 1 volt). The pulse recurrence interval, derived from a 1818.18-cps crystal oscillator, is 3300 μsec. On the Loran indicator oscilloscope this pulse recurrence interval produces a stationary pattern for the following basic and specific recurrence rates:

Basic PRR	Specific PRR
S (20 per sec)	5
L (25 per sec)	4
H ($33\frac{1}{3}$ per sec)	3

As indicated in the schematic drawing (Fig. 11·19) the crystal is of the duplex plate type. Its frequency varies only a few parts per million over the ordinary range of room temperature. A 6 to 1 divider provides the required recurrence interval, and a multivibrator and cathode follower drive the screen grid of a pentode oscillator that provides the output signal.

11·9. The Supersonic Trainer.—A simple pulse generator of the type discussed in the preceding section is adequate for training navigators in the use of the receiver-indicator for measuring time differences between simulated ground-wave signals. For training in the recognition of sky waves and in navigating by Loran from one point to another, a more elaborate trainer is required. Such a trainer, designed for the transmission and reception of supersonic pulses, has been developed by the Bartol Research Foundation.

The supersonic trainer simulates a Loran system of three ground stations (each of two transmitting at different recurrence rates and the third transmitting at both of the recurrence rates) and a mobile receiving station, representing the navigator. The three supersonic transmitters

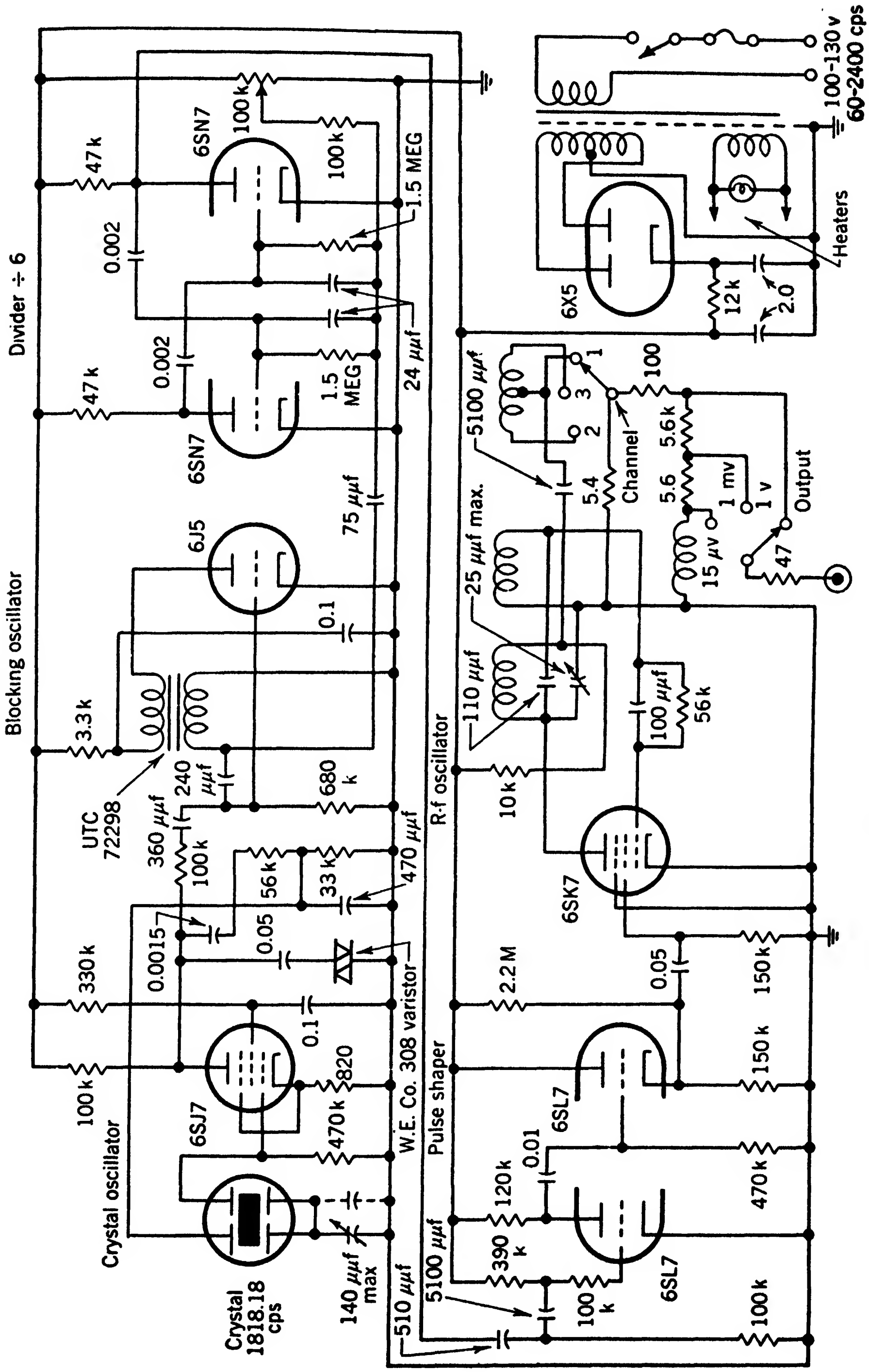


FIG. 11·19.—Schematic diagram of pulse-signal generator.

are set up on a flat table on which a moving crab, whose motion may be controlled by the instructor or by the navigator, carries the receiver, a piezoelectric crystal transducer. The receiving transducer transforms the supersonic (200-kc/sec) pulse signals to pulses of electrical energy which are converted to r-f (1950-kc/sec) signals and are amplified and radiated as electromagnetic energy. By means of a standard receiver-indicator the navigator receives the radiated energy and measures the time differences between the signals. A number of navigators, each

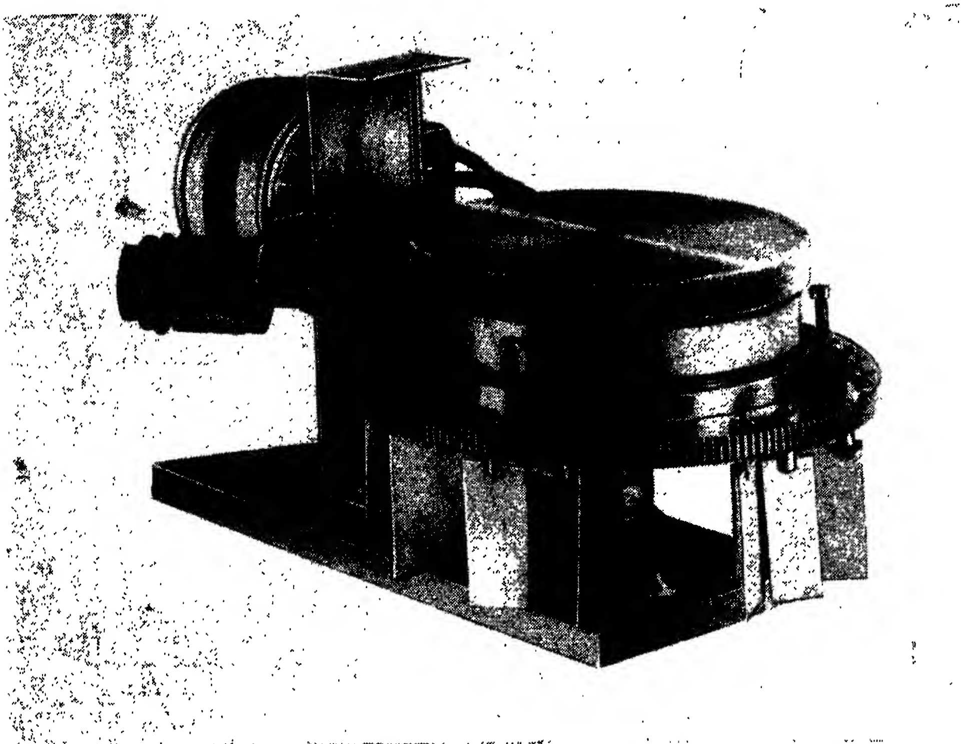


FIG. 11·20.—Supersonic pulse transmitter to simulate Loran ground station.

equipped with a receiver-indicator, can receive these signals at the same time. Interference in the form of random noise, radar interference, c-w signals, keyed c-w signals, or motor interference can be introduced at will.

Supersonic signals propagated over the surface of the table simulate ground-wave Loran signals. A ground-glass plate, upon which a latitude-longitude grid is drawn and upon which cross hairs are optically projected from the transmitters and from the mobile receiver, is supported several inches above the surface of the table. Reflections of the supersonic signals from the glass surface simulate reflections of Loran signals from the E-layer of the ionosphere. No attempt is made to simulate reflections from the F-layer. Splitting of sky-wave signals, caused by interference between sky waves that travel different paths and therefore reach the receiver in different phases, is produced by moving vanes in the vicinity of the transmitter, which introduce varying reflections of the sky waves.

The transducer unit representing the ground-station transmitter is shown in Fig. 11·20. Eight x-cut Rochelle salt crystals, in the form of 45° trapezoidal plates, are mounted with thin metallic electrodes between them in the form of a ring. The driving electric signal is applied between one set of alternate electrodes and the other. Since each electrode is common to two adjacent crystals, the electric field in any crystal is 180°

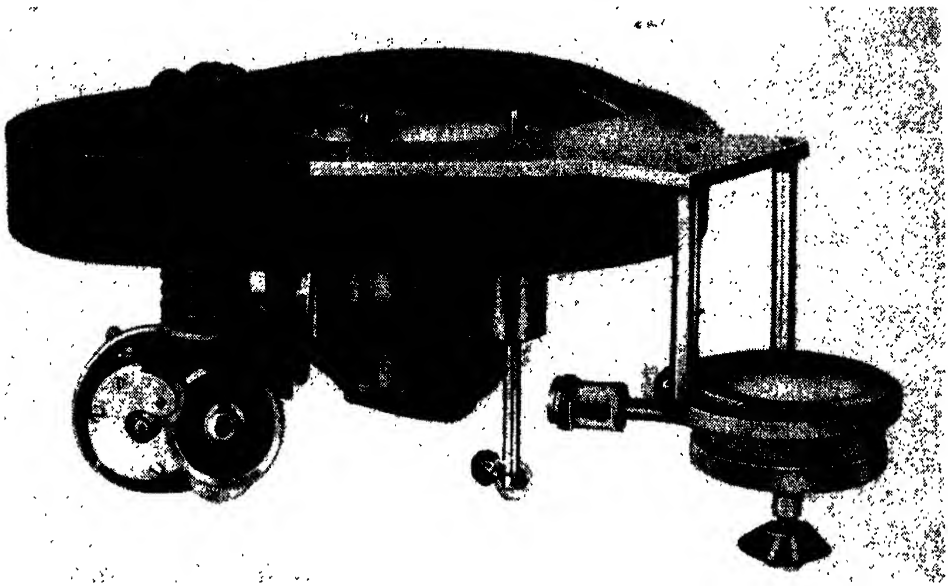


FIG. 11·21.—Mobile supersonic pulse receiver to simulate moving navigator's equipment.

out of phase with that of the crystal next to it. The crystals are so oriented that the direction of the positive x-axis of one crystal is opposite that of the two adjacent crystals, and the supersonic radiation from one crystal is therefore in phase with the radiation from adjacent crystals. The ring of crystals is immersed in oil, which damps the system and serves to match the impedance of the crystal system with that of the air. The supersonic radiation is directed downward through a quarter-wavelength of oil and a thin aluminum membrane into the air. It is reflected horizontally and slightly upward from a conic surface at the base of the transducer unit. A synchronous motor rotates a ring about the vertical axis sf the transducer. The ring supports a number of metallic vanes which produce the splitting of the first- and second-hop E-layer reflections.

The transducer unit representing the mobile receiver (Fig. 11·21) is mounted on a mobile carriage. Otherwise it is similar to the transmitter.

CHAPTER 12

SPECIAL TECHNIQUES AND MEASUREMENTS

BY G. H. MUSSELMAN

12·1. Receiver-design Notes. *Introduction.*—The circuits of Loran receivers in general use are similar in many respects to those in communications types. They differ principally because of requirements for wideband response and the need for a different amount of gain for alternate pulses. Aside from these restrictions and the modifications that they imply, the usual design practices for good superheterodyne receivers can be followed. The deviations from the normal will be discussed in somewhat greater detail.

Most Loran receivers are provided with four identical r-f channels that are tuned to assigned frequency bands in the range of 1700 to 2000 kc/sec. A selector switch with positions numbered 1, 2, 3, and 4 allows a choice of 1950, 1850, 1900, and 1750 kc/sec, respectively.

Early receivers were designed for high-impedance input with the idea that a short antenna could be terminated directly at the receiver. This arrangement proved to be undesirable, since better signal-to-noise ratios are obtained with an antenna resonated at the operating frequency by a loading coil, connected through a shielded coaxial cable to a receiver input of 50 to 100 ohms. The antenna is thus kept farther from sources of man-made noise.

One stage of amplification at radio frequency between the low-impedance input and the mixer is mandatory to provide image rejection and a signal well above the mixer noise. Successful receivers have been built with only one tuned circuit between the plate of the r-f stage and the signal grid of the mixer. This construction results in simplicity of switching and some saving of space but lacks the improved bandpass characteristics obtained with a double-tuned circuit that reduces cross modulation and response at spurious frequencies. A remote cutoff tube such as the type 6SK7 has been found superior in this stage to the type 6AC7, despite the higher mutual conductance of the latter. The inferior remote cutoff of the 6AC7 produces distortion of pulses of large amplitude.

A gain of 30 or 40 per stage is reasonable; with a gain of about 7 for the input transformer this gives a total gain of 210 to 280 from antenna terminal to the grid of the mixer.

A mixer stage employing a 6SA7 tube in either a Colpitts or Hartley oscillator circuit designed to prevent frequency drift is customarily used. The oscillator frequency is higher than the signal frequency by the amount of the intermediate frequency. Optimum injection voltage should be always used to secure the maximum conversion mutual conductance. A quartz crystal might be used in the oscillator circuit of each channel if operating extremes, such as temperature, required the additional expense and slight inflexibility of a more stable circuit.

Intermediate frequencies used in different receivers have varied from 500 to 1600 kc/sec. The latter frequency was used in early receivers mainly because of easy procurement. The most used frequency has been 1050 kc/sec, although the second harmonic is close to the r-f value and may produce undesirable effects with large signals. The 550-kc/sec channel does not suffer from this defect.

Double-tuned circuits, critically coupled with unity-turns ratio between primary and secondary, have been used with various values of tuning capacitance, the lower capacitances allowing higher values of damping resistors for the same bandwidth. The response of each stage is designed to be down 1 db or less at 25 kc/sec each side of the center frequency. By using a desirable type of tube such as the 6SK7, stage gains in the order of 30 to 40 are possible. Generally three stages are employed followed by a diode detector.

The problem of matching two pulses of generally unequal amplitude was first solved by applying a voltage square wave to the cathode of the last i-f amplifier and varying the gain of this stage differentially. The square wave is timed by the indicator circuits, the magnitude and relative polarity being controlled by a potentiometer known as the gain- or amplitude-balance control. In later receivers the control is put on the first r-f tube to prevent overloading by strong signals. This typical feature of the Loran receiver is discussed in greater detail in Sec. 12·2.

A diode detector can be arranged in a conventional circuit to provide either positive or negative swing corresponding to increased carrier. The polarity chosen depends both upon the number of phase reversals encountered between detector and oscilloscope and upon which vertical plate of the oscilloscope is used for the video signal. It has been common practice to use the detector connected so that the output is negative and to follow this with one high-gain video stage. The video stage, usually a 6AC7 with little bias and a 20,000-ohm plate load, is resistance-capacitance-coupled to that plate of the oscilloscope which gives an upward deflection for positive-going signals.

It is desirable to operate the detector at a carrier level of about 10 volts peak. Receivers designed for operation at lower levels than this showed nonlinearity of the detector with small signals. Furthermore, if the level at the detector is kept up, it is easier to design effective limiting circuits that prevent large bursts of noise from overloading the video stage.

The main gain of the receiver is controlled by varying the cathode voltage of all the remote cutoff tubes, bringing the cathodes to ground through a common gain potentiometer. Sufficient r-f filtering must be applied at the individual cathodes to prevent undesired interstage coupling through the control.

A high-pass filter section between the detector output and the input to the video stage reduces certain types of interference (mainly that from c-w stations) but should be normally switched out of the circuit, since it degrades the desired pulses. The filter usually takes the form of a simple resistance-capacitance network that cuts off at about 1000 cps. Normally, the video response is uniform from 100 cps to 50 kc/sec.

The over-all bandwidth from the antenna terminal to the oscilloscope should be 50 kc/sec measured at points 6 db down from the maximum. If, however, the r-f stage and the mixer stage are too broad, cross modulation between Loran signals and broadcast or other strong signals in the region of 2.0 Mc/sec will occur. Single-tuned parallel- or series-resonant trap circuits tuned to the intermediate frequency can be inserted in the antenna and r-f stages to reduce cross modulation. A parallel-tuned circuit in series with the screen grid of the r-f amplifier tube is effective. But because the screen is a nonlinear modulating element, when large increments of screen voltage occur, a similar circuit placed in series with the cathode of the same tube is even better.

General Requirements. Bandwidth.—Total receiver bandwidth should be 50 kc/sec at 6 db down and 150 kc/sec at 60 db down. This over-all measurement can be made by applying a 30 per cent modulated signal from a calibrated signal generator to the antenna terminals. The output is measured on the indicator oscilloscope or a d-c voltmeter connected to the diode-load resistor. As the input frequency is varied by 5-kc/sec increments, the input level is adjusted to maintain constant output. Plotting the required input level against frequency gives a selectivity curve that contains most of the bandwidth information at a glance. A second rough curve should be drawn for a greatly different input level; if its shape departs widely from that of the first curve it indicates the presence of regeneration in the i-f or r-f amplifier.

Image-rejection Ratio.—The receiver's effectiveness in rejecting images, signals having a frequency numerically twice the intermediate frequency plus the desired signal frequency, is expressed as the ratio between the image, frequency signal applied to the input and the signal of the desired frequency that, when applied to the input, produces the same output. The ratio should be 60 db or better.

Spurious Response.—The ratio of undesired signal amplitude to desired signal amplitude giving the same output from the receiver is measured with one or more signal generators. All spurious response should be down 60 db or more.

I-f Rejection Ratio.—The i-f rejection ratio is the ratio between the amplitude of an i-f signal applied to the input of the receiver and the amplitude of the desired r-f signal that when applied to the input of the receiver, produces the same output. Although some Loran receivers do not meet the figure, a ratio of 60 db is desirable.

Noise Factor.—The combination of r-f and i-f noise should not exceed the equivalent of 0.5 μv. It can be measured by introducing an unmodulated signal from a calibrated signal generator to the antenna terminals. At full gain, the ratio between this signal voltage and the resulting d-c voltage produced across the diode load resistor is determined. The calibrating voltage must be large compared with the residual-noise voltage but small enough to ensure linear response from the diode. A second d-c voltage reading is taken with the signal generator removed. (This voltage is actually a combination of noise and diode emission.) The product of the second voltage and the ratio is the residual noise expressed as an equivalent voltage referred to the antenna circuit.

Maximum Sensitivity.—About 1-in. peak-to-peak deflection on the indicator oscilloscope should be produced with a 5.0-μv signal (50 per cent modulated at 400 cycles) applied to the input terminals. Much greater sensitivity than this is not necessary because atmospheric noise at this frequency limits the usable over-all gain.

Sensitivity Range.—A receiver should be capable of reducing a 200,000-μv 50 per cent modulated signal applied at its input terminals to a 2-in. peak-to-peak deflection on the indicator oscilloscope, with the gain-balance control in the center position. The entire receiver should be designed to amplify a signal of 600,000 μv linearly, even though it produces more deflection than can be accommodated on the face of the indicator oscilloscope. If an iron-core choke is used as plate load for the video stage, for the same plate-supply voltage considerably more swing without overloading is possible than with resistance load. The frequency characteristic can be improved by introducing negative feedback. Several of the present receivers overload with a signal giving a little above 3-in. deflection.

Gain-balance Range.—The amplitude- or gain-balance circuit should have a maximum range of 1000 times with no more than 1 μsec of introduced error. This range should allow a maximum signal of about 2.0 volts rms to be matched with one of 2000 μv rms. Thus, a receiver embodying the specified sensitivity range should be capable of operating anywhere in the service area and within 10 miles of one station, assuming an antenna system of about 5 meters effective height for the receiver and a radiated power of 100 kw for the transmitters.

This measurement must be made with a special generator capable of emitting pulses similar to those of the Loran transmitters. The equipment has a calibrated attenuator; and, although the recurrence rate is not critical, it should have such a value that at least one pulse per trace is visible when the output is applied to a Loran receiver. The timing of this generator should be locked in with the Loran indicator associated with the receiver under test. A reliable differential-gain system with no phase error incorporated in such equipment would enhance its value. If, instead, a standard attenuator is used, it is desirable to operate the signal generator so that there is one pulse emitted per 40,000 μsec. As the signal amplitude from the generator is varied, the range of the receiver amplitude-balance circuit can be determined from the amount of change of the balance control required to maintain the pulse at constant height on the indicator oscilloscope. The shape of the pulse is traced on the screen with a crayon to facilitate the test. In checking the phase error in the receiver, the signal generator should be locked to the indicator recurrence rate so that there is no drift of the pulse on the indicator screen. As the attenuator and gain-balance controls are varied over the extreme range, any shifting of the pulse in phase will be immediately evident.

Although the above specifications seem desirable in the light of experience consistent with present-day standards for Loran, it should be noted that many receivers in current use vary widely from these standards.

12·2. Differential-gain Principles.—Most pulse systems depend entirely on fast-rising pulses in order to achieve precision. The limitations imposed upon pulse shape through the use of medium radio frequencies for Loran service require a superposition technique to attain the degree of precision necessary. Because each signal of a pair is usually received at a different amplitude, the time difference between two series of recurrent pulses is most accurately determined by amplifying each series by a proportionate amount; and thus when the two pulses are viewed on the oscilloscope trace, they are of equal amplitude.

Ground-station Requirements.—The average Loran ground-station receiving problem is one of matching two series of pulses that differ by between 20,000 and 200,000 to one in amplitude depending on station and system layout. The problem is still more complex because the larger of these two series of pulses (the local signal) has an amplitude of several hundred peak volts.

The present method accomplishes the desired result in two steps. An amplifier with negligible delay time passes the small remote signal but is biased to cutoff during the local-signal time. The desired amount of local signal is paralleled with the inactive amplifier output to the receiver input. The timing of the biased-off interval is controlled by the timer that also triggers the local transmitter. Leakage through the attenuating amplifier is negligible in the biased-off condition compared with the signal fed around by the resistance-attenuator network. It is desirable to have an even number of tubes in the amplifier so that a 180° phase difference is not encountered between the signal from the amplifier and that from the resistance network. This is particularly true when the cycle-matching system is used in the receiver.

The delay time through the biased amplifier is held to a low value by using resistance-capacitance coupling between stages, with a plate-load resistance small in comparison with the total shunt capacitance and the series coupling capacitors large so that their reactance is small compared with the grid resistors.

The signal leakage through the biased amplifier in the off condition is theoretically a function of the ratio of plate-load resistance to the grid-plate capacitive reactance. In practice, it is almost impossible to achieve as low a degree of leakage, because couplings from input to output of the amplifier by way of chassis currents and stray capacitances determine the lower limit. Vacuum-tube heater leads and plate-supply and bias leads must be equipped with adequate filter networks. It is possible to increase the over-all ratio by adding more stages, which increases the gain during the remote signal time without greatly increasing the leakage during the local signal time. The transmission band of the amplifier must, however, be kept extremely wide.

Navigator's Equipment.—The difference in signal amplitude at the navigator's receiver depends on the location of the equipment with respect to the stations being received and can vary from zero when the location is equidistant from the stations to a large number when the location is close to one of the stations. The extreme ratios encountered in the operation of ground-station equipment need not be considered in the design of mobile receivers. A large percentage of the service area can be utilized with a receiver capable of handling a ratio of 30/1, and all of the original Loran receivers were so designed. Current practice tends toward a 1000/1 ratio, which includes more of the service area close to the stations.

The receiver must equalize the amplitude of pulses seen on a cathode-ray tube without adding any appreciable differential delay. In standard 2.0-Mc/sec operation, circuits are designed so that no more than 1 μsec of error is introduced by the gain-balance circuit at its extreme range. In general, a variable-μ pentode tube is used in the i-f or r-f amplifier channel, the bias of which is controlled by a potentiometer to apply a square wave of variable polarity and variable amplitude. The source of the square wave is the Eccles-Jordan circuit in the indicator, and thus the gain of the receiver can be reduced during either the period of the upper trace or that of the lower trace. The amount of gain reduction and the trace on which it operates correspond to the amplitude and polarity respectively of the square wave as determined by the manual setting of the potentiometer.

An early form of amplitude-balance circuit used a cathode follower to raise or lower the current through the amplifier cathode resistance, increased current corresponding to higher bias or less amplification as shown in Fig. 12·1. The static current drawn by the amplifier limits the effect of the cathode follower to the positive-going portion of the square wave. As a result, when the potentiometer is set anywhere but

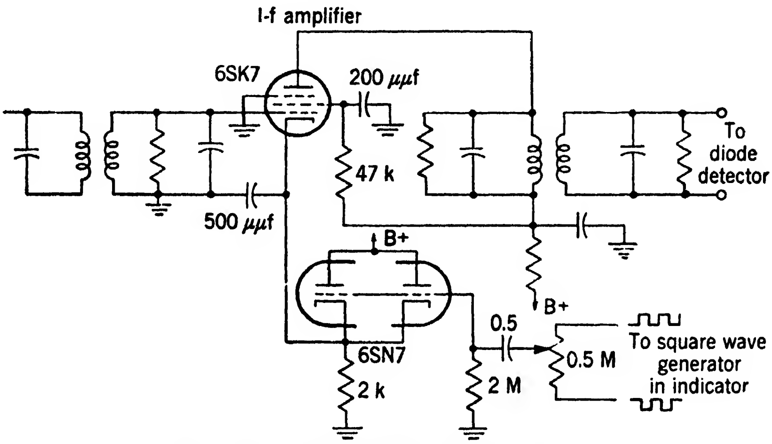


FIG. 12·1.—Early gain-balance circuit.

at the midpoint, the gain during the sensitive or unbiased trace remains constant, whereas the gain during the time of the less sensitive trace is decreased progressively as the control is advanced. This effect is desirable in that the main gain can be set for the proper amplitude of the smaller pulse, after which the balance control is adjusted to lower the amplitude of the larger signal.

In later Loran receivers the controlled stage is the first r-f amplifier. Because there is less danger of large signals overloading the receiver ahead of the gain-balance stage, the equipment can be used close to the transmitting stations.

In order to obtain optimum ratio of gain between the sensitive and attenuated traces, it is necessary to hold the screen voltage constant, with either a heavy-current bleeder or a regulator tube. The suppressor grid is grounded instead of being returned to the cathode.

It is comparatively easy to obtain ratios of the order of 30 or 40 with negligible distortion of the larger signal. Attempts to exceed this ratio result in a distortion of the larger pulse such that it cannot be accurately matched with the weaker. The distortion encountered is probably a combination of amplitude nonlinearity and leakage of the signal through stray capacitances around the amplifier tube. Ratios in the order of 100/1 have been accomplished by taking extreme care in circuit layout. For larger ratios it seems imperative to cascade two controlled amplifiers.

A system using two amplitude-balance stages separated by a conventional amplifier stage has been used in the portable cycle-matching receivers. Here each controlled stage consists of two cathode followers illustrated in Fig. 12·2. One tube, for example, is on by virtue of its plate voltage being at about 200 volts during the upper-trace time,

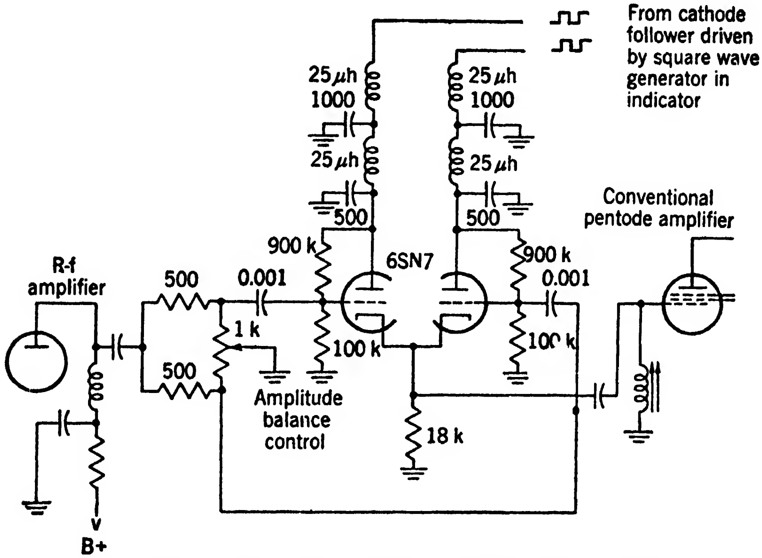


FIG. 12·2.—Dual cathode-follower gain-balance circuit.

whereas the other tube is off owing to the fact that its plate voltage is only slightly positive. During the period of the lower trace, the operating conditions of the tubes are interchanged so that a different tube is conducting for the duration of each trace. The Eccles-Jordan circuit provides this timing, and each tube experiences the same operating voltages regardless of the degree of amplitude balance desired. The difference in gain is obtained by varying the input signal applied to each tube by means of a potentiometer and resistance network. Using resistors and a potentiometer of about 500 and 1000 ohms respectively, it is possible to obtain ratios of about 30 per stage with little distorting of the pulses. It is important that the grid-to-cathode capacitive reactance of each tube be small compared with the effective resistance between cathode and ground. When these values begin to approach equality, the pulse at the cathode becomes the resultant of that from the capacitive path and the true pulse generated by the tube current through the cathode resistor. It is also important that the potentiometer resistance be small compared with the wiring and other shunt-capacitive reactances to avoid phase shift between the signal voltages applied to the two grids, resulting in the creation of differential delay for large ratios.

The 180-kc/sec frequency at which cycle-matching receivers are used is well suited for this type of gain-balance circuit because the reactances are high enough to allow reasonable values for the potentiometer and resistance network. Since both the input and output of the amplitude-balance stage are low-impedance terminations, series-resonant circuits are employed, the inductors and capacitors of which have such values that the terminations of the stage serve as the damping components to provide sufficient bandwidth.

The corresponding potentiometers in the two amplitude-balance stages are operated from common shafts. Radio-frequency filtering is employed in the plate circuits of the cathode followers to prevent the signal leakage between stages. A maximum range of 1000 to 1 is available with less than 1 μsec of introduced differential error, using the first stage in the receiver as an amplitude-balance stage.

All efforts toward perfecting amplitude-balance techniques have been restricted to the current use of Loran which requires matching only two pulses at a time. It may be desirable in an improved system to employ a master and two easily identified slaves at the same recurrence rate, the three matched simultaneously to provide the navigator with a fix from one operation rather than two as now. This development would necessitate a three-trace indicator and a gain-balance circuit capable of handling three different amplitudes instead of two. For this application, the variable-μ pentode controlled stage is more flexible than the cathode-follower type.

Some thought has been given to a receiver that would have automatic gain control for the pulses on the pedestals. Any simple refinement of the AVC principle seems doomed, because a large pulse would arrive at the oscilloscope electrodes before the gain of previous r-f amplifiers could be decreased. A rather elaborate modification would enable a sampling network to measure, for example, the pulse on the A-pedestal, generate a bias sufficient to reduce the gain of a controlled stage by the proper amount, and store this bias until just before the A-pedestal appeared, before applying the bias to the controlled stage.

By this method each individual pulse on the A-pedestal would be sampled, and the voltage created from it would control the gain of the next individual pulse. For three pedestals it would require sampling each signal and storing the appropriate bias in three separate circuits, together with a switching system, to apply the bias to the controlled tube at the proper time.

Another system would amplify all signals in several stages and then sample them for amplitude. A long delay line might be used to retard the pulse appreciably so that the gain of succeeding stages could be controlled and brought to the proper sensitivity by the time the pulse emerged from the delay line into the succeeding stages. It would, however, require a line of approximately 100-μsec minimum delay to provide sufficient time for the controlled stage to reach equilibrium before applying the actual pulse signal. Such a line would be prohibitive in size if composed of ordinary lumped constants. It might be entirely possible to construct an acoustic line employing supersonic frequencies for this purpose. The design of the sampling voltmeter capable of handling the necessary ratios is also interesting to contemplate.

The pressure of wartime Loran developments did not permit the expenditure of effort on operational refinements, but current progress in this direction is important, particularly since the use of automatic receivers for automatic pilotage of various sorts hinges to a great extent on a simple but foolproof automatic gain-balance system.

12·3. Pulse-signal Generator. *General Description.*—For the Low Frequency project a signal generator was built that proved to be exceedingly useful for general receiver and attenuator testing. The device generates 180-kc/sec pulses of the same shape as those emanating from the Loran transmitters operating at that frequency, although the shape can be varied somewhat from normal to suit individual test requirements. A crystal oscillator is used as the primary timing source, with a series of blocking-oscillator dividers and one multivibrator-type divider to count down to the desired recurrence rate. The pulse recurrence rate is 40, 50, or $66\frac{2}{3}$ pps, depending on a potentiometer adjustment in the last timing stage, which can divide by 10, 8, or 6.

The r-f pulse is generated by a Hartley *LC* oscillator circuit, which is screen-grid-pulsed by the timer and shaping circuits. The radio frequency is adjustable over a range of about 10 kc/sec each side of 180 kc/sec by means of a tuning capacitor controlled from the front panel.

The output amplitude of the pulses can be varied from 1 μv to 1 volt. A peak vacuum-tube voltmeter reads the input level to an attenuator; and when the level is properly set according to the meter, the output amplitude is read directly from the attenuator and a calibrated potentiometer. Accuracy of calibration is good to about 10 per cent for long periods of time.

Timer Circuit.—A triode oscillator controlled by a 100-kc/sec crystal drives the counter chain. The first stage, dividing by 2, is a blocking-oscillator divider with the time-constant circuit in the cathode, since it was found that the cathode current is less affected by changes in filament voltage than is the grid current. The next three dividers are of the same type, except that each divides by 5. The last divider stage is a cross-coupled multivibrator that favors even counts. The count can be adjusted for 6, 8, or 10 by varying the bias voltage applied to the control grids. If the d-c voltage is near ground potential, the count is long and decreases as the voltage is made more positive. The output of this stage is essentially a square wave, but during the decreasing voltage time there is sufficient undershoot so that a biased cathode follower is used to eliminate it. The output of the cathode follower is a clean square wave. Two additional tubes are used to shape and amplify the pulsing pip, and a cathode follower raises the screen grid of the 6V6 oscillator tube to several hundred volts during the pulse time. The cathode of the oscillator is held at a sufficiently positive voltage to cut the tube off at all other times.

Radio-frequency energy is taken from the oscillator by means of a small link coupled to the plate tank and fed through a concentric line to an *L*-pad. It is important that any setting of the pad present a constant resistance to the line so that there is no effect on the frequency of the oscillator. The output of the *L*-pad is connected to the vacuum-tube voltmeter and to the calibrated potentiometer.

The vacuum-tube voltmeter consists of a diode rectifier with a time constant that is long compared with the period between successive pulses.

A d-c amplifier follows the diode and drives a 0- to 200-μa d-c meter used only as a reference indicator. The equipment is calibrated by comparing the pulse (peak) output with the c-w output of a standard 180-kc/sec source using an oscilloscope as the indicator. With the General Radio attenuator dials set to the value of the known calibrating voltage the carrier-set control (*L*-pad) is adjusted until the two outputs are the same in peak amplitude. The meter reading under these conditions is used for the standard oscillator output setting.

A selector switch and inspection jack permit checking the operation of each divider stage with a small oscilloscope. Each divider is provided with an adjustable coupling capacitor to vary the count by one or more steps.

The 100-kc/sec oscillator has a frequency adjustment in the form of a variable capacitor across the crystal to permit slight changes so that the pulse signal can be stopped on the traces of the indicator associated with the receiver under test.

12·4. Pulse-bandwidth Measurements.—The action of tuned circuits on the shaping of pulses has been a subject of particular interest in the Loran development. Most other systems base their accuracy on the principle of using fast-rising pulses, so that a comparatively large percentage of shaping can be tolerated. Bandwidth requirements for such pulses are easily satisfied in the microwave region. At medium and particularly at low radio frequencies the bandwidth is appreciable compared with the carrier frequency, and the use of slow-rising pulses is mandatory. In order to realize adequate precision at these frequencies it is necessary to match two pulses closely by bringing them both to the same amplitude and to superimpose them. The accuracy of measurement obtainable depends to a great extent on the shape of the pulses.

A square-wave-pulsed 180-kc/sec oscillator, triggered by a Loran indicator, was built as a part of the experimental program summarized below. The pulse rises to full amplitude in two cycles, remains flat for 150 μsec, and then falls in several cycles. A cathode-follower type of pulser applied across the oscillator tank coil starts the oscillator at almost full amplitude, provided the static current drawn by the cathode follower through the inductance is carefully adjusted.

The output of the oscillator is taken through a cathode follower to obtain a low-impedance output. A wideband receiver (80 kc/sec at 3 db down, 95 kc/sec at 6 db down) operates into a conventional indicator with cathode-ray tube.

With the square-wave 180-kc/sec signal applied to the test receiver, the pulse rises in about 15 μsec to 95 per cent of full amplitude. This is within 16.7 per cent of the calculated value of 12.5 μsec which is given by the reciprocal of the bandwidth ($T = 1/80{,}000$) at the 3-db points. A slight error in measuring the bandwidth or a small error in reading the rise time of the pulse can account for the large apparent discrepancy. When a 20-kc/sec-wide circuit is placed between the generator and the receiver, the pulse rises in 55 μsec or within 9.1 per cent of the calculated value. A 12-kc/sec-wide circuit produces a pulse that rises in 80 μsec, within 4 per cent of the calculated value.

Other experiments have been carried out, shaping the pulse from the generator so that its rise time is 65 μsec. When this signal is applied to various tuned circuits, the resulting final pulse rise time may be expressed as follows: final rise time (in seconds) $= \sqrt{t^2 + (1/BW)^2}$, in which t is the rise time of the generator pulse in seconds and BW is the bandwidth of the receiver at the 3-db points in cycles.

12·5. Spectrum Measurements. *Field Equipment.*—Measurements have been made of the distribution of energy with respect to frequency of Loran transmissions at both 2 Mc/sec and 180 kc/sec. Development work associated with improving transmitting-antenna coupling systems or limiting the width of sideband radiation requires a measuring setup located several miles from the antenna to indicate when progress is being made.

A National HRO receiver with a General Radio ladder attenuator (identical with that used in the Model 605-B signal generator) connected between the antenna and receiver served satisfactorily. The receiver was operated with the selectivity controls set for narrow-band operation. Under these conditions the bandwidth is about 2 kc/sec. The connection between the attenuator and the input to the receiver must be well shielded, and the attenuator calibration must be checked with a reliable signal generator applied to the input of the attenuator before measurements are made.

The audio output of the receiver is connected to the vertical plate of the oscilloscope in a Loran indicator.

The nonlinear relationship between input and audio output for pulse emission in the receiver is such that it must be used at constant input. The voltage ratios between the various frequencies can be read from the calibrated attenuator that is adjusted for constant output to the oscilloscope. Readings are recorded against frequency and can later be converted into decibels and then plotted to show the complete energy-frequency distribution curve.

It is imperative that the gain of the receiver be set so that the reference output agreed upon does not overload any of the receiver circuits. Usually it requires a trial of several locations to determine a proper distance from the transmitting antenna that gives a high signal at the center frequency and still ensures reception from the antenna alone, well out of the induction field.

12·6. Cycle-matching Receivers. *Pulsed Injection.*—With the development of Low Frequency Loran at 180 kc/sec it became apparent that matching longer pulses to the same accuracy as in the 2.0-Mc/sec system would be difficult in the presence of a finite signal-to-noise ratio. Accordingly, the development of receivers for matching r-f cycles instead of the rectified-pulse envelopes was undertaken. The cycle-matching technique had been considered almost from the beginning of Loran, but only the LF system with its increased range but decreased accuracy of matching provided sufficient incentive to investigate the possibilities of cycle-matching. The system may be considered one in which phase is measured, the cycles being shaped into a pulse for purposes of identification.

The use of a tuned r-f receiver with no detector would necessitate a gain of about 4 million, in order to amplify an input signal of 10 μv rms to 120 volts peak to peak at the vertical plate of the oscilloscope. The anticipated instability owing to so great a gain at one frequency was discouraging.

The present experimental receivers are the superheterodyne type. The input signals are amplified through two 180-kc/sec r-f amplifiers and then heterodyned to 50 kc/sec by a frequency of 130 kc/sec. The resulting pulses of 50 kc/sec are amplified to about 200 volts peak to peak and applied to the vertical plate of the oscilloscope in a modified Model DAS-1 indicator. They are provided with 1-μsec markers and a superfine delay adjustment. The stability is ample even with no particular shielding precautions. A diode detector can be switched IN for making approximate measurements. After the pulse envelopes have been matched, the detector is switched OUT and the precision match of cycles is made. When the proper cycle is chosen, it is possible to match and read the time difference with an error not greater than 0.1 μsec.

The i-f cycles are phase sensitive to both the input signal and the heterodyning frequency. If the normal type of free-running oscillator were used for the heterodyning source, the i-f cycles would appear in constantly changing phase of a random nature related to the heterodyning frequency. In order to overcome this difficulty, the local oscillator is pulsed at the beginning of the fast-sweep trace, and thus there is no oscillation except during the trace time. This results in a heterodyning source that has no phase differential between upper and lower fast traces; and so when two pulses are matched exactly, they each experience the same effects from the heterodyne and, as a result, any differential effects are canceled out. Because the oscillator is triggered by the fast trace, the delay setting has no effect on the converting system.

The scheme of starting the local oscillator at the beginning of the fast-sweep trace has one annoying defect. The circuit that initiates the fast trace is the pedestal generator in the indicator. This generator is normally triggered from the output of a mixer, which combines the output of the *A*-delay and the fine *B*-delay multivibrators. When the local oscillator is turned on, there is a large transient produced in the plate current of the mixer in the receiver. This transient results from the sudden application of heterodyning voltage. In order to keep this transient from interfering with the received signal, the indicator is arranged so that the delay mixer starts the local oscillator and a multivibrator with a fixed delay of about 1000 μsec. When the pulse from this multivibrator collapses, it triggers the pedestal generator. The fast-sweep trace occurs, therefore, about 1000 μsec after the local oscillator has been started, and the transient has had plenty of time to degenerate by the time the signal arrives. Care must be taken to ensure that there is no differential phasing effect as a result of these linkages. In the experimental receivers a push-button switch is incorporated that transfers a portion of the heterodyning voltage to the vertical plate of the oscilloscope. When the switch is operated, the heterodyning voltage is plotted on a trace, and the delay controls can be adjusted while looking for any phase differential. The over-all operation of the circuits is such that time-difference readings accurate to 0.1 μsec are obtained. If greater precision were needed, some difficulty might be experienced using this particular technique because of the tie between the delay mixer, the start of the local oscillator, and the initiation of the fast trace.

The indicator has been further modified so that when the slow trace is used, the heterodyning voltage runs continuously; otherwise, there would be no signals observed until they were coincident with the pedestals.

To realize the full potentialities of this scheme it is necessary to control the phase of the cycles of the r-f pulse at the Loran transmitting stations. This control has been established using a cycle-matching receiver for monitoring at the slave station.

The greatest problem associated with cycle-matching at present is that of determining which cycles of the respective pulses should be matched. The long slow rise of the leading edge (100 to 150 μsec) makes identification of the initial cycle difficult. A preliminary investigation indicates that the pulse must rise within 10 or 12 cycles to remove this ambiguity completely. The shorter the rise time the easier it is for the navigator to pick the right cycle, but the bandwidth of the system is greater. This feature affects receiver design in that more noise is accepted and the stages must be designed for larger bandwidth with decreased gain per stage. Using an intermediate frequency of 50 kc/sec puts a very real and rapidly approached limitation on the amount of bandwidth possible; and even with narrow bandwidths, there is not much Q left in these circuits. Fortunately, the detector need not be used for the precision measurement.

It is noteworthy that when cycles are being matched, considerably greater amounts of impulse noise can be tolerated than when using rectification. This seems to be the result of using a truly linear receiving system. In any detector system for pulse reception, noise charges up the diode-charging capacitor that can be drained only as rapidly as the time constant employed permits. With large bursts of noise there is considerable bouncing of the oscilloscope traces which makes matching desired pulse envelopes difficult. This effect can be only partially eliminated with the best diode-limiting and restoring devices. On the other hand, the cycle-matching system allows noise to appear in the truly a-c sense, so that immediately after a large noise burst or impulse the trace is back in its neutral position on the oscilloscope, ready to handle the desired Loran pulse. If too large a burst occurs, the video stage overloads, with the resultant degrading effect of blocking and filtering capacitors changing charge. Even so, this effect occurs at much higher noise levels than can be tolerated with a rectifier system. The overloading can be minimized somewhat by incorporating a balanced diode limiter without capacitors in the stage preceding the video-amplifier stage. At the ground stations, where the delay is fixed and the operator concentrates on the leading edge of one cycle, large bursts of noise can be tolerated at the same time accuracy of synchronism is held to 0.1 μsec.

A few navigators' receivers built for cycle-matching are 12 kc/sec wide at 6 db down. The sensitivity is such that 10 μv applied to the antenna terminals produces a 2-in. deflection on the oscilloscope. The gain-balance circuit is capable of handling a differential ratio of 60 db with negligible distortion, and at least 40 db can be accommodated without exceeding a differential delay error of 0.1 μsec.

Controlled Injection.—A modified form of the cycle-matching receiver has been developed specifically for ground-station use. At the slave station the delay held is predetermined and fixed when the charts are drawn, with the result that the receiver need be much less flexible than a navigator's. When a heterodyning voltage of 130 kc/sec derived from the 50-kc/sec crystal oscillator in the timer is used at a timer (ground-station) receiver, any delays that are whole multiples of 100 μsec can be held, and the heterodyning voltages will be in the proper phase for both local and distant pulses.

This relationship is simply visualized by considering that there are 13 cycles for every 100 μsec of time; and hence whenever there is a whole number of 100-μsec intervals between the start of the top pedestal and the start of the bottom pedestal, there is a whole number of 130-kc/sec cycles between these two points. In addition to the above requirement, it is also necessary to use an even pulse recurrence rate, such as 0, 2, 4, 6. The necessity for such a relationship is clear if it is recognized that the feedback takes out 50 μsec per trace per rate so that on odd rates, there is an extra 50 μsec in the total time between the start of the upper pedestal and the start of the lower one. This condition results in the heterodyning voltage being exactly 180° out of phase for upper and lower pedestals when an odd recurrence rate is used. It may prove upon further investigation, however, that the interlaced pattern of i-f cycles resulting when the Loran pulses are matched may prove to be acceptable in operation.

The receiver has two r-f stages at 180 kc/sec, a mixer tube with 130 kc/sec injected as the heterodyning voltage, an i-f amplifier at 50 kc/sec, and a diode detector that can be switched in or out of the circuit. It also has a video amplifier good to about 70 kc/sec and of sufficiently low output impedance to drive the capacitance of the leads feeding the vertical plates of the timer oscilloscopes.

The heterodyning voltage is produced within the receiver chassis. Some 50-kc/sec voltage from the main crystal oscillator is used to excite a sine-wave divider, which divides by 5. It has been found that in the plate circuit of this divider a sufficient amount of 130-kc/sec current is available and can be utilized by segregating it by means of a circuit tuned to 130 kc/sec.

Between the first and second r-f stages, provision has been made to change the selectivity by switching in either of two bandpass coupling transformers. In operation, the wider band is employed to choose the correct cycle, and then the bandwidth is narrowed to exclude noise.

The cathode of the first r-f amplifier tube is connected to a high-Q tuned circuit, the inductance of which is variable so that the trap can be tuned with a front-panel control to any frequency from about 150 to over 200 kc/sec. The trap has been incorporated so that large unwanted signals in the region of 180 kc/sec can be rejected. A similar trap, but fixed-tuned to 130 kc/sec, is used in the cathode of the i-f amplifier to reject the 130 kc/sec that leaks through the mixer-plate circuits. Since these circuits between the mixer plate and i-f grids are low Q, their inherent rejection to 130 kc/sec without the additional trap is not sufficiently high to prevent an annoying amount of 130-kc/sec voltage from getting through the video stage to the oscilloscope.

The ground-station attenuator equipment determines the differential gain, and the local and remote pulses are mixed at the front end of the receiver. The resistance network associated with the first r-f transformer provides a means of mixing as well as damping the first circuit for the proper bandwidth.

The over-all bandwidth is 20 kc/sec at 6 db down with the selectivity control in the broad position, and in the narrow position the bandwidth is about 8 kc/sec total. The sensitivity is such that a 15-μv unmodulated 180-kc/sec signal applied to the input terminals produces a 1-in. peak-to-peak deflection. Since the attenuator used ahead of the receiver has considerable gain, the receiver is always used at much less sensitivity than maximum.

The whole cycle-matching technique needs reexamination in the light of current trends. Only the groundwork for the development has been laid.

APPENDIX A

THE LORAN PROGRAM IN THE HYDROGRAPHIC OFFICE[1]

The following statements are recorded to present in one binder an accurate chronological narrative of Loran, with particular emphasis upon the system as it has been administered by the Hydrographic Office from Jan. 1, 1943, to the end of 1945. No attempt will be made to discuss any of its technical aspects; such information may be found in technical reports issued by the Bureau of Ships, MIT Radiation Laboratory, Aviation Training Division of the office of the Chief of Naval Operations, and the Hydrographic Office. A complete list of publications is included at the end of this report.

HISTORY OF DEVELOPMENT OF SYSTEM

The Loran system was developed by the Radiation Laboratory during 1941 and 1942 from ideas proposed earlier. Specialists at Massachusetts Institute of Technology built experimental models of transmitting and receiving equipment, surveyed sites, installed transmitters, computed tables, and demonstrated the possibilities of the system. Original experiments were made in 1941 using frequencies of 2.5 to 8 Mc/sec with low power. Results were unsatisfactory for obtaining the ground-wave range sought. A frequency of approximately 2 Mc/sec produced the required results, and sky-wave usage was deemed practical.

First experimental transmitting stations were located at Montauk Point, Long Island, and Fenwick, Del., in two abandoned Coast Guard lifeboat stations. These stations operated on 1950 kc/sec, 25 pps, specific pulse recurrence rate 0. Synchronization of the stations was attempted in December 1941; success was attained by January 1942, when participants in the trials went to Bermuda to test the effectiveness of the system at long range.

The first demonstration of the use of Loran was made on June 13, 1942, with a laboratory model of the LRN receiver-indicator installed on the airship K-2 during a flight south from Lakehurst along the coast of New Jersey and Delaware to Ocean City, Md. Since only the Montauk-Fenwick stations were in operation, it was impossible to obtain fixes. Good ground-wave signals were observed, however, to the 250-mile

[1] Reprinted by permission of the Hydrographic Office, U.S. Navy.

extremity of the trip. The procedure of homing on a Loran hyperbola was used, and position-line accuracy of the system along the baseline was verified.

On July 4, 1942, the first readings from a plane were made on a laboratory receiver-indicator installed in a B-24 during a test flight from Boston to Cape Sable, Nova Scotia. Good signals were received and useful data obtained on signal range of stations *M* and *F*.

The first tests made aboard ship occurred on the CGC *Manasquan* during a weather cruise off Newfoundland from June 17 to July 17, 1942. Observations of both ground- and sky-wave signals during that period indicated a total range of 1300 nautical miles and an overlap of ground and sky coverage. The results were considered good enough to warrant the expansion of the system and its recommendation to navigational agencies.

Experimental service was extended by the construction of a slave station at Baccaro, Nova Scotia, to operate with the double-pulsed master at Montauk Point on specific pulse recurrence rate 1, and the construction of a second master at Deming, Nova Scotia, to operate with the slave at Baccaro on specific pulse recurrence rate 2. These stations were constructed during the late summer and went into operation under the Royal Canadian Navy on Oct. 1, 1942.

Preliminary tables for the three rates were computed at the Radiation Laboratory during August, September, and October 1942 and were reproduced by hectograph for temporary experimental use.

On Nov. 1, 1942, a test flight was made to Bermuda in a PBY for the purpose of demonstrating the use of Loran in obtaining fixes. Representatives of the Bureau of Aeronautics, Radiation Laboratory, Army Air Forces, and other interested activities were in the flight party. The demonstration was so successful that the observers were convinced that Loran could perform an important service in the war effort.

The Navy followed the development of the system with interest through the Office of Research and Inventions. The Hydrographic Office became involved because of the necessity for production of tables and charts. On June 13, 1942, Comd. G. A. Patterson, USN (ret.), Officer in Charge of the Division of Research of the Hydrographic Office, and E. B. Collins, senior nautical scientist of the division, met with Admiral Furer, Director of Research and Inventions, to review progress of Loran. On July 29 a conference of all interested parties was held. Progress report given at this meeting included the following statements: Experimental stations at Montauk and Fenwick were in operation; the Canadians were building two stations in Nova Scotia (Baccaro and Deming) under the supervision of the Radiation Laboratory; sites had been chosen for stations in Newfoundland; and Greenland was suggested as a possible location. On Aug. 15, 1942, F. G. Watson, then of the Radiation Laboratory, visited the Hydrographic Office to exhibit sample tables prepared at Radiation Laboratory and to report on further developments.

NAVY ADMINISTRATION

The administration of Loran was officially transferred to the Navy on Jan. 1, 1943. The Montauk and Fenwick stations were thereby transferred from the Radiation Laboratory to the operational cognizance of the U.S. Coast Guard. The Deming and Baccaro stations had been transferred on Oct. 1, 1942, to the Royal Canadian Navy. Monitor stations in the United States were established by the Coast Guard and Canadian monitors by the Canadian Navy as soon as the system passed from the experimental stage early in 1943.

The Coast Guard had been directed on Oct. 31, 1942, to establish three new stations as follows: single master station at Fredericksdal (Narsak), Greenland, double slave at Battle Harbor, Labrador, and single master at Bonavista, Newfoundland. Siting had already been done by the Radiation Laboratory, RCN, U.S. Navy, and USCG during the summer of 1942. Surveys were made during November and December to establish coordinates, and in December mechanics were set up on the Division of Research of the Hydrographic Office for the computation of a table for utilization of service from stations VL, at Bonavista and Battle Harbor.

While the computations for VL were being made, 100 copies of the Radiation Laboratory preliminary tables were printed by the Hydrographic Office and bound in pressboard. This publication contained instructions for the use of Loran tables, illustrated by examples, a chartlet and tables for each of the station pairs, MF (Montauk-Fenwick), MB (Montauk-Baccaro) and DB (Deming-Baccaro). The publication was distributed chiefly to a training activity sponsored by the Navy in Cambridge, Mass., and to naval vessels that had received the first sets of Loran equipment.

During the latter part of February 1943, arrangements were made in New York for the establishment of a unit composed of about 40 computers known as the Hydrographic Office New York Project for the purpose of computing Loran tables. It was located in the Hudson Terminal Building at 50 Church Street and officially began operations on Mar. 1, 1943, with Lieut. (jg) F. G. Watson as officer in charge. The first table to be computed was that for stations NL, Narsak, Greenland, and Battle Harbor, Labrador.

Montauk Point, Long Island, had been a suitable location for the experimental operation of the system, principally because of its accessibility and the availability of housing facilities in a Coast Guard building. It was not suitable propagationally, however, for the permanent transmitting station. It was decided, therefore, to replace that station by one located at Siasconset, Nantucket Island. On Nov. 27, 1942, the Coast Guard was directed to establish the replacement, and on Dec. 15, 1942, it was directed to establish a permanent station at Fenwick to replace the temporary experimental station already operating there.

The computation of new tables for SF and SB (rates 1L − 0 and 1L − 1) to replace the MF and MB sections of the Radiation Laboratory tables was made necessary by the transition. This was undertaken by the New York Project following the computation of the NL table and after the surveys of the new sites had been completed and the coordinates determined. It was completed by April 1943, when the first Hydrographic Office tables were published; H.O. No. 221 was assigned to Loran tables. Tabular values for SF, SB, DB (from the Radiation Laboratory table), and VL, together with a revision of the Introduction which had appeared in the earlier tables, were reproduced by multilith in black and bound as Vol. I, numbered serially 1 to 145 and 491 to 946. Table NL was bound separately as Vol. II, numbered 146 to 490 and 947 to 1200. These tables were termed preliminary, as were the earlier ones, and bound in pressboard. Distribution was made on May 1, 1943, to cognizant activities in the USN, AAF, British and Canadian Navies. The USN distribution list included approximately 40 ships of the Atlantic fleet: three battleships, two heavy cruisers, three light cruisers, and about thirty destroyers.

Drafting was begun on the first Loran charts in February 1943, by draftsmen from the Division of Air Navigation. It was decided to use a Loran-hyperbola overprint on a plotting sheet, Mercator projection, scale 1/1,094,400 (1°Lo = 4 in.). Loran curves were plotted at intervals of 20 μsec, and each separate rate was printed in an identifying color.

Original colors used were

Rate 0	Garland green
Rate 1	Autumn brown
Rate 2	Banner blue
Rate 3	Magenta
Rate 4	Sepia

When Rates 5 and 6 were added later they were shown in damage-control green and jewel blue, respectively.

Five hundred copies of the first edition were printed as follows:

Short title of chart	Rates*	Date
E-5-NW	0, 1, 2	April 1943
E-6-NW	0, 1, 2	April 1943
E-7-NW	0, 1, 2	April 1943
F-4-NW	2, 3, 4	April 1943
F-5-NW	0, 1, 2	April 1943
F-6-NW	0, 1, 2	April 1943
F-7-NW	0, 1, 2	May 1943
G-3-NW	3, 4	May 1943
G-4-NW	3, 4	May 1943
G-5-NW	1, 2, 3, 4	May 1943
G-6-NW	1, 2, 3, 4	May 1943

* Rate 0, SF; Rate 1, SB; Rate 2, DB; Rate 3, VL; Rate 4, NL.

Montauk remained in operation until July 1, 1943, when it was permanently discontinued at 1800 Z; at 2200 Z on the same date Siasconset went into operation replacing it. All Radiation Laboratory preliminary tables were directed to be destroyed by burning June 28, 1943. Both tables and charts had been distributed for the new rate well in advance of the institution of service.

Difficulties prevented the early completion of some of the stations, so that it was not until Dec. 1, 1943, that continuous service was confirmed for navigational use on stations NL and VL. Service was announced for the permanent Fenwick Station on Rate 0 on Dec. 10, 1943. The early transmitting stations operated only a partial daily schedule. For some weeks they maintained an 8-hr schedule, which was later prolonged to 16, to 20, and finally to 24 hr. This was true of all the stations in the Atlantic chain in operation before 1944, including the two rates operated by the British.

The New York Project devised an improved form for presenting the tables during the summer of 1943. In addition to the tables previously published in temporary binders, two new tables for stations UA and UK, installed and operated by British Admiralty, were prepared in the revised form. Originals were completed about Oct. 10, 1943. The tables were printed in the colors assigned to the respective rates and bound in permanent composition binders, stamped in gold leaf. Serial numbers 1001 to 2000 were assigned to this printing. The improved edition was completed about Nov. 13, 1943. All tables previously issued in pressboard binders were declared obsolete when complete distribution of the permanent book had been effected.

EXTENSION OF SERVICE TO NORTH PACIFIC

Imperative need for improved navigational methods in the Aleutian area gave impetus to an effort to introduce Loran coverage into that area early. A survey party from the AAF, Coast Guard, and Radiation Laboratory went into the Bering Sea area and surveyed sites on St. Matthew, St. Paul, and Umnak Islands during September 1942. The Coast Guard was directed on Jan. 28, 1943, to establish the three stations sited. Construction was in progress during the summer, and completion was expected in September 1943. Tables, the first to be set up in the improved form and bound in permanent binders, were ready for distribution in August 1943. Serial numbers 0 through 1000 were assigned and this volume was designated H.O. No. 221A—North Pacific. The Radiation Laboratory sent ten Loran receivers to Adak, Alaska, on Aug. 18, 1943. The stations began transmitting intermittently in September, but signals were not accepted as reliable for navigational use. Ten-hour service was instituted Oct. 18, 1943; 16-hr service on Nov. 10, 1943; 22-hr service on Jan. 1, 1944; and 24-hr service on July 10, 1944.

Additional service was ordered by directive of Aug. 11, 1943, to the Coast Guard to establish stations on Attu and Amchitka. These stations were placed on 24-hr operation June 8, 1944. Tables had been computed, printed, and distributed as addenda to H.O. No. 221A in January 1944.

Charts were designed for the Aleutian area on Mercator projection, scale 1/1,094,400 (1 in. = 15 nautical miles). The first edition of the charts contained only the two rates 1L-1 and 1L-2 from the Bering Sea stations. Five hundred copies of charts were printed as follows:

Short titles	Curves printed
F-10,11,12-N	September 1943
G-9,10,11-N	September 1943
H-6,7,8,9-N	September 1943
I-5,6,7-N	September 1943

These charts were reprinted to include Rate 1L-0 (Attu-Amchitka), and the following additional ones had been completed by the time distribution was made during March and April 1944: F-9-N and G-7,8-N. The Aleutian Islands had not been tied into a triangulation system at the time when the surveys were made. Gravitational errors and adverse weather conditions prevailing most of the time during the survey caused the coordinates of the Loran stations to be somewhat in error. By extensive observations a correction pattern was devised for each of the three rates, which enabled the Loran operator to use the system in that area with confidence. These corrections were issued in chartlet form and were distributed about Oct. 1, 1944.

SERVICE EXTENSIONS TO CENTRAL PACIFIC

As the war progressed, extensions of Loran service were demanded. Survey was completed Dec. 10, 1943, for three stations in the Hawaiian Islands located on French Frigate Shoals, Niihau, and Hawaii. On

Feb. 5, 1944, the Coast Guard was directed to establish three stations in the Phoenix Islands on Baker, Gardner, and Atafu Islands. Surveys for stations in the Marshall Islands (Kwajalein, Majuro, and Makin) were made in February and March 1944. The Army Air Forces were authorized on Feb. 10, 1944, to establish the Banda Sea chain, and coordinates were furnished to the Hydrographer on Mar. 9, 1944.

Tables and charts were prepared for these stations during the spring of 1944. A target date of July 1, 1944, was set for the completion of VL-30 and VL-70 charts of the area. On Apr. 14 standard channel designations for the high and low channels were assigned. The method of labeling Loran curves on charts was modified on the next printing to include the basic recurrence rate, the channel, and the specific rate in addition to the T-value of the curve. For example, each curve contained a legend such as 2L-0 or 1H-3 preceding the T-value on these and subsequent charts. On earlier charts Loran curves had been labeled with the T-value preceded only by the specific recurrence rate.

Stations were completed for testing as follows:

Niihau-Hawaii (Rate 2L-0) began testing July 11, 1944.

Niihau-French Frigate (Rate 2L-1) began testing July 27, 1944.

Majuro-Kwajalein (Rate 2L-2) began testing Sept. 28, 1944.

Majuro-Makin (Rate 2L-3) began testing Sept. 28, 1944.

Gardner-Baker (Rate 2L-4) began testing Sept. 28, 1944.

Gardner-Atafu (Rate 2L-5) began testing Sept. 28, 1944.

Service was approved for navigation for the Hawaiian chain (Rates 2L-0 and 2L-1) on Oct. 19, 1944, for the Phoenix chain (Rates 2L-4 and 2L-5) on Nov. 21, 1944, and for the Marshall chain (Rates 2L-2 and 2L-3) on Dec. 1, 1944.

Tables, bound permanently, numbered 2001 through 3000, and identified as H.O. No. 221B, Loran Tables, Central Pacific, were distributed during July 1944, as were the following charts:

Chart No.	Rates	Curves printed
VL-30-30	2L-0, 1, 2, 3	June 1944
VL-30-31	2L-0, 1	May 1944
VL-30-42	2H-4, 5	June 1944
VL-30-43	2H-4, 5; 2L-2, 3	June 1944
VL-30-44	2L-2, 3	June 1944
VL-30-45	2L-0, 1, 2, 3	June 1944
VL-30-56	2H-4, 5	May 1944
VL-30-57	2H-4, 5	May 1944
VL-30-58	2L-2, 3, 4, 5	June 1944
VL-30-70	2H-4, 5	May 1944
VL-30-71	2H-4, 5	May 1944
VRL-202	2L-0, 1, 2, 3, 4, 5	June 1944

Tables for the Banda Sea Chain, Rates 2H-4 and 2H-5, were bound in permanent binders numbered 3001 through 4000 and identified as H.O. No. 221C, Loran Tables, South Pacific. Original distribution was made July 24, 1944. Four additional sections were later added to this volume as service was extended westward.

CHINA-BURMA-INDIA

An acute need for an accurate navigational system for all weather conditions was felt by aviators operating "over the hump" in the China-Burma-India Theater. The Army Air Forces were given cognizance of establishing service in that area. Surveys were made in April 1944 for a chain of three stations near K'un-Ming and for another in Assam. The Hydrographic Office computed tables, which were completed in July, and plotted curves for Loran overlays on three AAF strip charts. These charts were printed and distributed by the Aeronautical Chart Service of the AAF. The Assam stations were in operation in September 1944. The K'un-Ming stations were relocated a few months later; surveys were made in October; tables were completed in December; and stations went into operation in February 1945. The first charts were produced by the Aeronautical Chart Service for AAF from tables computed by the Hydrographic Office. The earliest Hydrographic Office charts carrying these rates were distributed during March 1945.

In December 1944, the AAF also made surveys for two stations on the Bay of Bengal and two Sky-wave Synchronized links—one known as SS China and the other as SS Burma. A station in interior China was synchronized with the slave of the K'un-Ming trio for SS China, and the northernmost station of the Bengal trio was synchronized with one of the Assam slave stations for the SS Burma link. The first tables and charts were completed in February 1945; service was initiated in April.

Tables for the Bay of Bengal stations were issued in May 1945, bound in permanent binders, titled H.O. No. 221D, Loran Tables, Asiatic Area. Charts had been issued in March. In July the tables for the two SS links were incorporated in H.O. No. 221D.

Operation of the Bay of Bengal stations was transferred to the Royal Air Force soon after establishment. The Assam chain and the SS Burma link operated under the auspices of the AAF until Oct. 25, 1945, when they were discontinued. The K'un-Ming trio and SS China link went off the air in November 1945.

ON THE ROUTE TO JAPAN

Expansion of Loran in the Pacific from the Marshalls and Phoenix Islands westward was dependent upon the progress of the war and closely followed the invasion forces into occupied territory. In the Southwest Pacific service was extended early in 1945 by the installation of two Sky-wave Synchronized links that operated on Rates 4H-0 and 4H-1. Stations were established on the islands of Mapia, Suluan (Philippines), and Ulithi in March 1945. Charts were provided by a Coast Guard detachment located at Morotai and were ready for use by the time service was stabilized for navigational use about the middle of April 1945. Rate 4H-1 was synchronized for use only during the hours of darkness and was discontinued on Aug. 1, 1945. No tables or charts were issued for this rate by the Hydrographic Office. Service provided by Rate 4H-0 was synchronized by ground waves during the daytime and by sky waves during the darkness. This rate was shown on Hydrographic Office charts which appeared May 15, 1945. A table was printed for inclusion in H.O No. 221D, but service was discontinued on Sept. 25 shortly before the new reprint appeared; the section was destroyed before it was placed in distribution.

In order to provide service over the area northwest of New Guinea and east of the Philippines, the Coast Guard established mobile stations on Peleliu, Pulo Anna, and Morotai and issued temporary charts for the utilization of this service. The charts were one-color ozalid editions. The Coast Guard unit stationed at Morotai produced the charts and distributed them to the Loran users in the area. This type of chart was valuable because of the rapidity with which it could be produced in the field. Surveys were made during November and December 1944, and signals from the mobile stations went on the air Jan. 18, 1945. The temporary ozalid charts were issued Jan. 1. Later these stations were converted into permanent ones. Hydrographic Office issued permanent tables as addenda to H.O. No. 221C. Both tables and charts were en route to users in April 1945, and the mobile equipment was replaced by permanent on June 14, 1945.

As steppingstones toward Japan from the Marshalls and the Phoenix chains, stations were placed first in the Marianas and then on Iwo Jima and Okinawa in turn as soon after capture of those islands as installation could be completed. Surveys for stations on Saipan and Guam were made during September and October 1944. The Hydrographic Office gave high priority to production of charts and tables. Tables were en route to holders of H.O. No. 221C (viz., all Loran-equipped units in the Pacific area) on Nov. 28, 1944, and the charts followed one week later. Even though this service provided only a single line of position over the area of combat, its availability was of great value to ships operating in that area, which fact is evidenced by comments received from navigators. As soon as possible a station was installed on Ulithi to operate with the double master on Guam. Survey was made early in December, and charts including the new rate were sent out from the Hydrographic Office during the first week in January 1945. Tables followed to holders of H.O. No. 221C during the first week in February 1945.

As the spearhead of battle neared Japan, stations were established on Iwo Jima and Okinawa. Surveys were made in April and May 1945. Coast Guard Unit 203 at Guam arranged to produce temporary charts rapidly for use in the theater of operations. Temporary charts were ready in June, and the stations went into continuous operation on June 10, 1945. Permanent tables were en route from the Hydrographic Office to holders of H.O. No. 221D on July 2, and charts followed as they became available from July 3–20.

After the reconquest of the Philippines, three stations were erected on the west coast of these islands to generate signals on Rates 1L-6 and 1L-7 for the use of Loran users operating in the area west of the islands. Surveys were made in May and June 1945. Coast Guard Unit 203 produced temporary charts and had them ready for distribution about the time the stations went into continuous operation on July 19, 1945. Permanent tables were mailed from the Hydrographic Office to holders of H.O. No. 221D during the last week of August 1945. Charts were distributed at the same time.

EXTENSIONS TO ATLANTIC SERVICE

By early 1944 extended coverage in the Atlantic was greatly needed, particularly by training activities located in the southeastern states. The decision was made to relocate the Fenwick station southward. A site was selected on Bodie Island, N.C., near Cape Hatteras. CNO issued a directive for its establishment June 19, 1944. Survey was made in September, and tables were distributed to holders of H.O. No. 221 during December 1944. Revised charts were distributed during December and January. On Feb. 1, 1945, at 0000 GCT, the station at Fenwick was discontinued and new service from Bodie Island was instituted to replace it. The Coast Guard was also directed by CNO on Aug. 12, 1944 to build three stations along the southeastern coast. High basic rate was assigned for the two specific rates to be generated. Sites were selected at Folly Island, S.C., and Hobe Sound, Fla., to operate with a satellite station near the one on Bodie Island. Surveys were made during November and December 1944 for the two northernmost stations and in January 1945 for the Hobe Sound site. The stations went into full operation in April for Rate 1H-1 (Bodie Island-Folly Island) and in May for 1H-2 (Folly Island-Hobe Sound). Tables for the two new rates were distributed to holders of H.O. No. 221 on Apr. 12, 1945, and charts were available during the same month.

Because of a need for better crossing angles in the region near the British Isles a new station was established at Skaw in the Shetland Islands during the fall of 1944. This station operated with a characteristic blink on the same frequency and recurrence rate as station UA (rate 1L-6). Operation began in November 1944. The Hydrographic Office prepared tables that were added to H.O. No. 221 in January 1945, and charts including the new rate were ready in March.

The Royal Canadian Navy requested additional coverage to provide better crossing angles off the coast of Canada and in the Gulf of St. Lawrence region. Installation of a new slave station at Port-aux-Basques, Newfoundland, to operate with the single master at Deming was approved. Survey was made in July 1944. The Coast Guard had been directed to operate the Port-aux-Basques station, which was completed and signals went into service on an 8-hr daily schedule Mar. 15, 1945. Difficulties experienced in completing the installation of the master facilities at the Deming station were responsible for the delay in providing master signals. Master signals were on the air Sept. 10, 1945, and continuous navigational service was announced Oct. 26, 1945. Tables had been printed and issued as Vol. II of H.O. No. 221 in December 1944, and charts with the new rate appeared about the same time. A reprint of the Atlantic tables had become necessary by the time this new section was issued. The reprinted copies, numbered 6001 to 7000, were arranged in such manner that tables for the stations located on the Atlantic seaboard of North America were included in Vol. I and those for the North Atlantic and the Northeast Atlantic were placed in Vol. II.

ARMY AIR FORCES AIR TRANSPORTABLE STATIONS

The AAF established several Loran chains during the first six months of 1945 chiefly for the purpose of providing effective signals for training schools operating under the direction of that activity in the United States. To serve the training schools located near the Gulf of Mexico three stations were located on the coasts of Texas and Louisiana—at Port Isabel, Tex., on Matagorda Island, Tex., and at Cameron, La. This chain provided useful signals over the area of the Gulf of Mexico and for some miles inland over the Gulf states. Surveys were made during March and April, and the stations went into continuous operation on May 23, 1945. Temporary charts were made available by the Army Aeronautical Chart Service at Love Field, Dallas, Tex., during June. The Hydrographic Office computed tables and issued them in temporary form and limited quantity on July 26, 1945. The first permanent Hydrographic Office charts carrying these rates appeared Aug. 31, 1945.

An urgent need had been felt for a considerable period of time for signals on the West Coast of the United States for use by aviation activities near the coast and for approach to the coast from the Pacific. To fulfill these requirements, an AT chain was located at Point Arena, Point Sur, and Point Arguello on the coast of California. Surveys were completed during March and April and temporary charts were prepared by the AACS in June. The stations went into continuous operation on 1 July. The Hydrographic Office issued tables in limited quantity on

Aug. 14, 1945, and the first Hydrographic Office chart carrying the two Pacific Coast rates appeared Oct. 15, 1945.

The third chain was located at Danville, Illinois, George Field, Ill., and Sturgis, Ky. This chain was designed primarily for the training of navigators to man the B-29's, which operated so effectively during the last months of the war against Japan. Surveys were made during June, and temporary charts were available during the same month. The Hydrographic Office computed tables which were available in August 1945, but these rates were not shown on any Hydrographic Office chart. Service was available in July and operated on an 8-hr daily schedule.

All Hydrographic Office tables issued for AT stations were published in temporary form and in limited quantity.

RECENT PERMANENT WEST COAST AND PACIFIC INSTALLATIONS

To provide permanent service on the West Coast the Coast Guard established stations at Point Grenville, Washington, and Cape Blanco, Oregon, in June and July 1945. Temporary charts were produced by the Coast Guard charting unit on the West Coast and issued by the District Coast Guard Officer at Seattle. These charts were available in July 1945. They were of the temporary, one-color, ozalid type. Corrected coordinates were not furnished the Hydrographic Office for these stations until October 1945, when coordinates were received for the site surveyed during that month on Spring Island, Vancouver, for a station to operate with the double master at Point Grenville.

During October, coordinates for a station on 0 Shima, off Kyushu, to operate with the double master on Iwo Jima, were received. Table had been computed by Nov. 1. Work was in progress on charts carrying the new Rate 4H-5.

PAUSE TO LOOK BACKWARD AND FORWARD

On Nov. 1, 1945, there were in operation throughout the world 61 transmitting stations emitting 41 separate signals; 7 stations had been discontinued; 2 were in process of construction, and plans were under way for additional stations on the West Coast of the United States, along the great circle route from Seattle to Tokyo, and in the South Pacific along the air route from San Francisco to Sydney.

LORAN PUBLICATIONS ISSUED BY THE HYDROGRAPHIC OFFICE

Preliminary Loran Tables (Reprint of Radiation Laboratory Tables) (obsolete)	January 1943
Preliminary Loran Tables, Hydrographic Office Vols. I and II (obsolete)	May 1943
H.O. No. 221, Loran Tables, 2d ed., North Atlantic Chain, Vol. I	February 1943 Reprint December 1944 Reprint June 1945
H.O. No. 221, Loran Tables, 2d ed., North Atlantic, Vol. II	December 1944 Reprint July 1945

H.O. No. 221A, Preliminary Loran Tables, North Pacific	January 1944 Reprint October 1944 Reprint October 1945
H.O. No. 221B, Loran Tables, Central Pacific	June 1944 Reprint January 1945 Reprint June 1945
H.O. No. 221C, Loran Tables, South Pacific	June 1944 Reprint February 1945 Reprint May 1945
H.O. No. 221D, Loran Tables, Asiatic Area	May 1945 Reprint October 1945
Loran Tables for Strait of Belle Isle	1943
Entrance, Halifax Harbor	1943
Loran Tables for CBI Chain:	
AB, AC	July 1944
DE, DF (superseded)	Original July 1944 Revised December 1944
XB, GF	February 1945
Loran Tables, European Chain (SS)	August 1944
H.O. No. 221S, Multiplication Table	October 1944
Loran Tables, Gulf of Mexico Chain	July 1945
Loran Tables, West Coast AAF Chain	August 1945
Loran Tables, Central Interior Chain	August 1945
Loran Technical Report No. 1, "Graphical Methods"	August 1944
Loran Technical Report No. 2, "Corrections in the Aleutians"	December 1944
Loran Technical Report No. 3, "Simplified Method of Deriving Accurate Distance on the Earth's Surface"	April 1945
Loran Technical Report No. 4, "Analysis of Ship Reports from the Southwest Pacific"	September 1945
Table for the Construction of Plane Hyperbolae	August 1945
Grid Tables:	
0° to 20°	October 1945
21° to 45°	December 1945
H.O. No. 1-L, Loran Charts and Service Areas Catalog:	
1st ed.	September 1944
2d ed.	February 1945
H.O. No. 1-L, Catalog of Loran Charts and Service Areas	October 1945
NHO No. 958, Loran Work Log*	January 1944
NHO No. 1040, Loran Navigation Report Form	December 1944
NHO No. 1042, Loran Navigation Report Form	December 1944
Loran Operational Report No. 1, "Navigators' Comments"	November 1944
H.O. Misc. 11,701, Loran Research Flight*	November 1944
Loran Operational Notes:	
No. 1	February 1945
No. 2	April 1945
No. 3	May 1945
No. 4	July 1945
No. 5	August 1945
No. 6	December 1945
Loran Interpolator	March 1945

* Prepared by Aviation Training Section, Chief of Naval Operations.

TABLE A1

Survey made	First signals on air	Continuous operation	Tables available	Charts available
VL (1L-3) July 1942	Mar. 1943	Jan. 15, 1944	May 1, 1943	May 1943
NL (1L-4) July-Aug. 1942	Mar. 1943	Jan. 15, 1944	May 1, 1943	May 1943
MF (1L-0) CG sites used	Dec. 1941	May 1942	Jan. 1942	None
SF (1L-0) Dec. 1942	July 1, 1943	Dec. 10, 1943	May 1, 1943	May 1943
SB (1L-1) Dec. 1942	July 1, 1943	Dec. 10, 1943	May 1, 1943	May 1943
DB (1L-2) Summer 1942	Oct. 1, 1942	Oct. 1, 1942	Oct. 1942	May 1943
UK (1L-5) June 7, 1943*	Nov. 25, 1943	July 16, 1944	Nov. 13, 1943	Apr. 1944
UA (1L-6) June 7, 1943	Dec. 15, 1943	July 16, 1944	Nov. 13, 1943	Apr. 1944
UW (1L-6b)	Nov. 3, 1944	Nov. 15, 1944	Jan. 1, 1945	Mar. 1945
SH (1L-0) Sept. 1944	Dec. 18, 1944	Feb. 1, 1945	Dec. 1944	Jan. 1945
MB (1L-1) Summer 1942	Sept. 1942	Oct. 1, 1942	Fall 1942	None
DP (1L-7) July 1944	Mar. 15, 1945	Oct. 26, 1945	Dec. 4, 1944	Dec. 1944
CT (1L-0) Fall 1943	Dec. 1943	June 8, 1944	Jan. 1944	Mar. 1944
PM (1L-1) Sept. 1942	Sept. 1943	July 10, 1944	Aug. 1943	Sept. 1943
PU (1L-2) Sept. 1942	Sept. 1943	July 10, 1944	Aug. 1943	Sept. 1943
LB (1L-6) May–June 1945	July 4, 1945	July 19, 1945	Aug. 29, 1945	CG 203-20 July 1945 H.O. Aug. 31, 1945
RB (1L-7) May–June 1945	July 4, 1945	July 19, 1945	Aug. 29, 1945	CG 203-20 July. H.O. Aug. 31, 1945
QJ (2L-0) Dec. 1943	July 11, 1944	Oct. 19, 1944	June 24, 1944	July 11, 1944
QG (2L-1) Dec. 1943	July 27, 1944	Oct. 19, 1944	June 24, 1944	July 11, 1944
DK (2L-2) Mar. 1944	Sept. 28, 1944	Dec. 1, 1944	June 24, 1944	July 11, 1944
DL (2L-3) Mar. 1944	Sept. 28, 1944	Dec. 1, 1944	June 24, 1944	July 11, 1944
RE (2L-4) Feb. 1944	Sept. 28, 1944	Nov. 22, 1944	June 24, 1944	July 11, 1944
RF (2L-5) Feb. 1944	Sept. 28, 1944	Nov. 22, 1944	June 24, 1944	July 11, 1944
MR (2L-5) Mar.–Apr. 1945	May 1, 1945	May 23, 1945	July 26, 1945	AACS Temp. June 1945 H.O. Aug. 31, 1945

MT (2L-6) Mar.–Apr. 1945	May 1, 1945	May 23, 1945	July 26, 1945	AACS Temp. June 1945
				H.O. Aug. 31, 1945
GF (4L-0) Dec. 1944	Apr. 1945	Apr. 1945	Temp. Feb. 6, 1945	Feb. 22, 1945
			H.O. 221 July 2, 1945	Mar. 31, 1945
DF (4L-1) Orig. Apr. 1944	Dec. 16, 1944	Feb. 1945	Orig. July 1944	Feb.–Mar. 1945
Rev. Oct. 1944			Rev. Dec. 1944	
DE (4L-2) Orig. Apr. 1944	Dec. 16, 1944	Feb. 1945	Orig. July 1944	Feb.–Mar. 1945
Rev. Oct. 1944			Rev. Dec. 1944	
AC (4L-3) Apr. 1944	Sept. 1944	Sept. 1944*	July 1944	Mar. 20, 1945
AB (4L-4) Apr. 1944	Sept. 1944	Sept. 1944*	July 1944	Mar. 20, 1945
XB (4L-5) Dec. 1944	Mar. 1945	Mar. 1945*	Temp. Feb. 6, 1945	Mar. 20, 1945
			H.O. 221 July 2, 1945	
XY (4L-6) Dec. 1944	Feb. 1945	Feb. 1945	May 17, 1945	Mar. 31, 1945
ZY (4L-7) Dec. 1944	Feb. 1945	Feb. 1945	May 17, 1945	Mar. 31, 1945
CH (1H-1) Nov.–Dec. 1944	Mar. 25, 1945	Apr. 11, 1945	Apr. 12, 1945	Apr. 19, 1945
		(Aug. 21, 1945)		
CG (1H-2) Nov.–Jan. 1945	Jan. 17, 1945	May 15, 1945	Apr. 12, 1945	Apr. 19, 1945
SA (1H-6) Mar.–Apr. 1945	June 15, 1945	July 1, 1945	Aug. 14, 1945	Oct. 15, 1945
SG (1H-7) Mar.–Apr. 1945	June 15, 1945	July 1, 1945	Aug. 14, 1945	Oct. 15, 1945
WN (2H-4) Jan. 1944	July 1945	Aug. 1944	June 14, 1944	June 21, 1944
WA (2H-5) Jan. 1944	July 1945	Aug. 1944	June 14, 1944	June 21, 1944
(2H-4) April–May 1945	June 6, 1945	July 24, 1945		Temp. CG13ND—July 1945
(2H-5) Oct. 1945				
PD (2H-6) June 1945	July 1945	July 1945	Aug. 1945	Temp. AACS—June 1945
PS (2H-7) June 1945	July 1945	July 1945	Aug. 1945	Temp. AACS—June 1945
NP (4H-0) Feb. 1945	Mar. 24, 1945	Apr. 7, 1945	Mar. 19, 1945	Temp. CG—Apr. 1945
				Perm. H.O.—May 15, 1945
HP (4H-1) Feb. 1945	Mar. 24, 1945	Apr. 7, 1945	Mar. 23, 1945	Temp. CG—April 16, 1945
				Not on H.O. charts
HV (4H-2) Dec. 1944	Dec. 27, 1944	Jan. 12, 1945	Feb. 5, 1946	Jan. 5, 1945
SV (4H-3) Sept.–Oct. 1944	Nov. 28, 1944	Dec. 16, 1944	Nov. 28, 1944	Dec. 2, 1944

* Date coordinates sent from British Admiralty.

TABLE A1.—(*Continued*)

Survey made	First signals on air	Continuous operation	Tables available	Charts available
KJ (4H-4) Apr.-May 1945	May 16, 1945	June 10, 1945	July 2, 1945	Temp. CG 203—June 1945
KO (4H-5) Oct. 1945				Perm. H.O. July 20, 1945
TU (4H-6) Nov. 1944 (mobile)	Dec. 6, 1944	June 14, 1945 (perm.)	Apr. 19, 1945	Temp. CG—Jan. 1, 1945
				Perm. H.O.—Mar. 30, 1945
TM (4H-7) Nov. 1944 (mobile)	Dec. 6, 1944	June 14, 1945 (perm.)	Apr. 19, 1945	Temp. CG—Jan. 1, 1945
				Perm. H.O.—Mar. 30, 1945

* Discontinued 25 Oct. 1945.

APPENDIX B

LORAN GROUND STATIONS[1]

HATTERAS—FLORIDA CHAIN
Frequency: 1950 kc (channel No. 1)
Basic pulse rate: $33\frac{1}{3}$ pps (high)

Recurrence rate	M/S	Station	Location	Coordinates
1-H-1	*S*	H	Bodie Island, N.C.	35° 49′ 04.″697N 75° 34′ 00.″128W
1-H-1 1-H-2	*M*	C	Folly Island, Charleston, S.C.	32° 41′ 02.″787N 79° 53′ 13.″131W
1-H-2	*S*	G	Hobe Sound, Fla.	27° 04′ 41.″098N 80° 07′ 14.″574W

NORTH ATLANTIC CHAIN
Frequency: 1950 kc (channel No. 1)
Basic pulse rate: 25 pps (low)

Recurrence rate	M/S	Station	Location	Coordinates
1-L-0	*S*	H	Bodie Island, N. C.	35° 50′ 07.″96N 75° 33′ 32.″53W
1-L-0 1-L-1	*M*	S	Siasconset, Nantucket	41° 14′ 59.″752N 69° 58′ 21.″732W
1-L-1 1-L-2	*S*	B	Baccaro, Nova Scotia	43° 27′ 33.″45N 65° 28′ 16.″33W
1-L-2 1-L-7	*M*	D	Deming, Nova Scotia	45° 12′ 53.″49N 61° 10′ 32.″34W
1-L-7	*S*	P	Port-aux-Basques, Newfoundland	47° 33′ 53.″80N 59° 09′ 50.″69W
1-L-3	*M*	V	Bonavista, Newfoundland	48° 41′ 45.″66N 53° 05′ 18.″24W
1-L-3 1-L-4	*S*	L	Battle Harbor, Labrador	52° 14′ 51.″3N 55° 36′ 43.″2W
1-L-4	*M*	N	Narsak, Greenland	59° 58′ 57.″0N 44° 39′ 51.″3W
1-L-5	*S*	K	Vik, Iceland	63° 24′ 08.″N 19° 02′ 17.″W
1-L-5 1-L-6	*M*	U	Skuvanes, Faeroes	61° 27′ 22.″N 6° 49′ 21.″W
1-L-6	*S*	A	Mangersta, Hebrides	58° 11′ 11.″N 7° 05′ 51.″W
1-L-6b	*S*	W	Skaw, Shetlands	60° 49′ 47.″N 0° 46′ 41.″9W

[1] Revised to Oct. 15, 1945.

EUROPEAN SS SYSTEM
Frequency: 1900 kc (channel No. 3)
Basic pulse rate: 33⅓ pps (high)

Recurrence rate	M/S	Station	Location	Coordinates
3-H-4	*M*	700	Port Errol, Scotland	57° 24′ 40.″224N 1° 50′ 21.″959W
3-H-4	*S*	23001	Bizerte, North Africa	37° 19′ 57.″1N 9° 51′ 30.″1E
3-H-5	*M*	23002	Oran, North Africa	35° 53′ 15.″8N 0° 19′ 17.″2W
3-H-5*	*S*	23003	Apollonia, North Africa	32° 54′ 07.″54N 21° 59′ 03.″42E
3-H-5	*S*	.....	Brindisi, Italy	40° 40′ 48.″1N 17° 56′ 09.″0E

* No longer transmitting.

NORTH PACIFIC CHAIN
Frequency: 1950 kc (channel No. 1)
Basic pulse rate: 25 pps (low)

Recurrence rate	M/S	Station	Location	"Adopted" coordinates
1-L-0	*M*	C	Amchitka Island	51° 22′ 01.″34N 179° 12′ 09.″25E
1-L-0	*S*	T	Attu Island	52° 45′ 09″N 172° 54′ 31″E
1-L-1	*S*	M	St. Matthew Island	60° 21′ 30″N 172° 42′ 56″W
1-L-1 1-L-2	*M*	P	St. Paul Island	57° 09′ 40″N 170° 24′ 41.″5W
1-L-2	*S*	U	Umnak Island	52° 56′ 05.″5N 168° 57′ 23.″5W

Central Pacific Chain
Frequency: 1850 kc (channel No. 2)
Basic pulse rate: 25 pps (low)

Recurrence rate	M/S	Station	Location	Adopted coordinates
2-L-0	*S*	J	Hawaii Island	20° 15′ 16″.5N 155° 53′ 23″.3W
2-L-0 2-L-1	*M*	Q	Niihau Island	21° 48′ 16″.4N 160° 14′ 13″.5W
2-L-1	*S*	G	French Frigate Shoals	23° 47′ 04″.7N 166° 12′ 39″.5W
2-L-2	*S*	K	Kwajalein Atoll	9° 00′ 52″.35N 167° 43′ 52″.42E
2-L-2 2-L-3	*M*	D	Majuro Atoll	7° 13′ 01″.34N 171° 04′ 29″.96E
2-L-3	*S*	L	Makin Atoll	3° 16′ 19″.8N 172° 40′ 35″.9E
2-L-4	*S*	E	Baker Island	0° 11′ 46″.23N 176° 28′ 26″.14W
2-L-4 2-L-5	*M*	R	Gardner Island	4° 41′ 41″.65S 174° 29′ 50″.61W
2-L-5	*S*	F	Atafu Island	8° 31′ 53″.6S 172° 31′ 06″.0W

SOUTHWEST PACIFIC CHAIN
Frequency: 1750 kc (channel No. 4)
Basic pulse rate: 33⅓ pps (high)

Recurrence rate	M/S	Station	Location	Coordinates
4-H-0*	*M*	N	Mapia	0° 50′ 29″N 134° 18′ 15″E
4-H-0* 4-H-1*	*S*	P	Suluan, Philippines	10° 46′ 13″.9N 125° 56′ 28″.4E
4-H-1* 4-H-2	*M*	H	Potangeras, Ulithi	10° 04′ 14″.5N 139° 40′ 24″.3E
4-H-2 4-H-3	*S*	V	Guam	13° 13′ 42″.1N 144° 38′ 40″.5E
4-H-3	*M*	S	Saipan	15° 07′ 50″.17N 145° 41′ 40″.20E
4-H-4 4-H-5	*M*	K	Iwo Jima	24° 48′ 26″.1N 141° 17′ 30″E
4-H-4	*S*	J	Okinawa	26° 23′ 49″.4N 128° 00′ 04″.5E
4-H-5	*S*	. .	O Shima, Japan	34° 40′ 36″.0N 139° 26′ 33″E
4-H-6	*S*	U	Ngesebus Island, Palau	7° 03′ 51″N 134° 15′ 16″E
4-H-6 4-H-7	*M*	T	Pulo Anna	4° 39′ 21″N 131° 56′ 42″E
4-H-7	*S*	M	Morotai	2° 35′ 05″N 128° 36′ 16″E
4-H-0 4-H-1	. .	. .	Aguni, Okinawa	26° 35′ 01″N 127° 12′ 27″E

* No longer transmitting.

BANDA SEA CHAIN
Frequency: 1850 kc (channel No. 2)
Basic pulse rate: 33⅓ pps (high)

Recurrence rate	M/S	Station	Location	Coordinates
2-H-4	*S*	N	Bathurst Island	11° 45′ 38″S 130° 01′ 43″E
2-H-4 2-H-5	*M*	W	Sir Graham Moore Island	13° 52′ 18″S 126° 30′ 10″E
2-H-5	*S*	A	Champagny Island	15° 16′ 56″S 124° 16′ 25″E

China-Burma-India (CBI) Chain
Frequency: 1750 kc (channel No. 4)
Basic pulse rate: 25 pps (low)

Recurrence rate	M/S	Station	Location	Adopted coordinates
4-L-4 4-L-3	*M*	A	Hoogrijan, Assam, India	27° 22′ 51″.5N 95° 14′ 41″.3E
4-L-4 4-L-5*	*S*	B	Paya, Assam, India	27° 51′ 46″.0N 95° 59′ 05″.2E
4-L-3	*S*	C	Amguri, Assam, India	26° 45′ 45″.0N 94° 36′ 15″.0E
4-L-2 4-L-1	*M*	D	Kunyan, Yunnan, China	24° 39′ 34″.4N 102° 37′ 56″.7E
4-L-2	*S*	E	Lutze Yunnan, China	25° 22′ 49″.5N 102° 17′ 54″.2E
4-L-1 4-L-0*	*S*	F	Ami, Yunnan, China	23° 40′ 22″.4N 103° 14′ 56″.7E
4-L-0*	*M*	G	Hanchung, Szechwan, China	33° 09′ 02″.5N 107° 11′ 46″.4E
4-L-6 4-L-5*	*M*	X	Char Chapli Island, Bengal, India	21° 47′ 50″.6N 90° 09′ 08″.9E
4-L-6 4-L-7	*S*	Y	Puri, Orissa, India	19° 48′ 12″.4N 85° 51′ 10″.6E
4-L-7	*M*	Z	Coconada, Madras, India	16° 55′ 06″.3N 82° 14′ 24″.0E

* Sky-wave Synchronized.

Gulf of Mexico Training Chain
Frequency: 1850 kc (channel no. 2)
Basic pulse rate: 25 pps (low)

Recurrence rate	M/S	Station	Location	Coordinates
2-L-5 2-L-6	*M*	M	Matagorda Island, Tex.	28° 20′ 18″.6N 96° 25′ 22″.4W
2-L-5	*S*	R	Cameron, La.	29° 45′ 52″.9N 93° 22′ 19″.0W
2-L-6	*S*	T	Port Isabel, Tex.	26° 04′ 48″.0N 97° 09′ 55″.8W

Central Interior United States Training Chain

Frequency: 1850 kc (channel no. 2)
Basic pulse rate: 33⅓ pps (high)

Recurrence rate	M/S	Station	Location	Coordinates
2-H-6 2-H-7	*M*	P	George Field, Ill.	38° 46′ 59.″7N 87° 39′ 08.″9W
2-H-6	*S*	D	Danville, Ill.	40° 06′ 13.″3N 87° 32′ 26.″4W
2-H-7	*S*	S	Sturgis, Ky.	37° 32′ 54.″0N 87° 57′ 58.″1W

West Coast Chain

Frequency: 1850 kc (channel no. 2)
Basic pulse rate: 33⅓ pps (high)

Recurrence	M/S	Station	Location	Coordinates
2-H-4 2-H-5	*M* *M*	......	Point Granville, Wash.	....
2-H-4	*S*	......	Cape Blanco, Ore.	....
2-H-5	*S*	......	Spring Island, Vancouver Island	....

Army Stations
West Coast Chain

Frequency: 1950 kc (channel no. 1)
Basic pulse rate: 33⅓ pps (high)

Recurrence rate	M/S	Station	Location	Coordinates
1-H-6 1-H-7	*M*	S	Point Sur, Calif.	36° 19′ 01″N 121° 53′ 34″W
1-H-6	*S*	A	Point Arena, Calif.	38° 55′ 08″N 123° 43′ 23″W
1-H-7	*S*	G	Point Arguello, Calif.	34° 34′ 59.″5N 120° 38′ 37.″0W

South China Sea Chain

Frequency: 1950 kc (channel no. 1)
Basic pulse rate: 25 pps (low)

Recurrence rate	M/S	Station	Location	Coordinates
1-L-6	*M*	L	Nawlo Point, Luzon	15° 42′ 22.″01N 119° 53′ 45.″35E
1-L-6 1-L-7	*S*	B	Talampulon	12° 07′ 54.″69N 119° 50′ 31.″42E
1-L-7	*S*	R	Palawan, Tarumpitao	09° 02′ 57.″5N 117° 37′ 44.″3E

APPENDIX C

DEMONSTRATIONS CONCERNING THE GEOMETRY OF LORAN LINES

By B. W. Sitterly

C·1. The Factor of Geometrical Precision (Supplementary to Sec. 3·4).—The factor of geometrical precision w is the ratio of the linear distance between a point on a Loran line and the nearest point on an adjacent line of the same family to the interval between the corresponding

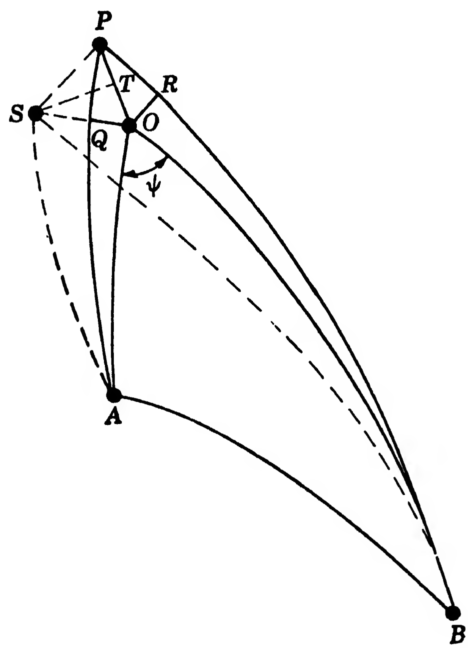


Fig. C·1.—The factor of geometrical precision.

time differences. The linear distance is expressed in light-microseconds; the interval in microseconds of time. If the angle between the directions from the point to the two Loran transmitting stations is ψ,

$$w = \tfrac{1}{2} \csc \tfrac{1}{2}\psi.$$

This relation may be simply demonstrated geometrically.

Consider the triangle ABO (Fig. C·1), where A and B are the stations and O is the observer. The triangle may be plane, spherical, or spheroidal. Let the difference between lengths AO and BO be v. Let P be a point such that in the triangle ABP, $AP = AO + x$ and $BP = BO + x$, x being small enough to be regarded as negligible compared with AO and BO. Then in the neighborhood of O and P, AP is considered as parallel to AO and BP to BO, and all the small triangles in the following discussion are considered as plane.

Connect O to P by a straight line. The difference between the lengths AP and BP is the same as between AO and BO, and therefore OP is an infinitesimal segment of the hyperbola v. Drop a perpendicular from O upon AP, meeting it at Q, and one upon BP, meeting it at R. Since these perpendiculars are of infinitesimal length, $AQ = AO$, $BR = BO$, and thus $QP = RP = x$. The right triangles PQO and PRO are therefore congruent, and the angles OPQ and OPR equal. Consequently the hyperbola bisects the angle APB and, if extended beyond O, bisects the equal angle AOB, which is the difference between the directions of the stations from O or its neighborhood. Denote this angle by ψ.

Erect a perpendicular upon BP at P, and extend it to meet at S the extension of OQ (which is perpendicular to AO at O). S is a point on the hyperbola $(v + x)$, for in the triangle ABS, $AS = AO$ and

$$BS = BP = BO + x.$$

Drop a perpendicular ST from S upon OP. ST is then the distance apart of the hyperbolas v and $(v + x)$ in the neighborhood of O. Denote this distance by y.

Now the angles OPQ and TSP are equal, having respectively perpendicular sides. For the same reason, the angles OPR and TSO are equal, so all four angles are equal to $\frac{1}{2}\psi$, and T bisects OP.

Hence

$$ST = \tfrac{1}{2}OP \cot (\text{angle } OST \text{ or } PST), \qquad \text{or} \qquad y = \tfrac{1}{2}OP \cot \tfrac{1}{2}\psi.$$

But

$$OP = PQ \sec (\text{angle } OPQ) = PR \sec (\text{angle } OPR) = x \sec \tfrac{1}{2}\psi.$$

Therefore

$$y = x(\tfrac{1}{2} \csc \tfrac{1}{2}\psi).$$

If x is expressed in light-microseconds, it is equal to the change in the time difference observed in passing from O to S, from the hyperbola v to the hyperbola $(v + x)$. Since y is the distance between these hyperbolas, in the same units as x, k is unity and

$$w = \tfrac{1}{2} \csc \tfrac{1}{2}\psi.$$

If y is desired in nautical miles, statute miles, kilometers, or feet, w must be multiplied by the appropriate value of k, giving

$$\begin{aligned} kw &= 0.08086 \csc \tfrac{1}{2}\psi && \text{(nautical miles/}\mu\text{sec)} \\ &= 0.09311 \csc \tfrac{1}{2}\psi && \text{(statute miles/}\mu\text{sec)} \\ &= 0.14985 \csc \tfrac{1}{2}\psi && \text{(km/}\mu\text{sec)} \\ &= 491.62 \csc \tfrac{1}{2}\psi && \text{(ft/}\mu\text{sec).} \end{aligned}$$

C·2. The Probable Ellipse (Supplementary to Sec. 3·5).—In the theory of simple correlation it is demonstrated that if the position of a point is defined by two independent rectilinear (but not necessarily rectangular) coordinates, both subject to errors that are normally distributed, all these infinitesimal equal areas within which the point has some numerically specified chance of falling lie along an ellipse. All these ellipses are concentric and have the same eccentricity. Since Loran readings define coordinates of this sort over a small area, the theory may be applied to Loran fixes. Let rectangular coordinates be taken, with origin at the intersection of hyperbolas P and Q and x-axis along P, x being positive in the direction in which time differences of the family of T'' increase, y in the direction in which those of the family of T' increase. (The notation here and below is that of Sec. 3.5.) The point $(T_1 - T', T_2 - T'')$ or (p',p'') has rectangular coordinates

$$\left.\begin{aligned} x &= p' \cot \Phi + p'' \csc \Phi, \\ y &= p'. \end{aligned}\right\} \tag{1}$$

Though the possible values of p' and p'' are not correlated, those of x and y are. Their standard deviations s_x and s_y and correlation coefficient r_{xy} are given by the expressions

$$\left.\begin{aligned} s_x^2 &= \frac{\Sigma x^2}{n} = s_1^2 \cot^2 \Phi + s_2^2 \csc^2 \Phi, \\ s_y^2 &= \frac{\Sigma y^2}{n} = s_1^2, \\ r_{xy} &= \frac{\Sigma xy}{n s_x s_y} = \frac{s_1^2 \cot \Phi}{s_1 \sqrt{s_1^2 \cot^2 \Phi + s_2^2 \csc^2 \Phi}} \\ &= \frac{s_1 \cot \Phi.}{\sqrt{s_1^2 \cot^2 \Phi + s_2^2 \csc^2 \Phi.}} \end{aligned}\right\} \tag{2}$$

In forming the right-hand members of these equations, terms in $\Sigma p'p''$ vanish because for any given pair of numerical values p', p'' that have the same sign there is another numerically equal pair having opposite signs, since p' and p'' are independent and normally distributed. It may be shown[1] that the probability that the true point has coordinates between given values x, y and $x + dx$, $y + dy$ is

$$\frac{dx\,dy}{2\pi s_x s_y \sqrt{1 - r_{xy}^2}} \exp\left[-\frac{1}{2(1 - r_{xy}^2)}\left(\frac{x^2}{s_x^2} - \frac{2xyr_{xy}}{s_x s_y} + \frac{y^2}{s_y^2}\right)\right], \tag{3}$$

the equation applying generally to normally correlated pairs of quantities

[1] H. C. Plummer, *Probability and Frequency*, Macmillan, London, 1940, pp. 224–231; G. U. Yule, *Introduction to the Theory of Statistics*, Griffin, London, 1927, pp. 317–322.

x, y. The ellipses

$$\frac{x^2}{s_x^2} - \frac{2xyr_{xy}}{s_xs_y} + \frac{y^2}{s_y^2} = 2(1 - r_{xy}^2)c^2 \tag{4}$$

are curves of constant probability, and the probability that the true point is within one of these ellipses is

$$1 - \exp(-c^2).$$

Substitution of Eq. (2) into Eq. (4) and of p_1 and p_2 for s_1 and s_2, with recombination of terms, gives

$$\frac{\sin^2 \Phi}{p_2^2} x^2 - \frac{2 \sin \Phi \cos \Phi}{p_2^2} xy + \left(\frac{\cos^2 \Phi}{p_2^2} + \frac{1}{p_1^2}\right) y^2 = 4.396c^2 \tag{5}$$

as the equation of the ellipses in this case. If the arbitrary constant c is given the value 0.8326, the probability that the point is within the ellipse is one-half. This ellipse is equivalent to the probable parallelogram and has been called the *probable ellipse*. Its conjugate diameters along P and Q have length $3.49p_2 \csc \Phi$ and $3.49p_1 \csc \Phi$ respectively. Its major axis (FG in Fig. 3·18) lies within the acute angle between P and Q and makes the angle Ω with the x-axis (the angle PCG). If we represent Eq. (5) by

$$Ax^2 + 2Hxy + By^2 = C,$$

in terms of the rectangular coordinates x, y, it may be transformed to the standard central equation of the ellipse

$$\frac{\xi^2}{\alpha^2} + \frac{\eta^2}{\gamma^2} = C,$$

in terms of a rectangular coordinate system with ξ- and η-axes coinciding with the axes of the ellipse, by means of the relations

$$\tan 2\Omega = \frac{-2H}{B - A},$$

$$\alpha^2 + \gamma^2 = \frac{A + B}{AB - H^2},$$

$$\alpha^2 - \gamma^2 = \frac{(B - A) \sec 2\Omega}{AB - H^2},$$

from which follow directly

$$2\alpha^2 = \frac{A(1 - \sec 2\Omega) + B(1 + \sec 2\Omega)}{AB - H^2},$$

$$2\gamma^2 = \frac{A(1 + \sec 2\Omega) + B(1 - \sec 2\Omega)}{AB - H^2}.$$

Putting in the values of A, B, and H and reducing, we obtain

$$\left.\begin{aligned} \tan 2\Omega &= \frac{2p_1^2 \cot \Phi}{p_1^2(\cot^2 \Phi - 1) + p_2^2(\cot^2 \Phi + 1)} = \frac{p_1^2 \sin 2\Phi}{p_1^2 \cos 2\Phi + p_2^2}, \\ \alpha &= \sqrt{\tfrac{1}{2}(p_1^2 + p_2^2) \csc^2 \Phi + p_1^2 \cot \Phi \csc 2\Omega}, \\ \gamma &= \sqrt{\tfrac{1}{2}(p_1^2 + p_2^2) \csc^2 \Phi - p_1^2 \cot \Phi \csc 2\Omega}. \end{aligned}\right\} \quad (6)$$

The two axes of the ellipse (FG and HJ in Fig. 3·18) have lengths 3.49α and 3.49γ respectively, and these lengths, with the angle Ω between the x- and ξ-axes, give a definite picture of the theoretical distribution of errors of fix around a point. The probability that the true position is within an ellipse similar to the probable ellipse and similarly placed, but with dimensions multiplied by 1.82, is nine-tenths.

C·3. The Probable Error of a Fix (Supplementary to Sec. 3·5).—The probable error p_1 or p_2 is the "expected" distance between the hyperbola P or Q specified by the observed time difference and the true line of position at the time of observation, in the sense that it is equally probable that the actual distance is greater or less. An expected or probable distance, in the same sense, between the intersection of P and Q and the true fix is for many purposes the most useful measure of the error of fix. Unfortunately, this distance cannot be simply specified. The quantity $\sqrt{(\Sigma d^2)/n}$, where $d = \sqrt{x^2 + y^2}$, is the standard deviation of distances between the observed fix and the true fix. It may be denoted by D. Squaring, adding, and summing the expressions in Eq. (1) and remembering that terms in $\Sigma p'p''$ vanish, we obtain

$$\begin{aligned} D^2 &= \frac{\Sigma d^2}{n} = \frac{\Sigma x^2}{n} + \frac{\Sigma y^2}{n} \\ &= s_1^2(\cot^2 \Phi + 1) + s_2^2 \csc^2 \Phi. \\ D &= \csc \Phi \sqrt{s_1^2 + s_2^2}. \end{aligned}$$

Though values of x and y are normally distributed, d is not. The probability that d is less than D varies with the shape of the error ellipses; when these are circular, the probability is 0.632; and when they are extremely eccentric, the probability approaches 0.683, the value for the standard deviation of a single variable. The quantity $0.6745D$ is not the median value of d, or probable error of a fix, for the probability that d is less than $0.6745D$ is 0.366 if the error ellipses are circular and tends to 0.500 only as their eccentricity approaches unity.

The distribution of the values of d is investigated[1] by transforming Eq. (3) into polar coordinates r and θ and integrating over all values of θ and from $r = 0$ to $r = R$. The value of the integral is the probability

[1] Operational Research Staff, Office of the Chief Signal Officer, "The Range, Reliability, and Accuracy of a Low Frequency Loran System," Report ORS-P-23, Appendix II, Washington, 1946, pp. 77–81. The discussion below is adapted from that given in this reference.

that d is less than R. It is necessary to perform the integration with respect to r by numerical quadratures. The probability is found to be a function of R/D and of s_ξ/s_η or α/γ. If $R = 1.2D$, the probability is about 0.77 for all values of α/γ; for any value of R much smaller, the probability increases as α and γ become more unequal, whereas for any value much larger, it decreases. If $R = 0.775D$, the probability that d is less than R is 0.452 if $\alpha = \gamma$ and approaches 0.562 as α and γ become very unequal, whereas for error ellipses of moderate eccentricity it is quite close to one-half. This value of R is therefore an approximation to the probable error of a fix, close enough for practical purposes. It may be denoted by P; and since

$$D = \csc \Phi \sqrt{s_1^2 + s_2^2} = \frac{\csc \Phi}{0.6745} \sqrt{p_1^2 + p_2^2},$$

we have

$$P = 1.15 \csc \Phi \sqrt{p_1^2 + p_2^2} = \frac{1.15 p_2}{\sin \Phi} \sqrt{1 + \left(\frac{p_1}{p_2}\right)^2}, \tag{7}$$

where the latter form of the right-hand member is handy for computation if p_2 is taken larger than p_1, since the radical varies only between 1 and $\sqrt{2}$. In Fig. 3·18 P is the radius of the dotted circle, which is analogous to the probable parallelogram and probable ellipse in that it contains approximately half the possible locations of the true fix.

P may be found by measurement on the Loran chart if the probable errors ϵ_1 and ϵ_2 of the time difference measures are the same ($\epsilon_1 = \epsilon_2 = \epsilon$). Consider the parallelogram formed by two pairs of hyperbolas, printed on the chart and equally spaced in time difference, enclosing the fix as determined by the measures. The time interval between the pairs may be 20, 50, or 100 μsec, according to the chart scale; let us denote it by m. The distances between hyperbolas are kmw_1 and kmw_2; the sides of the parallelogram have lengths $kmw_1 \csc \Phi$ and $kmw_2 \csc \Phi$; and the diagonals have lengths $km \csc \Phi \sqrt{w_1^2 + w_2^2 \pm 2w_1w_2 \cos \Phi}$. The square root of the sum of the squares of the diagonals is $km \csc \Phi \sqrt{(w_1^2 + w_2^2)}$; let us denote it by S. Now $p_1 = kw_1\epsilon$ and $p_2 = kw_2\epsilon$; so

$$S = \frac{m}{\epsilon} \csc \Phi \sqrt{p_1^2 + p_2^2},$$

or

$$P = 1.15 \frac{\epsilon}{m} S. \tag{8}$$

Therefore if the diagonals of the printed parallelogram are measured in miles or kilometers by means of the chart scale, squared, and added and the square root taken, P is immediately obtained from Eq. (8).

It is to be noted that P is not the *average* error of fix, derived in A.

Bravais' classic paper[1] and appearing in some statistical texts.[2] The average error is a little larger than P. It is mathematically more elegant, for it may be evaluated directly from D by means of a table of elliptic integrals, but it is not so convenient as P.

In all the discussion, it was assumed that no correlation between the errors of the two measurements existed. But there may well be some correlation. Then the relations given above are replaced by more complicated ones. A detailed exposition of this case is given in the reference on page 429.

[1] A. Bravais, *Analyse mathématique sur les probabilités des erreurs de situation d'un point*, Academie des Sciences. Memoires par divers savants, 2me serie, Tome 9, Paris, 1846, p. 225.

[2] Plummer, *op. cit.*, p. 231.

APPENDIX D

DETERMINATION OF ERRORS IN THE POSITIONS OF LORAN TRANSMITTING STATIONS[1]

By B. W. Sitterly

It is often necessary to place Loran transmitting stations at points whose geographic positions cannot be tied into geodetic triangulation networks. The astrometric determination of these positions can be corrected for deflection of the vertical only by estimation. Consequently, appreciable errors may affect the station positions, and these errors will cause the time differences T_o observed at various points in the service

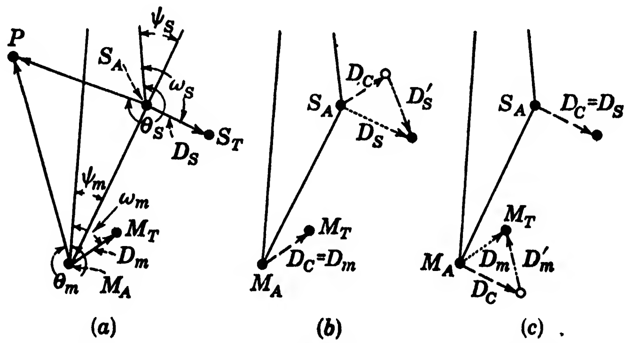


Fig. D·1.—Displacement of stations. M_A and M_T are the assumed and true positions of master station; S_A and S_T those of slave. P is a point of observation. D_s and D_m are separate displacements of stations; D_s' and D_m' relative component; D_c common component.

area to differ from the time differences T_c that have been calculated for the same points and indicated on the Loran charts. The difference $(T_o - T_c)$ at a point is a function of the distance D and direction ω *from* the position of each station *as assumed* in the calculations *to* its *true* position, and also of the directions θ from the stations to the point of observation. The functional relations are simple if no other errors are present. They have been given by Lieut. Comdr. F. G. Watson (Loran Report No. 26 of the Radiation Laboratory and Loran Technical Report No. 2 of the U.S. Hydrographic Office) in substantially the form

$$\Delta T - \Delta\beta = -D_s \cos(\theta_s - \omega_s) + D_m \cos(\theta_m - \omega_m). \tag{1}$$

$$\Delta\beta = D_s \cos(\omega_s - \Psi_s) - D_m \cos(\omega_m - \Psi_m) = \tfrac{1}{2}\Delta T_m, \tag{2}$$

in which $\Delta T = T_o - T_c$; $\Delta\beta$ is the true baseline length (in microseconds) minus the baseline length calculated from the assumed station positions;

[1] Loran Memorandum No. 149.

D_s and D_m are the distances in microseconds and ω_s and ω_m the directions (Fig. D·1*a*) from the assumed station positions to the true station positions, *s* indicating the slave and *m* the master station; θ_s and θ_m are the directions from the slave and master station respectively to the point at which ΔT was obtained; ΔT_m is the value of T observed on the extended baseline behind the master station, minus the calculated value of $(2\beta + \delta)$; Ψ_s is the direction from the slave station along the extended baseline *away* from the master; and Ψ_m is the direction from the master station along the baseline *toward* the slave (these differ slightly because the meridians converge). All the directions must be measured in the same sense of rotation from the same initial direction; either sense and any initial direction may be chosen, but clockwise and north are convenient choices, making all the angles true bearings. They have been used in all the examples below.

Values of T_o are directly observed. Values of T_c, θ, and Ψ may be read from a chart or calculated, since the locations of all points of observation are known. The only unknowns in the equations are D_s, ω_s, D_m, and ω_m.

If four values of ΔT have been obtained by observation at properly distributed points, it is ideally possible to compute the magnitudes and directions by which the actual stations are displaced from their assumed locations, by solving four equations simultaneously for the four unknown quantities. Equations (1) and (2) are not of suitable form for the solution, but they may be combined and transformed into the single equation

$$\begin{aligned}\Delta T = {} & D_s \cos \omega_s(\cos \Psi_s - \cos \theta_s) + D_s \sin \omega_s(\sin \Psi_s - \sin \theta_s) \\ & - D_m \cos \omega_m(\cos \Psi_m - \cos \theta_m) - D_m \sin \omega_m(\sin \Psi_m - \sin \theta_m), \qquad (3)\end{aligned}$$

which is linear if $D_s \cos \omega_s$, $D_s \sin \omega_s$, $D_m \cos \omega_m$, and $D_m \sin \omega_m$ are taken as the unknowns. When these have been determined, the equations

$$\left.\begin{aligned} D_s &= \sqrt{(D_s \cos \omega_s)^2 + (D_s \sin \omega_s)^2}, \\ \tan \omega_s &= \frac{D_s \sin \omega_s}{D_s \cos \omega_s}, \end{aligned}\right\} \qquad (4)$$

together with two similar expressions in D_m and ω_m, will give the displacements and their directions. If the directions are true bearings,

$$\left.\begin{aligned} \Delta\phi_s &= \pm 9.7 D_s \cos \omega_s. \\ \Delta\lambda_s &= \frac{\pm 9.7 D_s \sin \omega_s}{\cos \phi_s}, \end{aligned}\right\} \qquad (5)$$

where ϕ_s is the assumed latitude of the slave station, $\Delta\phi_s$ is its true latitude minus its assumed latitude, and $\Delta\lambda_s$ its true longitude minus its assumed longitude. $\Delta\phi_s$ and $\Delta\lambda_s$ are in seconds of arc. The positive signs are used in north latitude and east longitude; the negative in south latitude and west longitude. Two similar equations give $\Delta\phi_m$ and $\Delta\lambda_m$ for the master station.

This ideal solution is possible only if the errors in the station locations are wholly responsible for the values of ΔT. Actually, the position of any point at which ΔT is observed may be as much in error as that of a station; the observation itself is also subject to error. Therefore a method of solution is generally preferable that utilizes many observed values of ΔT, enough so that the random errors peculiar to the individual points tend to cancel each other. The standard method in this case is that of least squares, but with four unknowns it is quite laborious. Since

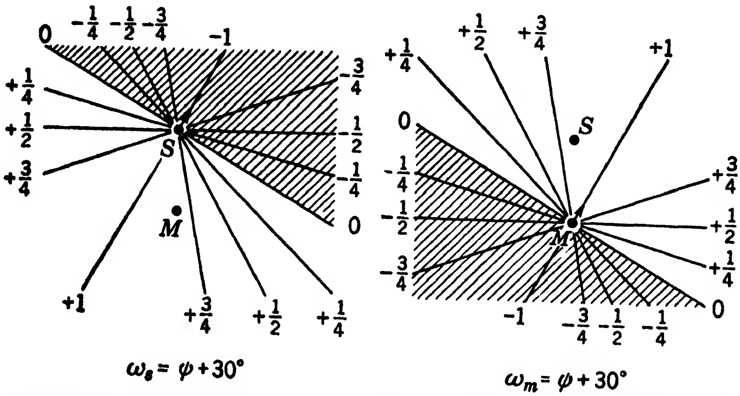


Fig. D·2.—Displacement of one station, or relative displacement. Numbers give $\Delta' T$ as a fraction of D_s or D_m.

observations will not usually be numerous enough or distributed advantageously enough to give *accurate* values for the station displacements, a graphical form of solution will save time and labor, give results as definite as the observations warrant, and exhibit clearly the uncertainties in the quantities determined. Such a graphical solution is described below.

A set of expressions in the form of Eq. (1) gives a definite pattern of errors over the chart. The two terms on the left are observed quantities. The values of their difference are distributed over the chart in accordance with the combined effects of the two terms on the right. Each of these right-hand terms, *by itself*, would give the pattern a simple, symmetrical form. Along any great circle radiating from the station the difference $(\Delta T - \Delta\beta)$ would be constant; in two opposite directions it would be zero, and in two opposite directions at right angles to these it would be an extreme, the maximum in one direction and the minimum, of equal magnitude but opposite sign, in the other (Fig. D·2). In the case of the first term, the maximum would be equal in magnitude to D_s and lie along a great circle in the direction $\theta_s = \omega_s + 180°$ from the slave station;

in the case of the second term the maximum would be equal to D_m and lie along a great circle in the direction $\theta_m = \omega_m$ from the master station. To express the symmetry differently, if Δ_m were zero, and if $(\Delta T - \Delta\beta)$ were plotted against θ_s, its values would define a cosine curve of amplitude D_s, with its *minimum* value at phase $(\theta_s = \omega_s)$. If D_s were zero, a similar plot against θ_m would exhibit the magnitude and direction of D_m. In either case such a plot would furnish an immediate graphical solution for the displacement of one station if the other were known to be correctly located.

Since the locations of both stations must generally be considered as doubtful, neither term can be ignored in practice. But over the outer parts of the service area of a pair, θ_m does not differ greatly from θ_s; therefore in these regions the two cosine terms are nearly equivalent to a single cosine term, with either θ_s or θ_m as angular argument, and amplitude and phase which represent the vector difference of the displacements of the two stations, which is the relative displacement of one station *with respect to the other*. The equivalence is not exact; a plot of $(\Delta T - \Delta\beta)$ against either θ_m or θ_s will give a curve that departs from true cosine shape because in addition to the relative displacement there is a common displacement of the two stations, the effect of which is large upon values of T observed near the baseline and center line and small but appreciable at large distances. If θ_s is taken as argument in the plot, the curve will show the effect of the displacement of the slave station relative to the master, plus the effect of a common displacement equal to the actual amount that the master is out of place (Fig. D·1*b*). If θ_m is argument, the curve will represent the displacement of master relative to slave, plus a common displacement equal to the actual displacement of the slave (Fig. D·1*c*). The combinations are equivalent, of course, but the components are not the same. The two relative displacements are equal in magnitude but opposite in direction; the two common displacements are quite different. The curves drawn with arguments θ_s and θ_m will differ from each other as well as from true cosine form, and a correct interpretation of the general form and of the differences should in theory yield values of the sizes and directions of both relative and common displacements and therefore of the separate displacements of the two stations.

In practice, the presence of random observational errors will make a correct interpretation of the differences between two curves of similar form almost impossible. But if Eqs. (1) and (2) are restated in terms of the relative and common displacements so that the effect of each is expressed explicitly and separately, this difficulty is avoided. Let the relative displacement be assigned to the slave station and its magnitude and direction denoted by D'_s and ω'_s. Let D_c denote the magnitude of the common displacement, and let $(\omega_c + \frac{1}{2}\Delta\Psi)$ denote its direction at the slave station and $(\omega_c - \frac{1}{2}\Delta\Psi)$ its direction at the master station, $\Delta\Psi$ being $(\Psi_s - \Psi_m)$. Then the equations

$$\left.\begin{aligned} D_m &= D_c, \qquad \omega_m = \omega_c - \tfrac{1}{2}\Delta\Psi, \\ D_s \cos\omega_s &= D_s' \cos\omega_s' + D_c \cos(\omega_c + \tfrac{1}{2}\Delta\Psi), \\ D_s \sin\omega_s &= D_s' \sin\omega_s' + D_c \sin(\omega_c + \tfrac{1}{2}\Delta\Psi) \end{aligned}\right\} \tag{6}$$

define the separate displacements in terms of the relative and common displacements. Equation (1) may be written as

$$\begin{aligned} \Delta'T = -D_s \cos\theta_s \cos\omega_s - D_s \sin\theta_s \sin\omega_s \\ + D_m \cos\theta_m \cos\omega_m + D_m \sin\theta_m \sin\omega_m, \end{aligned}$$

where $\Delta'T = \Delta T - \Delta\beta$. Substituting the relations (6) gives

$$\begin{aligned} \Delta'T &= -D_s' \cos\theta_s \cos\omega_s' - D_c \cos\theta_s \cos(\omega_c + \tfrac{1}{2}\Delta\Psi) \\ &\quad - D_s' \sin\theta_s \sin\omega_s' - D_c \sin\theta_s \sin(\omega_c + \tfrac{1}{2}\Delta\Psi) \\ &\quad + D_c \cos\theta_m \cos(\omega_c - \tfrac{1}{2}\Delta\Psi) + D_c \sin\theta_m \sin(\omega_c - \tfrac{1}{2}\Delta\Psi) \\ &= -D_s' \cos(\theta_s - \omega_s') \\ &\qquad - D_c\{\cos[\theta_s - (\omega_c + \tfrac{1}{2}\Delta\Psi)] - \cos[\theta_m - (\omega_c - \tfrac{1}{2}\Delta\Psi)]\}, \end{aligned}$$

which reduces to

$$\Delta'T = -D_s' \cos(\theta_s - \omega_s') + 2D_c \sin h \sin(H - \omega_c), \tag{7}$$

where $h = \frac{1}{2}[(\theta_s - \theta_m) - \Delta\Psi]$, $H = \frac{1}{2}(\theta_s + \theta_m)$. Equation (2) may be written as

$$\begin{aligned} \Delta\beta = D_s \cos\omega_s \cos\Psi_s - D_m \cos\omega_m \cos\Psi_m \\ + D_s \sin\omega_s \sin\Psi_s - D_m \sin\omega_m \sin\Psi_m, \end{aligned}$$

and substitution of relations (6) leads to

$$\Delta\beta = D_s' \cos(\omega_s' - \Psi_s) = \tfrac{1}{2}\Delta T_m. \tag{8}$$

The pattern of errors corresponding to a set of expressions in the form of Eq. (7) is, of course, the same as that corresponding to a set in the form of Eq. (1). But the two right-hand terms of Eq. (7) contribute to the pattern very differently. The first term is similar to either right-hand term of Eq. (1) and gives by itself the same form of distribution (Fig. D·2). The second term by itself gives a much more complicated distribution (Fig. D·3) in which the skew shape is due to the combined effects of the two sine factors, which vary in different ways with direction from the center of the baseline, whereas the confining of large values to regions not far from the center is due to the first sine factor. The distribution is symmetrical in the sense that the term has the same value in amount and sign at any two points equally distant from the center in opposite directions. The pattern has different forms for different values of ω_c, but values of $\Delta'T$ further from zero than $\pm D_c/2$ cannot occur outside a "figure-eight" area bounded by two circles that pass through the stations and through two points on the center line that are 1.9 baseline lengths away from the baseline on either side (the dashed circles in Fig. D·3). At every point on this boundary, $\sin h = \pm 0.25$. A larger figure eight, cutting the center line at 4 baseline lengths from the baseline, encloses all possible values of $\Delta'T$ further from zero than $\pm D_c/4$.

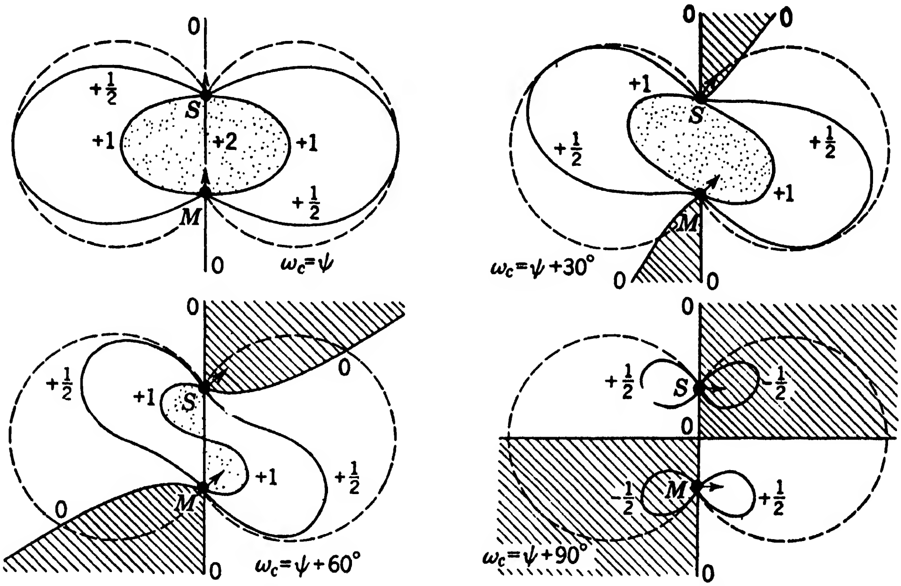


FIG. D·3.—Common displacement of stations, first quadrant. Reversing directions and signs gives patterns for third quadrant. Interchanging right and left of each pattern (mirror image) gives fourth quadrant patterns.* Both changes together give second quadrant. Angles clockwise from vertical.

The second right-hand term of Eq. (7) represents the departure of the $\Delta'T$-curve from the cosine form expressed by the first term. It is evident that for points of observation where h is small—points that are well outside the figure-eight areas—the second term has little influence on the value of $\Delta'T$, and this influence does not have a simple 360° period. Therefore if the points of small h are plotted against θ_s, it will be possible to draw a cosine curve that will represent their distribution reasonably well. The amplitude and phase of this curve will furnish fair approximations to the values of D'_s and ω'_s.

Now if we set

$$\Delta''T = \Delta'T + \underline{D'_s} \cos (\theta_s - \underline{\omega'_s}) \tag{9}$$

(where the underlined quantities are the approximate values just read from the curve) and rewrite Eq. (7) in the form

$$\frac{\frac{1}{2}\Delta''T}{\sin h} = D_c \sin (H - \omega_c), \tag{10}$$

values of $\underline{D'_s}$ and $\underline{\omega'_s}$ may be inserted into Eq. (9) and $\Delta''T$ computed for all points of observation where h is *not* small. Then the left-hand member of Eq. (10) may be plotted against H for these points. This plot has the form of a sine curve. Its amplitude is approximately D_c, and it crosses the horizontal axis, from the negative to the positive side, nearly at the phase $H = \omega_c$.

The values of $\underline{D'_s}$ and $\underline{\omega'_s}$ obtained from the first curve, and of $\underline{D_c}$ and $\underline{\omega_c}$ obtained from the second, constitute the first approximation to the solution of the problem. This solution is to be tested by inserting these values into the equation

$$\left.\begin{aligned} \Delta T - D'_s \cos(\omega'_s - \Psi_s) + \underline{D'_s}\cos(\theta_s - \underline{\omega'_s}) \\ - 2\underline{D_c}\sin \underline{h} \sin(H - \underline{\omega_c}) = \underline{\Delta T}, \end{aligned}\right\} \tag{11}$$

where the first term is the observed error, the next three make up the corrective effect of the approximate displacements just found, and the last term is the *residual*, which would be zero for every observation if the displacements exactly corrected the errors. The residuals are due partly to the approximate character of the graphical solution, partly to errors not caused by incorrect station positions. To improve the approximation, $\underline{\Delta T}$ is plotted against θ_s, as was $\Delta'T$, but on a larger vertical scale. No improvement is possible if the plotted points are distributed at random; but if their arrangement shows traces of a cosine curve, its amplitude and phase represent a correction $\underline{\underline{D'_s}}$, $\underline{\underline{\omega'_s}}$ to the relative displacement of the slave station. $\underline{\underline{D'_s}}$ and $\underline{\underline{\omega'_s}}$ are found from this curve as before, and $\Delta''T$ computed for the points. Then $\underline{\tfrac{1}{2}\Delta''T/\sin h}$ is plotted against H. If the distribution on this plot is random, no further improvement can be made; but, if a sine curve is indicated, a correction $\underline{\underline{D_c}}$, $\underline{\underline{\omega_c}}$ to the common displacement is obtained. Residuals from the second approximation are given by

$$\underline{\Delta T} + \underline{\underline{D'_s}}\cos(\theta_s - \underline{\underline{\omega'_s}}) - 2\underline{\underline{D_c}}\sin h \sin(H - \underline{\underline{\omega_c}}) = \underline{\underline{\Delta T}}. \tag{12}$$

Since a correction to one displacement may reveal a correction to the other, the process described should be repeated until a random distribution of residuals is reached. Under actual field conditions, if reasonably good judgment has been used in fitting curves in the first approximation, the observational errors will scatter the points on the plots for the second approximation to an extent that will make curve-fitting a matter of guesswork, and hence the first displacements obtained will be final. Three approximations will almost never be possible.

Since the first approximate displacements and subsequent corrections are vectors, they must be added vectorially. This may be done graphically (see Fig. D·4) or by means of the equations

$$\left.\begin{aligned} D'_s \cos \omega'_s &= \underline{D'_s} \cos \underline{\omega'_s} + \underline{\underline{D'_s}} \cos \underline{\underline{\omega'_s}} + \cdots \\ D'_s \sin \omega'_s &= \underline{D'_s} \sin \underline{\omega'_s} + \underline{\underline{D'_s}} \sin \underline{\underline{\omega'_s}} + \cdots \\ D_c \cos \omega_c &= \underline{D_c} \cos \underline{\omega_c} + \underline{\underline{D_c}} \cos \underline{\underline{\omega_c}} + \cdots \\ D_c \sin \omega_c &= \underline{D_c} \sin \underline{\omega_c} + \underline{\underline{D_c}} \sin \underline{\underline{\omega_c}} + \cdots \end{aligned}\right\} \quad (13)$$

where the symbols not underlined are the final values. Equations (6) followed by Eqs. (4) and (5) are then used to obtain the separate displacements of the stations.

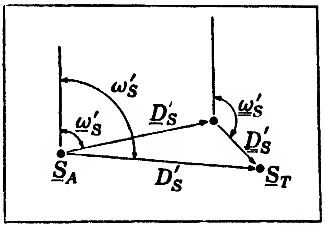


FIG. D·4.—First and second approximation.

As a final check, these displacements may be inserted into Eqs. (1) and (2) or (3), and ΔT computed for all the points of observation. These *computed* values, subtracted from the *observed* values of ΔT, should give residuals identical with the last ones found in the solution, except for occasional differences of a unit (rarely 2) in the last figure, due to rounding off in the calculations.

The detailed procedure of a solution may be illustrated first by an ideal example, in which the quantities ΔT are due only to incorrect positions of the stations. The first step in the procedure is to put the observed data into a suitable form. The actual observations are various values of T_o measured at specified locations. These locations are marked on the Loran chart (or any other), and their directions θ_s and θ_m from the two stations read off accurately enough with a protractor. The directions Ψ_s and Ψ_m are also read off; if their difference $\Delta\Psi$ is smaller than 2°, it may be considered as zero and Ψ_s and Ψ_m replaced by their mean Ψ taken to the nearest degree. If the distances are long and the chart a Mercator in high latitudes, the correction from Mercator to great-circle bearings should be applied, as in radio direction-finding. Values of T_c should be computed by standard formulas; if read from the chart, they will be affected by any chart errors that may exist. Usually values of T_o will not be accurate within 1 μsec, nor will the locations at which they were observed be known within 10″, and thus an accuracy of 1 μsec in T_o is sufficient. If T_o has been observed at a monitor station so that the mean of the observations is considered to be trustworthy to 0.1 μsec, and, if the location of the monitor station is thought to be *accurately* known (to 2 or 3″ including geodetic "station error"), T_c may be computed to 0.1 μsec and T_o *for this point* taken to this precision.

The values of $(T_o - T_c)$, or ΔT, are now tabulated, with the directions θ_s and θ_m and the quantities h and H. In computing h, the order of subtraction and the sign of $\Delta\Psi$ must be watched. Table D·1 presents the example; the corresponding points of observation are charted with the stations in Fig. D·5. Since this is an *ideal* example, ΔT is given to 0.1 μsec throughout, contrary to the statement above, and computations are carried to 0.01 to protect the first decimal.

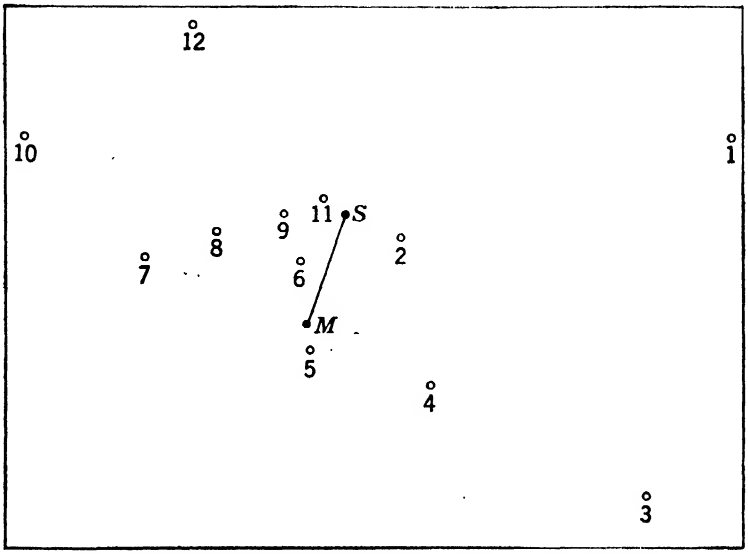


FIG. D·5.—Points of observation in Examples I and II.

It has been assumed throughout the previous discussion that the time difference on the extended baseline behind the master (which may be denoted by T_m) has been observed, and hence ΔT_m, which is equal to $[T_m - (2\beta + \delta)]$, is determined along with the other values of ΔT. In theory, T_m is the reading obtained from the master timer, but in practice it is extremely desirable to obtain it by making readings in the immediate neighborhood of the extended baseline, far enough from the station so that a standard airborne or shipborne indicator may be used for the measurement. This is so because a systematic error may possibly be introduced into the reading at the station by the action of the circuits that pick up and attenuate the local signal. Since readings close to the extended baseline are almost unaffected by small errors in the location of the observer, and, since several series of readings back and forth across the line may be made and the maximum value—which is the reading on the line—determined, ΔT_m should be taken to 0.1 μsec and considered more reliable than any other value of ΔT. In the method of solution outlined above, it is assumed to be *correct*, and half its value (which is $\Delta\beta$) is subtracted from every value of ΔT, giving $\Delta' T$ (Table D·1 Column 7). This subtraction completes the first step of the solution. In order to avoid introducing the small systematic error that would result from rounding off $\frac{1}{2}\Delta T_m$, all the values of $\Delta' T$ should be recorded to 0.1 μsec, though individually they have not this precision. Note that ΔT_m is tabulated with the rest (last line of Table D·1, with the label M); for it,

$$\left.\begin{aligned} \theta_s = \Psi_s + 180^\circ, \qquad \theta_m = \Psi_m + 180^\circ, \qquad h = 0^\circ, \\ \Delta T_m - \Delta\beta = \Delta' T_m = \tfrac{1}{2}\Delta T_m. \end{aligned}\right\} \tag{14}$$

The second step in the solution is the determination of approximate values of D'_s and ω'_s. For this purpose it is convenient to divide the data

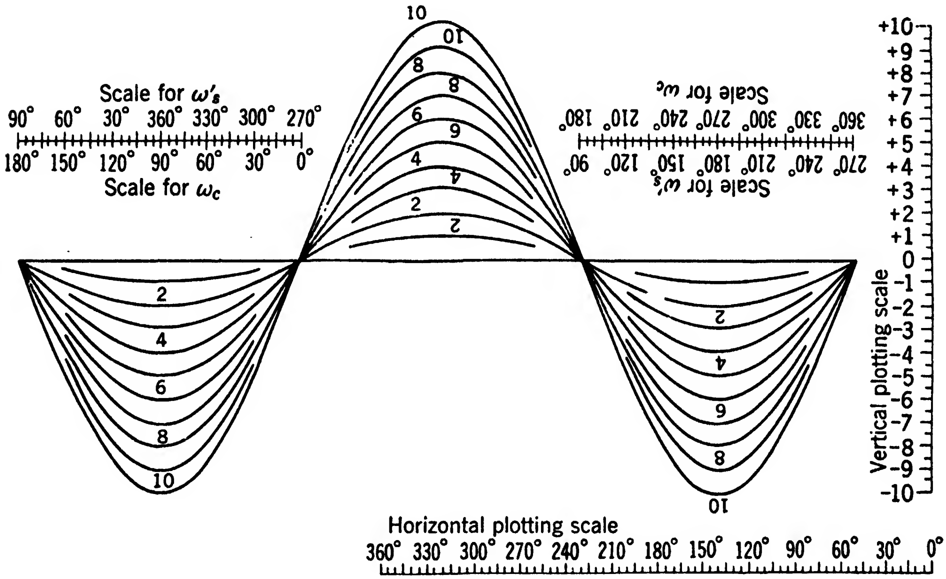


FIG. D·6.—Family of curves.

of observation into three classes, (Table D·1, Column B), Class A including values for which h is less than 15°, Class B including those for which it is between 15° and 30°, and Class C those for which it is 30° or more. These limits are arbitrary, simply dividing up the data according to the importance of the sine term in Eq. (7). As the classes are chosen here, Class A includes all points outside the dashed "figure eight" in Fig. D·3. A rectangular graph is prepared, on which $\Delta' T$ is plotted vertically against θ_s horizontally. The different classes are identified by different symbols so that in fitting a cosine curve to the points, those of Class A may be given the greatest weight. Points of Class C, for which influence of the sine factor may predominate, should be practically ignored in fitting the curve and may well be omitted from the graph.

A simple and rapid way to fit a cosine curve to the points is to use a family of such curves of different amplitudes, drawn on transparent material. Figure D·6 may be carefully copied on tracing cloth or paper to serve this purpose. Horizontal and vertical plotting scales to match the curves are graduated along the edges of the transparency. These scales are to be used to construct the graph on plain paper, as follows:

A horizontal axis ($\Delta'T = 0$) is drawn across the middle of the paper, and a vertical axis ($\theta_s = 0°$) perpendicular to the other near the left-hand edge of the paper. To plot a point having, for example, $\Delta'T = +7.3$, $\theta_s = 128°$, the transparency is laid upon the paper, with its central horizontal axis (*not* its horizontal plotting scale) in coincidence with the horizontal axis ($\Delta'T = 0$) on the paper and with the vertical axis ($\theta_s = 0°$)

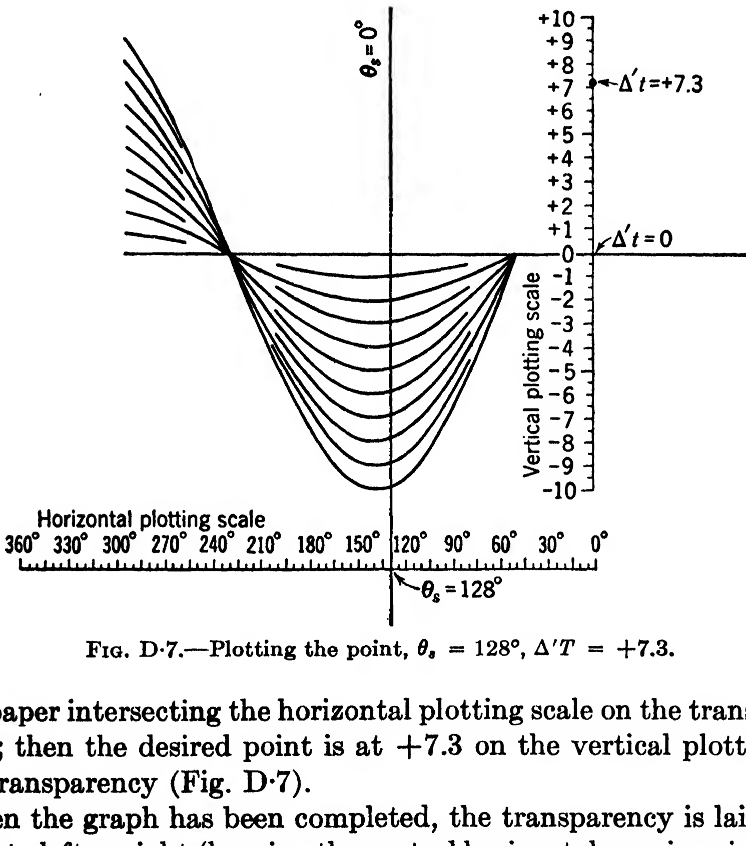


FIG. D·7.—Plotting the point, $\theta_s = 128°$, $\Delta'T = +7.3$.

on the paper intersecting the horizontal plotting scale on the transparency at 128°; then the desired point is at +7.3 on the vertical plotting scale of the transparency (Fig. D·7).

When the graph has been completed, the transparency is laid over it and slid to left or right (keeping the central horizontal axes in coincidence) until a position is found in which one of the curves may be chosen as fitting the points as well as possible; or an interpolated choice may be made, between two curves (Fig. D·8*a*). The value of $\underline{D'_s}$ is the amplitude of the chosen curve (indicated for every alternate curve by an attached number). The value of $\underline{\omega'_s}$ is read from the *scale for* ω'_s at the point where the axis intersects it.

The curve chosen must pass right through the point on the graph that represents $\Delta'T_m$, for this quantity has been assumed to be correct. This should be checked, when D'_s and $\underline{\omega_s}$ have been read, by verifying that

$$\Delta' T_m + \underline{D}'_s \cos (\Psi_s + 180° - \underline{\omega}'_s) = \Delta'' T_m = 0 \tag{15}$$

and $\underline{\omega}'_s$ adjusted if necessary to make the equality exact. The curve will not pass through the other points, in general, because they may be expected to be individually in error and also because the sine term has

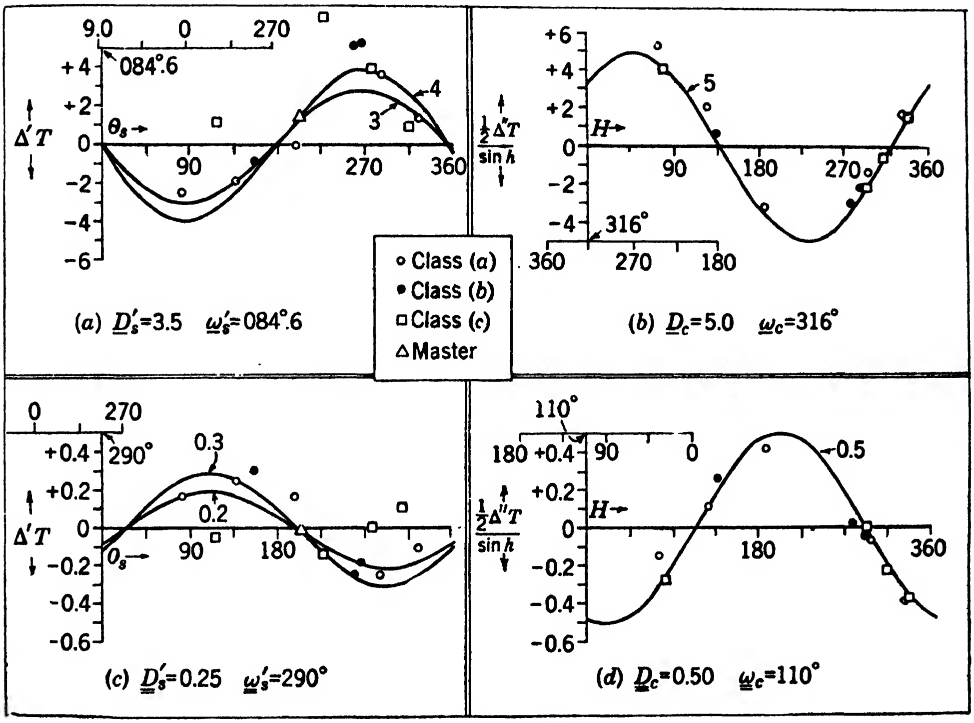


FIG. D·8.—Plots, Example I.

some effect upon even the points of Class A. In the example given here, individual error is absent, but the effect of the sine term is evident. In Fig. D·8*a* the points of Class A follow fairly closely the curve

$$\Delta' T = -3.5 \cos (\theta_s - 085°),$$

whereas some of the Class B points diverge considerably, and some of Class C widely from this curve. The divergence tends to be positive-negative-positive-negative, with the positive swings much more pronounced. (Note that this is similar to the second or third pattern in Fig. D·3 with right and left interchanged, suggesting that ω_c is in the fourth quadrant. The next step will confirm this supposition.) Since, on the whole, the divergence decreases the negative amplitude of the curve with respect to the axis ($\Delta' T = 0$) and increases the positive amplitude, it does not seriously affect the average amplitude, which is what the cosine curve on the transparency must represent. The criterion that D'_s cos $(200° - \underline{\omega'_s})$ must exactly equal -1.50 requires $\underline{\omega'_s} = 084°.6$ if $\underline{D'_s} = 3.50$. The tenths of a degree have no real significance but are retained so that subsequent computations shall check out to 0.01 μsec. The phase $(\underline{\omega'_s} = 084°.6)$ is the horizontal interval from the vertical axis $(\theta_s = 0°)$ to the abscissa at which the curve attains its extreme negative ordinate, but the *scale for* ω'_s gives this interval directly at the point where the vertical axis intersects it.

The third step is the determination of approximate values of D_c and ω_c. Adopting the values found above as first approximations to D'_s and ω'_s, $\Delta''T$ and then $(\frac{1}{2}\Delta''T/\sin h)$ are computed for all points (first five columns of Table D·2), and the latter quantity is plotted against H (Fig. D·8*b*). The computations may be performed very rapidly with a slide rule having a sine scale. Note that $\Delta''T_m = 0$, as it should be, and that since $\sin h = 0$ for the extended baselines, the quotient is indeterminate and therefore the point representing the master reading T_m cannot appear on this plot. In fitting a curve to the plot, it must be borne in mind that points of Class C should be given highest weight and points of Class A almost no weight. Ideally, they should all fit the curve, but actual small divergences will be greatly magnified in the case of a Class A point by the small denominator of the quotient $(\frac{1}{2}\Delta''T/\sin h)$ so that a large departure of the point from the curve will indicate only a small divergence in $\Delta''T$. Class B points behave similarly, in less degree. The points are in effect weighted in proportion to h and should be treated so.

The points of Class C in Fig. D.8*b* fit the curve of amplitude 5, on the transparency, very well, in the position where the interval is about 316° from the axis $(H = 0°)$ to the rising intersection of the curve with the axis $(\frac{1}{2}\Delta''T/\sin h = 0)$. The *scale for* ω_c (just below the scale for ω'_s on the transparency) reads 316° at the point where the axis $(H = 0°)$ crosses it. Since no one point on the curve has to be exactly fitted, ω_c is not determined to a fraction of a degree, as was $\underline{\omega'_s}$. The departure of points of Classes A and B from the curve defined by the Class C points is very slight, considering the weighting effect just described, but it is systematically positive, indicating that the previous determinations of $\underline{D'_s}$ and $\underline{\omega'_s}$ are slightly in error. The second approximation will take care of this.

The first approximation to the solution of the example has been found to be

$$\underline{D'_s} = 3.50 \ \mu\text{sec}, \qquad \underline{\omega'_s} = 084°.6,$$
$$\underline{D_c} = 5.00 \ \mu\text{sec}, \qquad \underline{\omega_c} = 316°.0.$$

The fourth step is to compute the residuals $\overline{\Delta T}$, by Eq. (11), and plot them against θ_s. If the plot shows a systematic trend, a second approximation is made. The first three terms of Eq. (11) add up to $\Delta''T$, for $\underline{D'_s}\cos(\underline{\omega'_s} - \Psi)$ was made exactly equal to $\Delta\beta$. Consequently

$$\Delta''T - 10.00 \sin h \sin (H - 316°) = \underline{\Delta T},$$

in this example. The sine term is computed for each observation (again a rapid slide-rule process) and set down in Column 7, Table D.2, and Column 4 minus Column 7 gives ΔT in Column 8.

For the second approximation,

$$\left.\begin{aligned} \Delta\beta &= 0, \\ \underline{\Delta T} &= -\underline{\underline{D'_s}} \cos (\theta_s - \underline{\underline{\omega'_s}}) + 2\underline{\underline{D_c}} \sin h \sin (H - \underline{\underline{\omega_c}}), \\ \underline{\Delta T_m} &= 0, \end{aligned}\right\} \qquad (16)$$

corresponding to Eqs. (7) and (8), $\Delta\beta$ and $\underline{\Delta T_m}$ being the residuals to the baseline length and to the master extension reading. These are zero because $\Delta\beta$ was exactly fitted in the first approximation. When the residuals of Table D·2 are plotted against θ_s (Fig. D·8c), the periodic distribution of the points of Classes A and B shows that $\underline{\underline{D'_s}}$ is of appreciable size, and the separation of the Class C points from the others suggests that $\underline{\underline{D_c}}$ is also appreciable.

We therefore proceed to the second approximation. The point representing the master extension reading ($\underline{\Delta T_m} = 0$, $\theta_s = 200°$), which the curve must again pass through, requires $\underline{\underline{\omega'_s}} = 110°$ or $290°$ (expressing the fact that $\underline{\underline{D'_s}}$ must make right angles with the baseline if β is not to be corrected further). Evidently the latter value is the right one, and the curve $\underline{\underline{D'_s}} = 0.25$ fits the Class A and B points quite well. Now the quantities $0.25 \cos (\theta_s - 290°)$ are computed and added to $\underline{\Delta T}$, giving $\Delta''T$, which is halved and divided by $\sin h$ (Table D·3, first five columns). These last quantities are plotted against H, on the large scale again. From this plot the values $\underline{\underline{D_c}} = 0.50$, $\underline{\underline{\omega_c}} = 110°$ are obtained (Fig. D·8d).

To test the adequacy of the second approximation, new residuals $\underline{\underline{\Delta T}}$ are now obtained by computing the quantities $1.00 \sin h \sin (H - 100°)$ (Column 7 of Table D·2) and subtracting this column from Column 4. Only two residuals exceed 0.05; and since the original errors were given only to 0.1, this is a practically perfect agreement, and there is no need to make another plot.

The last step is to combine the first approximations with the corrections to obtain the second approximations, which are taken as final, and to compute from these the separate station displacements. Equations (13) and then (6), (4), and (5) are solved by slide rule. The computation is given in Table D·4, the results being

$$\begin{aligned} D_m &= 4.56\ \mu\text{sec}, & \omega_m &= 317°.8, & \Delta\phi_m &= +33'', & \Delta\lambda_m &= -39'', \\ D_s &= 3.91\ \mu\text{sec}, & \omega_s &= 004°.6, & \Delta\phi_s &= +38'', & \Delta\lambda_s &= +4'', \end{aligned}$$

assuming that the stations are in east longitude, the master and slave being in 42° and 44° north latitude, respectively. The displacements actually used in setting up the example are

$$D_m = 4.55\ \mu\text{sec}, \qquad \omega_m = 318\overset{\circ}{.}0, \qquad D_s = 3.90\ \mu\text{sec}, \qquad \omega_s = 005\overset{\circ}{.}0.$$

The extremely close agreement, though the given values of ΔT were rounded off to 0.1 μsec, is, of course, due to the absence of random errors.

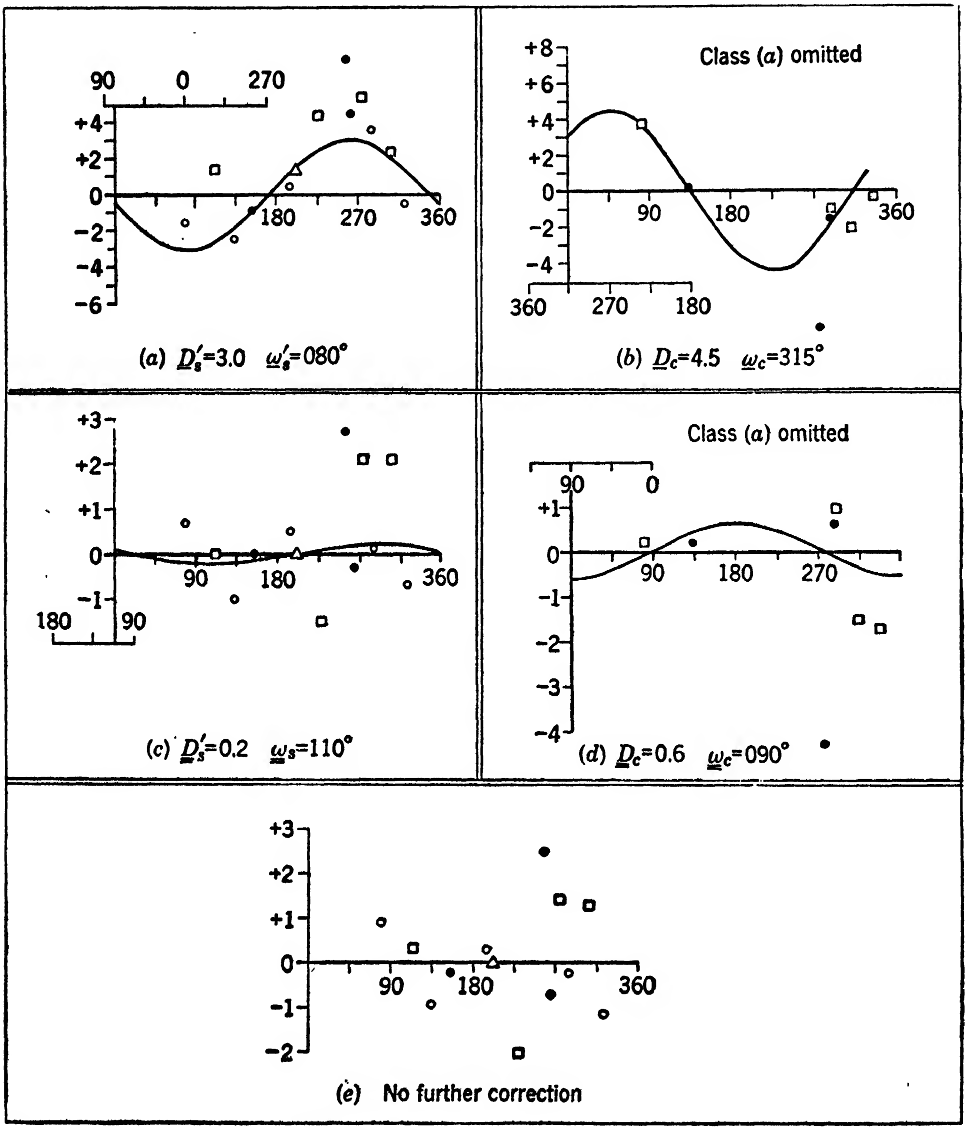


FIG. D·9.—Plots, Example II.

To simulate actual field conditions, the foregoing example may be modified by rounding off values of ΔT to the nearest microsecond and altering some values by 1 and some by 2 μsec to introduce "random errors." One value of ΔT, to represent an accurately located monitor station, is given correctly to 0.1 (this is observation 4). The modified values of ΔT appear in Table D·5, Column 2 (θ_s, θ_m, h, and H are the same as in the first example), and the first approximation fills the remaining columns of the table, whereas the plots are shown in Fig. D·9*a* and *b*. The points of Class A are omitted from the second plot; their low weight and their scatter make them practically useless here. The curve for $\underline{D_c}$ and $\underline{\omega_c}$ is made to fit the monitor station exactly. When the residuals $\overline{\Delta T}$ are plotted against θ_s (Fig. D·9*c*), it is evident that the "errors" leave little meaning to a second approximation, but a slight improvement in D'_s is suggested. When $\frac{1}{2}\Delta''T/\sin h$ is plotted (Fig. D·9*d*), it appears that if a small error at the monitor station is admitted, the other Class C points can be satisfied a little better. The second approximation is detailed in Table D·6; and when $\underline{\underline{\Delta T}}$ (Column 6) is plotted (Fig D·9*e*), it is evident that no further approximation will mean anything. The residuals that are introduced into the example (Table D·5, Column 2, minus Table D·1, Column 2) are given in Column 7. They are not quite so small as those resulting from the solution. This, of course, should be so, for the solution accommodates itself to the erroneous "observed readings," not to the "true" values. The final values are given in Table D·7.

The relative displacement of the slave with respect to the master was used in Eq. (7) instead of that of the master with respect to the slave, because Loran stations are commonly operated in triplets, one master working with two slaves. When this is the case, solution is made for the displacements of the three stations. The relative displacement of each slave is determined from the observations on the pair of which it is a member, but the master displacement, which is D_c for *all three stations*, is found by combining the observations on both pairs in a single sine curve. Of course all directions for both pairs must be measured from the same zero direction. If a triplet operates with two masters and one double slave, the relative displacements must be assigned to the masters and D_c made equal to the slave displacement. The subscripts s and m must be interchanged in all the equations, and the signs of the cosine terms in Eqs. (7) to (12) and (15) and (16) must be reversed.

Example III, which appears in Tables D·8, D·9, and D·10 and Fig. D·10, deals with an actual triplet. Evidently larger errors of observation are present than in Example II. These errors appear to obscure the common displacement altogether, though the relative displacements are conspicuous. The curve in Fig. D·10*c* was made to fit the two monitor readings (observations 3 and 16). It represents the other points for the first pair about as well as any curve (though not much better than a straight line), but the points for the second pair call for a larger displacement in the opposite direction. In Fig. D·10*d*, residuals from the first approximation are plotted against θ_s for the two pairs. These plots (which are not expanded in vertical scale) give no encouragement toward a second approximation; so the first is taken as final. Table D·10 includes values of the displacements of these stations as obtained from geodetic data, for comparison with the results of the solution. If the geodetic values are inserted into Eq. (11), the sum of the squares of the residuals obtained is 50 per cent larger than the sum of $\underline{(\Delta T)^2}$ from Table D·9, suggesting that the geodetic data are somewhat questionable.

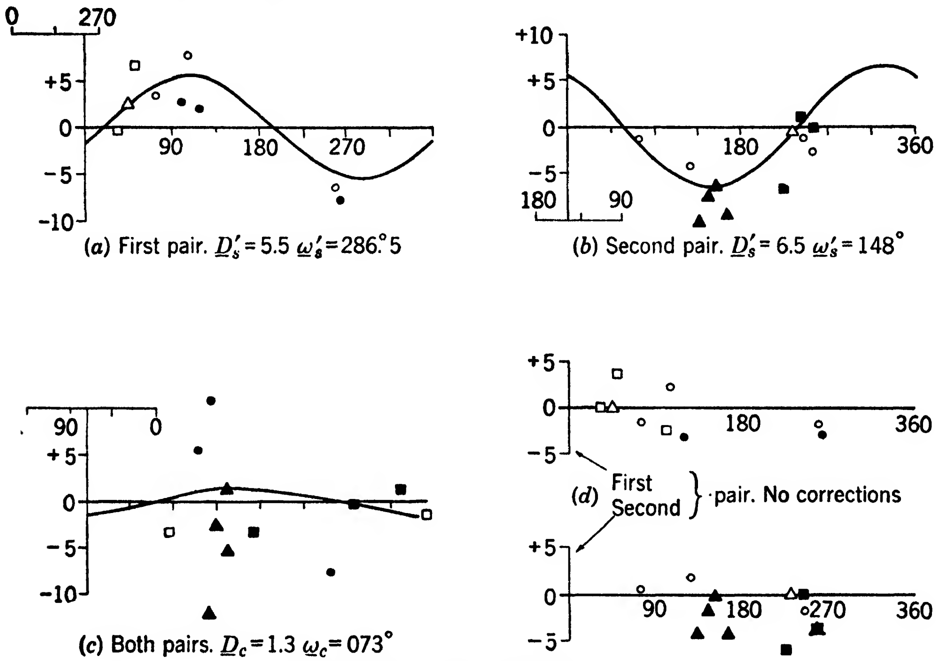


FIG. D·10.—Plots, Example III.

As already mentioned, it has been assumed throughout that the time difference T_m on the extended baseline behind the master station has been correctly observed. It has also been assumed that the correct coding delay has been held at the slave station. The coding delay should be checked by observation on the extended baseline behind the slave, for the delay set on the timer may not be the actual delay in transmission. A systematic error may occur here, as in monitoring at the master station, and for the same reason. If the delay that actually occurs is greater than that set for the pair, all observed readings will be greater than corresponding computed readings by the amount of the excess, and the quantity δ (observed) minus δ (computed), which may be denoted by $\Delta\delta$, should be subtracted from all readings including T_m, before the values of ΔT are taken.

If for any reason trustworthy observed values of δ and T_m have not been obtained, it is possible, in theory at least, to obtain them in the course of the graphical solution. Considering $\Delta\delta$ and $\Delta\beta$ as unknowns, Eq. (7) is written in the form

$$\Delta T = [\Delta\delta + \tfrac{1}{2}\Delta\beta - D'_s \cos(\theta_s - \omega'_s)] + 2D_c \sin h \sin(H - \omega_c). \quad (17)$$

On the first plot, ΔT is plotted against θ_s. A vertical line is drawn on the plot at ($\theta_s = +180°$). The central horizontal axis of the family of curves is not constrained to remain in coincidence with the axis

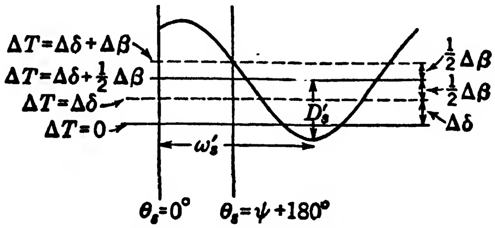


FIG. D·11.—Graphical solution if $\Delta\beta$ and $\Delta\delta$ are unknown.

($\Delta T = 0$) of the plot, but the curves are moved both vertically and horizontally until the points of Class A are fitted. $\underline{D'_c}$ and $\underline{\omega_c}$ are read as before, but now in addition (Fig. D·11) the vertical distance, from the axis ($\Delta T = 0$) of the plot to the central horizontal axis of the curves, is equal to $\underline{\Delta\delta} + \tfrac{1}{2}\underline{\Delta\beta}$, whereas the vertical distance, from the central horizontal axis of the curves to the point where the curve of amplitude D'_c crosses the line ($\theta_s = \Psi + 180°$), is equal to $\tfrac{1}{2}\underline{\Delta\beta}$, the upward (downward) direction in either case indicating the positive (negative) sign. Then Eq. (9) becomes

$$\Delta''T = \Delta T - (\underline{\Delta\delta} + \tfrac{1}{2}\Delta\beta) + \underline{D'_s} \cos(\theta_s - \underline{\omega'_s}), \quad (18)$$

and the rest of the first approximation is performed as before. In Eq. (11) defining the residuals, the term $-\underline{\Delta\delta}$ is added to the left-hand member. In the second approximation the process described above is repeated, yielding corrections $\underline{\underline{\Delta\delta}}$ and $\underline{\underline{\Delta\beta}}$ along with the other corrections.

In dealing with real observations, the introduction of two more unknowns into the solution tends to make the convergence of the approximate process slower, and thus an additional approximation may be required to reduce residuals to minimum size and random distribution. A more serious effect is that the individual uncertainties of the quantities determined are increased, because $\Delta\delta$, $\Delta\beta$, and the component of D_c perpendicular to the baseline contribute to ΔT in very much the same way, over a large part of the service area. So the solution in a given case, obtained by any method of analysis, may be quite misleading because of a few errors of observation if the extended baseline readings have not been obtained.

Of course, the displacements as determined will be affected by the computer's judgment in giving relative weights to discordant observations.

This difficulty is unavoidable. No method except the laborious least-squares solution will apportion the influence of the several observations automatically or will assign separate probable errors to the quantities determined. The graphical treatment has the advantage of making the uncertainties evident and providing some basis for their estimation. For instance, in Example II it is clear from the plots that Observation 7 is particularly discordant, and that the relative displacement of the slave station is determined much more definitely than the common displacement, which is very dependent upon the relative weights given Observations 2, 6, and 9 and 11 (assuming that the "monitor reading" No. 4 is of high weight). Actually, the first approximation, in which Observations 9 and 11 were almost ignored and Observation 2 and the monitor were considered exactly correct, is nearer the "truth" than the finally adopted value, which distributes the discordances more evenly. In Example III, the directions of the relative displacements are very definite. Their magnitudes are more doubtful, but the true values are probably not less than half or more than twice those adopted. However, the individual locations of all the stations remain quite uncertain because even the quadrant in which the common displacement lies is not sure. This situation is often to be expected if a solution is made from observations taken on routine missions, for there will usually be a deficiency and a poor distribution of Class C points, because of the small area within which they must lie. To locate the stations definitely, observations must be obtained in numbers sufficient to cancel out local errors, in all four quadrants, both well within the figure-eight area (near the baseline) of each pair and well outside it. In this case a least-square solution may be worthwhile, using Eq. (3) with a constant term $\Delta\delta$ added to the right-hand member and treating the readings made on the baseline extensions simply as single observations of very high weight.

Although the solution of Example III gives geographic station positions that are uncertain in an absolute sense, a Loran chart calculated from these positions will be in good accordance with observation over most of the service area, for only near the baselines do the absolute positions have much effect on the readings, and here the time-difference errors in microseconds have the least equivalents in miles. In general, the final results $\Delta\phi$ and $\Delta\lambda$ are to be regarded as formal corrections by means of which a chart fitting the observations may be computed, not as accurate station displacements. It may well be that the real principal cause of observed discrepancies is systematic error in the survey data by which features of the terrain have been charted. In this case the solution will bring the locations of the stations into the frame of reference defined by the terrain, whatever that may be. But, after all, this is what the navigator wants.

TABLE D·1.—EXAMPLE I. OBSERVATIONS

$\phi_s = 44°$, $\phi_m = 42°$, $\Psi_s = 020°$, $\Psi_m = 018°$, $\Delta T_m = +3.0$ μsec

1 Obs. No.	2 ΔT	3 θ_s, degrees	4 θ_m	5 h, degrees	6 H, degrees	7 $\Delta' T$	8 Class
1	−0.9	079	065	+ 6	072	−2.4	A
2	+2.8	112	046	+32	079	+1.3	C
3	−0.3	132	114	+ 8	123	−1.8	A
4	+0.7	153	113	+19	133	−0.8	B
5	+1.5	195	171	+11	183	0.0	A
6	+8.2	226	352	−64	289	+6.7	C
7	+6.7	258	290	−17	274	+5.2	B
8	+6.9	263	313	−26	288	+5.4	B
9	+5.6	274	346	−37	310	+4.1	C
10	+5.3	283	301	−10	292	+3.8	A
11	+2.5	306	006	−31	336	+1.0	C
12	+3.0	321	337	− 9	329	+1.5	A
M	+3.0	200	198	0	199	+1.5	..

TABLE D·2.—EXAMPLE I. FIRST APPROXIMATION

$D'_s = 3.50$, $\omega'_s = 084°.6$, $D_r = 5.00$, $\omega_r = 316°$

1 Obs. No.	Class	2 θ_s − 084°.6, degrees	3 3.50 cos (θ_s − 084°.6)	4 $\Delta'' T$	5 $\frac{1}{2}\Delta'' T/\sin h$	6 H − 316°, degrees	7 10.00 sin h sin (H − 316°)	8 $\overline{\Delta T}$
1	A	354.4	+3.48	+1.08	+5.26	116	+0.94	+0.18
2	C	027.4	+3.11	+4.41	+4.16	123	+4.45	−0.04
3	A	047.4	+2.37	+0.57	+2.05	167	+0.31	+0.26
4	B	068.4	+1.29	+0.49	+0.75	177	+0.17	+0.32
5	A	110.4	−1.22	−1.22	−3.19	227	−1.40	+0.18
6	C	141.4	−2.74	+3.96	−2.20	333	+4.08	−0.12
7	B	173.4	−3.47	+1.73	−2.96	318	+1.96	−0.23
8	B	178.4	−3.50	+1.90	−2.16	332	+2.16	−0.26
9	C	189.4	−3.45	+0.65	−0.54	354	+0.63	+0.02
10	A	198.4	−3.32	+0.48	−1.38	336	+0.71	−0.23
11	C	221.4	−2.63	−1.63	+1.58	020	−1.76	+0.13
12	A	236.4	−1.94	−0.44	+1.40	013	−0.35	−0.09
M	..	115.4	−1.50	0.00	......	...	0.00	0.00

TABLE D·3.—EXAMPLE I. SECOND APPROXIMATION

$\underline{D'_s} = 0.25$, $\underline{\omega'_s} = 290°$, $\underline{D_c} = 0.50$, $\underline{\omega_c} = 110°$

1 Obs. No.	(Class)	2 θ_s − 290°, degrees	3 0.25 cos (θ_s − 290°)	4 $\underline{\Delta''T}$	5 $\frac{1}{2}\Delta''T/\sin h$	6 H − 110°, degrees	7 1.00 sin h sin (H − 110°)	8 $\underline{\underline{\Delta T}}$
1	A	149	−0.21	−0.03	−0.14	322	−0.06	+0.03
2	C	182	−0.25	−0.29	−0.27	329	−0.27	−0.02
3	A	202	−0.23	+0.03	+0.11	013	+0.03	0.00
4	B	223	−0.18	+0.14	+0.21	023	+0.13	+0.01
5	A	265	−0.02	+0.16	+0.42	073	+0.18	−0.02
6	C	296	+0.11	−0.01	+0.01	179	−0.02	+0.01
7	B	328	+0.21	−0.02	+0.03	164	−0.08	+0.06
8	B	333	+0.22	+0.04	−0.05	178	−0.02	+0.06
9	C	344	+0.24	+0.26	−0.22	200	+0.22	+0.05
10	A	353	+0.25	+0.02	−0.06	182	+0.01	+0.01
11	C	016	+0.24	+0.37	−0.36	226	+0.37	0.00
12	A	031	+0.21	+0.12	−0.38	219	+0.10	+0.02
M	..	270	0.00	0.00	......	......	0.00	0.00

TABLE D·4.—EXAMPLE I. FINAL VALUES

Equations (13)

$$D'_s \cos \omega'_s = +0.33 + 0.09 = +0.42$$
$$D'_s \sin \omega'_s = +3.48 - 0.23 = +3.25$$
$$D_c \cos \omega_c = +3.60 - 0.17 = +3.43$$
$$D_c \sin \omega_c = -3.47 + 0.47 = -3.00$$

Equations (4)

$$D_m = D_c = \sqrt{3.43^2 + 3.00^2} = 4.56\ \mu\text{sec}$$
$$\tan \omega_c = -3.00/+3.43,\quad \omega_c = 318^\circ\!.8$$
$$\omega_c + \tfrac{1}{2}\Delta\Psi = 319^\circ\!.8$$
$$\omega_m = \omega_c - \tfrac{1}{2}\Delta\Psi = 317^\circ\!.8$$
$$D_s = \sqrt{3.90^2 + 0.31^2} = 3.91\ \mu\text{sec}$$
$$\tan \omega_s = 0.31/+3.90,\quad \omega_s = 004^\circ\!.6$$

Equations (6)

$$D_s \cos \omega_s = +0.42 + 3.48 = +3.90$$
$$D_s \sin \omega_s = +3.25 - 2.94 = +0.31$$

Equations (5)

$$\Delta\phi_m = +33'' \qquad \Delta\phi_s = +38''$$
$$\Delta\lambda_m = -39'' \qquad \Delta\lambda_s = +4''$$

TABLE D·5.—EXAMPLE II. OBSERVATIONS AND FIRST APPROXIMATIONS
Stations, observation points, angles, and ΔT_m same as in Example I
$\underline{D'_s} = 3.0$, $\underline{\omega'_s} = 080°$, $\underline{D_c} = 4.5$, $\underline{\omega_c} = 315°$

1 Obs. No.	(Class)	2 ΔT	3 $\Delta' T$	4 3.0 cos (θ_s − 080°)	5 $\Delta'' T$	6 $\frac{1}{2}\Delta''T/\sin h$	7 9.0 sin h sin (H − 315°)	8 $\underline{\Delta T}$
1	A	0.0	−1.5	+3.0	+1.5	+7.2	+0.8	+0.7
2	C	+3.0	+1.5	+2.5	+4.0	+3.8	+4.0	0.0
3	A	−1.0	−2.5	+1.8	−0.7	−2.5	+0.3	−1.0
4	B	+0.7	−0.8	+0.9	+0.1	+0.2	+0.1	0.0
5	A	+2.0	+0.5	−1.3	−0.8	−2.1	−1.3	+0.5
6	C	+6.0	+4.5	−2.5	+2.0	−1.1	+3.5	−1.5
7	B	+9.0	+7.5	−3.0	+4.5	−7.7	+1.8	+2.7
8	B	+6.0	+4.5	−3.0	+1.5	−1.7	+1.8	−0.3
9	C	+7.0	+5.5	−2.9	+2.6	−2.2	+0.5	+2.1
10	A	+5.0	+3.5	−2.8	+0.7	−2.0	+0.6	+0.1
11	C	+4.0	+2.5	−2.1	+0.4	−0.4	−1.7	+2.1
12	A	+1.0	−0.5	−1.5	−1.0	+3.2	−0.3	−0.7
M	..	+3.0	+1.5	−1.5	0.0	.....	0.0	0.0

TABLE D·6.—EXAMPLE II. SECOND APPROXIMATION
$D'_s = 0.2$, $\omega'_s = 110°$, $D_c = 0.6$, $\omega_c = 090°$

1 Obs. No.	(Class)	2 0.2 cos (θ_s − 110°)	3 $\underline{\Delta'' T}$	4 $\frac{1}{2}\Delta''T/\sin h$	5 1.2 sin h sin (H − 090°)	6 $\underline{\underline{\Delta T}}$	7 True $\underline{\underline{\Delta T}}$
1	A	+0.2	+0.9	+4.3	0.0	+0.9	+0.9
2	C	+0.2	+0.2	+0.2	−0.1	+0.3	+0.2
3	A	+0.2	−0.8	−2.9	+0.1	−0.9	−0.7
4	B	+0.1	+0.1	+0.2	+0.3	−0.2	0.0
5	A	0.0	+0.5	+1.3	+0.2	+0.3	+0.5
6	C	−0.1	−1.6	+0.9	+0.4	−2.0	−2.2
7	B	−0.2	+2.5	−4.3	0.0	+2.5	+2.3
8	B	−0.2	−0.5	+0.6	+0.2	−0.7	−0.9
9	C	−0.2	+1.9	−1.6	+0.5	+1.4	+1.4
10	A	−0.2	−0.1	+0.3	+0.1	−0.2	−0.3
11	C	−0.2	+1.9	−1.8	+0.6	+1.3	+1.5
12	A	−0.2	−0.9	+2.9	+0.2	−1.1	−2.0
M	..	0.0	0.0	.....	.....	0.0	0.0

TABLE D·7.—EXAMPLE II. FINAL VALUES

Eqs. (3) and (6)	Eqs. (4)	Eqs. (5)
$D'_s \cos \omega'_s = +0.4$	$D_c = D_m = 4.1\ \mu$sec	....
$D'_s \sin \omega'_s = +3.2$	$\omega_c = 321°$	....
$D_c \cos \omega_c = +3.2$	$\omega_c + \frac{1}{2}\Delta\Psi = 322°$	$\Delta\phi_m = +30''$
$D_c \sin \omega_c = -2.6$	$\omega_m = 320°$	$\Delta\lambda_m = -34''$
$D_s \cos \omega_s = +3.6$	$D_s = 3.7\ \mu$sec	$\Delta\phi_s = +35''$
$D_s \sin \omega_s = +0.7$	$\omega_s = 011°$	$\Delta\lambda_s = +\ 9''$

TABLE D·8.—EXAMPLE III. OBSERVATIONS

First pair, $\Psi = 223°$, $\Delta T_m = +4.9\ \mu$sec

1 Obs. No.	(Class)	2 ΔT	3 θ_s, degrees	4 θ_m, degrees	5 h, degrees	6 H, degrees	7 $\Delta' T$
1	A	− 4.3	259	254	+ 2.5	256.5	− 6.6
2	B	− 5.2	263	243	+10	253	− 7.6
3	C	+ 2.2	033	307	+43	350	− 0.2
4	C	+ 9	051	120	−34.5	085.5	+ 6.6
5	A	+ 5.6	075	086	− 5.5	078.5	+ 3.2
6	B	+ 5.0	100	130	−15	115	+ 2.6
7	A	+10	106	115	− 4.5	110.5	+ 7.6
8	B	+ 4.5	119	137	− 9.0	128	+ 2.0
M	..	+ 4.9	043	043	0	043	+ 2.45
Second pair, $\Psi = 053°$, $\Delta T_m = -1.1\ \mu$sec							
9	A	− 2	074	060	+ 7	067	− 1.4
10	A	− 4.8	126	116	+ 5	121	− 4.2
11	B	−11	133	113	+10	123	−10.4
12	B	− 8	145	126	+ 9.5	135.5	− 7.4
13	B	− 6.8	153	136	+ 8.5	144.5	− 6.2
14	B	−10	165	129	+18	147	− 9.4
15	C	− 7	224	120	+52	172	− 6.4
16	C	+ 0.4	242	307	−32.5	274.5	+ 1.0
17	A	− 1.7	243	247	− 2	245	− 1.2
18	A	− 3.3	253	256	− 1.5	254.5	− 2.8
19	C	− 1	253	039	−73	326	− 0.4
M	..	− 1.1	233	233	0	233	− 0.55

Observations given to 0.1 (except Nos. 3 and 16) are means of reading at three or more neighboring points. These were given extra weight in drawing the curves. Observations 3 and 16 were made at a monitor station and are means of many readings. The boundary between Classes A and B has been shifted to $h = 8°$ to give a better apportionment.

TABLE D·9.—EXAMPLE III. SOLUTION

1 Obs. No.	(Class)	2 $5.5 \cos (\theta_s - 286\overset{\circ}{.}5)$	3 $\Delta''T$	4 $\frac{1}{2}\Delta''T/\sin h$	5 $2.6 \sin h \sin (H - 073°)$	6 $\underline{\Delta T}$
1	A	+4.9	−1.7	−19.5	0.0	−1.7
2	B	+5.0	−2.6	− 7.5	0.0	−2.6
3	C	−1.6	−1.8	− 1.3	−1.8	0.0
4	C	−3.1	+3.5	− 3.1	−0.3	+3.8
5	A	−4.7	−1.5	+ 7.8	0.0	−1.4
6	B	−5.5	−2.9	+ 5.6	−0.4	−2.5
7	A	−5.5	+2.1	−13.4	−0.1	+2.2
8	B	−5.4	−3.4	+10.9	−0.3	−3.1
M	..	−2.45	0.0	......	0.0	0.0
		$6.5 \cos (\theta_s - 148°)$				
9	A	+1.8	+0.4	+ 1.6	0.0	+0.4
10	A	+6.0	+1.8	+10.3	+0.2	+1.6
11	B	+6.3	−4.1	−11.8	+0.3	−4.4
12	B	+6.5	−0.9	− 2.7	+0.4	−1.3
13	B	+6.5	+0.3	+ 1.0	+0.4	−0.1
14	B	+6.2	−3.2	− 5.2	+0.8	−4.0
15	C	+1.6	−4.8	− 3.0	+2.0	−6.8
16	C	−0.5	+0.5	− 0.5	+0.5	0.0
17	A	−0.6	−1.8	+26.0	0.0	−1.8
18	A	−1.7	−4.5	+86.0	0.0	−4.5
19	C	−1.7	−2.1	+ 1.1	+2.4	−4.5
M	..	+0.57	0.0	......	0.0	0.0

TABLE D·10.—EXAMPLE III. RESULTS

	Values from computations		Values from geodetic data	
First slave:	$D'_s = 5.5\ \mu\text{sec}$	$\omega'_s = 286\overset{\circ}{.}5$	$D'_s = 5.4\ \mu\text{sec}$	$\omega'_s = 295°$
	$D_s = 4.5\ \mu\text{sec}$	$\omega_s = 296°$	$D_s = 6.8\ \mu\text{sec}$	$\omega_s = 318°$
$\phi = 27°$	$\Delta\phi_s = +19''$	$\Delta\lambda_s = -44''$	$\Delta\phi_s = +44''$	$\Delta\lambda_s = -55''$
Second slave:	$D'_s = 6.5\ \mu\text{sec}$	$\omega'_s = 148°$	$D'_s = 3.5\ \mu\text{sec}$	$\omega'_s = 154°$
	$D_s = 7.0\ \mu\text{sec}$	$\omega_s = 138°$	$D_s = 1.6\ \mu\text{sec}$	$\omega_s = 125°$
$\phi = 28°$	$\Delta\phi_s = -50''$	$\Delta\lambda_s = +51''$	$\Delta\phi_s = -9''$	$\Delta\lambda_s = +15''$
Master:	$\left.\begin{matrix} D_c \\ D_m \end{matrix}\right\} = 1.3\ \mu\text{sec}$	$\left.\begin{matrix} \omega_c \\ \omega_m \end{matrix}\right\} = 073°$	$\left.\begin{matrix} D_c \\ D_m \end{matrix}\right\} = 2.3\ \mu\text{sec}$	$\left.\begin{matrix} \omega_c \\ \omega_m \end{matrix}\right\} = 356°$
$\phi = +27\overset{\circ}{.}5$	$\Delta\phi_m = +4''$	$\Delta\lambda_m = +14''$	$\Delta\phi_m = +22''$	$\Delta\lambda_m = -2''$

LORAN BIBLIOGRAPHY

The material has been arranged with a view to the user's interest so that the items generally appear in a chronological sequence that is the key to their present importance. Many of the reports having historical significance may be practically accessible only at some cost for photostating.

The bibliography has been divided into four main categories and subgroups as follows:

1. Reports
   - *a.* Of the Loran system
   - *b.* Aspects of the system
2. Magazine articles
   - *a.* Of a technical nature
   - *b.* Of popular descriptions
3. Instruction books describing
   - *a.* The system
   - *b.* Ground-station equipment
   - *c.* Navigators' equipment by type number
4. Internal memoranda reporting on
   - *a.* The system
   - *b.* Ground stations
   - *c.* Navigators' equipment

The availability of magazine articles is apparent; some titles are followed by a number prefixed by the letters "PB" and the rest are followed by a superscript that indicates the most likely source of further information, described below.

PB, Department of Commerce, Office of Technical Services, Washington 25, D.C.

3, War Department, Army Air Forces, Air Communications Office, The Pentagon, Washington 25, D.C.

4, Navy Department, Bureau of Ships, Washington 25, D.C.

5, Librarian, MIT Library, 77 Massachusetts Ave., Cambridge 39, Mass.

6, Navy Department, Hydrographic Office, Washington, D.C.

7, Treasury Department, Coast Guard Headquarters, Washington, D.C.

8, Navy Department, Chief of Naval Operations, Washington, D.C.

9, War Department, Office of the Chief Signal Officer, The Pentagon, Washington 25, D.C.

10, Sperry Gyroscope Company, Inc., Great Neck, Long Island, New York.

1*a*. Reports of the Loran System

Cruft Laboratory, Harvard University, "Electronic Navigation Systems," OSRD Report No. 6279, Dec. 1, 1945, p. 12·01–12·29 (Confidential).

Descriptive and critical survey of electronic navigation systems. Loran described in 29 pages with bibliography appended.

Coast Guard, "Electronic Navigational Aids," Public Information Div., 1945.[7]

Basic description of Loran, radar, and racon as applied for commercial use.

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MCKENZIE, A. A., "Harvey 170-T Loran Transmitter Manual," RL Report No. M-162, May 10, 1944.[5]
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Radiation Laboratory, *Installation Notes, Parts List, and Drawings for Loran System Transmitter Timer Model* C-1, D-11-12, NLO, Apr. 1, 1944.[5]
———, "Instruction Book for Model C and C-1 Switching Equipment," *Navships* 900,294-IB, Navy Dept., July 1944.[4]

Use of equipment usually employed to connect transmitter timers in a shielded room to a Loran transmitter and allow the synchronizing function of the timers by blanking out the local transmitter pulse from the receiver.

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The automatic synchronizing equipment to be used at slave stations employing Model C timers is described.

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Fada Radio and Electric Company, Inc., *Equipment Spare Parts List for Model DAS-4 Radio Navigation Equipment Receiver and Indicator*, Navy Dept., Bureau of Ships, PB-24916.

The spare parts list is for shipboard Loran equipment that is described in PB-24915.

———, "Instruction Book for Radio Navigation Equipment Model DAS-4 (Loran System)," *Ships* 322, Navy Dept., PB-24915, April 1945.

Information on a late model shipborne receiver-indicator.

McKenzie, A. A., "Handbook of Maintenance Instructions for Loran Low Frequency Converter CV-27/UPN," RL Report No. M-225, PB-40630, July 6, 1945.

The converter described can be connected between the antenna and Standard receiver to adapt the equipment for reception of either Standard or Low Frequency signals.

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Navy Department, "Catalog of Loran Charts and Service Areas," H.O. No. 1-L, Oct. 1, 1945.[6]

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Operator training equipment.

———, Bureau of Ships, "Supplement 1 to Model DAS-1, LRN-1, and LRN-1A Shipboard Loran Instruction Books," Oct. 1, 1943.[4]

Operating and alignment instructions.

———, "Supplement 2 to Model DAS-1, LRN-1, and LRN-1A Shipboard Loran Preliminary Instruction Books," *Navships* 929-1B, PB-18107, Mar. 1, 1944.

Instructions for use of basic recurrence rate 33⅓ pps and errata.

Philco Corporation, *Handbook of Maintenance Instructions for Radio Set* *AN/APN-4, CO-AN 08-25CA-1, revised Mar. 10, 1944.[3]

The airborne Loran navigation equipment comprising *R-9/APN-4 receiver and *ID-6/APN-4 indicator operating on either 80 or 115 volts, 400 to 2400 cycles, is described. See supplements for further modifications.

———, *Handbook of Operating Instructions for Radio Set* *AN/APN-4, AN 08-10-184, June 24, 1943.[3]

Installation and operating instructions for airborne Loran receiver-indicators.

———, "Model *AN/APN-4, *Bull.* 1 and 2, Apr. 12, 1944.[3]

Replacement of glass tubes in receiver units and change of resistors.

———, "Model *AN/APN-4," *Bull.* 3, 4, and 5, May 22, 1944.[3]

Replacement of power transformer, parts changes, test procedure for Modification III.

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———, "Model *AN/APN-4," *Bull.* 8 and 9, Aug. 25, 1944.[3]

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———, "Model *AN/APN-4," *Bull.* 10, Sept. 20, 1944.[3]

Description of the Modification V indicator.

———, "Model *AN/APN-4," *Bull.* 11 and 12, Sept. 9, 1944.[3]

Modification IV receiver and Modification V indicator.

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Test procedure Modification IV receiver.

Radiation Laboratory, "Loran System Receiver-indicator LRN-1-A Operation and Maintenance Instructions," NLOD Div. 11, Feb. 2, 1943.[5]

Description of first large-production model of Loran navigation receiver and indicator.

———, "Preliminary Instruction Book DAS-1 Loran System Receiver-indicator," *Navships* 929-1, Navy Dept., PB-17823, 1943.[4]

The shipborne navigation equipment described was manufactured by Fada Radio and Electric Co.

Radio Corporation of America, *Handbook of Operating Instructions for Radar Set* AN/APN-9, AN 08-30APN9-2, Nov. 15, 1944.[3]

Description, alignment, and use of airborne Loran navigation equipment.

Radiomarine Corporation of America, "Instruction Book for Loran Receiving Equipment, Navy Model X-DBS," *Navships* 900,755, PB-17887, PB-37923, June 1945.

The equipment described is a modified R-65/APN-9 receiver-indicator operating from 60-cycle, 115-volt lines.

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Shipboard units and their use are described.

———, "Loran Receiving Equipment, Mark I, Mod. 1," *Sperry Instruction Book No.* 23-205, June 1946.[10]

The equipment described is a direct-reading indicator for shipboard use. It is similar in most respects to the Navy type DBE.

———, "Loran Receiving Equipment Model DBE," *Navships* 900,659, June 27, 1945.[4]

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General description, operating instructions, diagrams of an airborne Loran receiver-indicator.

———, *Handbook of Maintenance Instructions for Radar Set* AN/APN-9, AN 16-30APN9-3, PB-14878, September 1945.

Description of an airborne receiver-indicator.

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———, "Report on Loran System Tests Made aboard the USCG *Manasquan*," RL Loran Report No. 22, Div. 11, Aug. 15, 1942.[5]

Both ground and sky waves were used from a pair of experimental, synchronized Loran transmitters to obtain navigational fixes that were compared with the results of conventional navigation methods.

———, "Some Observations, Comments, Recommendations of the Operation of Project C Equipment—USS *Manasquan*," Loran Memorandum No. 106, July, 1942.[5]

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Duvall, G. F., Lieut. USN (ret.) "Conventional Navigation-USCG *Manasquan*" RL Loran Report No. 17, Div. 11, July 1942.[5]

A report of conventionl navigation methods during the period of Loran tests. See Loran Report No. 22.

Elmore, W. C., *et al*, "Third Report on Crystal Clock Project," NDRC Report No. 14:145, PB-19646, May 1943.

Report of research on development of crystal oscillator for Loran system use, including special thermostat and Meacham-type circuits.

———, "Fourth Report on the Crystal Clock Project and Preliminary Report on 10-kc Oscillator," NDRC Report No. 14:175, PB-19645, August 1943.

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Office of the Chief Signal Officer, "Measurement Technique and Analysis of a Low Frequency Loran System," Report No. ORS-P-23-S, May 1946.[9]

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PIERCE, J. A., "Group C Test Report, Jan. 2–Jan. 17, 1942," RL Loran Report No. 16, Div. 11, Jan. 22, 1942.[5]

A test of the hyperbolic navigation system using ionospheric reflection was made in Bermuda. E-layer signals at various frequencies indicated the usefulness of such a system, but F-layer signals were judged to be too unstable.

———, "170-kilocycle Noise and Pulse Transmission Measurements," Loran Memorandum No. 148, RL Report No. 11, Nov. 3, 1944.[5]

———, "LRN Tests at Lakehurst, June 13, 1942," RL Loran Report No. 13, Div. 11, June 17, 1942.[5]

First edition of a report on the use of Loran aboard a Navy blimp. Ground-wave signals from the experimental, synchronized stations at Montauk and Fenwick were used.

War Department, "Radio Navigational Accuracy Charts with Application to Low Frequency Loran," Office of the Chief Signal Officer, June 1946.[9]

Prepared charts are used to plot contours for various arrangements of transmitters for optimum coverage.

WATSON, F. G., "Flight Tests over Bermuda," Loran Memorandum No. 116, Nov. 18, 1942.[5]

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