An Introduction to Loran

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SUMMARY

In less than five years, loran, the American embodiment of a new method of navigation, has grown from a concept into a service used by tens of thousands of navigators over three tenths of the surface of the earth. Even under the stress of military urgency, the direct development cost of this system has been less than two percent of the seventy-five million dollars so far spent for operational equipment.

The first part of the present paper describes the history of this program as an example of the efficient "mass production" of research and development under the National Defense Research Committee. A second section deals with the fundamental concepts of hyperbolic navigation and gives some details regarding the kinds of equipment now employed for transmission, reception and interpretation of pulse signals for this service. The third part of the paper discusses the potential usefulness of hyperbolic navigation and suggests some of the many devices which will simplify the navigation of the future and enhance its reliability. The final section mentions the organizational problem immediately before us.

HISTORY

Project 3

In November, 1940, the Microwave Committee of the National Defense Research Committee, in its third project, placed a number of contracts for equipment to be used as an ultra-high-frequency radio aid to navigation which had been suggested by A.L. Loomis. The system was intended to permit navigators to determine lines of position, and therefore fixes, by the measurement of the difference in transmission time of pulses of radio-frequency energy arriving from widely separated synchronized transmitting stations. The initial specifications were controlled by two obvious facts. Since the velocity of propagation of radio waves is about 983 feet per microsecond, the time of transmission of the pulses would have to be controlled to a few millionths of a second and the resolving power of the receiving equipment would need to be equally good, if the method were to yield fixes of an accuracy comparable to that of other methods of navigation. Second, if the transmissions were to be of use over sufficient area to be of interest to aircraft, it was necessary that the power be high.

Two transmitters were therefore ordered, from two large corporations, to emit short pulses at about 30 megacycles at an output level of two megawatts. Receiving and indicating equipment was ordered from two other sources, according to two proposed methods of indication, and very versatile timing equipment, capable of operation under any of several proposals, was ordered to control the emission of the transmitters. These contracts represented a total expenditure of about $400,000, a figure which indicates the energy with which this problem was attacked at the start.

In the clear light of retrospect, it is obvious that two defects, one technical and one administrative, existed in these original

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arrangements. The technical limitation lay in the fact that none of the proposed schemes for indication of the time difference could now be described as other than cumbersome and inaccurate, while the administrative difficulty was that the technical control was exercised in occasional meetings of busy men, so that revision of the original plans was essentially impossible.

In the spring of 1941, during the long procurement interval necessitated by the new and high standards set for the equipment, a small technical group was formed to receive and test the gear when it should be delivered. This group, headed by Melville Eastham of the Microwave Committee, was organized under the newly formed Radiation Laboratory of the Massachusetts Institute of Technology, from which it drew two or three of its key personnel, while other members were recruited from outside sources. The new group fully realized the severe range limitations of the ultra-high frequencies and began to wonder whether waves reflected from the ionosphere in the high-frequency region might not be used to extend the service radius without encountering intolerable errors. After a preliminary paper investigation had indicated that maximum reasonable slopes of the E layer might cause errors not greater than five miles at distances of a few hundred miles, an experimental study of the time stability of ionospheric reflections was begun in the summer of 1941.

Standard Loran

Until experiments in September, 1941, indicated clearly the potential stability of sky-wave transmission, the lower-frequency work was considered only as an extension of the proposed ultra-high-frequency system. By that time, it was realized that the measuring methods proposed for the ultra-high-frequency system would not be satisfactory and that entirely new treatment would have to be worked out. This factor, as well as a growing realization that an ultra-high-frequency system could not give ranges commensurate with the operational requirement for a system to aid convoy operations in the North Atlantic, served to discourage further effort on the Project 3 proposal. Work on that system was therefore immediately abandoned, even before the delivery of much of the equipment on order. The entire Radiation Laboratory group began the development of new indicating equipment and of methods for synchronization of the transmitting stations which would permit what is known as loran to exist in its own right.

During this first year of the project, some information became available about a British system, now known as gee, which was under development. Operating upon identical principles, the gee system is exactly what the National Defense Research Committee ultra-high-frequency system might have become, given equally good techniques and development skill. Loran copied gee concepts rather than techniques and may be said to have been invented in America in the sense in which Galileo is said to have invented the telescope.

The first two loran transmitters, in Delaware and on Long Island, were operated in synchronism at radio frequencies of 3, 5, or 8 megacycles; and a receiver and indicator were sent to Bermuda for a study of the apparent "drift" of that island. Only one family of lines of position was available and the transmitter peak power of 5 kilowatts did not provide a ground-wave signal at that distance, yet the experiments constituted the first proof that the timing accuracy of sky waves was good and that the indicator design was sound. The average of all the readings agreed with the computed figure within a microsecond, and the average deviation of the readings correpsonded to a lateral shift of only 2.8 miles.

Aside from this proof that the system could be made to work, two factors of great importance to the future program were discovered in Bermuda. The first was that it would be very difficult to operate the wide-band receivers necessary for reception of short pulses without encountering overpowering interference from other services at frequencies between 5 and 10 megacycles. Since lower frequencies cannot successfully penetrate the daytime atmospheric absorption, there seemed relatively little hope of achieving a range of more than a few fundred miles by sky-wave transmission in the daytime. A second and more surprising fact was that the nighttime E-layer transmission at a frequency of 3 megacycles failed to exhibit the expected skip effect associated with penetration of the reflecting layer. This meant that transmission at 3 megacycles or below might well be available throughout the night at distances overlapping and extending beyond the range of the ground waves. The combined effect of these two factors was to discourage the use of the higher frequencies, so that the development of the system, became concentrated in the upper part of the medium-frequency spectrum where a ground-wave range of 700 or 800 miles could be expected in the daytime and where sky waves, although effective only at night, would be useful to about twice the daytime range.

The success of the Bermuda experiments led to acceleration of the development of higher-powered transmitters, which had already begun, and to the development of new and simplified transmitter timers. The new timing and monitoring equipment and new 2-megacycles 65-kilowatt pulse transmitters were installed in the two original test stations. The first air-borne and sea-borne trials were conducted with the cooperation of the United States Navy. These trials were so successful that high-level interest within the Navy was immediately aroused. The National Defense Research Committee was requested to build and install a chain of stations extending from Delaware to Greenland, and to procure a few hundred sets of navigator's equipment for shipboard use. The Royal Canadian Navy exhibited an immediate and sustained interest in the system and proceeded at once, under the supervision of Radiation Laboratory engineers, with the construction of two transmitting stations in Nova Scotia. At the same time, other sites were chosen, and the United States Navy, through its operating agency, the Coast Guard, began preparations for the construction of stations in Newfoundland, Labrador and Greenland.

On October 1, 1942, a chain of four stations, comprising the two original experimental stations and the two in Nova Scotia, began operation. By this date, a few of the navigators' instruments had been delivered, and installation on selected naval vessels was begun by a group of radio technicians assigned by the Commander-in-Chief of the Atlantic Fleet. Within the next six months some forty of fifty shipboard installations were made and a great deal of data were gathered on sky-wave propagation and on the operational behavior of the system. With the realization that an effective new aid to navigation had come

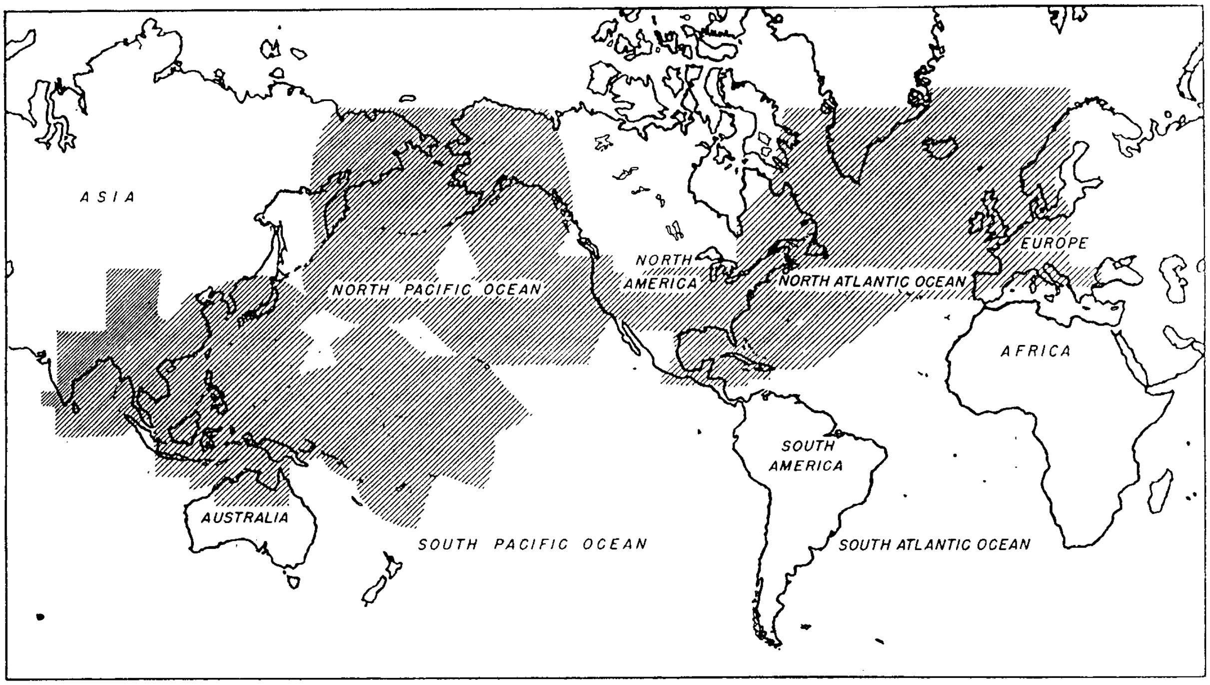

Fig. 1. The shaded area shows where loran can be used for navigation at night (as of August 15, 1945). By day the service area is about one fourth as great.

into being, a Naval Training School for station operators and navigators was set up and the operation of the transmitting stations was turned over by the Radiation Laboratory to the Coast Guard and the Canadian Navy. The three northern stations came into operation in the spring of 1943, and were also turned over to the Coast Guard after operation had become routine. The Bureau of Ships began to take over the procurement of ground-station equipment, while the Army Air Forces were contracting for the development of an air-borne receiver-indicator.

SS Loran

At this time, the Radiation Laboratory loran division had grown to its stable size of about 60 people. Its efforts, in the summer of 1943, were about equally divided between the construction and procurement of standard loran equipment, of which some $1,750,000 worth was delivered to the Navy, and the development and testing of a new form of operating system called "sky-wave synchronized (SS) loran." This modification consisted chiefly in the use of pairs of 2-megacycle stations separated by 1000 or 1200 nautical miles, rather than the 200 or 300 miles in general use at that time. Such a system can only be used at night when sky waves are strong, but the average accuracy increases approximately in the proportion that the baseline is lengthened.

The most obvious use for such a system was to provide a nighttime aid to navigation over the continent of Europe. The concept was therefore introduced to the Royal Air Force as well as the United States Army and Navy, and preparations were made to conduct fullscale trials of the system in the United States. A network of stations was set up, linking Florida, Long Island, Cape Cod and Minnesota, to provide fixes over most of the United States east of the Mississippi. A number of Army, Navy and Royal Air Force aircraft participated in tests in October and November, 1943, and in addition many thousands of observations were made at several fixed monitor stations. The average fix error was found to be only about 1.5 miles and the serviceability of the system was good, except that the more northern pair suffered somewhat from being too close to the magnetic pole. The tests were considered successful and equipment for the necessary stations was shipped to the United Kingdom and to North Africa as soon as possible, together with about ten members of the Radiation Laboratory to assist with the installation and training programs. At about the same time, the first air-borne receivers were beginning to come from the production lines, and a large fraction of the earliest sets were sent to the Royal Air Force.

Because of difficulty in obtaining a frequency allocation, as well as slow shipment and the other more usual delaying factors, it was found impossible to get the system ready for operation before the first of May, 1944. Since the summer nights in Northern Europe are short, it was decided to defer use of the system until September, when it could be used more effectively. In spite of these delays, the system was very useful for the last months of the European war; so effective, in fact, that the Royal Air Force's Mosquito Force used it regularly for blind bombing of Berlin.

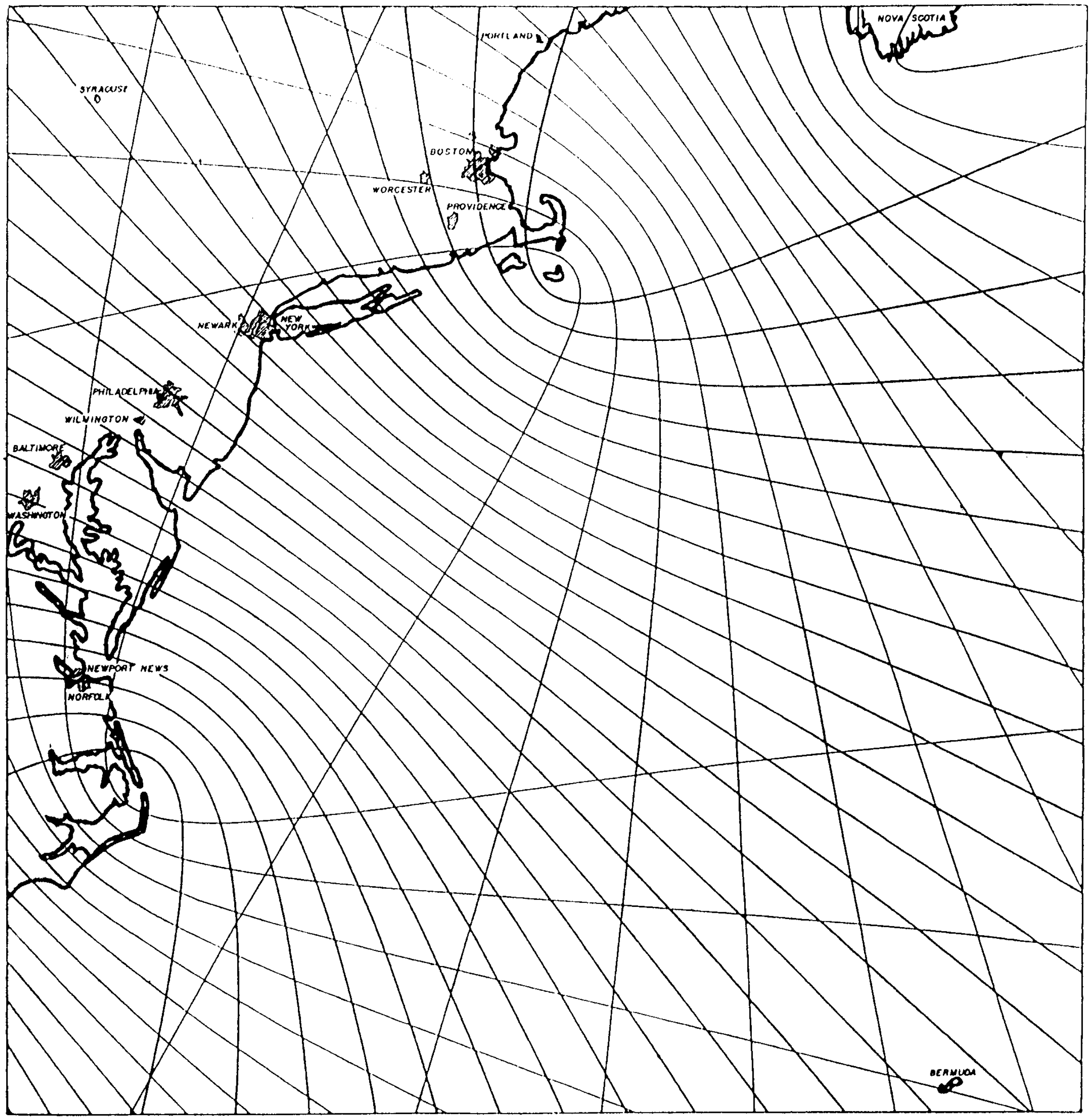

Fig. 2. A tracing of the more important features of a loran chart. Readings are ordinarily made to 1/200 of the spacing of the lines in the figure. On the actual chart the lines are more frequent and are numbered directly in the units indicated by the receiving equipment, so that no computation is required.

Other Radiation Laboratory and Service Efforts

While this SS loran system was being set up in Europe, the Radiation Laboratory group undertook crash production of a number of air-transportable loran ground stations which were required by the Army Air Forces. These stations were essentially a redesign of equipment which had been very hurriedly constructed for a half-dozen stations to provide navigation across the Hump between Burma and China. These Hump stations have given very good service, but the air-transportable

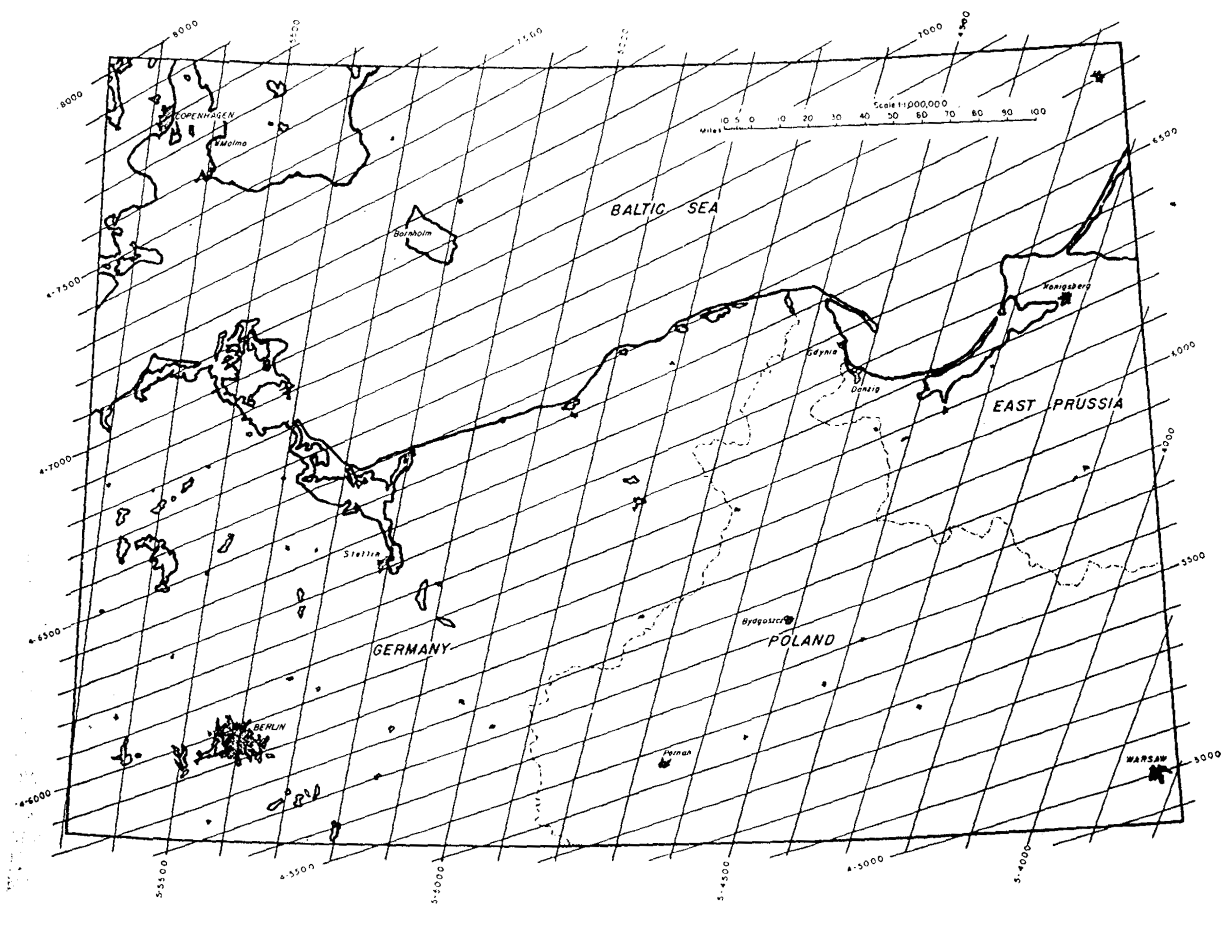

Fig. 3. A portion of the area served by sky-wave synchronized loran over Europe. In this sytem, which was used by the Royal Air Force for blind bombing in the last months of the European war, the average errors are about one twelfth of the line spacing shown.

equipment, although it had absorbed about eight months full-time effort of the Radiation Laboratory group, had not found its way into operation at the end of the war, with the exception of six stations which were used in the United States to provide signals for air-borne training of B-29 crews.

As soon as the air-transportable loran construction program was completed, the Radiation Laboratory had its first opportunity to begin effective work toward loran operation at low radio frequencies, a change which seemed to offer hope of a system with about twice the range of standard loran over sea water, and vastly improved range over land, without any serious loss of accuracy. This program was interrupted, while still in the development stage, by the end of the war, although a trial system had been in operation along the east coast of the United States for about four months. While it did not lead to tactical operation during the war, this program provided the first opportunity to reexamine the concepts and standards of hyperbolic navigation so that the prototype equipment constructed for low-frequency loran represents a tremendous technical improvement over the equipment now in operation.

In the summer of 1943, the United States Coast Guard made its first independent installations of loran transmitting stations in the Aleutian Islands. The equipment in this case had been constructed in the Radiation Laboratory, as Naval procurement had not yet come into effect. Since then, the Coast Guard has installed some twenty-five more stations in the Pacific, climaxing its efforts with stations at Iwo Jima and Okinawa, which were erected closely upon the heels of the invading forces. Of special significance in the Pacific warfare were stations in the Mariannas, which provided very effective guidance for the 20th Air Force in its bombing of Japan.

At the end of the war some seventy loran transmitting stations were in operation providing nighttime service over 60 million square miles or three tenths of the earth's surface, the approximatge area being shown in Fig. 1. About 75,000 shipborne and air-borne navigator's receivers had been delivered by a number of manufacturers. The Hydrographic Office, which had been preparing loran charts since the early days of naval use of the system, had shipped two-and-a-quarter million charts to various operating agencies.

The total cost of the loran research, development and procurement program of the Radiation Laboratory (including the abandoned Project 3 work) was about $5,300,000, but over $3,800,000 of this represented the cost of equipment delivered the Army or Navy for operation. The actual costs of the research and development which produced the loran system may therefore be set at about $1,500,000. The total investment in loran, neglecting shipping, installation, and operating costs which are difficult to assess in the military system, has been estimated by the Services at as much as $130,000,000. This figure is certainly excessive; it presumably includes the contract figures for orders which were cut back at the cessation of hostilities. A careful survey, however, indicates that at least $75,000,000 worth of equipment had been delivered before V-J Day. We may, therefore, conclude that, even if no further orders should ever be placed, the charges for the research and development which produced the loran system can be assessed at no more than 2 percent of the investment in equipment. This would be a very favorable figure in any organization and clearly indicates that research and development can exist and be efficient even under the difficult conditions obtaining in wartime.

TECHNIQUE

The Loran Idea

The basic operation performed by a loran navigator is the determination of a line of position. He does this by measuring the relative time of arrival of two pulses, which are known to have left two separated transmitters at times differing by a known interval. He observes the received time difference, which is equal to the transmitted time difference only if he is equidistant from the two stations. If, for example, the time difference between pulses received from Nantucket Island and from Cape Sable is found to be 2500 microseconds, while the Cape Sable pulse is known to have been transmitted 3000 microseconds after that from Nantucket, the navigator knows that he is farther from Nantucket, the station whose signal is transmitted first and received first, and that the difference in the distances from the two points is the distance traveled by a radio wave in 500 microseconds, or about 93 miles.

With this information, a chart, and a pair of compasses, the navigator could find a number of points which would satisfy this relation and could connect these points with a smooth curve which would represent his line of position; but he would have no way of determining his position along this line without additional information, which might be obtained from a similar observation on a second pair of stations, say at Nantucket and Cape Hatteras. The crossing of this second line of position with the first gives the navigator his position, or fix.

These lines of position are approximately spherical hyperbolas, and would be exactly plane hyperbolas, with the transmitting stations at the focuses, if the earth were flat. Because of this, the method is usually called "hyperbolic navigation." The observations are made by a sort of electronic stop watch, which uses a cathode-ray tube and reads to a millionth of a second. The required synchronism between the transmitted pulses is established by a similar device. Since the stations are fixed, the lines of position do not change; thus they can be presented to the navigator on a chart or in a table, eliminating the computation usually associated with taking a fix. Fig. 2 is a sketch of such a chart, showing some of the lines established by a chain of stations. In practice, the lines in the different families are presented in different colors and each line is marked with its distinctive number which is read directly from the indicator. In Fig. 2, the interval between lines is 200 microseconds, which is about 200 times the ordinary error of a measurement at these short distances. Charts are prepared in various scales and with various intervals between the lines depending upon the use for which they are intended.

A sample chart for the SS loran system of operation is shown, with considerable deletion of detail, in Fig. 3. The transmitting stations are in Scotland and North Africa. In this case, the average timing error is larger, about 8 microseconds. In the SS loran service area, however, traveling a mile across a set of lines changes the reading by from 5 to 10 microseconds, so that the average positional error is little more than a mile.

In all loran practice, each of the two stations of a pair transmits its pulses in an indefinitely long train, in which the pulses recur at a precisely controlled rate. To facilitate instrumentation, the pulses from the two stations are transmitted alternately instead of nearly simultaneously, making the time difference to be measured always of the order of half the recurrence interval.

Range and Accuracy

Standard loran was developed primarily for overwater navigation. It operates on one of several frequencies between 1700 and 2000 kilocycles, and therefore enjoys propagation characteristics determined primarily by soil conductivity and ionospheric conditions. The transmitters currently in use radiate pulses of about 100 kilowatts and give a ground-wave range over sea water of about 700 nautical miles in the daytime. The daytime range over land is seldom more than 250 miles even for high-flying aircraft, and is scarcely 100 miles at the surface of the earth. At night, the ground-wave range over sea water is reduced to about 500 miles by the increase in atmospheric noise, but sky waves, which are almost completely absorbed by day, become effective and increase the reliable range to about 1400 miles. The transmission times of the sky waves are somewhat variable, thus reducing the accuracy of the system, but the timing errors grow smaller with increasing distance and partially compensate for the increasing geometrical errors; therefore, navigation by sky waves, appropriately enough, compares tolerably well with celestial navigation. Except in the case of over-land ground-wave transmission, the signal strength, and therefore the usefulness of the system does not vary at all with the altitude of the receiver. Even in the over-land case, the signals increase rapidly with height so that there is little improvement to be had by going to altitudes greater than 3000 feet.

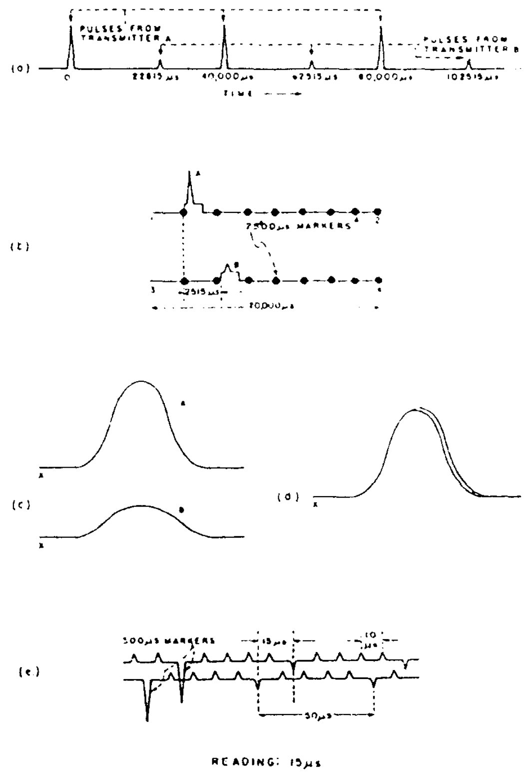

Fig. 4. Diagrams of Various Oscilloscope Patterns Exhibited on a Loran Indicator

If three loran stations are used as a triplet, the average error at short distances is of the order of 300 yards and increases smoothly throughout the ground-wave service area to a little more than one mile at 700. At night, the sky waves may be used at distances beteween 300 miles and 1400 with average errors ranging from 1½ to about 8 miles.

The average errors of fix are frequently smaller than these estimates at long ranges, because pairs can often be found with crossing angles better than those obtainable from a triplet. Loran stations are often installed in a chain, along a coast line, or between islands. The number may be anything greater than two, and each station may or may not operate as a member of two pairs with the stations at each side.

The navigator can choose from among the pairs he will use for determining a fix in the same way that he would choose stars for celestial navigation; that is, by taking those whose lines of position cross at the most favorable angle. In fact, he frequently uses three or four line fixes if he wishes to attain maximum precision, the reading of a single line of position at a time permitting great freedom of choice. This arrangement stems directly from the concept that loran navigation is to be effective over an area large in comparison to that which could be served by a single pair or triplet.

The operation of selecting and matching the pulses and reading the time difference ordinarily occupies somewhat less than one minute, so that the taking of a fix may be thought of as requiring about three minutes; one minute each for two lines of position and a third minute for finding the corresponding point on a chart on the form of Fig. 2 or Fig. 3.

The Navigator's Instrument

Neglecting, for the moment, the method of establishing synchronism between two transmitters, let us examine the method of measurement of the time interval with a navigator's receiver-indicator. Assume that, as indicated in Fig. 4(a), a series of pulses is received from transmitter *A* at a recurrence rate of 25 per second, and a similar series is received from a more distant solution *B* with each *B* pulse arriving 22,515 microseconds after an *A* pulse, and consequently 17,485 microseconds before the succeeding *A* pulse. These pulses are displayed, as shown in Fig. 4(b), as vertical deflections on an oscilloscope whose beam is deflected horizontally by a 50-cycle, or 20,000 microseconds, saw-tooth wave and vertically by a 25-cycle square wave, so that alternate traces appear as parallel lines. The sequence may be thought of as beginning at the left of the upper trace (1). A nearly linear sweep (1-2) of almost 20,000 microseconds duration is followed by a fast retrace (2-3) with a downward component; the lower trace begins (3) exactly 20,000 microseconds after the beginning (1) of the upper trace, is equally long ($3-4=1-2$), and is followed by a retrace ($4-1$) with an upward displacement to complete the cycle. The pulse intervals are always such that when the *A* pulse (which is defined as the one followed by the longer interval) is placed on a pedestal near the beginning of the upper trace, the *B* pulse will fall somewhere to the right and on the lower trace. The *A* and *B* pedestals are small square-wave deflections, indicating regions of the total picture which can be examined later in detail. The *A* pedestal is fixed near the beginning of the upper trace, while the *B* pedestal is always on the lower trace and can be continuously adjusted to occupy any posotion to the right of the *A* pedestal.

If the recurrence rate of the horizontal sweeps on the indicator is exactly twice the recurrence rate of the received signals, a single *A* pulse and a single *B* pulse will be seen, and both will stand still on the pattern, provided the receiver is not moving.[1] A small temporary change in the recurrence rate of the indicator may be made to cause the pulses apparently to slide around the oscilloscope pattern from their original random positions until the *A* pulse occupies the upper pedestal. Then the pedestal on the lower trace may be brought into position under the *B* pulse to produce the pattern illustrated in Fig. 4(b). After this adjustment has been made, the oscilloscope may be switched so that its horizontal deflections are provided by a fast sweep circuit which operates only during the intervals indicated by the tops of the pedestals. This produces a much magnified exposition of the pulses, as shown in Fig. 4(c). Most of the horizontal separation of the pulses has now disappeared, although small readjustments of the "delay controls," which establish the position of the *B* pedestal, now cause the *B* pulse apparently to slide to the left or right.

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[1] If the receiver is on a moving vehicle, the Doppler effect will, in general, be of different magnitude for the *A* and the *B* pulses. The crystal which times the sweeps may be adjusted to make either pulse stand still, but cannot stop the apparent motion of both pulses.

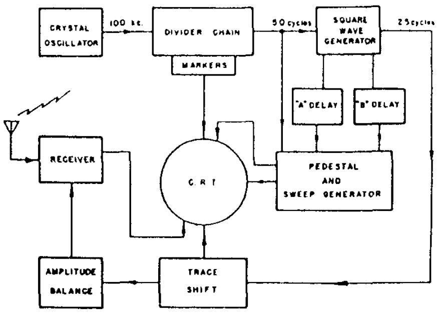

Fig. 5. A Block Diagram showing the Major Components of a Loran Navigator's Receiver-Indicator

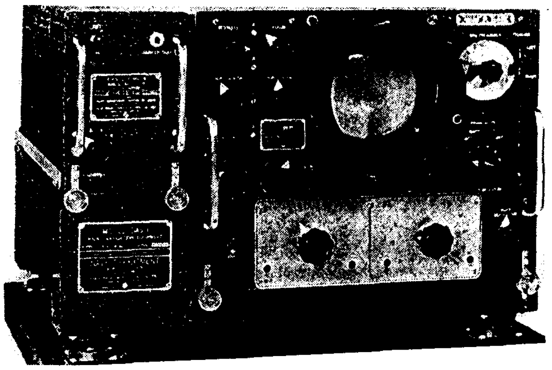

Fig. 6. A Typical Ship-Borne Navigator's Set. The small unit at the left is the receiver. A separate loading coil is ordinarily used at the base of the antenna.

The pulses are now to be "matched" by removing the separation between the upper and lower sweeps and attempting to produce visual coincidence, as shown in Fig. 4(d), by small readjustments of the delay controls. Because the *B* pulse, in our illustration, is the smaller in amplitude, it is necessary to make the gain of the receiver greater during the time occupied by the lower, or *B*, sweep than during the *A*sweep. This is done by introducing into the receiver a voltage obtained from the square-wave generator which establishes the trace separation.

When the pulses have been matched, the knowledge of their time difference has been stored in the indicator, because the pips which trigger the fast sweeps and the pedestals on the *A* and *B* traces, at $X - X$ in Fig. 4(c), have now exactly the same time separation as the *A* and *B* pulses. The receiver is, therefore, disconnected from the indicator and the time difference is read from families of marker pulses which are switched on to the traces as in Fig. 4(e), where a reading of 15 microseconds may be obtained by intercomparison of 50 and 10 microsecond markers and by interpolation. Other families of markers (not shown, but often at intervals of 500 and 2500 microseconds) may be switched onto traces of appropriate lengths so that the 15 microseconds shown may be added to one 2500-microsecond interval (there are no 50-microsecond or 500-microsecond intervals included in this example) seen on the pattrern of Fig. 4(b) between the point on the lower trace directly below the beginning of the *A* pedestal and the beginning of the *B* pedestal. This establishes the time interval from the *A* pulse to the *B* pulse at 22,515 microseconds, although, for convenience, half the recurrence interval is neglected and the "reading" or "time difference" is considered to be 2515 microseconds. The making of this reading is simplified by locking the *A* pedestal at the first 2500-microsecond marker on the upper trace, so that the interval is read from the first similar marker on the lower trace to the beginning of the *B* pedestal.

Because of the large bandwidth of pulse transmissions, about 100 kilocycles for the pulses used in loran, it is necessary to operate a number of pairs of stations in each of the three radio-frequency channels in use. This is done by establishing each pair of pulses at an individual recurrence rate so that, when the receiving equipment is adjusted for that rate, the selected pulses will stand still while pulses from other pairs drift around the screen. The relative rates are so chosen that the interfering effects of unwanted pulses are not noticeable on the fast sweep, while the motion visible on the slow sweep is slow enough not to be distracting. The first loran operations were at repetition frequencies of the order of 25 per second, or pulse intervals of about 40,000 microseconds. The various "rates" were established by successively substracting 100 microseconds from the basic interval. Thus, eight pairs of stations operate at 40,000-, 39,000-, and 39,600 . . . 39,800 microsecond intervals, or approximately 23, 25-1/16, and 25-2/16, . . . 25-7/16 cycles per second. When crowding made it advisable to add more discrete rates, a family based on 33⅓ cycles was chosen. In that case the intervals are 30,000, 29,000, and 29,800 . . . 29,300 microseconds.

Fig. 5 shows a very much simplified block diagram of a loran receiver-indicator. A crystal oscillator, at 100 kilocycles, drives a divider chain of the step-counter variety which reduces the frequency to fifty cycles and incidentally provides several families of marker pulses at intermediate frequencies. The output of the divider chain operates a square-wave generator, which further divides the frequency by two, and also drives a saw-tooth sweep generator when "slow sweeps" are desired on the oscilloscope. The output of the square-wave generator is used to provide trace shift for separating the traces on which the *A* and *B* pulses are exhibited and also, if necessary, to decrease the gain of the receiver throughout the trace displaying the stronger signal. The delay circuits *A* and *B* are operated, respectively, by the positive and negative fronts of the square-wave cycles and, after suitable intervals, trip the pedestal generator and, if desired, the coincident "fast-sweep" generator. The *A* delay circuit controls the position of the pedestal and fast sweep on the upper trace (see Fig. 4(b)) and is locked at a suitable position. The *B* delay performs the same functions on the lower trace, but is adjustable with coarse and fine controls. The recurrence-rate control is comprised in the divider chain. It is operated by a switch which is often marked "station selector." This switch, the *B* delay controls, the amplitude balance, and a sequence switch, (which selects the sweep speeds and trace separation, and which connects the markers or received pulses to the oscilloscope) are the primary operating controls.

One of the more common ship-borne receiver-indicators is shown in Fig. 6, and an air-borne receiver-indicator, which is

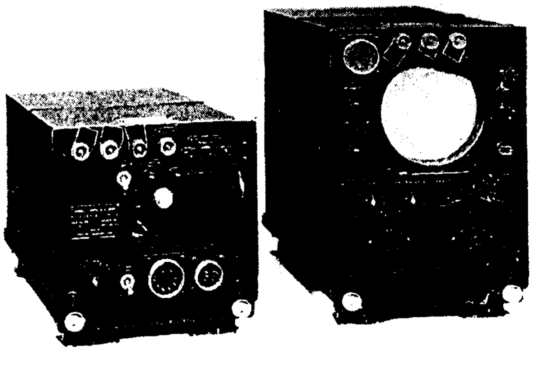

Fig. 7. An Air-Borne Loran Receiver-Indicator, shown without the interconnecting cables. The smaller unit contains the receiver and the main power supply for both units, and need not be immediately accessible, 45,000 of these sets had been delivered by August 1, 1945.

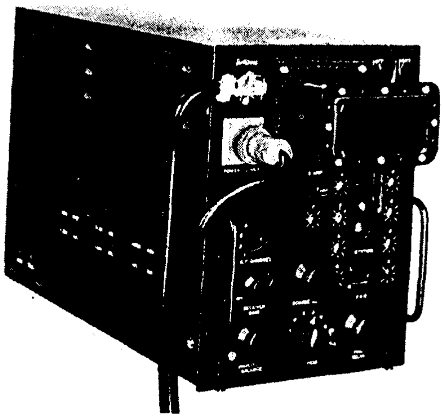

Fig. 8. A Later Form of Air-Borne Set which weighs about 40 pounds. Production had almost completely swung to this set at the end of the war, but only about 25,000 had been delivered.

roughly similar although considerably lighter, is shown in Fig. 7. In an effort to conserve valuable space, the receiver and power supply are consigned to a separate box which need not be immediately accessible to the navigator. A later model of the air-borne set, in which the weight is about halved, is shown in Fig. 8.

The Transmitter Timer

Synchronization of the transmitting stations in a pair is achieved through the use of a "timer," which is very similar to the navigator's indicator, as seen in the block diagram of Fig. 9. The philosophy of operation differs in this case, because the time difference is established in advance. This means that the delays, here adjusted by selector circuits rather than simple delay multivibrators, are preset to the required time difference so that synchronism is reached and maintained by operating upon the oscillator frequency. One station of the pair is designed as "master" and usually emits the *A* pulse of the pair. Its only primary duty is to establish the pulse repetition frequency within a few parts in a million of the nominal frequency and to maintain the frequency constant over short periods with an accuracy of the order of one part in a billion. The second station is called the "slave" and is charged with maintainingg its emissions at the same repetition frequency and at constant phase (or "time difference"). This is done by tripping the local (slave) transmitter with the same trigger pulse which initiates the *B* fast sweep, so that the local pulse always appears in the same position on the oscilloscope trace, while the distant pulse drifts about as the crystal-oscillator freqeuncy is varied. With the *A* and *B* pedestals and sweeps set for the desired time difference, the master pulse may be drifted to obtain and maintain visual coincidence. Since highly stable oscillators are used, it is necessary to use a phase shifter between the oscillator and the divider chain so that momentary changes of frequency can be induced without creating a residual permanent change in the oscillator frequency. A mechanical link between the phase shifter and the oscillator frequency control is a great operating convenience. If the phase shifter is being consistently rotated in one direction to maintain synchronism, the oscillator frequency is automatically corrected in the proper sense. Thus, the necessary phase shifting reduces to zero and the frequency converges upon the frequency of the master station. When this condition is obtained, in about half an hour in most cases, an adjustment every ten or fifteen minutes is adequate to maintain synchronism to about half a microsecond.

In addition to the inclusion of the phase shifter, the diagram of Fig. 9 differs in only two major respects from that of Fig. 5. Two cathode-ray tubes are used (neglecting one provided for inspection and maintenance) so that both the "slow-sweep" and "fast-sweep" pictures can be seen without switching. The second, and more serious, difference stems from the fact that the timer is used in the same station, and usually in the same room, with a 100-kilowatt transmitter. As a result the amplitude of the local signal is typically some hundreds of thousands of times greater than that of the distant signal, while, as noted above, the two must be displayed at very nearly the same amplitude if errors are to be kept small. Further, the curcuits in which the attenuation of the local signal is obtained must have a bandwidth of several megacycles if the time difference is to be trustworthy to better than a microsecond. These requirements have been satisfied in an electronic attenuation which operates as a wide-band amplifier with small gain except during an interval within which the local signal is transmitted. At this time, it sensibly disconnects the receiving antenna from the receiver, leaving the local signal to be introduced through a special network which may operate from the transmitting antenna coupling unit, from a separate "sampling" antenna, or from the receiving antenna itself. Each of these arrangements is in use to some extent, as none has been which combines all their minor advantages.

Since space, weight, and cost are not serious problems in the ground-station equipment, the construction of the transmitter timers is, as shown in Fig. 10, not hampered by considerations of economy. The design is such as to lead to easy operation and maintenance and to over-all reliability.

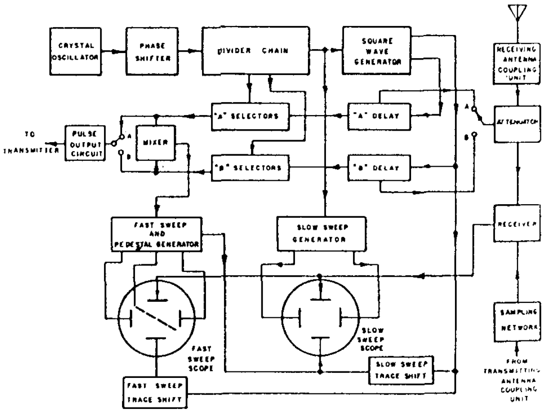

Fig. 9. A Block Diagram of the Major Units in the Timer which is used to maintain synchronism between transmitting stations.

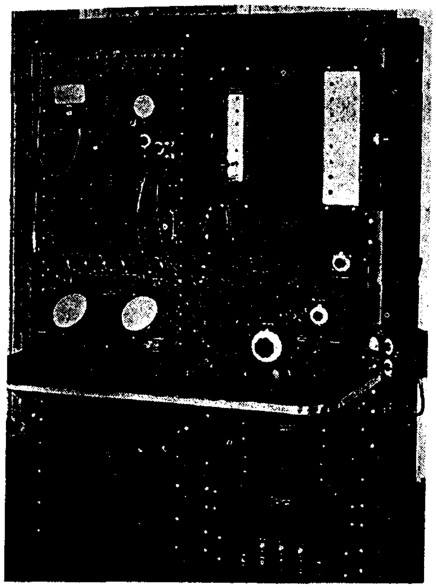

Fig. 10. A Typical Transmitter Timer. The High-Precision Crystal oscillator is at the right, with the "central," or timer proper, above it. The twin oscillopscopes are at the left, surmounted by a control panel, receiver and oscilloscope for servicing th eequipment. Power supplies are below the shelf. At the right is a small control box for an automatic-frequency-control unit which may be used with the oscillator.

The Station Assembly

The transmitters used for loran are not (with the exception of some improved varieties so far used only experimentally unorthodox, except in the sense that pulse transmitters are still a little unusual. As the duty cycle is low, about one part in a thousand, the problems of power consumption and heat dissipation are minor, but the voltage requirements are the same as for any 100-kilowatt transmitter. A simple push-pull oscillator is used with a form of grid modulation. A sharp trigger pulse is received from the timer and formed in the modulator into a square wave about forty microseconds long which effectively reduces the oscillator bias from far beyond cutoff to the operating value. Rather surprisingly, there is little tendency to instability, so that successive pulses are not only similar in shape but start always in the same radio-frequency phase. Transmission lines and antenna-coupling networks are normal, and the antenna usually consists of a guyed tower about 110 feet high set upon a good ground system. A typical transmitter is shown in Fig. 11, in which the unit at the right is the 25-kilovolt power supply, and that at the left contains the radio-frequency oscillator and modulators. A monitor oscilloscope, used for checking the radio frequency and pulse shape, stands on a shelf bolted on the left side of the transmitter.

To enhance the reliability of operation, all units appear in duplicate with provisions for quick interchange of operating and stand-by units. In addition to this, a "double" station, which is simultaneously a member of two pairs at two recurrence rates, has two timers for each rate. The two operating timers both trigger a common transmitter, thus creating a slight irregularity at times when the two timers request pulses almost simultaneously. This effect is fortunately infrequent and is negligible, as far as the navigator is concerned, so that the net result is a considerable saving in equipment. Fig. 12 shows the major equipment and the approximate interconnections in a double station. The shielded room is ordinarily used to protect the timers and receivers from the ambient field of the transmitter, although it may be dispensed with when very careful attention is given to construction and assembly.

It will be noticed that there is no distinction in the equipment of master and slave stations. They differ only in the operating instructions given to them. As shown in Fig. 9, the transmitter may be connected to provide either an *A* or *B* pulse and, in other ways, the equipment may be preset for either use. A secondary duty of the master station is to provide the primary check on improper operations of the pair. Because the time at which the slave pulse should reach the master station is known, the master continuously monitors this quantity and is prepared to alert the slave station if a discrepancy is observed. Either station may initiate a signal of warning to navigators, if, for any reason, the operation of the pair is below standard. In practice, even with the relatively primitive gear so far in use, the emissions of a pair are satisfactory about 99 percent of the time.

It is always difficult to locate transmitting stations where the coverage will be that desired, because, in general, the world does not have enough islands in the right places. This results in a sort of natural law that stations will be erected in the most inconvenient places which can be found. A station in the Faeroes is shown in Fig. 13. Installations run the gamut from this sort of location to atolls so small as to be completely covered by the ground system.

POTENTIAL USES

Potential Accuracy and Range

The factors which control the timing accuracy with which two pulses can be compared do not, in general, vary except with radio frequency. If the pulses are visually superimposed

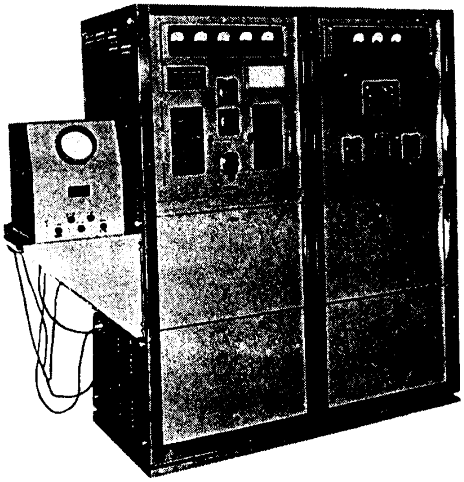

Fig. 11. A Loran Transmitter, capable of about 100-kilowatt pulse output. The high-voltage power supply is at the right, with the modulator and radio-frequency unit in the center. On the shelf at the left is a monitor oscilloscope used to check the output frequency and pulse shape.

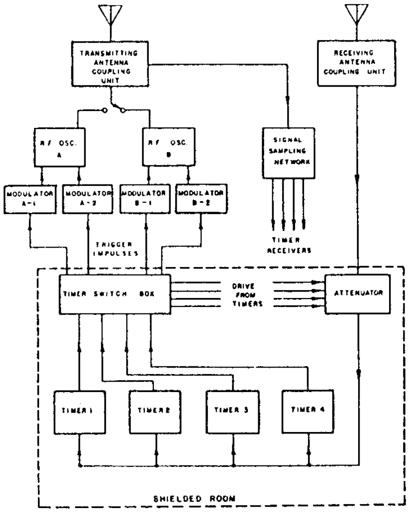

Fig. 12. A Block Diagram showing the General Scheme of Interconnections Between the Major Operating and Stand-By Units in a Double Transmitting Station.

and have their amplitudes made equal, and if the signal-to-noise ratio is really good, the precision of measurement is of the order of one percent 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, so that 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 fifty of sixty cycles of the radio frequency employed. Combination of this estimate with that of the preceeding paragraph indicates that a loran system should yield matches are accurate to about a half wavelength. This accuracy corresponds to a minimum position-line error of a quarter wavelength, or 125 feet at the freqeuncy used for standard loran. Actually the minimum error in standard loran is about 500 feet, an increase due in part to the use of pulses of about twice the length quoted above, and in part to the use of reading techniques which are not as 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 which seldom permit an average error of less than two microseconds, which is twice the current reading error.

The low-frequency loran system which was under development at the end of the war should, on this argument, give average errors of about a quarter-mile in the best areas.[2] Unfortunately, propagational factors as well as geometrical factors 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 ultra-high-frequency band, ranges are not more than about 1½ 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 discouraging from the point of view of navigation.

As the frequencies decrease through the high- and medium-frequency regions, ground-wave ranges increase and the differential between high- and low-altitude behavior 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, which vary tremendously with the time of day and which, at the higher freqeuncies, 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 wide-band antenna systems are not available (because the required size is prohibi-

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[2] A new technique, however, shows promise of permitting drastic revision of this estimate, at least for distances up to six or eight hundred miles. The method is mentioned in the last section of this paper.

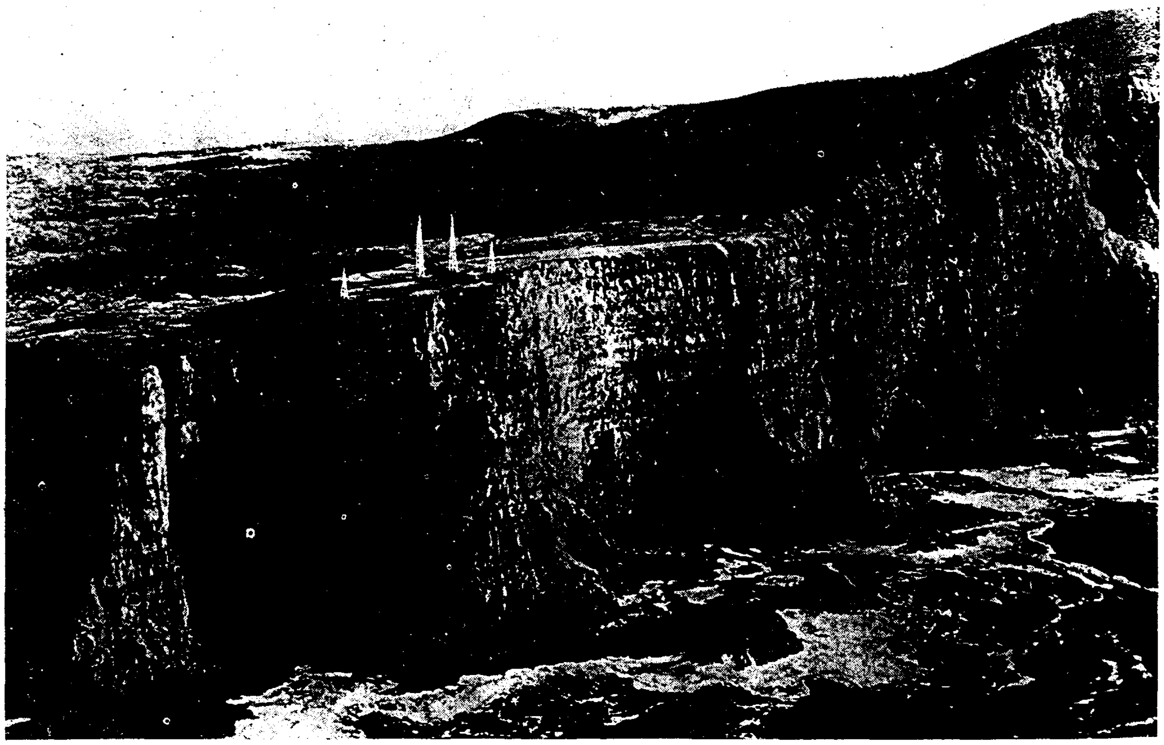

Fig. 13. An Aerial View of a Loran Transmitting Station in the Faeroes Islands. The wooden antenna towers are about 120 feet high. The height of the cliff is not an advantage.

tive) so that, as long as current techniques prevail, the pulse methods cannot be expected to operate there. It seems at present that 100 to 150 kilocycles is about the lower limit at which pulse systems can be used. At these freqeuncies, ranges of 1500 miles should be obtained by day or night, over land or sea, and at any altitude.

Automatic Data Analysis

It requires only limited acquaintance with a loran receiver to realize that it will be simple to perform all of the set manipulations automatically. That is, there is no technical problem in producing a receiver which will automatically present, say, the loran readings on two lines of position at two selected rates on a pair of dial counters. 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 which 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 a great 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, essentially by recording loran charts or tables in mechanical form, the machine be made to read directly in latitude and longitude rather than in loran coordinates. This is a natural but a misguided desire, as there is little that is inherently more desirable in latitude and longitude than there is in the loran coordinates themselves. The two things a navigator always wants to know are the distance and direction to one or to several points.

The next picture which 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 degrees." 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, with either the black box or the latitude-longitude indicator, proceed to plot his position on a chart before he can understand the in-

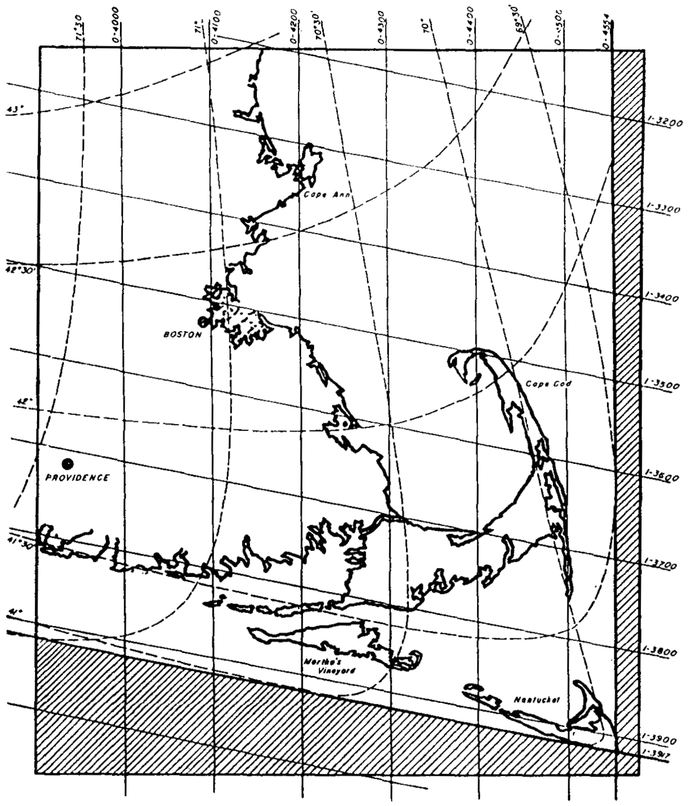

Fig. 14. A Map Drawn by Assuming that Loran Lines of Position are straight and parallel. By use of this sort of map the construction of devices for automatically plotting position becomes easy. The example shown exhibits almost the worst possible distortion.

terrelations between his position and all other interesting points.

Obviously, the only really effective automatic aid to navigation will plot the vessel's position 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 worthwhile here only to point out a single concept which, while 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 proporational 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 which define a point on the earth's surface 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 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.

Fig. 14 is a chart in these loran coordinates which represents nearly the worst possible conditions. In this case, as seen in Fig. 2, both of the families of lines have a focus at a station

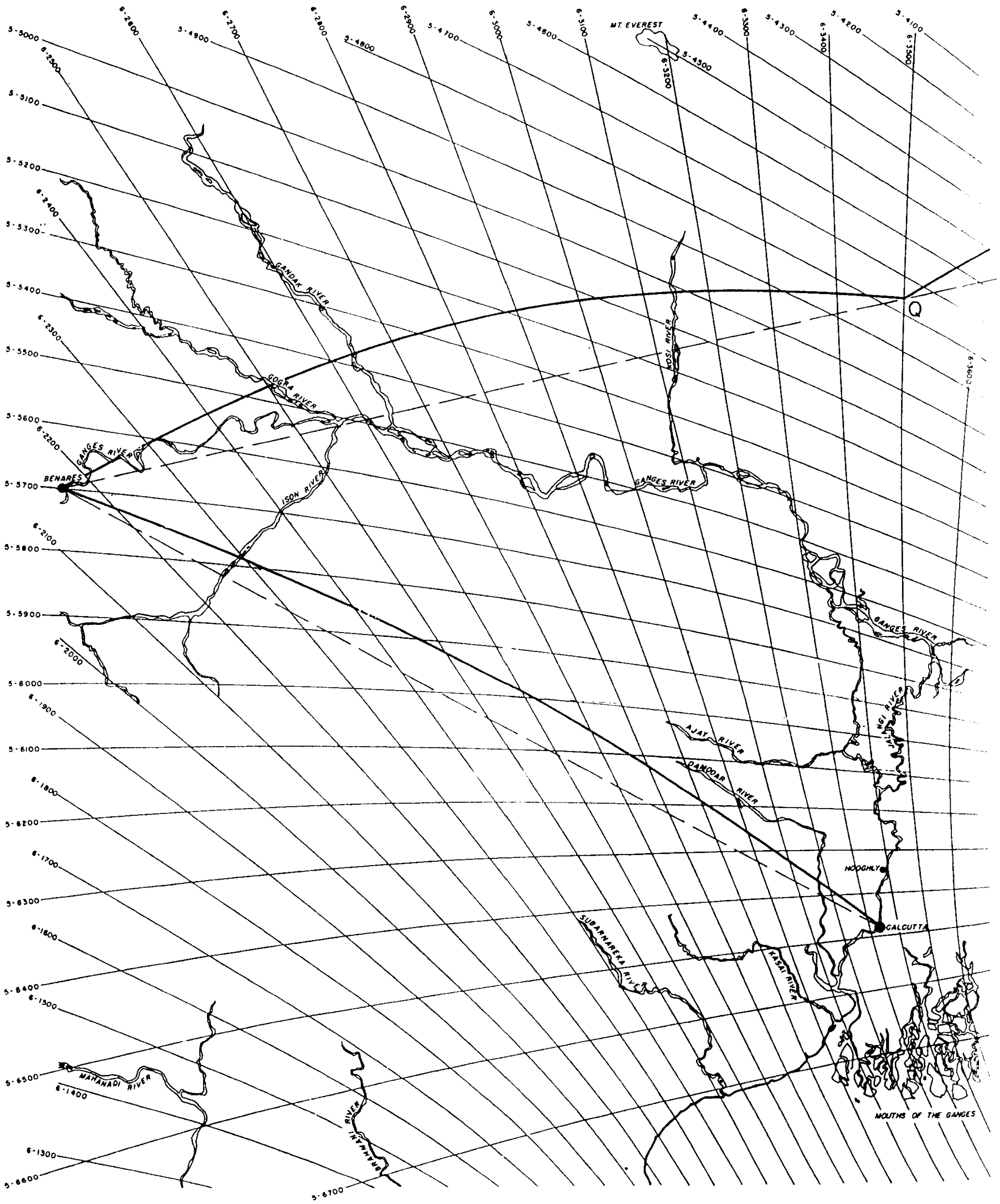

Fig. 15. Two Examples of the Lorhumb Line, or Curve which intersects two families of loran hyperbolas at a constant ratio. These lines can be followed automatically by the use of relatively simple equipment.

on Nantucket Island, so that the curvature and the 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.

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 be followed automatically. The means are easy to visualize and are already at hand. Only a little incentive and time are required, so that, 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, may be made instantaneously. When a hyperbolic sysatem is used, however, a change of course does not lead to any change of indication until after the new course has been laid for a finite time. That it, 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 be built to show an airplane pilot whether he is to the right or left of a loran line 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 following the line. This is so because there is no appreciable relation between the indication on the meter and the course the pilot should follow, so that 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 very zigzag track which does, in fact, pass nearly over the objective but which wastes unconscionable quantities of time, fuel, and pilot's energy on the way.

This difficulty could be removed theoretically 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 which 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; so 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 he wishes to follow. Thus he may be shown two meter readings, one of which tells him, perhaps, that he is a thousand feet to the left of the line, while the other shows him he is approaching the line at fifty feet per second. It is immediately clear that, if he continues on the same course he has been holding, he will reach the line in twenty seconds 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 the two meters mentioned in the preceeding paragraph, the pilot could be presented with a single indicator calibrated in terms of the appropriate course correction such as "two degrees 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.

The Lorhumb Line

The mechanicsm suggested above is the simple and natural way to build a device which will automatically follow a loran line. This is worthwhile 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 which 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 only stem 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 previously to the rudder of the vessel, so that any desired loran line in the corresponding family could be followed automatically. 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 constantly bore 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 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.

Fig. 15 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 while the proposed curve, or "lohrumb line," which crosses the east-west 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 percent 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, so that the proposed course is 2.0 percent, 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 percent of the total distance.

This sort of path has been called the lorhumb line because it is the exact parallel, in hyperbolic navigation, or the rhumb line in Mercator sailing. Various lorhumb lines might be connected together by the navigator as indicated in Fig. 15 to form an approximate great-circle or any other desired path. Devices utilizing this principle probably will be adequate for navigational purposes (as distinguished from problems of pilotage) and will presumably be more simple than others which, 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.

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 which 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 intermedciate 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 staitons, 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.

Guidance of Pilotless Aircraft

Since hpyerbolic 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 which 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 insure 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, while 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; and all this control could be exercised without any cooperation from the launching crews who would, like the loaders on a battleship, simly 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 beam must 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. While 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 insure that none of the boundary conditions of the system shall inhibit the free choice of radio freqeuncy. 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, while 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 air-borne 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, while 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.

Hyperbolic Surveying

A version of low-frequency loran which may become extremely important, at least for certain applications, is called "cycle matching" and consists in comparing the phase of the radio-frequency or intermediate-frequency cycles of a pair of pulses, rather than in 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 a tenth of a microsecond 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 six or eight hundred miles.

Whatever the merits of cycle-matching low-frequency 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 the order of ten feet 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 one hundred 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 side 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 which 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 base line, and the process could be repeated. Thus a precise triangulation would be extended over immense areas in a relatively short time, while 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 earth's surface which could not otherwise be surveyed for many years to come. By this method, of course, islands and shoals which 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 which 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 so 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 which are relatively inaccessible and therefore not well known, but which nevertheless may be of actual or potential military or economic importance.

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 which could be shown to be reasonably satisfactory. While the present equipment is obsolete, it cannot be abandoned immediately because of the financial investment 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 only mean that control of loran in the United States must be vested in an authority which 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 Massachusetts Institute of Technology Radiation Laboratory, there exists no central technical organization. The Naval Research Laboratory should accept much of this responsibility but has, so far, 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 United States 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 United States Navy in all technical matters.

The problem of integrating all the varied activities which 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 decision of the future. The organizational problem is severe enough on a national basis. Internationally, it is acute.

Probably those of us who have been close to loran throughout its development feel too strong an urge to see it find its place in the sun, and find it quickly. We believe that hyperbolic navigation, now less than five years old, will become the primary method of the future. It may be that our desire to see the infant trained and guided leads us to expect too much from its young strength. We should, perhaps, have faith in the inherent power of the method and trust that the system which can best serve the public cannot fail eventually to find its place in the spectrum, if not in the sun.

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