Upon the application of an alternating voltage the retardation oscillates at the applied frequency, 120 cps, between plus and minus a quarter wave. A Nicol prism follows this plate, the two fixed elements thus constituting an oscillating circular analyzer.

Two slits are used at the exit of the spectrograph just before the detectors, each slit being placed at the point of steepest slope on each side of a spectral line. Thus, as the retardation of the quarter wave plate is oscillated, one measures the difference between the two exit slits first for the right-hand and then the left-hand circularly polarized components of solar line radiation. Magnetic fields of one gauss, causing a Zeeman splitting of 10^{-5} angstroms, can be measured accurately, and the rms shot noise of the system corresponds to about 0.1 gauss.

However, it is readily apparent that such an instrument as the Babcock magnetograph, capable of measuring an optical Doppler velocity with a precision of perhaps 3 to 5 ft/sec, is hardly practical from the standpoint of space-borne missions, because of its enormous weight and size. Limitations of instruments have been discussed by Franklin and Birx;[1] the best velocity resolution to be hoped for on the basis of detector noise considerations is 60 ft/sec. Possibilities exist for the use of interferometric techniques in order to obtain high dispersion and narrow instrumental profiles with nonbulky equipment; such an instrument might consist of a fixed-plate Fabry-Perot interferometer crossed with a small spectrograph, whose function is to separate the orders. It is interesting to note, however, that the original Fabry-Perot interferometer designed for the Babcock magnetograph was replaced by the present plane grating spectrograph because it was found impossible to maintain the temperature equilibrium necessary. Such an instrument would have to withstand the rigors of space-borne guidance maneuvers.

Conclusions

Calculations have been made on the assumption that the physical characteristics of stellar electromagnetic sources, as for example the sun, vary in such a manner that a variability of approximately ±200 ft/sec may be expected in the observer's measured optical Doppler velocity. It is the authors' opinion that it is this that imposes a fundamental limitation on the accuracy with which Doppler measurements may be made optically, rather than the instrumentation.

Timing Potentials of Loran-C*

R. H. DOHERTY†, SENIOR MEMBER, IRE, G. HEFLEY†, AND R. F. LINFIELD†, SENIOR MEMBER, IRE

***Summary*—The Loran-C navigation system is capable of synchronizing and setting clocks to a relative accuracy of better than 1 μsec throughout the system's service area. A Loran-C receiver functions as a slaved oscillator and a trigger generator. The generated triggers bear a time relationship to the triggers at the master transmitter, which is known to within a microsecond. Clocks operating from these sources are compared with clocks operating from independent free-running oscillators.**

A fundamental relationship between time and position is considered. Loran-C as a navigation and timing system can provide both position and time simultaneously. The East Coast Loran-C chain will be time synchronized. The national frequency standards and uniform time source located at Boulder will be used to monitor these signals. Time synchronization and time distribution have been demonstrated on the Atlantic Missile Range. Inter-range time synchronization and precise time for large areas of the world could be provided in the future.

Appendix I describes briefly the results of ground wave measurements made on the Loran-C (Cytac) system. Appendix II describes the results of sky wave measurements made with the system.

* Received by the IRE, June 30, 1960; revised manuscript received, August 28, 1961.

† Radio Systems Division, National Bureau of Standards, Boulder, Colo.

I. Introduction

In the majority of timing applications a problem exists in setting two or more clocks to agree with one another. The greater the requirement for precise agreement between these clocks, the more difficult the problem becomes and, if the clocks are in widely separated locations, the difficulty is further increased. The reading of a single clock is meaningful only as it relates to its own frame of reference. For example, a clock may gain or lose with respect to the periodicity of the earth as it revolves about its own axis or about the sun.

Accurate astronomical time depends on long-term observations, but is ultimately limited by unpredictable variations in the earth's rotation. Furthermore, any astronomical time can be determined only to an accuracy of several milliseconds for a single set of observations. The initial settings of individual clocks may, therefore, differ by amounts of the order of milliseconds. These differences combined with the gains or losses of individual clocks are of such magnitude that independently operating clocks or clocks synchronized by existing radio timing signals are unable to make measurements more precise than a millisecond at different locations.

When it is necessary to measure time at two or more locations to an accuracy of 1 μsec or better, such measurements must all be made within the same frame of reference, that is within a single clock system. The term "clock system" as used in this paper means a master clock at a convenient central location and other clocks at widely separated locations which are slaved to the master in such a way that each will track the master. Such a clock system must also provide for a means to synchronize or set each slave clock to agree accurately with the master clock. A number of Loran-C clocks will function as such a clock system with initial setting or synchronizing accuracies of 1 μsec or better using ground wave reception. Accuracies of 10 μsec or better should be obtainable using sky wave reception. Other methods may be used to set remote clocks, such as flying atomic standards from place to place, but they do not offer the convenience or reliability of Loran-C.[1]

The National Bureau of Standards at Boulder, Colo., maintains the nation's primary frequency standard. A fail safe clock operating from this standard would provide an extremely uniform time source that could be related in retrospect to any astronomical time measurements. This uniform time source is the proposed means for monitoring the aforementioned master clock.

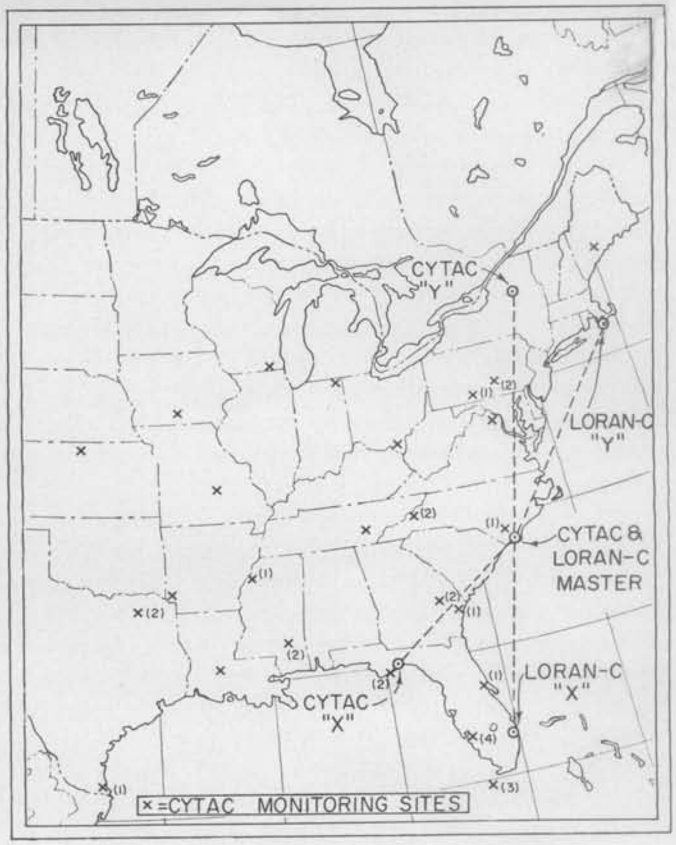

Fig. 1—Loran-C and Cytac locations.

II. Loran-C Operation and Its Timing Application

Loran-C[2] is a pulse navigation system operating on a basic frequency of 100 kc and normally consisting of a master station and two or more slave stations. Several Loran-C chains are operational or under construction. The presently operating U. S. East Coast Loran-C chain, and the previously operated Cytac (later named Loran-C) chain are shown in Fig. 1. The master station is located at Cape Fear, N. C., and the two slave stations at Martha's Vineyard, Mass., and Jupiter Inlet, Fla. The area over which a ground wave could be received for timing purposes would extend approximately 3000 km seaward or 2000 km landward from any one transmitter.

The Loran-C system utilizes synchronous detection techniques for measuring phase, and methods for determining a fixed sampling point early on the pulse, independent of pulse amplitude. By this means the ground wave is completely resolved from the sky waves. See Fig. 2. To a first approximation the ground wave transmission time is proportional to distance. Secondary corrections, however, usually have a magnitude in the range of 1 to 10 μsec. These corrections are determined

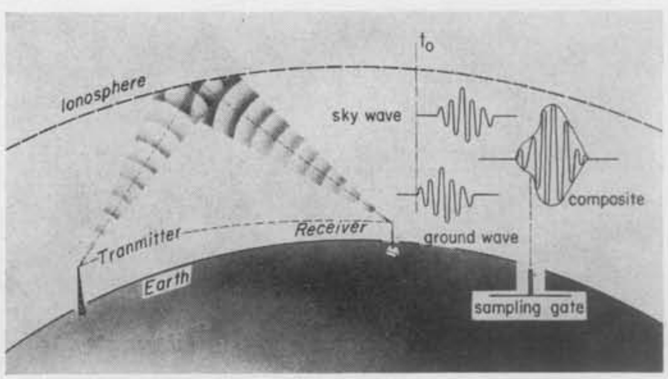

Fig. 2—Ground wave resolution with Loran-C.

largely by the conductivity of the path and to a much smaller extent by the dielectric constant and the index of atmospheric refraction.[3,4] Both the conductivity and the dielectric constant of sea water are accurately known. Consequently, the transmission time over sea water can be computed accurately. Transmission times over paths involving land cannot be as accurately calculated since the conductivity of land is not well known. However, by correlating time difference measurements[5]

[1] F. H. Reder, M. R. Winkler and C. Vickart, "Results of a long range clock synchronization experiment," Proc. IRE, vol. 49, pp. 1028–1042; June, 1961.

[2] W. P. Frantz, W. Dean and R. L. Frank, "A precision multipurpose radio navigation system," 1957 IRE National Convention Record, pt. 8, pp. 79–97.

[3] J. R. Johler, W. J. Kellar and L. C. Walters, "Phase of the Low Radiofrequency Ground Wave," Natl. Bureau of Standards, Boulder, Colo., NBS Circular No. 573; June, 1956.

[4] K. A. Norton, "The propagation of radio waves over the surface of the earth and in the upper atmosphere," Proc. IRE, vol. 25, pp. 1203–1236; September, 1937.

[5] All time difference measurements are determined by phase differences at 100 kc.

with generalized assumptions of ground conductivity, individual path conductivities may be deduced. For example, it has been demonstrated that the best single value of conductivity which can be assigned to the eastern half of the U. S. is 0.005 mho/meter. The average error between time differences computed using this conductivity and those measured in a test program (see Appendix I) was approximately 0.8 μsec. The algebraic average was nearly zero and the maximum error among all sites was 2.5 μsec. The largest errors were associated with sites located in mountainous terrain. Until better prediction methods are developed it must be assumed that systematic errors of the order of 1 μsec may exist for land and mixed paths unless the transmission time has been measured by the use of two transmitters, such as is done over the Loran-C baselines.

The East Coast Loran-C chain operates on a basic repetition rate of twenty pulse groups per second.[6] A pulse group consists of eight phase coded pulses with a uniform spacing of 1 msec. The Loran-C system, as presently operated, does not resolve time increments larger than the repetition period or 50 msec. Larger increments could be resolved without interference to the system, but at this time there appears to be no pressing requirement for such a change. The 50-msec interval between pulse groups can be resolved conveniently by the WWV seconds' pulses. In order to use WWV and Loran-C in such a manner the two transmitting systems must be synchronized, as they would be since WWV is transmitting uniform time.[7] See Fig. 3.

The Loran-C navigation system operating on a basic frequency of 100 kc performs the vitally important function of slaving all oscillators in the system to the oscillator at the master transmitter. By virtue of the technique of slaving a number of relatively cheap oscillators to a master oscillator, all clocks operated from such oscillators will, by definition, have an average drift rate of zero. The instantaneous deviation of any one clock from the average is primarily determined by the factors listed below:

1) Signal-to-noise ratio.
2) Relative and absolute quality of slave and master oscillators.
3) Integration time.
4) Tightness of coupling of the slave oscillator.

The positioning system requires a means for selecting a given cycle and a point on that cycle. It is obvious that this criteria for the positioning system satisfies the requirements for synchronizing a timing system. The instrumentation being utilized in the navigation system has a resolution of a few hundredths of

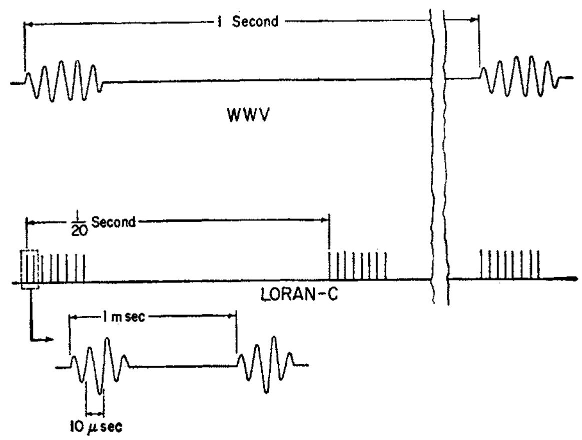

Fig. 3—Synchronization of Loran-C with WWV time signals.

1 μsec. The time variations in propagation due to changes in refractive index, conductivity, etc. are substantially less for all times than the previously mentioned prediction capability. Standard deviations of 0.2 to 0.3 μsec may be expected. (See Appendix I.)

In order to relate the Loran-C system to the primary frequency standard it has been proposed that an extremely high quality secondary frequency standard be installed at the Loran-C master station, and that the master transmissions be monitored at Boulder and that corrections be published periodically.

Measurements of Loran-C sky wave signals from the East Coast made in Boulder in 1955 and 1961 (Appendix II) showed that the propagation time can be determined to an absolute accuracy of about 1 μsec with an integration time of less than one minute. The standard deviation of such measurements (daytime) is less than 0.5 μsec. A better receiving antenna has made it possible to use the ground wave signal and achieve a substantially better measurement of the Loran-C master oscillator frequency.

III. Setting a Loran-C Clock

In order to set a slave clock to agree with the master clock it is first necessary to determine the amount by which the apparent time at the slave is slow with respect to the master.

After the signal has reached the antenna, additional time is required for it to pass through the receiver and produce a trigger suitable for starting or synchronizing the clock. This time depends solely on the receiver design. For timing purposes the Loran-C receiver should be designed in such a way that the transmission time through it remains constant over a wide range of environmental conditions.

The apparent time at the receiver is slow by the amount of time required for the signal to propagate from the master transmitter and through the Loran system to the receiver, plus the transmission time through the receiver plus any additional systematic delays such as the coding delay normally used in a Loran system. This is illustrated by the following example:

[6] Fractional Loran rates can also be used for the operation of a clock by gating the received pulses and using only those transmitted on the second to set the clock.

[7] A. H. Morgan, "Precise Time Synchronization of Widely Separated Clocks," Natl. Bureau of Standards, Boulder, Colo., NBS Tech. Note No. 22; July, 1959.

Given: 1) Receiver 2000 km from slave transmitter.
2) Sea water path.
3) Receiver delay 25.0 μsec.

Propagation time 2000 km sea water	6,675.3
Propagation time Master to Slave	2,711.8
Slave coding delay	12,000.0
Receiver delay	25.0
Total Delay	21,412.1

It is assumed that a pulse is transmitted from the master station precisely at each second. The corresponding pulse from the slave station would produce a time trigger at the receiver output 21,412.1 μsec later. Therefore, the clock at the receiver should read 0.021412 second when this time trigger is used as a read command. The calibration of this clock to read the correct fraction of a second is accomplished by adding counts to the divider chain, and the clock will maintain the same uniform time as the master clock. A one second or one minute output from the clock will occur within 1 μsec of the respective output from any other Loran-C clock in the system.

Fig. 4 is a front view of the developmental model of a Loran-C clock.[8] The panel immediately above the oscilloscope contains a 15-digit visual display covering from 1 μsec to 1000 days. When the clock is given a read command this display reads out the time and holds the reading until the next read command is received.

Fig. 4—Loran-C clock.

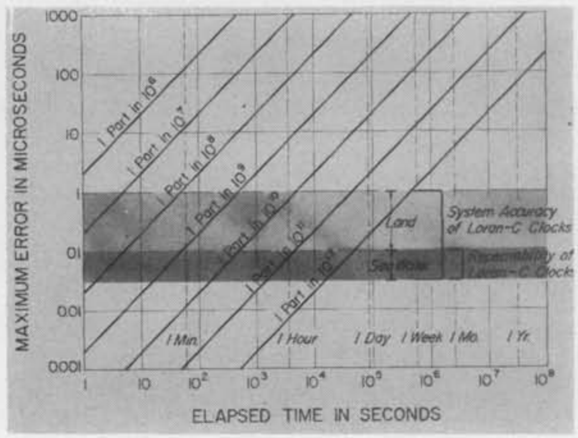

Fig. 5—Comparison of slaved and independent clocks.

IV. Slaved Clocks vs Independent Clocks

The comparison of Loran-C clocks (slaved clocks) with independent clocks running from oscillators of different qualities is shown in Fig. 5. This comparison assumes that two independent clocks are drifting apart at a drift rate equal to the maximum rate indicated. The independent clocks must be initially synchronized and must run continuously without interruption. The Loran-C clocks may be interrupted and resynchronized at random without affecting the accuracy.

If a clock operating from the slaved oscillator of a Loran-C receiver is correctly set and if that clock and receiver are moved a distance of 300 meters toward the Loran-C transmitter, the clock will then be 1 μsec fast. Similarly, if the clock is moved 300 meters in the opposite direction it will be 1 μsec slow. In contrast, if the same clock were operating from an independent oscillator it would neither gain nor lose as a result of motion.

If a Loran-C clock is used in a moving vehicle its position must always be taken into account. In either ships or aircraft the fixes available from the Loran-C navigation system can provide the necessary information. However, the computations required to convert the time difference readings to distance from the transmitters are rather involved and may necessitate the use of a separate computer. An independent clock may be more satisfactory than a slaved clock in a moving vehicle if the clock does not have to maintain the correct time for a long period. Even the best clocks (or oscillators) will drift with respect to other clocks. In cases where drifts of the order of a microsecond are important, the slaved clock is a virtual necessity.

As the accuracy of clocks within a timing system is increased, the location of each clock becomes correspondingly more important. Fig. 6 illustrates this simple relationship. The timing precision of Loran-C and WWV are also shown for an integration time of approximately one minute. Much longer integration times would improve the accuracies obtainable with WWV.[7]

V. Missile Range Timing

The National Bureau of Standards demonstrated Loran-C timing potentials on the Atlantic Missile Range in October, 1960. These tests were conducted using two experimental Loran-C clocks and a UHF timing distribution system.[8] The clocks were rather complex devices consisting of modified Loran-C receivers and counting and read-out circuits. The two clocks were synchronized on two separate transmitters and an external read command was used to check any variation

[8] T. L. Davis and R. H. Doherty, "Widely separated clocks with microsecond synchronization and independent distribution systems," IRE Trans. on Space Electronics and Telemetry, vol. SET-6, pp. 138–146; December, 1960.

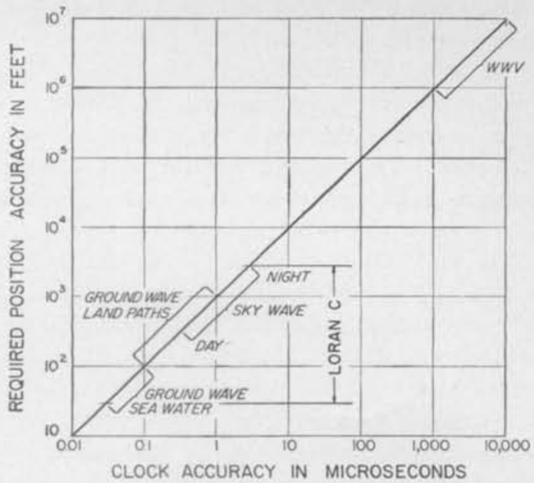

Fig. 6—Time-position accuracy relationship.

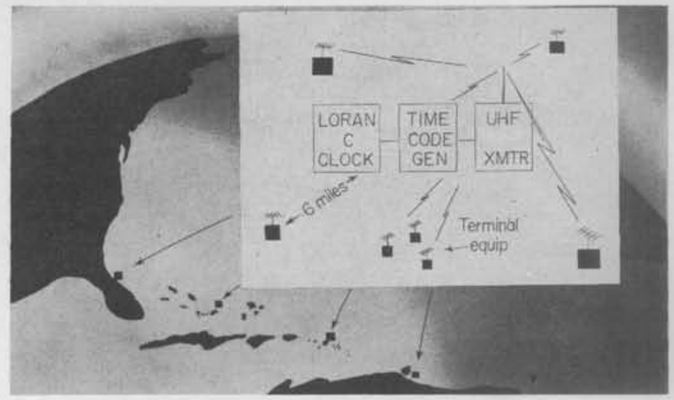

Fig. 7—UHF time distribution system.

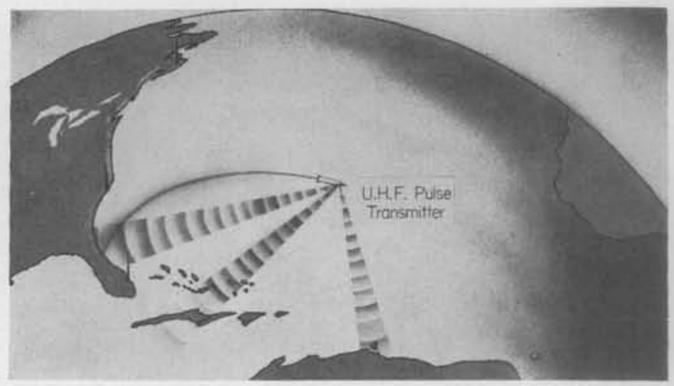

Fig. 8—Trajectory determination by precise timing.

between the clocks. When a large number of equipments requiring time are operated in close proximity, a single clock can serve them all by means of an appropriate UHF timing distribution system.[8] This basic system of time measurement and distribution could be duplicated at any number of locations within the coverage area of a Loran-C chain. See Fig. 7.

Loran-C ground wave coverage extends down range as far as Trinidad. The various down-range sites to that distance can be provided with absolute timing accuracy of approximately 1 μsec. Beyond Trinidad and down to Ascension Island the Loran-C clocks must be synchronized on sky waves. It is important to note that the absolute accuracy involves an allowance for *systematic* propagation errors which cannot be measured independently by any existing system or method. The repeatability of time measurements at any one station, however, will in general be better than 0.1 μsec. In some cases, repeatability may be at least as important as absolute accuracy. For example, the trajectory of a missile or the position of a satellite[9] could be determined by transmitting very short pulses at UHF or microwave frequencies from the missile and recording their time of arrival at a number of time synchronized stations. See Fig. 8. Systematic time errors among the observing stations would result in a corresponding error in the absolute position of the trajectory, but the changes from reading to reading would be influenced only by the stability of the individual clocks and the stability of the propagation medium between the missile and the ground stations.

On the basis of theory[10] and measurements (Appendix II) there is little doubt that Loran-C clocks can be quite accurately synchronized even on second and/or third hop sky waves. Second hop sky wave time differences from the Cytac (Loran-C) transmitters (Forestport, N. Y., Cape Fear, N. C., and Carrabelle, Fla.) were measured at distances up to 5000 km. Standard deviations of these differences were less than 2 μsec day or night. Sunrise and sunset effects corresponding to 18 to 20 km change in ionospheric height were observed. When only the first reflected signal was utilized these sunrise and sunset effects rarely lasted more than 30 minutes. The height variations agree well with other observations for oblique incidence.[11,12] At distances beyond ground wave range there is no satisfactory way to accurately measure sky wave delays. But there is no reason to distrust computed values based on theoretical calculations, former observations and recent electron density rocket information.[10–13] Based on this information, it should be possible to establish time at ranges from 2000 to 8000 km at least within 10 μsec.

The Atlantic and Pacific missile ranges can be linked with a common timing system which will provide 1 μsec accuracy. The link between the two ranges requires the

[9] G. Hefley, R. F. Linfield and R. H. Doherty, "Timing and Space Navigation with an Existing Ground Based System," presented at AGARD 10th General Assembly, Istanbul, Turkey, October, 1960, Pergamon Press Inc., New York, N. Y.; 1961.

[10] J. R. Johler and L. C. Walters, "On the theory of reflection of low and very-low radiofrequency waves from the ionosphere," *J. Res. NBS*, vol. 64D, pp. 269–285; May–June, 1960.

[11] J. R. Wait, "Diurnal change of ionospheric heights deduced from phase velocity measurements at VLF," Proc. IRE (Correspondence), vol. 47, p. 998; May, 1959.

[12] J. M. Watts, "Oblique incidence propagation at 300 kc using pulse techniques," *J. Geophys. Res.*, vol. 57, pp. 487–498; December, 1952.

[13] A. H. Waynick, "The present state of knowledge concerning the lower ionosphere," Proc. IRE, vol. 45, pp. 741–749; June, 1957.

installation of additional Loran-C stations in a generally east-west direction across the Continental U. S. Possible locations for these stations are shown in Fig. 9. Such a configuration would provide inter-range synchronization as well as excellent navigational coverage over the Continental U. S.

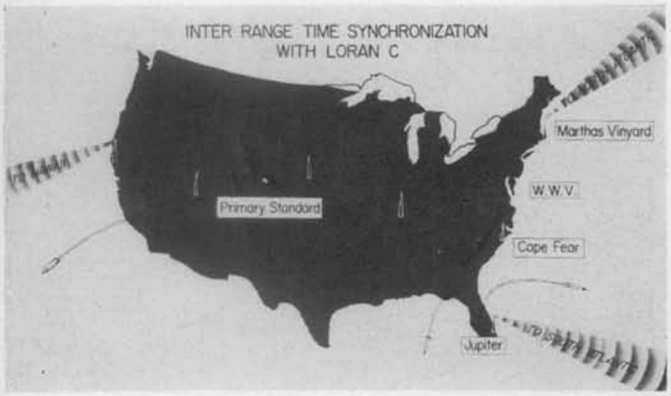

Fig. 9—Possible transmitter locations.

The inter-range synchronization only could be obtained on a very reliable basis by providing a transmitter in Illinois and another transmitter and secondary frequency standard near the West Coast. The western transmitter would be located within ground wave range of Boulder and could be steered by the primary frequency standard. If a number of Loran-C chains were synchronized, one to another, in order to provide coverage over very long ranges, the synchronization accuracy would be degraded to some extent. As far as is known, synchronization errors are of a random nature and therefore can be expected to add as the root-sum-square. For example, if the synchronization error in each transmitter is 0.03 μsec, the accumulated error in synchronizing six stations would be $\sqrt{6(0.03)^2}$ or 0.073 μsec.

The synchronization accuracy of the present Loran-C system could be improved by the use of better oscillators and longer integration times. It is not obvious, however, how much improvement could be achieved before reaching the point of diminishing returns.

The total noise or synchronization errors which can be expected in synchronizing a chain in the Hawaiian Islands from the U. S. should be substantially less than the prediction error in a land or mixed path.

VI. Additional Uses of Precise Time

Some scientific and commercial uses of a precise timing system that may have direct or indirect military applications are:

1) The positioning of high-altitude aircraft from the ground by using the UHF pulse technique.

2) The location of thunderstorms by precisely measuring the location of the lightning discharge.

3) The accurate position-fixing of nuclear detonations by a similar means.

4) A precise evaluation of the fluctuations of the periodicity of the earth's rotation and other astronomical phenomena by relating observations made at widely separated points.

5) The precise measurement of time variations on high-frequency transmissions such as WWV as an aid to better understanding of propagation phenomena.

6) Similar measurements on forward scatter communication links and other types of communication could also be made.

7) The surveying of offshore islands and remote areas.

8) The investigation of Loran-C sky waves to give a better understanding of ionospheric conditions.

9) The precise time from a single Loran-C clock could be made economically feasible for a variety of users in industry and research by the application of a VHF or UHF distribution system. Relatively inexpensive distribution would result if sufficient users were located within range of the distribution system. Existing facilities such as television transmitters could be utilized for this purpose.

Appendix I

Loran-C Ground Wave Measurements

The data presented in this appendix have been abstracted from a report concerned with the position fixing aspects of the Loran-C (formerly Cytac) system.[14]

The data were obtained primarily in the service area (see Fig. 1) during 1954 and 1955. The data are presented in the form of time difference measurements, since the position-fixing information was of prime concern. Although individual propagation paths were not resolved, these measurements were entirely consistent with the individual round-trip paths observed at the transmitters. Since no appreciable differences were detected, the time difference data in the service area were considered to be representative of single path propagation times. Data presented in Appendix II, comparing various sky wave time modes with the ground wave signal, are also consistent with this assumption.

These time-difference (TD) measurements were made in two stages. An envelope measurement was made automatically by subtracting the derivative of the envelope from the envelope and detecting an axis crossing with a servo loop. A cycle measurement was made automatically using synchronous detection techniques and a null seeking servo system. In all cases, the master signal was used to control the reference frequency, and the time differences (X−M and Y−M) were measured with respect to the master. The difference between the envelope TD readings and the cycle TD readings was denoted as the discrepancy. If this discrepancy did not exceed plus or minus 5 μsec, cycle identification was assured by the envelope reading. A typical plot of the cumulative distribution of this reading is illustrated in Fig. 10. Within ground wave recep-

[14] R. F. Linfield, R. H. Doherty, and G. Hefley, "Evaluation of the Propagation Aspects of the Cytac System," private communication; March 18, 1957. (Originally classified confidential.)

tion, the discrepancy was always well within reasonable limits.

The differences between observed and predicted readings were either position dependent or time dependent. The variations related to the position are thought to be caused by an incorrect assumption of the value of the conductivity. Fig. 11 shows a plot of data from locations where the signals arrived over land path. It appears that 0.005 mho/meter is a good average for the M-X pair, but that a higher value of conductivity from the Y transmitter would better approximate the M-Y paths.

The mean of the observed phase readings was compared to predicted phase readings calculated using an assumed conductivity of 0.005 mho/meter for land and 5 mhos/meter for sea water. Differences between the mean and the calculated readings are listed in Table I. Also shown are the distances from the transmitters, the hours of observation, and the standard deviations of the two time differences. The hours of observation were distributed randomly, day or night, throughout the period of operation at each location.

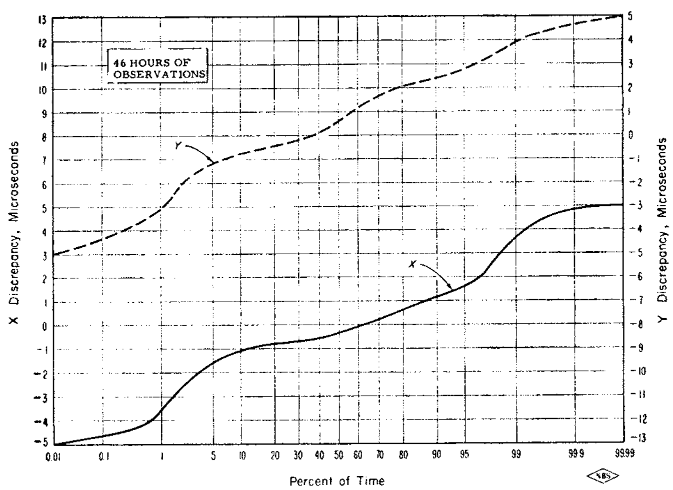

Fig. 10—Cumulative distribution of discrepancy readings—Wisconsin.

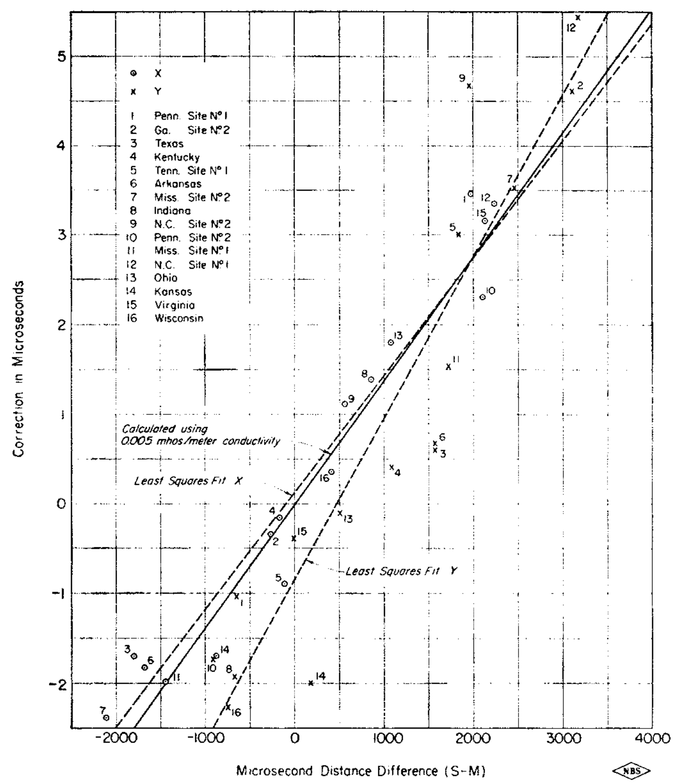

Fig. 11—Comparison of theoretical phase of secondary field difference corrections and measured data.

TABLE I

Results of Cytac Monitoring Program

Receiver Location	Distance to Transmitters km M	X	Y	Total Observations (hours)	Days At Site	Mean (all Observations) Minus Predicted (μsec) M-X	M-Y	Std. Deviation of the Observations M-X	M-Y
Miss.—1	1187	753	1704	800	341	+0.10	−0.47	0.11	0.47
N. C.—1	84	756	1028	750	316	+0.35	+1.01	0.16	0.53
Ohio	670	993	825	200	102	+0.48	−1.20	0.10	0.21
Texas—1	2055	1312	2781	98	64	−1.25		0.15	
Maine	1322	2051	437	92	11		−0.07		0.23
Tenn	663	630	1214	58	5	−0.76	+0.78	0.10	0.24
Missouri	1339	1120	1556	52	5	−0.04	−2.88	0.14	0.25
Penn.—1	666	1252	472	52	3	+1.30	−0.09	0.12	0.05
Indiana	1039	1294	839	51	5	+0.29	−1.04	0.07	0.09
Wisconsin	1324	1430	1101	46	5	−0.13	−1.33	0.11	0.13
Florida	656	401	1717	34	7	−0.51	+0.89	0.16	0.27
Kansas	1939	1696	2010	30	5	−0.60	−2.22	0.17	0.19
N. C.—2	499	670	1084	27	2	+0.54	+2.24	0.05	0.09
Iowa	1573	1469	1542	22	2	+0.28	−1.58	0.11	0.10
Penn.—2	681	1314	409	17	3	−0.15	−0.43	0.09	0.07
Virginia	545	1184	544	16	2	+0.63	−0.33	0.26	0.06
Georgia—1	412	368	1408	16	3	+0.32	+0.14	0.12	0.15
Georgia—2	440	359	1371	14	2	−0.05	+0.38	0.11	0.07
Florida—2	816	37	1754	9	1	−0.01	+0.65	0.06	0.17
Louisiana	1414	780	2063	9	2	−0.81	−1.59	0.05	0.23
Arkansas	1519	1015	1990	8	2	+0.48	−1.37	0.04	0.22
Florida—3	1118	655	2182	8	2	−0.03	−0.03	0.08	0.12
Miss.—2	1079	449	1818	8	2	+0.43	+0.07	0.10	0.18
Florida—4	927	454	1983	7	2	+0.02	+0.02	0.06	0.10
Texas—2	1669	1133	2141	7	1	+0.80	−1.19	0.03	0.16

The standard deviation of the mean minus the predicted values listed in Table I for the M-X pair is 0.5 μsec, the mean deviation is 0.43 μsec and the algebraic average is +0.06 μsec. For the M-Y pair the standard deviation is 1.17 μsec, the mean deviation is 0.92 μsec, and the algebraic average is −0.41 μsec. The Millington[15] method for combining conductivities was used for evaluating predictions for 13 sites, but this did not appreciably improve the standard deviations. However, the only conductivity values[16] that were available were measured at broadcast frequencies and over limited areas and are, therefore, not considered applicable at 100 kc. By assuming conductivities for the Y path ranging from 0.004 to 0.008 mho/meter, the standard deviation of the mean-predicted values for the M-Y pair was reduced to 0.69 μsec, and the average error was reduced to 0.51 μsec. Even though the two paths (receiver to M and receiver to X or Y) cannot be separated this method could provide a means for empirically evaluating conductivity at 100 kc in areas where Loran-C measurements are available.

Figs. 12–16 present cumulative distributions of the time difference readings taken at 2.5 minute intervals for sites where the total observation time was limited. Figs. 17–20 present cumulative distributions of the daily average readings for sites where observations were made for several months.

From these figures it can be seen that variations were within 1 μsec during a very high percentage of the time. It may be noted that the M-Y (northern) pair generally had greater deviations than the M-X (southern) pair. This is also quite obvious from Figs. 21–24 where the daily averages are plotted for the fixed sites. Figs. 25 and 26 indicate some typical diurnal variations on the M-X and M-Y pairs. Again it can be seen that the M-Y variations were greater than the M-X variations.

The reason for the larger time variation associated with the northern path was never completely resolved although many contributing factors can be listed. Errors of this magnitude do not exist on the northern pair of the present east-coast Loran-C system.

Most of the data presented here were obtained from signals that were not phase coded. Multihop sky wave contamination was not eliminated and could contribute toward time variations (see Fig. 27). During the first few months of operation some variations were probably due to inexperience of operating personnel.

The operation was not continuous and evidently instabilities accompanied shut down periods. Fig. 28 shows such changes recorded at four stations when the operating periods were compressed into a single plot. Correlation coefficients were calculated using simultaneous data from these four sites. The correlation coefficients are shown in Table II.

In a further investigation, the variations were divided into two categories or components: 1) purely random variations and 2) variations which would produce correlation at the observation points. Since servos in the different pieces of equipment were not adjusted to have identical damping characteristics, the data were normalized to the average characteristics of the four equipments. The results indicated in Table III demonstrate that the maximum variations that could positively be attributed to propagation did not exceed 0.03 to 0.04 μsec.

Although the time fluctuations have sometimes been shown to correlate with weather phenomena, particularly temperature, it has not been conclusively established that the variations were not partially within the antenna system. The typical Loran-C installation includes a 600-foot top loaded transmitting antenna, and a 30- to 90-foot receiving whip within a few hundred meters of the transmitting antenna. Impedance changes of the transmitting antenna would affect the phase characteristics of the receiving antenna. An attempt to check this effect was made by using a receiver on the base-line extension. Any effect due to the antenna impedance change was evidently masked by larger variations.

The large time variations on the northern pair (M and Y) were probably the result of a combination of multihop sky wave contamination, and the first-hop sky wave contamination. The first-hop contamination could occur if the signal were sampled too late, that is, after the first-hop sky wave had started to arrive. The base-line path of the northern pair during the Cytac tests was quite long (over 1000 km); it was all over land (causing maximum delay of the ground wave), and it was at a high geomagnetic latitude.

A subsequent Loran-C chain located in the arctic (high geomagnetic latitude) has encountered trouble with very short first-hop sky wave delays because of the lower ionospheric heights at these latitudes. This situation was encountered even though the base lines were over sea water.

The Loran-C chain located on the East Coast of the United States has been relocated since 1955. The northern base line is now partially over sea water and the northern station is at a slightly lower geomagnetic latitude. With continuous operation and the new locations, the variations have been reduced by an order of magnitude.

Amplitudes of the ground wave signal out to ranges as great as 3700 km are shown in Fig. 29. The paths that the signals traversed were partially land, but primarily sea water. The agreement between predicted and measured values is fairly good in the range of 2400 to 3700 km. The deviation from the predictions at ranges less than 2400 km is greater than can be explained by experimental error.

[15] G. Millington, "Ground wave propagation over an inhomogeneous smooth earth," *Proc. IEE*, vol. 96, pt. III, pp. 53–64; January, 1949.

[16] R. S. Kirby, *et al.*, "Effective Radio Ground Conductivity Measurements in the United States," Natl. Bureau of Standards, Boulder, Colo., NBS Circular No. 546; February, 1954.

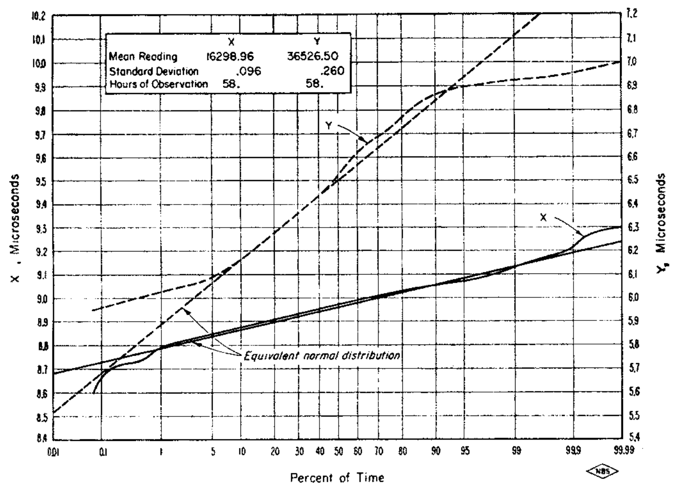

Fig. 12—Cumulative distribution of time difference readings—Tennessee Site 1 (2.5 minute intervals).

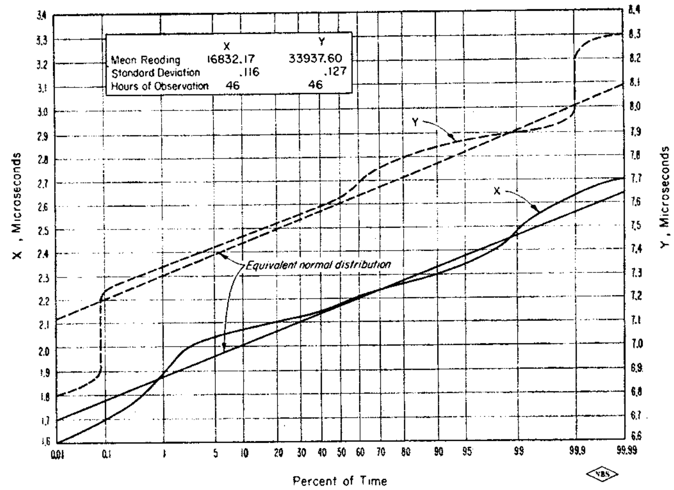

Fig. 13—Cumulative distribution of time difference readings—Wisconsin (2.5 minute intervals).

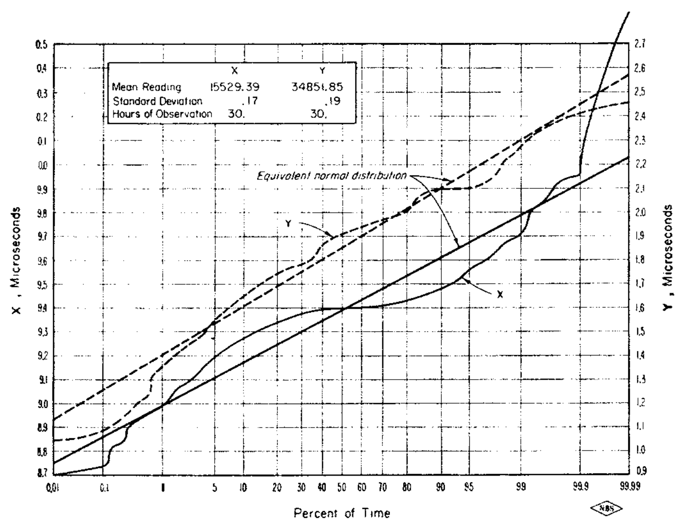

Fig. 14—Cumulative distribution of time difference readings—Kansas (2.5 minute intervals).

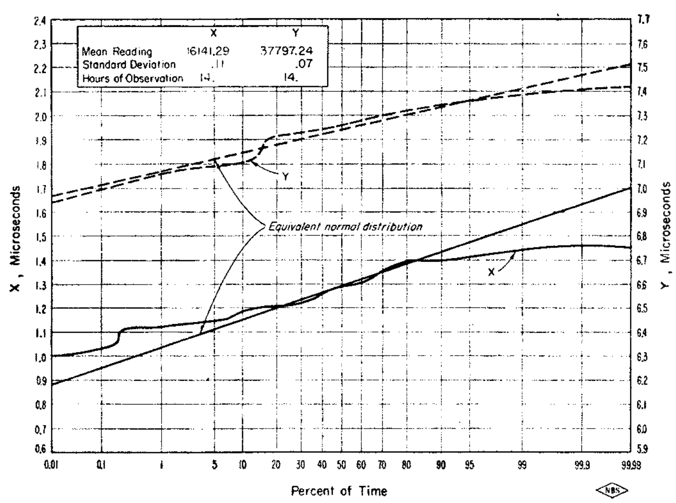

Fig. 15—Cumulative distribution of time difference readings—Georgia Site (2.5 minute intervals).

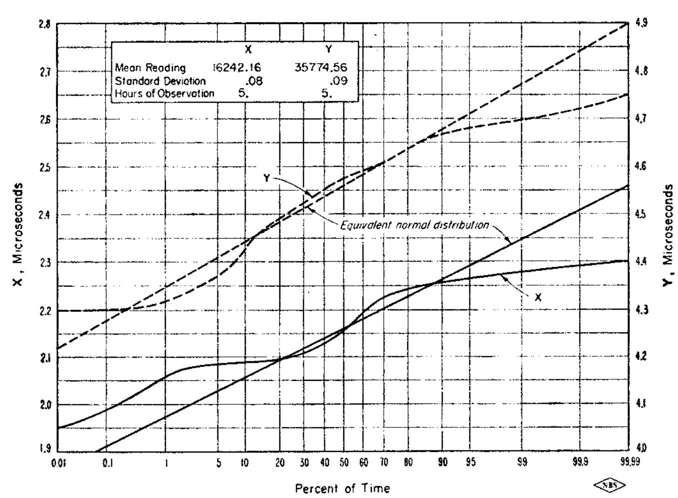

Fig. 16—Cumulative distribution of time difference readings—Kentucky (2.5 minute intervals).

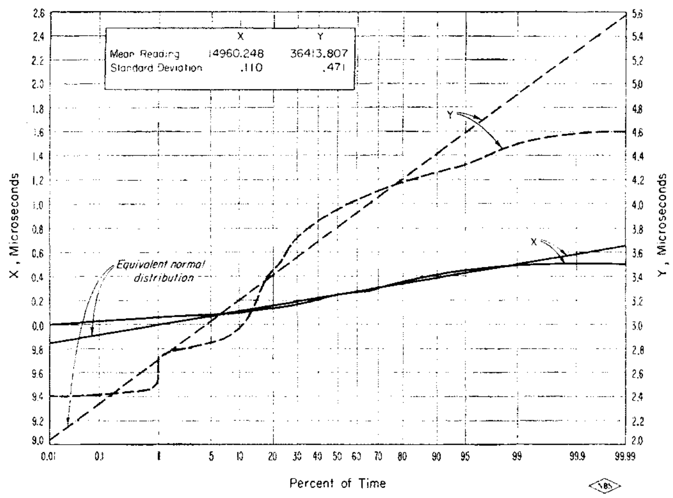

Fig. 17—Cumulative distribution of daily averages —Mississippi Site 1 (November 1954–1955).

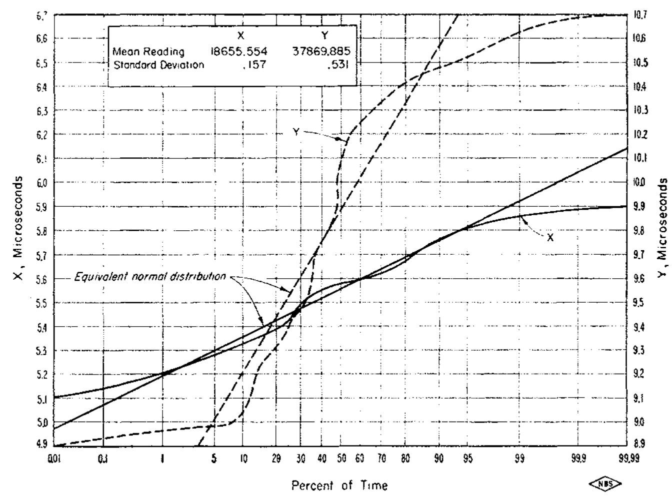

Fig. 18—Cumulative distribution of daily averages —North Carolina Site (January–October 1955).

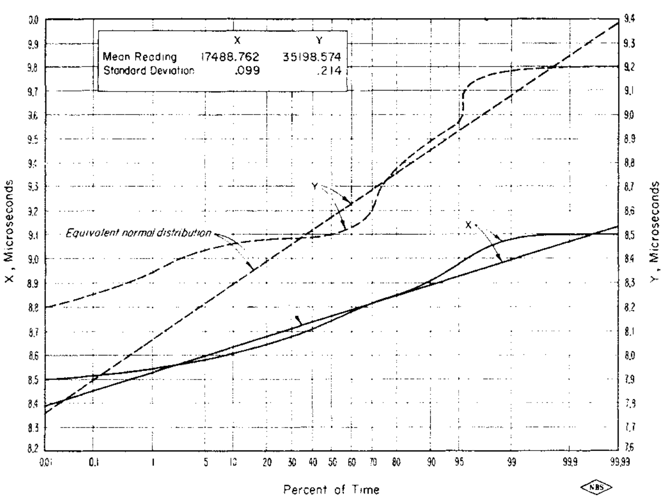

Fig. 19—Cumulative distribution of daily averages —Ohio (January–February 1955).

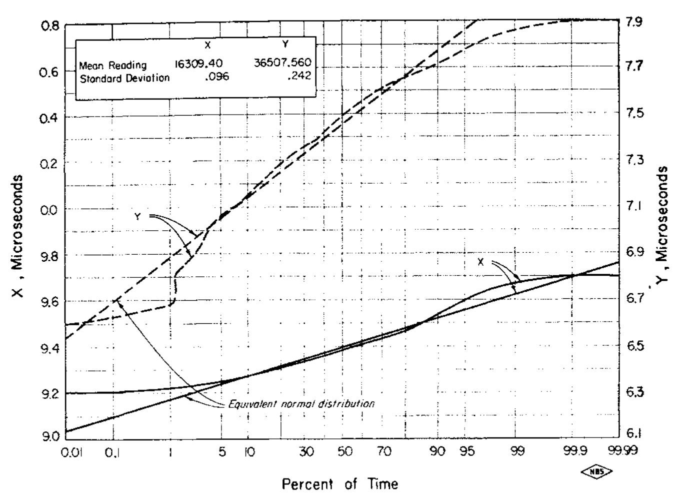

Fig. 20—Cumulative distribution of daily average —Tennessee Site 1 (March–November 1955).

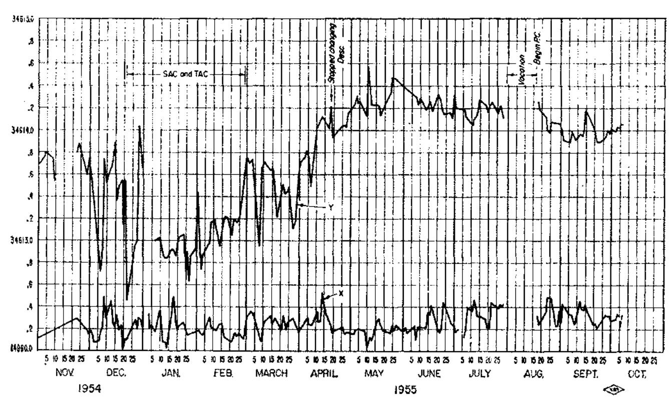

Fig. 21—Daily average X and Y cycle readings—Mississippi Site 1.

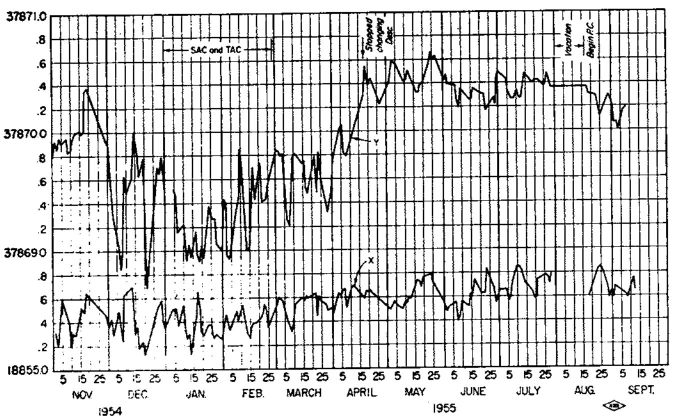

Fig. 22—Daily average X and Y cycle readings —North Carolina Site 1.

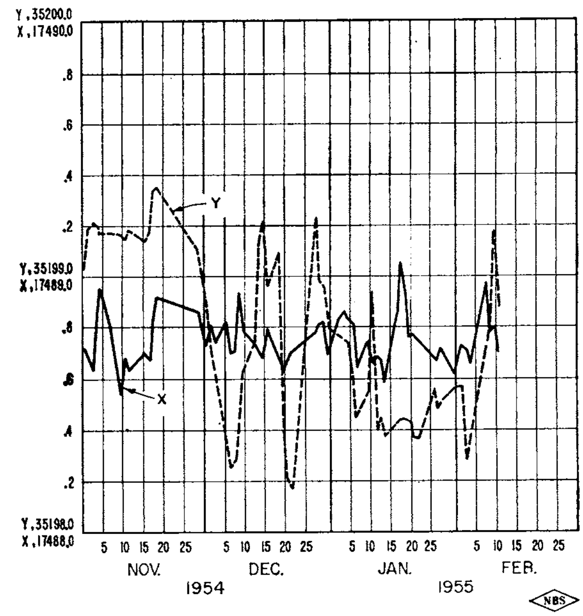

Fig. 23—Daily average X and Y cycle readings—Ohio.

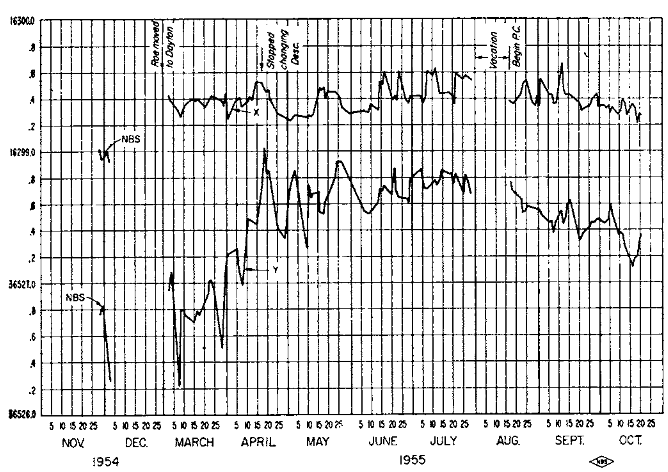

Fig. 24—Daily average X and Y cycle readings—Tennessee Site 1.

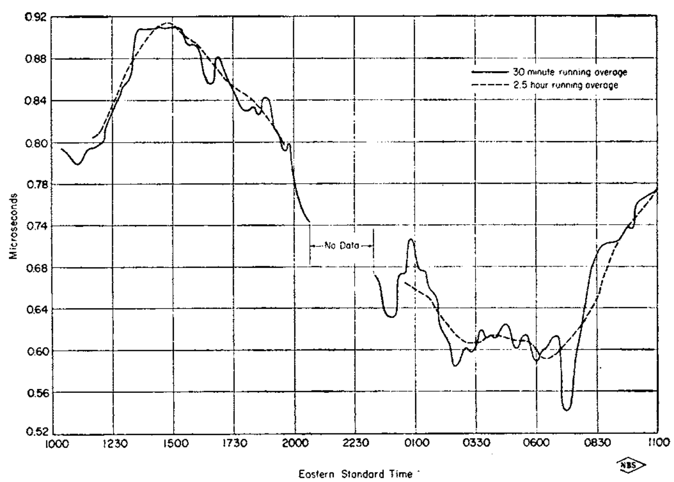

Fig. 25—Running average of Y time difference—North Carolina Site 1 (November 30–December 1, 1954).

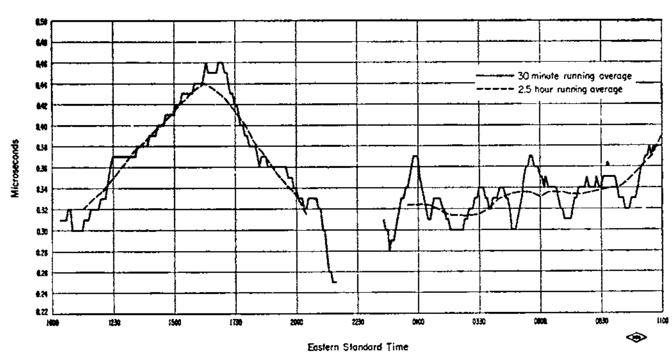

Fig. 26—Running average of X time difference—North Carolina Site 1 (November 30–December 1, 1954).

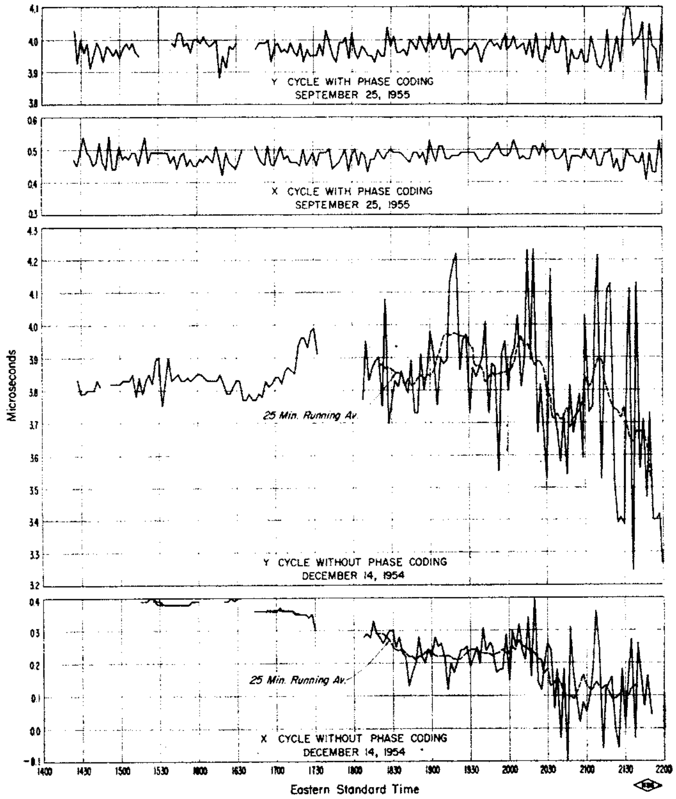

Fig. 27—Cycle readings with and without phase coding—Mississippi Site 1.

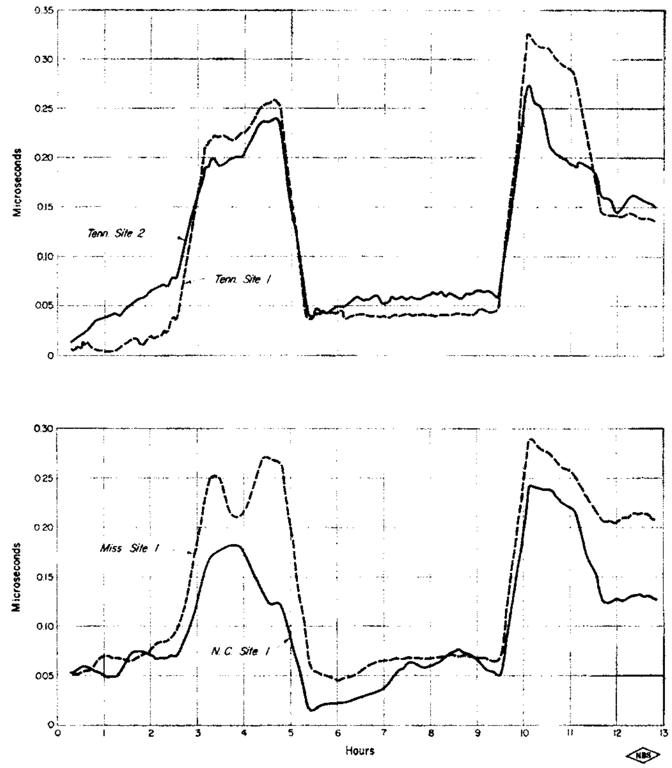

Fig. 28—37.5 minute running averages of X readings (13.1 hours of data, September 1–13, 1955).

TABLE II

CORRELATION OF S_1 PAIR

	Tenn. Site 1	Tenn. Site 2	Miss. Site 1	N. C. Site 1
Tenn. Site 1		0.930	0.934	0.901
Tenn. Site 2	0.930		0.934	0.855
Miss. Site 1	0.934	0.934		0.870
N. C. Site 1	0.901	0.855	0.870	

CORRELATION OF S_2 PAIR

	Tenn. Site 1	Tenn. Site 2	Miss. Site 1	N. C. Site 1
Tenn. Site 1		0.526	0.658	0.620
Tenn. Site 2	0.526		0.543	0.442
Miss. Site 1	0.648	0.543		0.669
N. C. Site 1	0.620	0.442	0.669	

TABLE III

	Measured	Normalized	Noise Component	Synchronous Component
S_1 PAIR				
Tenn. Site 1	0.107	0.077	0.011	0.076
Tenn. Site 2	0.081	0.081	0.009	0.076
Miss. Site 1	0.092	0.081	0.003	0.076
N. C. Site 1	0.068	0.082	0.032	0.076
S_2 PAIR				
Tenn. Site 1	0.057	0.038	0.024	0.029
Tenn. Site 2	0.043	0.043	0.032	0.029
Miss. Site 1	0.043	0.035	0.019	0.029
N. C. Site 1	0.105	0.037	0.022	0.029

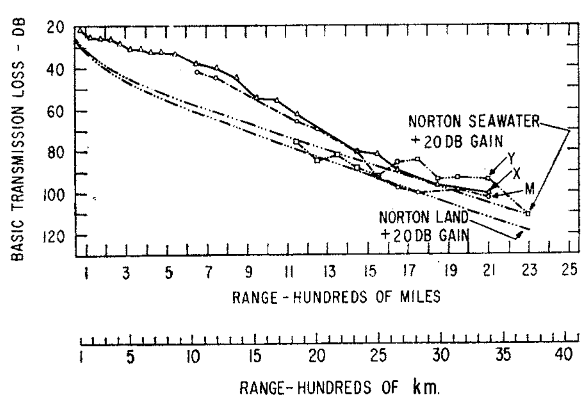

Fig. 29—Predicted and measured ground wave signal amplitude.

Appendix II

Loran-C Sky Wave Measurements

Loran-C is a pulse navigation system utilizing sampling techniques to select the ground wave and discriminate against the sky wave signal. These same sampling techniques can be utilized to select one sky wave signal and discriminate against all other sky wave signals at ranges beyond ground wave reception. This provides a means for measuring the phase and amplitude of a particular sky wave time mode rather than a composite signal as is done in CW measurements. Many measurements that have been made with Loran-C indicate that the phase of a particular time mode is very stable, but the amplitude of that time mode is quite unstable. Furthermore, the variations occurring on one time mode do not necessarily correlate with variations occurring on another time mode.

If a number of vectors of different fixed phases but of variable amplitudes are added together, the phase of the resultant will change as a result of the amplitude variations. Similarly, the phase of a CW signal varies in accordance with the amplitudes of the different time modes. Consequently, the phase variations do not necessarily indicate phase changes in the individual time modes nor changes in ionospheric height.

At ranges beyond ground wave reception the first signal arriving via the ionosphere was normally observed. At shorter ranges uncontaminated higher order multihop sky wave signals were observed. Sky wave signals have been observed at distances as great as 12,000 km (Johannesburg, S. A. from Jupiter, Fla.). A large number of measurements listed in Table IV have been made between 3000 and 5000 km. Multihop measurements listed in Table V have been made at ranges as short as 500 km.

Figs. 30–31 illustrate typical daytime first-hop sky waves observed at Boulder, Colo. (about 3000 km from the transmitters). All of the data available suggest an excellent sky wave phase stability when a single propagation mode is studied. The Boulder data recorded over a period of more than one month had short term variations of only 0.25 μsec and day to day variations of only 0.5 μsec. This data was obtained by comparing a first-hop sky wave from one transmitter with the ground wave from another (southern pair). Nighttime measurements were not made in 1955 because the transmitters did not operate on a 24-hour basis during September and October. Similar measurements made at Boulder in 1961 indicate nighttime stabilities to be at least within 5 μsec (see Fig. 32).

TABLE IV

Mode	Distance (Kilometers)	Time (Day or Night)	Delay (μsec)	σ Standard Deviation (μsec)
Belize, British Honduras				
X Gnd. Y Gnd.	1425 3133	D	− 0.4	0.944
X Gnd. Y 1st	1425 3133	D	+ 29.9	1.012
X Gnd. Y 1st	1425 3133	N	+ 43.1	1.219
X Gnd. Y 3rd	1425 3133	D	+102.8	0.541
X Gnd. Y 2nd	1425 3133	N	+103.9	1.460
X Gnd. Y 4th	1425 3133	N	+267.7	0.904
Kingston, Jamaica				
M Gnd. X Gnd.	1786 1539	D	− 0.7	0.551
X Gnd. Y Gnd.	1539 3829	N	+ 0.3	0.366
M Gnd. Y Gnd.	1786 3829	D	+ 1.0	0.356
Puerto Cabezas, Nicaragua				
X Gnd. Y Gnd.	1763 3356	D	− 2.21	1.235
X Gnd. Y 1st	1763 3356	D	+ 30.0	1.436
X Gnd. Y 1st	1763 3356	N	+ 49.7	1.234
X Gnd. Y 3rd	1763 3356	D	+211.4	1.018
M Gnd. X Gnd.	2286 1763	N	− 1.9	0.255
Buenaventura, Colombia				
M Gnd. X Gnd.	3339 2983	D	− 2.64	0.590
M 1st X 1st	3339 2983	N	− 2.06	0.415
M 1st Y 1st	3339 4385	N	+ 0.0	0.936
M Gnd. Y 2nd	3339 4385	D	+ 37.5	1.864
M Gnd. Y 3rd	3339 4385	D	+105.3	0.909
X 1st Y 4th	2983 4385	D	+222.7	1.309
X Gnd. Y 4th	2983 4385	D	+235.9	1.015
Guayaquil, Eduador				
M 1st X 1st	4024 3574	N	− 1.98	0.299
M 1st Y 2nd	4024 5086	N	+ 56.6	0.527
M 1st X 1st	4024 3574	D	− 0.50	1.812

TABLE V

Distance Kilometers	Transmitter	Total Delay (μsec)	Amplitude (in μv/m)	Most Probable Hop	Corresponding Layer Height km
Woodstock, Kentucky					
817	X	304	9.6	3rd	65.0
817		Nothing could be observed for 4th			
817	X	784	10.3	5th	65.5
817	X	1024	10.8	6th	63.6
1051	Y	285	19.2	3rd	69.5
1051	Y	505	14.4	4th	71.8
1051	Y	753	11.2	5th	71.7
1051	Y	993	9.6	6th	69.6
Spring Creek, North Carolina					
496	M	815	24.4	4th	68.0
496	M	1050	20.0	5th	64.0
676	X	454	—	3rd	74.2
676	X	752	13.2	4th	74.0
1078	Y	1083	—	6th	74.0
Boulder, Colorado					
2526	Y	32	—	1st	*
2526	Y	448	—	5th	78.8
2526	Y	618	—	6th	78.3
2518	Y	34	—	1st	*
2518	Y	298	2.0	4th	77.4
2518	Y	440	—	5th	77.5
2510	M	34	—	1st	*

* Since the apparent heights are obtained from a graph based on geometrical-optical considerations, and the distance for first-hop sky wave is far beyond that obtainable by geometrical-optical theory, any apparent heights assigned to these first-hop reflections would be completely meaningless.

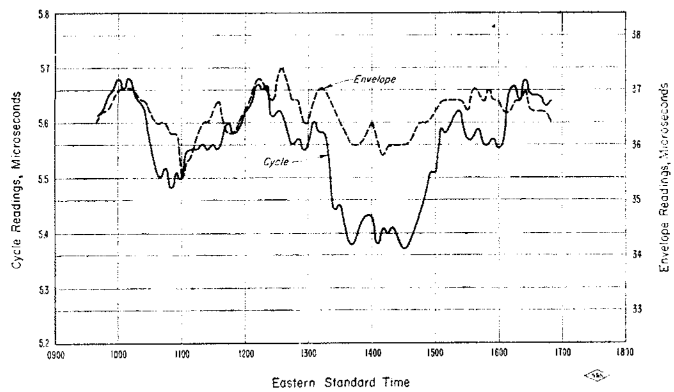

Fig. 30—Envelope and cycle readings, first-hop sky wave—Boulder, Colo. (September 13, 1955).

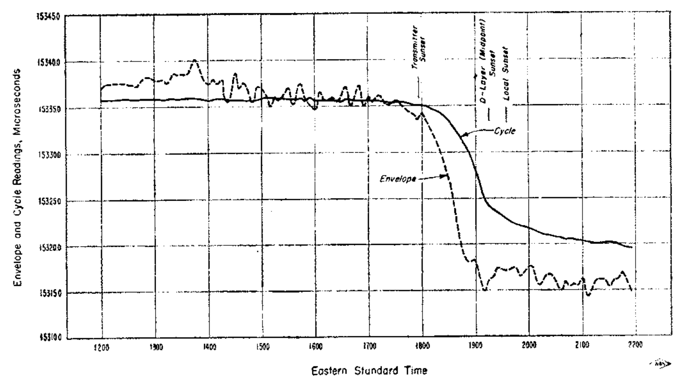

Fig. 31—First-hop sky wave measurements—Boulder, Colo. (October 6, 1955).

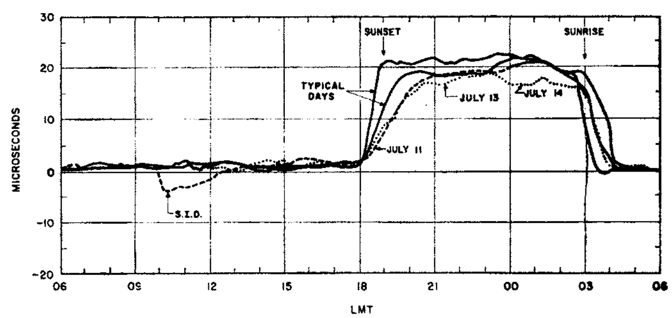

Fig. 32—First-hop sky wave from Cape Fear, N. C.—Boulder, Colo. (1961). Approximately 3000 km.

The standard deviations listed in Table IV were typical of observations for an entire day or night made in Central and South America in 1956. These standard deviations again suggest excellent stability of the sky wave phase. The delays listed are delays as compared to the predicted arrival time of the ground wave signal. These delays seem to be quite reasonable for the propagation mode being measured. Fig. 32 illustrates the phase change resulting from an S.I.D. occurring on July 11, 1961. The event was rated at about $3\frac{1}{2}$ on a scale of 4. VLF records indicated a change of up to 30 μsec. This first-hop sky wave signal showed a total phase change of 4.5 μsec. This phase decrease was accompanied by an amplitude increase of more than 12 db. The slower sunset effect seems to be related to the flare and the magnetic storm that followed the event. On July 13th and 14th (dotted curves) a magnetic storm occurred that disturbed the phase of VLF CW measurements.

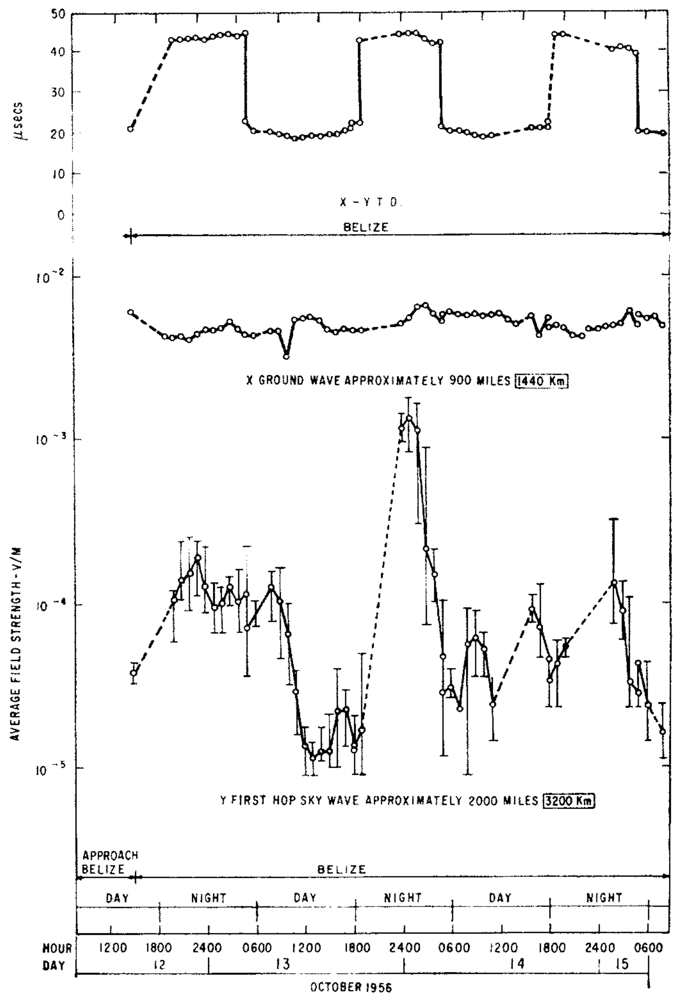

Fig. 33—Phase and amplitude of Loran-C sky wave referred to ground wave.

Fig. 33 presents a three-day plot of both the phase and amplitude of a first-hop sky wave signal, the upper plot representing the T.D. between a first-hop sky wave signal from 3200 km and the ground wave signal from 1440 km. Again rather good phase stability is suggested. The lower plots are the measured amplitudes of the two signals. The amplitude of the sky wave signal is quite variable and not obviously correlated with any phase changes.

The amplitudes of the various time modes present vary relative to one another, often quite rapidly. Fig. 34 illustrates several time modes of the Loran-C master pulses observed at Boulder. The relative amplitudes of the several time modes obviously do not correlate. A CW measurement made at this frequency would show phase changes due to these relative amplitude changes alone.

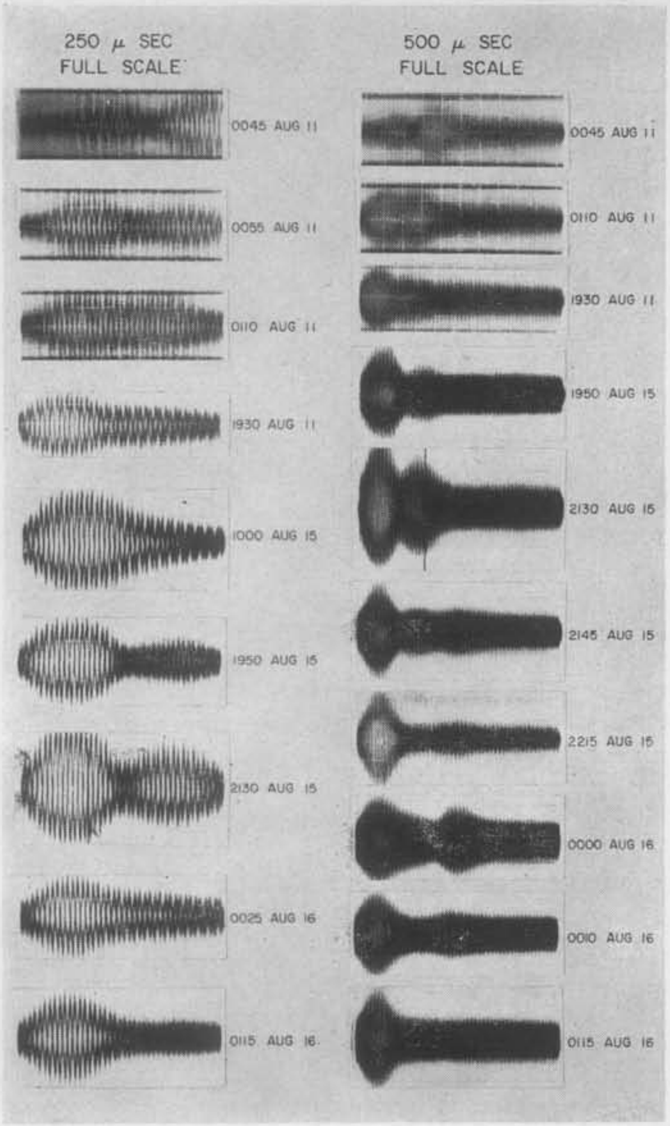

Fig. 34—Multihop sky waves master signal observed at Boulder, Colo.

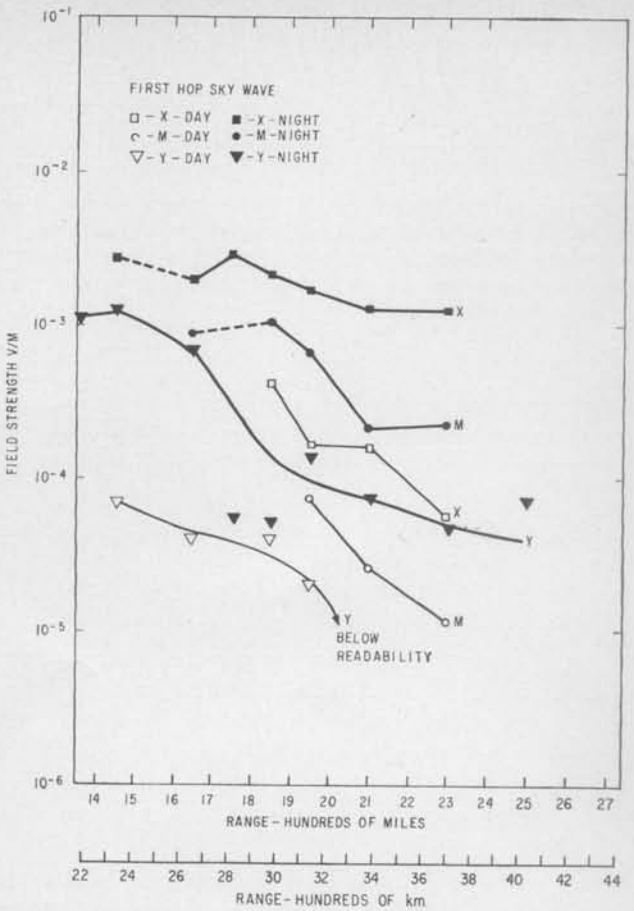

Fig. 35—Field strength of Loran-C sky wave on north-south paths.

Fig. 35 represents average amplitudes observed on a predominantly north-south path. Since these plots are strictly amplitude versus distance and the Y transmitter was about 15° farther north than the X transmitter, a strong latitude effect on signals propagated by the ionosphere is suggested. The average nighttime sky wave field intensity was about 20 db larger than the average daytime field intensity.

Table V presents other interesting observations made at relatively short ranges. It was noted that high-order multihop sky waves were present at most locations. It was further noted as can be seen from the tabulations that often the amplitude of the *n*th hop would be as great as or greater than the amplitude of the *n*th-1 hop. Assumptions made as to predominant time modes or negligible time modes for CW measurements may be somewhat questionable in view of these observations.

VII. Acknowledgment

Special acknowledgment is given to P. J. Kiser, of the Air Force Eastern GEEIA Region, for his engineering contributions to the Loran-C clock and his assistance in the preparation of this paper.

The entire Loran-C clock and UHF distribution system has been developed by the National Bureau of Standards, Boulder Laboratories under the sponsorship of Headquarters, Eastern GEEIA Region.