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A GENERAL DESCRIPTION OF LORAN-C: PRESENT AND POTENTIAL APPLICATIONS

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ABSTRACT

Loran-C is a low frequency (100 kHz) pulse navigation system. The pulse format and phase stability of the system are of paramount importance for both navigation and time synchronization using this system.

The need for a low frequency loran system was born out of the shortcomings of the standard loran system used during World War II. Many early tests of low frequency loran culminated in the testing of Cytac by the U. S. Air Force in the early and mid 1950's. This was a tactical bombing system, and was a direct predecessor to Loran-C.

Present Loran-C installations operated by the U. S. Coast Guard cover much of the northern hemisphere. A recent government-wide decision has declared that Loran-C will be the U. S. Coastal confluence navigation system for the immediate future. Therefore, Loran-C stations are presently being installed or planned to cover the entire U. S. coastline.

In addition to standard navigation and timing applications of Loran-C, auxiliary navigation and timing applications are presently being considered or are potentially available. These include differential or relative Loran-C for high precision positioning, urban vehicle or residence location by the AEC, the FBI and the Census Bureau, off shore oil drilling, and collision avoidance by ships or aircraft.

Finally, the unique nature of the Loran-C pulse transmission allows one to separate ground wave and sky-wave transmission. Also, the pulse provides a transient capable of validating transient propagation theory. Therefore, the Loran-C transmissions have proven to be very effective diagnostic tools for validating propagation theories. Continued efforts in this direction will undoubtedly lead to improved prediction and calibration procedures for use with all Loran-C systems.

INTRODUCTION

Loran-C is a hyperbolic radio navigation system utilizing 3 or more transmitters in a simple chain configuration (see figure 1). The transmitters radiate fast rising pulses so that a phase and envelope measurement can be made on the early part of the pulse (ground wave), before the arrival of the first hop sky wave (the first signal to arrive after reflecting once from the ionosphere D-region--see figure 2). By tagging a point in time on the ground wave portion of the radio wave pulse, stabilities of about one order of magnitude more accurate than the combined ground wave and sky wave phase measurement on the propagated pulse are observed (i.e. to propagation time measurement error less than one microsecond). The above description explains the method for deriving time information from Loran-C within the ground wave range of any transmitter.

For navigation purposes, the user must also be within ground wave range of two or more slaves. A similar propagation time measurement is made on the slave and the master and the difference between these measurements is shown as a TD (time difference). A single TD measurement will define an LOP (line of position) relative to the master and slave. Two LOP's relative to a master and two slaves will then define a position fix as indicated in figure 1.

To insure that the master and subsequent slave signals will not overlap in time within the service area, coding delays are introduced into the slave transmissions in a sequential order. Each station radiates groups of 8 pulses, and the master station radiates a ninth pulse for identification purposes. All stations transmit the phase of the pulse in a 0 or 180° coded format. This phase code aids in automatic receiver identification and automatic phase synchronization of the receiver with the master and slave signals. The phase coding also gives protection against synchronous CW interference.

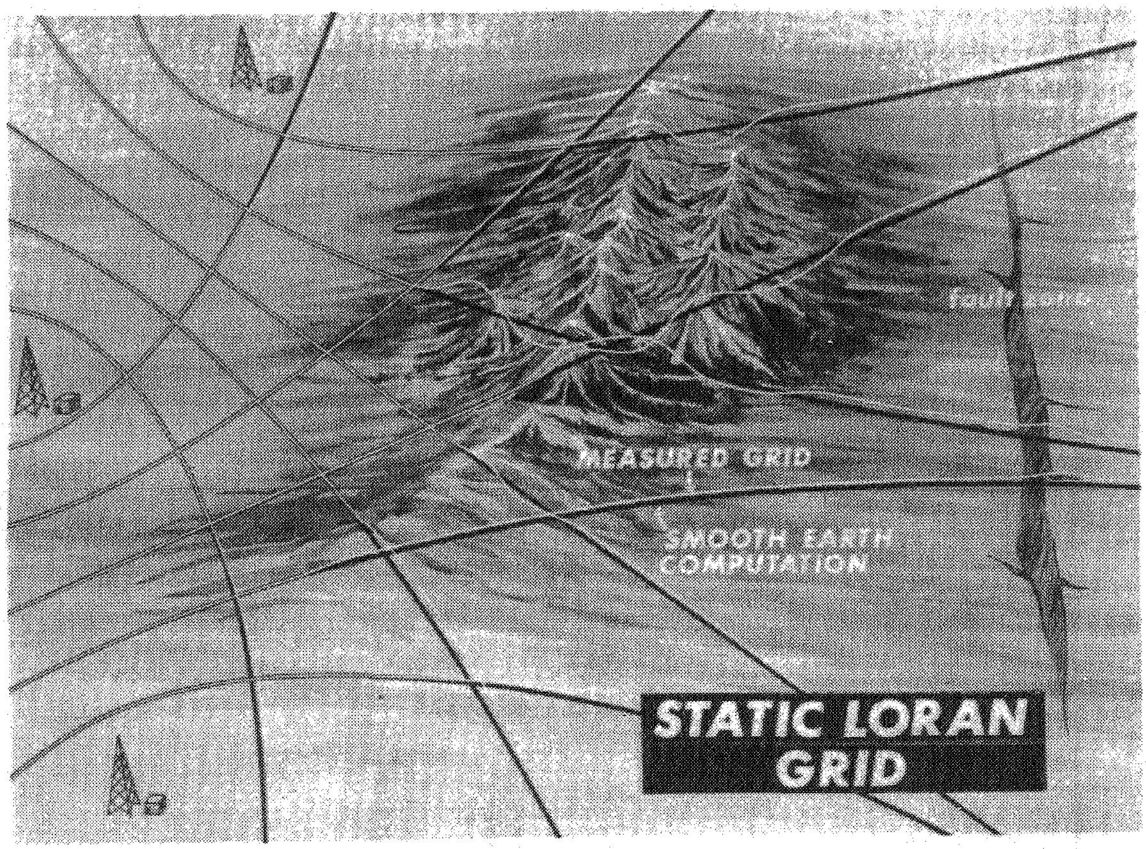

Figure 1. Loran-C static grid depicting the effect of terrain anomalies in a three station chain.

This 100 kHz pulse type loran radio navigation system was first developed in the early and mid 1950's by the U. S. Air Force as a tactical system under the name Cytac. The objective of the development was a ground based bombing system for use in aircraft [1] targeting. In the early tests on this system it was recognized that radio signal propagation time was influenced by the electrical properties of the ground over which the signals propagated. These electrical properties can be represented compactly as a ground impedance. Thus, the impedance of the ground was considered to be primarily determined by such ground electrical constants as the conductivity, the dielectric constant, and the permeability. At 100 kHz the effect of conductivity is dominant and theoretical calculations [2] used impedance calculators [3] which converted conductivity into impedance and then calculated a secondary phase correction, or the phase correction due to the fact that the signals travels slower than the speed of light in microseconds. Early attempts to evaluate the effect of ground conductivity and indeed to predict and update predictions by using measured data have been reported [1].

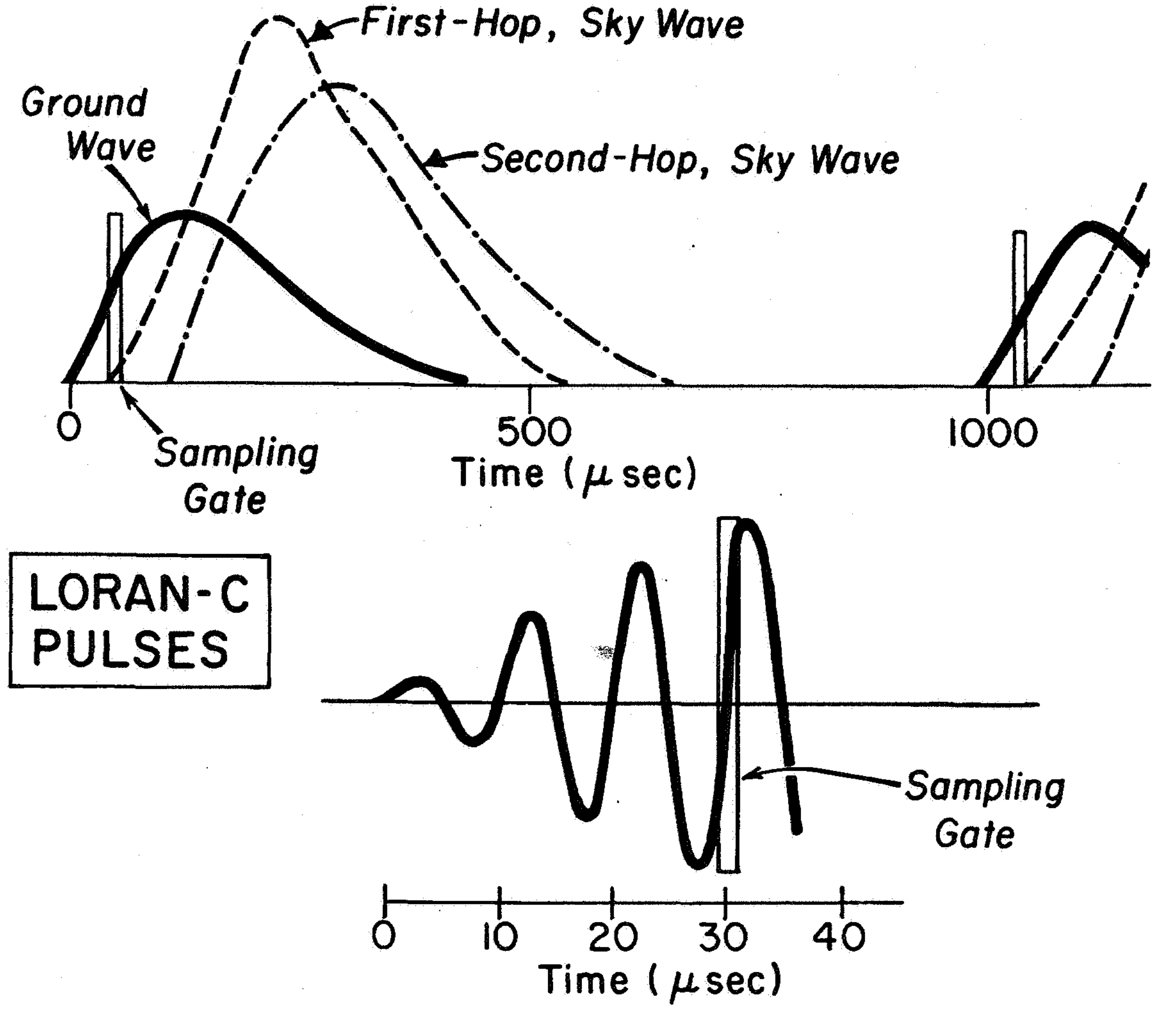

Figure 2. Loran-C pulse as transmitted along with the effect of ground wave and sky wave signals received. This figure also demonstrates the ground wave sampling prior to the sky wave arrival time.

The early measuring equipment was quite complex and required considerable size and power to operate as demonstrated in figure 3.

Figure 3. Vehicle housing Cytac (predecessor to Loran-C) receiving equipment in 1954.

Attempts to measure effects in rough terrain, such as those depicted in figure 1, were very difficult as shown in figure 4. Recent advances in electronic miniaturization have allowed back pack receivers shown in figure 5 to replace two 15 kw diesel generators and seven relay racks of equipment that were housed in the tractor trailer during the Cytac tests. Today, rough terrain spatial variation may be more readily investigated. Complete resolution of a propagation change on an individual path requires the direct phase measurement of propagation time from a particular station. To make these measurements today, the equipment shown in figures 6 and 7 is employed.

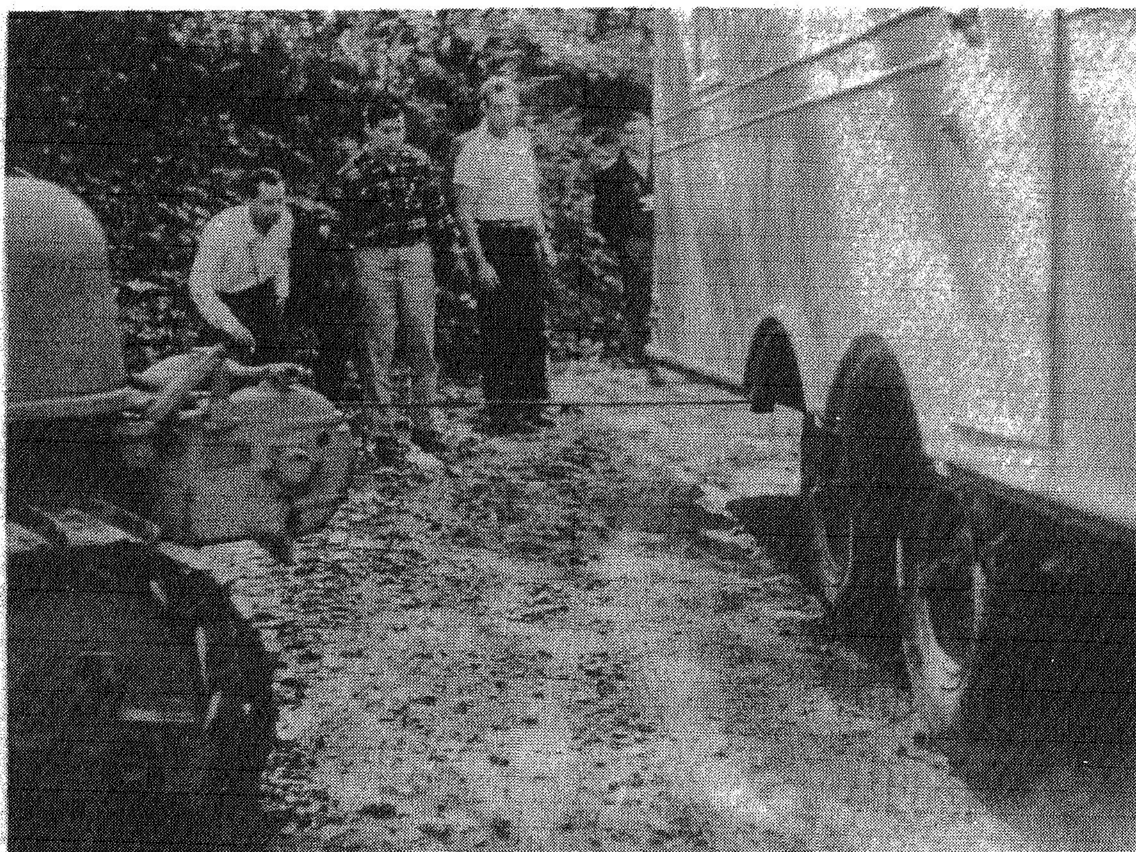

Figure 4. Difficulty with 1954 vehicle in attempting to make measurements particularly in irregular terrain.

Following the U. S. Air Force development of this loran system, the U. S. Coast Guard adopted the system for navigation on the high seas. The system was named Loran-C by the U. S. Coast Guard, and a number of loran chains (comprising a master station and two or more slaves) for over the ocean coverage were subsequently installed [4]. The impedance of sea water has a value, $\Delta = 0.001055 \exp (i\ 0.7854)$ relative to free space or 377 ohms. This corresponds to a conductivity of 5 mhos per meter and a dielectric constant of $\epsilon_2 = 80$ where the permeability of a propagation medium, $\epsilon = \epsilon_2 \epsilon_0$ and ϵ_0 is a universal constant of nature, $\epsilon_0 = 8.8542(10^{-12})$F/m. It can also be noted that sea water is an excellent conductor at 100 kHz and a good approximation for sea water would be: $\Delta = 0$ and the conductivity, $\sigma = \infty$.

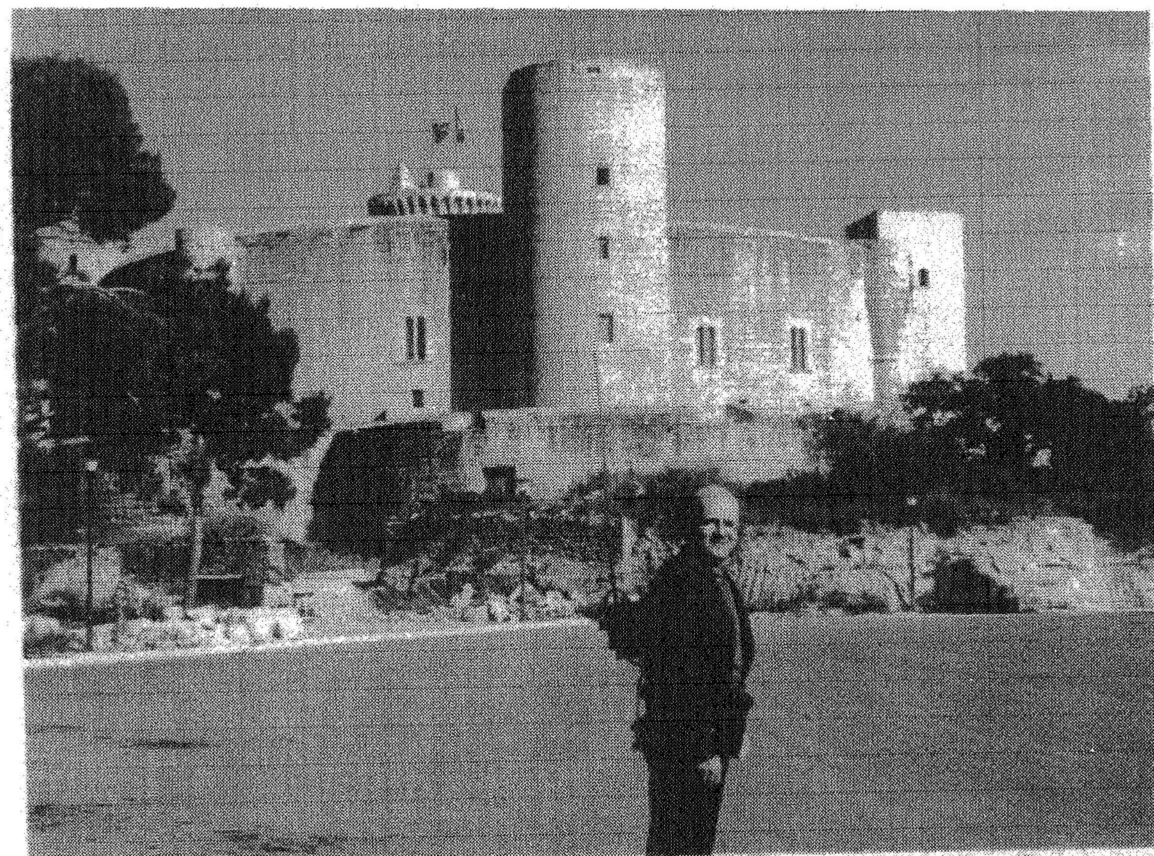

Figure 5. Back pack Loran-C receiver used in measurement program in 1973.

The salt water model for secondary phase correction was relatively simple and using the salt water curve in reference [1], algorithms for this model were programmed into several receivers. Although the secondary phase correction is directly related to physical parameters of the path of propagation, the salt water model has sometimes been accepted as a standard, and corrections over and above the salt water corrections are termed "additional secondary phase" (ASP) corrections. These "additional secondary phase" corrections have no physical significance, because it is the total secondary phase correction that is significant. The "additional secondary phase" correction cannot be derived directly from theory, but can only be deduced by differencing two separate theoretical calculations. The physical cause of the secondary phase correction is (1) the ground impedance discussed above and (2) the earth curvature. In exceedingly irregular terrain as indicated in figure 1, the earth curvature factor may become a significant contributor to the secondary phase corrections as pointed out by Johler [3].

Figure 6. Vehicle housing modern Loran-C equipment capable of measuring both direct propagation time (U) and time difference (y) for calibration purposes.

Two points relative to this secondary phase factor in irregular terrain are quite significant: (1) The spatial variations are essentially static, that is, the measurements are repeatable with time; (2) The spatial variations can be uniquely predicted using Maxwell's equations and existing propagation theory, if one is sufficiently thorough in defining the propagation path from the transmitter to the receiver. Therefore spatial variations in the Loran-C system can be calibrated or predicted.

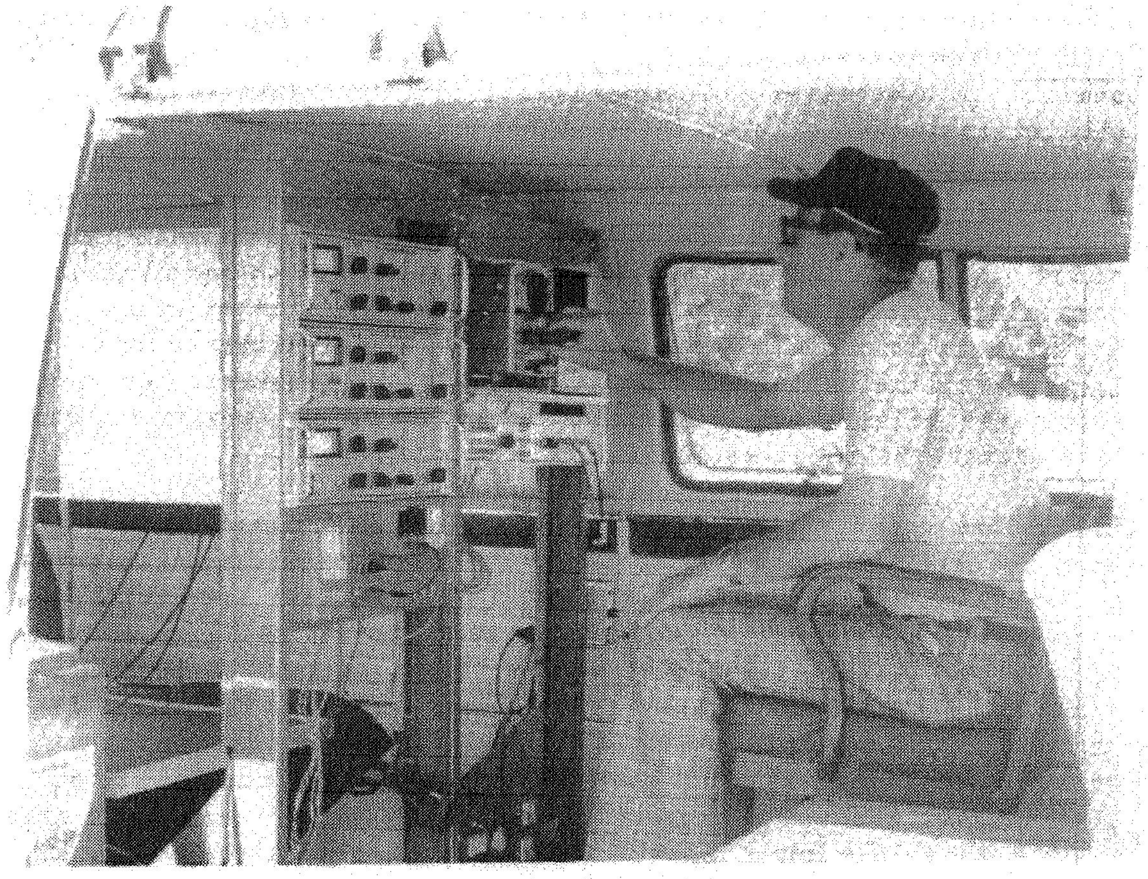

Figure 7. Close up of equipment housed in vehicle shown in figure 6.

Loran-C Applications Present and Potential

Loran-C Ground Wave Applications

Loran-C is and always has been a navigation or position fixing system, and this context always dictates its area deployment and the specific transmitter locations. These dictates, however, do not necessarily limit the use of the system for other reasons, such as timing or diagnostic propagation studies. Conversely the lack of stations, for example in western U.S. have often limited the auxiliary usage of the system. The recent U.S. decision to make Loran-C the coastal confluence navigation system should help this problem. The present and future deployment of Loran-C chains is adequately covered in a subsequent paper in this proceedings by LCDR J. F. Roeber.

The decision to employ Loran-C as the coastal confluence navigation system does not require mid continental deployment of the Loran-C system. A number of governmental and civilian agencies are potentially interested in using Loran-C in the continental U.S. There is a specific interest in using Loran-C to located non-urban or rural residences in the 1980 census; there is interest in vehicle tracking and locating by both the F.B.I. and the A.E.C.; and there is considerable interest in using Loran-C for locating off shore oil drilling platforms. There has also been considerable interest in using Loran-C or the mini loran version of Loran-C for urban vehicle tracking. This last application is most difficult because large steel structures and power and telephone lines can act as reradiators and thus destort the received signal.

In addition to the long range navigation system, Loran-C, some shorter range systems variously known as Loran-D, mini loran, augmented loran, etc. have entered the picture. All of these systems have been developed to meet specific needs in areas where Loran-C coverage is not available. The only notable change between these short range systems and the Loran-C long range system is the use of 16 rather than 8 pulses in the Loran-D system and the changing of the ground wave sampling point from 30 to 50 microseconds (3^{rd} to 5^{th} cycle). Both of these changes are possible because it is a short range system where one hop sky wave time delays are greater, and multi hop sky wave interference is less severe.

Loran-C low frequency ground wave propagation, as mentioned previously, differs from the speed of light propagation by the small correction, denoted as the secondary phase correction. For example, figure 8 shows predicted and observed variations of approximately 2 microseconds over a small change in path distance on a path where the total propagation time is approximately 1000 microseconds. The solid cruve represents predictions along a path that crosses Death Valley California. The Xs represent measurements at points that lie essentially on this path including point D that was directly below the precipitous drop into Death Valley. The ⊡ marked 1 through 9 represent measurements made along the highway that decended gradually into Death Valley. A much more complete description of the experiment is given in reference [5]. This is considered to be a severe or maximum deviation case in the navigation or timing predictability of the system. Although this variation represents only 1 part in 250 to 300 of the predicted propagation time, such a variation could develop an error of several thousand feet in a navigational fix.

This size of error, if not corrected, is unacceptable in many applications. Fortunately, the prediction ability exists, but it is not simple.

The spatial variations described above are essentially time invariant i.e. you would always return to the same place with the same measurement. As one probes further and further into the measurement capability of this system, one finds that the system is capable of measuring temporal phase changes in the ground waves [6]. These changes have been correlated with weather variations such as temperature changes, as well as the passage of frontal systems. The degree of correlation of these signals with weather phenomena suggest that measurements of the signal might be used as an adjunct to weather predictions. The temporal variations can approach one or two microseconds in the most severe case. This case is a long propagation path over land subjected to sub freezing conditions. Over shorter propagating paths, in temperate climatic regions and propagation paths over sea water temporal variations seldom exceed 0.1 or 0.2 microseconds.

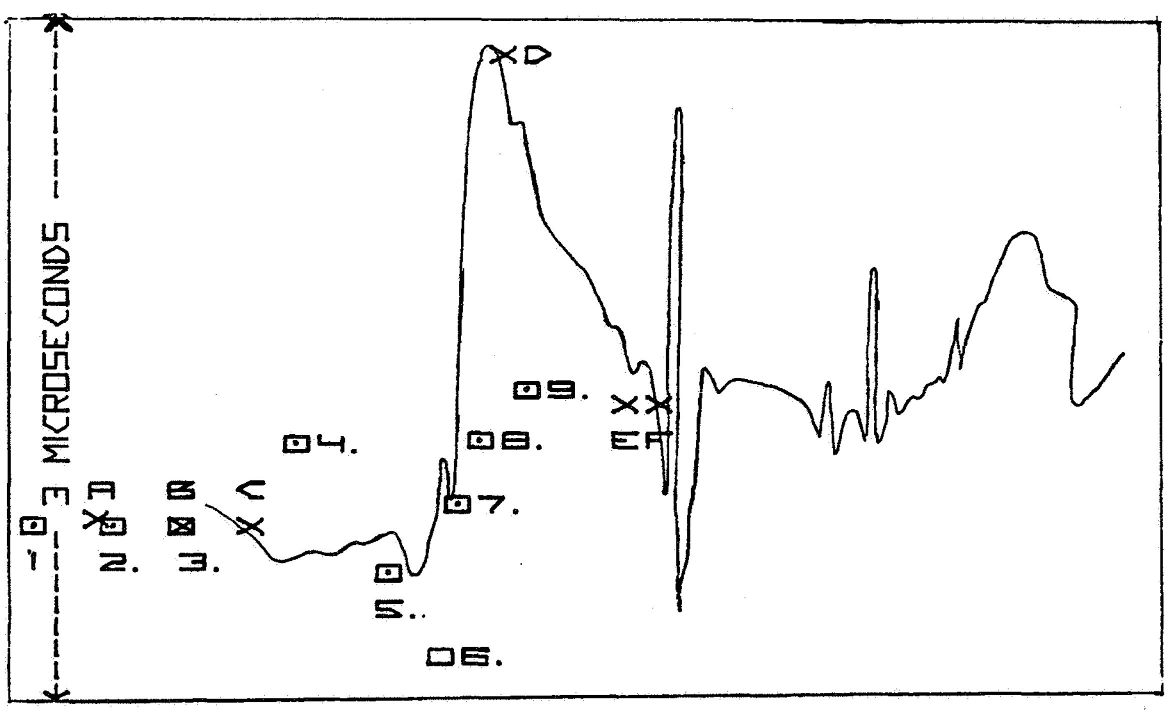

Figure 8. Predicted and observed direct propagation time (U) for a Loran-D signal in rough terrain.

One obvious method for eliminating the error caused by temporal variations over long paths is by using "differential" or relative Loran-C. In this mode of operation a station at a known control location will observe and broadcast corrections to users within the vicinity of the control station. Figure 9 and reference [7] show some initial comparisons between differential loran and differential Omega. The upper solid curve designated A shows a differential Loran-C measurement over a 10 day period where the distance between the two receivers was 300 km. The lower solid curve designated B shows measurements over the same 10 day period for receiver separation of 700 km. The standard deviations for these measurements were $\sigma_A = .08$ and $\sigma_B = .11$ microseconds. For comparison the bars representing 1.62 microseconds and 2.63 microseconds were given by Nard [8] for differential Omega. Also peak deviations for differential Omega give by Beukers [9] exceeded the scale of the graph. These measurements are explained in greater detail in reference [7]. A subsequent study [10] has shown that a U. S. Coast Guard harbor and estuary requirement for 50 feet positional accuracies could be met using a relative loran concept. Continuing studies of the same data used in the "differential" or relative Loran-C study [10] has shown that major temporal variations during summer months are due to chain variations. New data will be collected during the winter months in early 1975 for direct comparison with the summer data previously reported.

The use of loran in a relative or "differential" mode can improve position fixing capability and potentially could be used for aircraft or ocean vessel collision avoidance through retransmission of the measured TDs to other craft in the immediate vicinity. Accuracies of this order of magnitude are also potentially competitive with the extensive DME-VOR system used by commercial aircraft.

It was recognized prior to 1960 [11] that Loran-C would be capable of time synchronization of remotely separated clocks. Furthermore, if time synchronization can be established periodically, time interval measurement capability also exists. In the 1961 publication, it was suggested that synchronization capability of 1 microsecond or better could be achieved operationally using ground wave propagation. The paper also stated that operational capabilities of 10 microseconds could be achieved using sky waves. A subsequent publication [12] in 1972 reported ground wave synchronization capability with $\sigma = 0.28$ microseconds, and that initial tests by NASA suggested sky wave synchronization capabilities on the order of several microseconds were possible.

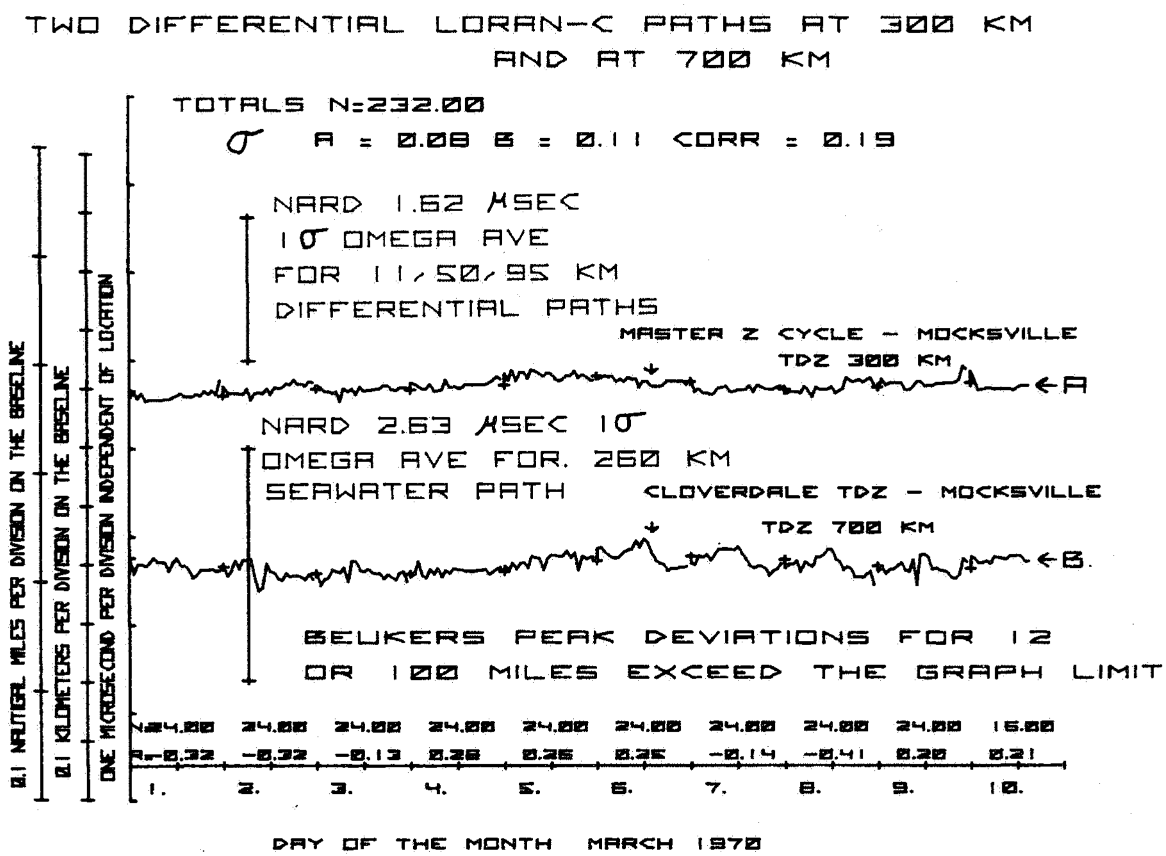

Figure 9. Differential Loran-C compared to differential Omega.

Loran-C has been used extensively for synchronizing clocks at widely separated locations where there was a need to measure a common event. Specifically, this timing capability was very important in the early space program, and in measuring the arrival time of pulses from nuclear detonations. It should be recognized that the prediction capabilities discussed earlier will be of paramount importance in a time synchronization application if the ultimate timing potential of the system is desired.

Loran-C Sky Wave Applications

Sky wave signals will always be delayed relative to ground wave signals, because they travel further in reflecting from the ionospheric

D-region as shown in figure 10. By sampling the received Loran-C pulse at a later time, it is possible to monitor a signal primarily related to a single reflection from the ionosphere. This is particularly true at ranges where the ground wave signal is weak relative to the sky wave signal. Many sky wave measurements have been made at existing Loran-C transmitting locations through the courtesy of the U. S. Coast Guard. To date these measurements have been used primarily for diagnostic purposes to validate propagation theory and for ionospheric studies.

There has been interest in using sky wave signals for both navigation and timing purposes. The limitation for sky wave use of the system has been the inability to resolve the proper cycle of the sky wave pulse. Resolving the proper cycle on the leading edge of the uncontaminated ground wave signal is possible by making a separate envelope measurement. In the sky wave case, the ground wave and sky wave mix as shown in figure 11 [13].

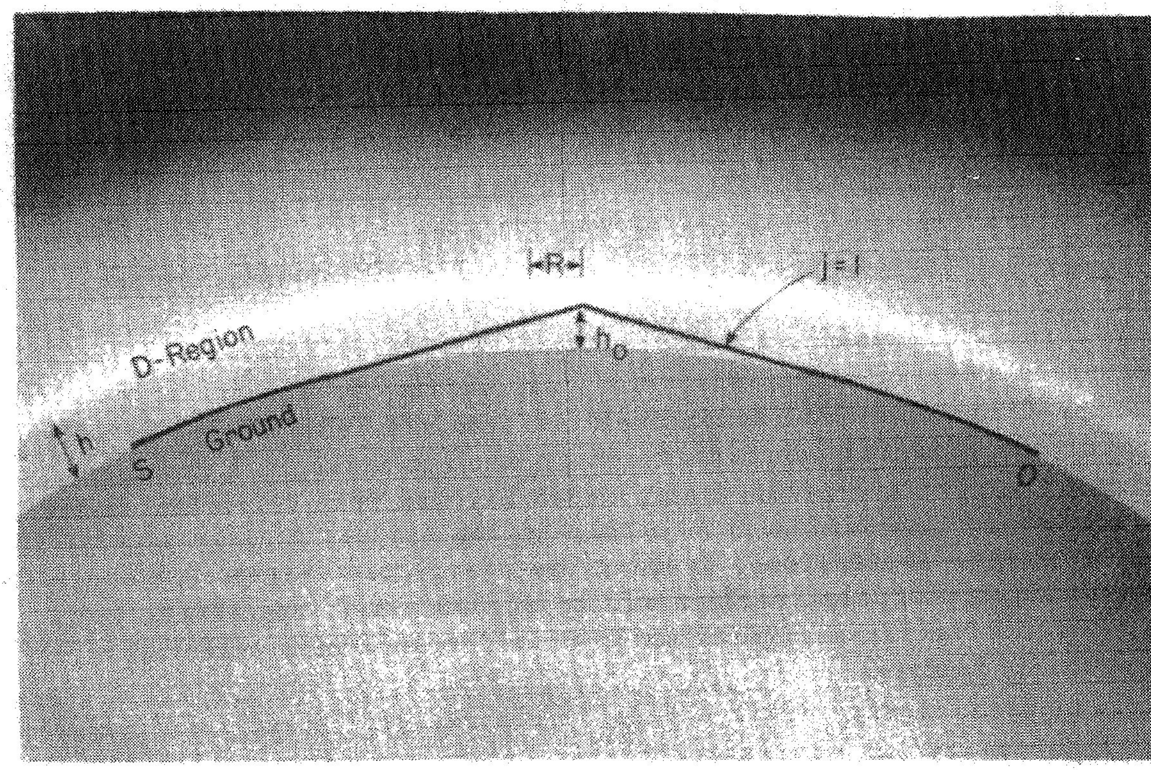

Figure 10. Pictorial display of surface wave path and D-region ionospheric propagation path.

The theoretically predicted signal in figure 11 looks quite similar to the measured signal in figure 12. An example of the diagnostic use of these sky wave signals was the interpretation of the solar eclipse measurements in figures 12 and 13 in terms of oxygen and ozone changes in the ionospheric D-region during an eclipse [14,15,16]. In references [15] and [16] many other observed phenomena on the Loran-C sky wave signals are noted and explained. Also, observations of nighttime sky waves yielded identification of particle precipitation events in the D-region at lower latitudes than had been previously suspected [17]. Continuous observations of these signals have indicated that changes in the D-region occur seasonally as well as diurnal changes shown in figure 14. Variations with geomagnetic latitude have also been noted [15].

Problems and Limitations of Loran-C

The propagation limitations on the Loran-C ground wave systems have been previously noted. By way of review, spatial variations of 1 to 3 microseconds will produce positioning errors 1,000 to 2,000 feet if not properly removed. Removal of these large errors is possible by calibration or prediction using physiographic features of the surface. Temporal variations of tenths of microseconds will produce positioning errors in the hundreds of feet if not properly removed. Temporal variations over sea water and temperate land paths will be much smaller. Removal of temporal variations can best be achieved by using differential or relative loran. It may be possible after further studies to predict temporal variations similar to the way spatial variations can be predicted now.

System or chain variations of approximately tenths of microseconds or hundreds of feet presently occur in the Loran-C chain operation. These variations could probably be reduced or removed by different chain operating procedures or by installation of new equipment. This type of variation is also removed by using differential or relative Loran-C techniques.

A Loran-C problem that will increase with increasing density of Loran-C installations is the cross rate interference problem. As can be seen from figure 14, any interference problem Loran-C has with itself will be worse at night. The cross rate interference (one Loran-C chain interfering with another) can be minimized by proper selection

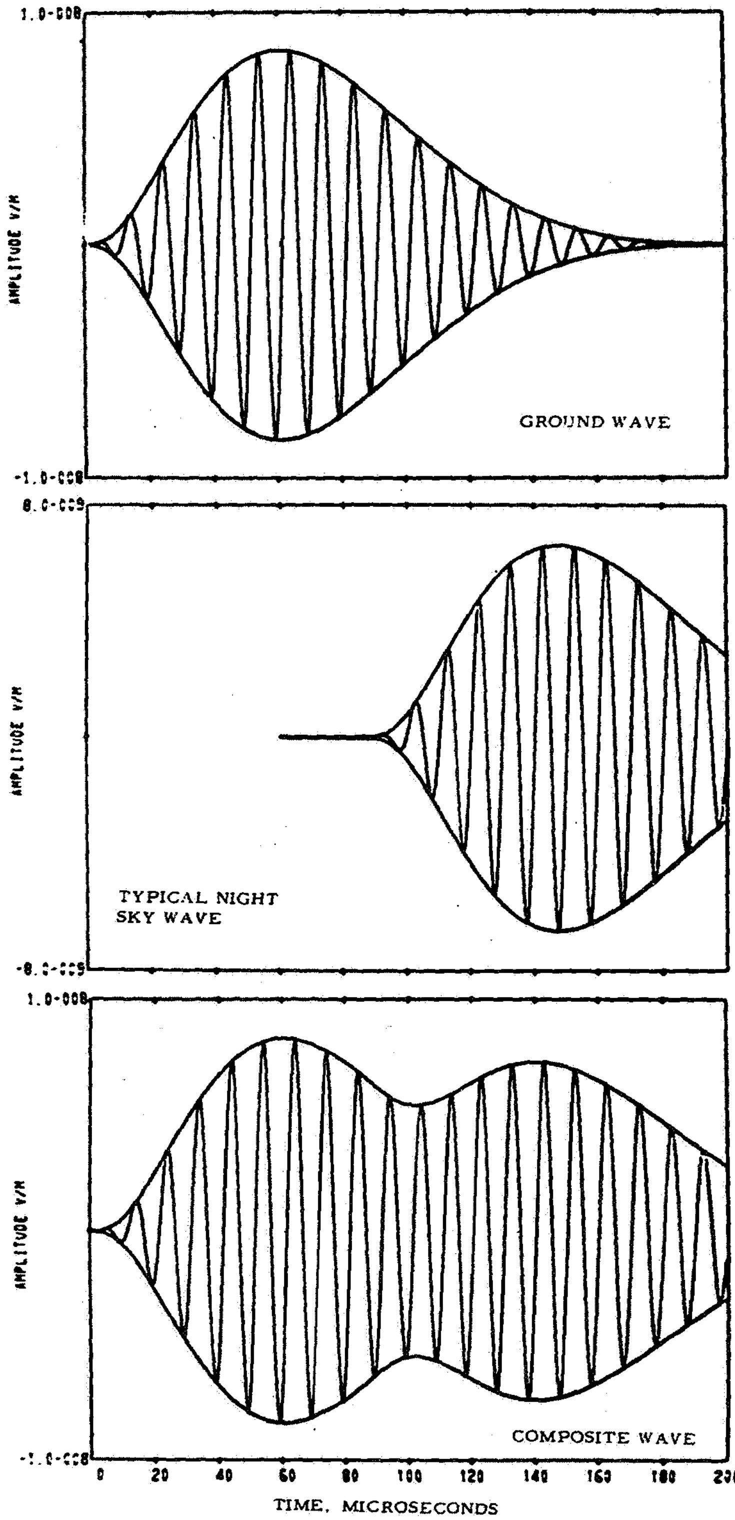

Figure 11. Theoretically predicted ground wave and sky wave pulse arrival times.

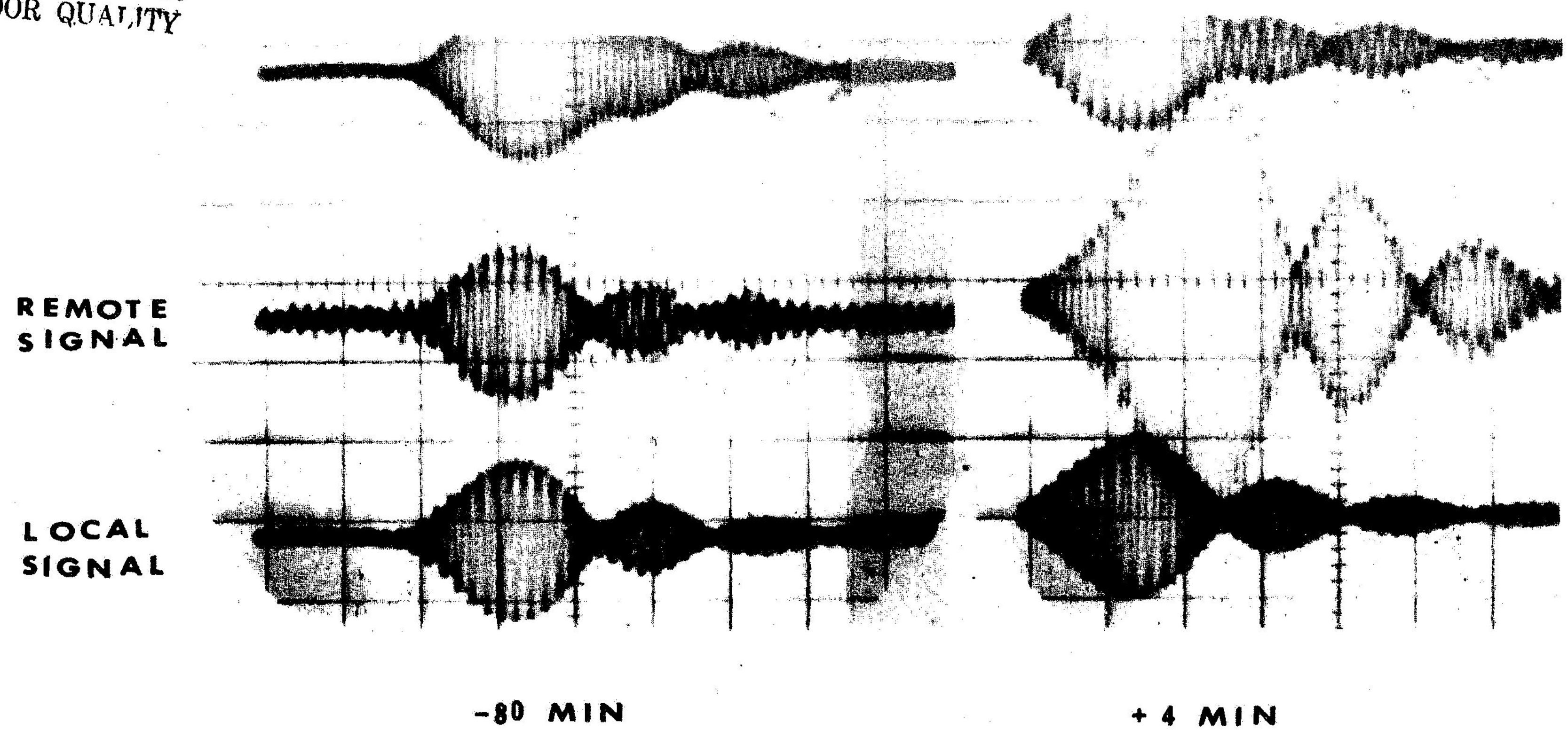

Figure 12. Observed ground wave and sky wave propagated signals during a solar eclipse.

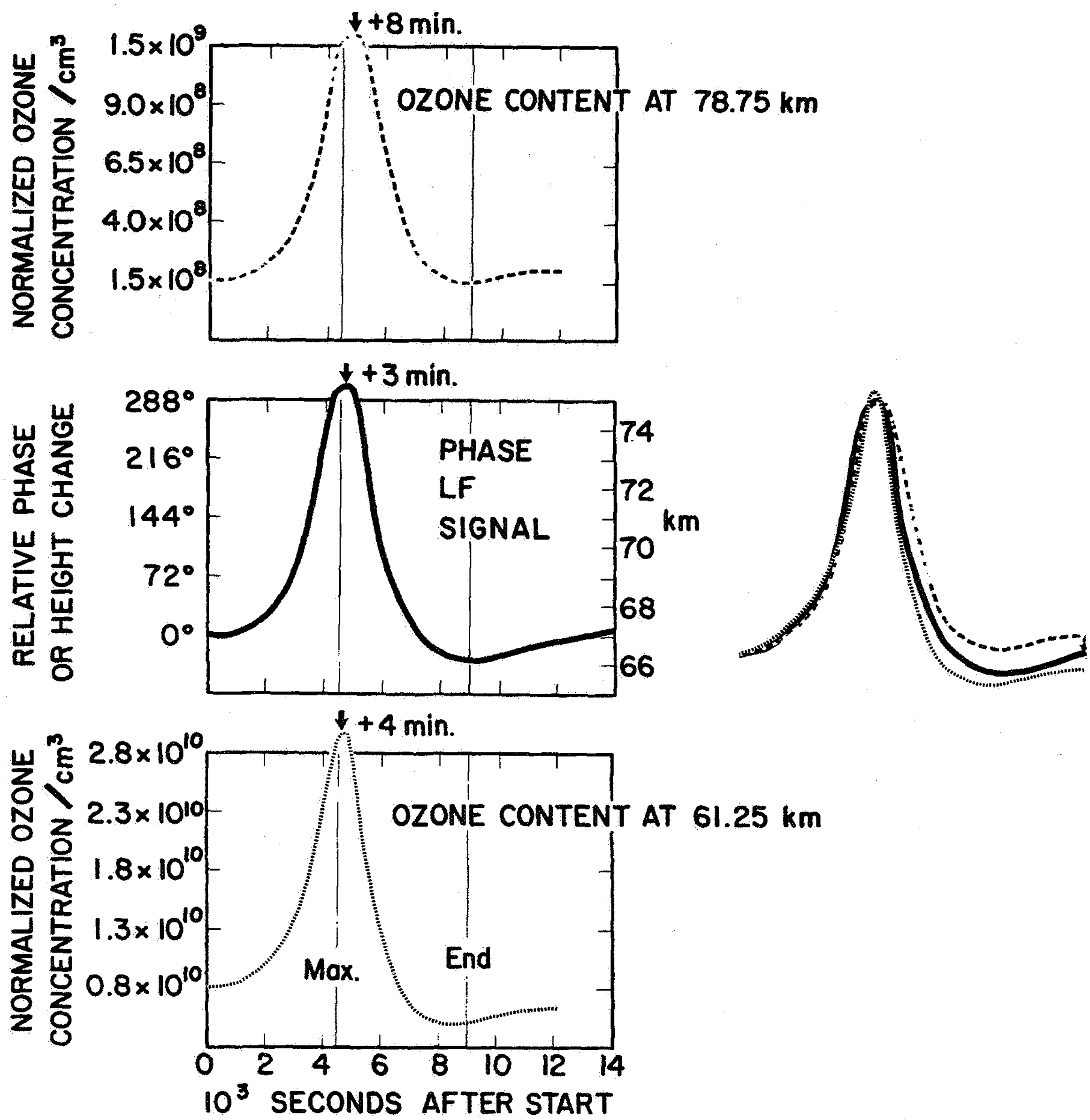

Figure 13. Relative phase measurements of a Loran-C sky wave signal compared to computed ozone changes for a solar eclipse occurring in July 1963.

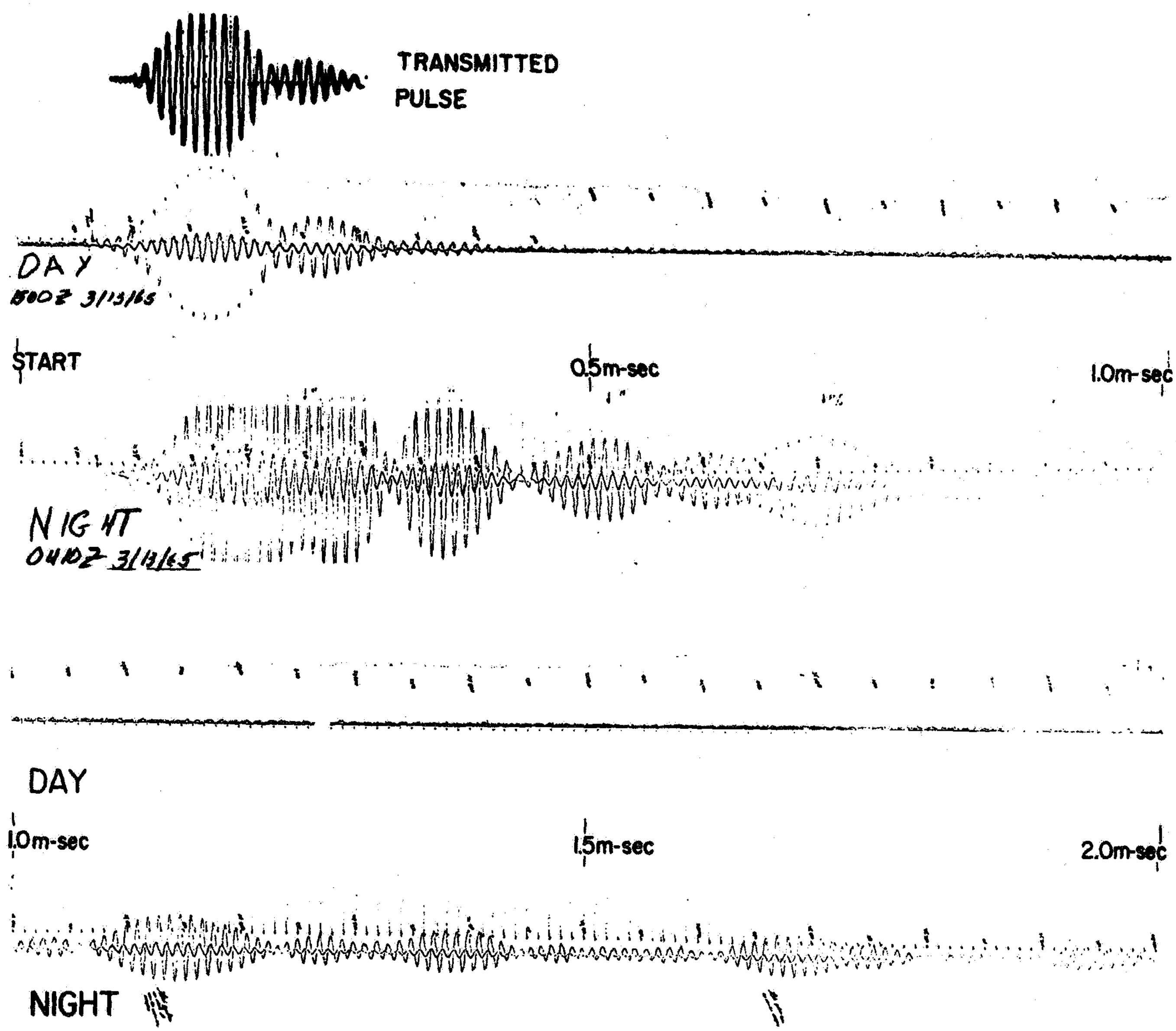

Figure 14. Multiple hop Loran-C sky waves observed at night compared to one hop sky wave observed during the day on a path from east coast to Boulder, Colorado.

of pulse repetition rates. The problem cannot be eliminated entirely by repetition rate selection, and as more chains are added more signals will be radiated, and the problem will become more severe.

Proper cycle identification is a Loran-C problem because loss of proper cycle identification is nearly always the limiting factor in establishing the usable range of the system. This problem is more a function of different receiving equipment rather than propagation conditions. Fundamentally all Loran-C receivers measure an envelope arrival time and phase or cycle arrival time. The envelope arrival time determines the coarse time and the phase or cycle arrival time gives the ultimate accuracy in units, tenths, and hundreths of microseconds. The difference between the envelope and cycle reading is denoted as the envelope to cycle "difference" or discrepancy (ECD). From this description, it can be seen that an ECD occurs for each signal and two ECDs are involved in a time difference (TD) measurement. The propagation theory predicts ECD as a function of distance from the transmitter. To the author's knowledge, no receiver manufacturer has attempted to program this ECD correction into their receivers. The theory also predicts large ECD variations in the vicinity of irregular terrain [16]. The ECD variations associated with irregular terrain are unique to each particular terrain path.

Finally, one of the most serious problems with Loran-C is the "jargon" used by the Loran-C community. It is difficult to communicate with people outside the Loran-C community when those within understand a complete set of acronyms and speak in terms of them. As a result of these problems in communications between the loran community and the non loran community, a new set of nomenclature is proposed here. This nomenclature uses subscripts freely, and letters previously unassociated with Loran-C measurements. For example, y is used to denote a time difference measurement rather than TD; u is used to denote a direct measurement of the propagation time of a Loran-C signal from a single transmitter. The propagation of Universal time through the system, which includes the baseline propagation time and the coding delay for the slaves, is designated by U. Formerly this measurement was called TOA to stand for time of arrival. For the ECD (envelope to cycle difference) described above, the Greek symbol Γ was selected. The envelope propagation time correction is designated by T_c and the cycle or phase propagation time secondary phase correction by t_c, such that $\Gamma = T_c - t_c$. The secondary phase correction is denoted t_c and time delays associated with receivers are denoted R. A subscripting system $y_{i,j}$, $U_{i,j}$, $\Gamma_{i,j}$ etc is used to refer to locations i and j, such that φ_i, λ_i, or φ_j, λ_j are the latitude and longitude of these locations. In all cases, the i refers to a transmitter location, $i = 0$ is used for the master transmitter, $i = 1$ for the slave with the lowest coding delay (formerly called slave A, slave X, or slave W), $i = 2$ for the slave with the second lowest coding delay, etc. In all cases the j stands for the receiver location φ_j, λ_j. If the j subscript for a particular measurement is 4 or less, then the receiver is located at a transmitting site. The j subscript may become as large as necessary to describe a given set of Loran-C measurements. Since the time difference measurements always involve the slave arrival time minus the master arrival time, there will be no y values with an i subscript of 0.

The East Coast Loran-C chain will be used as an example to demonstrate how this system works. For the master at Carolina Beach, $i = 0$,; for the Z slave (4th slave in the East Coast chain) at Dana, Indiana, $i = 4$. For an arbitrary location where $j = 7$, the arrival time of the master signal will be $U_{0,7} = \eta / c(d_{0,7}) + t_c(d_{0,7}) + R_7$, and the arrival time of the Dana slave signal will be $U_{4,7} = \eta / c(d_{4,7}) + t_c(d_{4,7}) + R_7 + \beta_4$, where d stands for distance, η for the surface index of refraction, c for the speed of light in a vacuum, and β_4 for the coding delay associated with the no 4 slave, Dana, plus the propagation time from the Master to the Dana slave. Following this, the time difference will be simply $y_{4,7} = U_{4,7} - U_{0,7}$. At the master station the direct phase measurement of the Dana slave signal would be $U_{4,0}$, and the time difference would be $y_{4,0}$. At the Dana slave the direct phase measurement of the master would be $U_{0,4}$ and the time difference would be $y_{4,4}$. The Γ's at these sites would have the same subscripting as the U's and they would relate to the envelope measurement or prediction minus the phase measurement or prediction [16]. This same nomenclature has been expanded to include the differential Loran-C measurements and their associated time constants.

CONCLUSIONS

It would appear, in view of the great user interest and recent government wide decisions, that Loran-C will remain a viable and useful system for the forseeable future. At the present time it would appear that Loran-C is one of the better long range timing and time interval standards available for general use. Loran-C still has a considerable unexploited potential in differential usage, such as collision avoidance and high precision position fixing. Loran-C has been very useful for validating low frequency propagation theory for both ground wave and sky waves. It has also been useful as a diagnostic tool for probing the ionospheric D-region to better evaluate its characteristics. This particular usage of the Loran-C system could be exploited and extended much further.

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