Library of Congress Catalog Card Number: 72-600267

National Bureau of Standards Monograph 129

Nat. Bur. Stand. (U.S.), Monogr. 129, 157 pages (Oct. 1972)
CODEN: NBSMA6

For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402
(Order by SD Catalog No. C13.44:129). Price $4.50.
Stock Number 0303-01060

The Development of Loran-C Navigation and Timing

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Issued October 1972

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ABSTRACT

The Loran-C timing and navigation concept and its implementation in the form of the Loran-C system has taken on considerable importance in a variety of military and civilian applications such as microsecond clock synchronization, precision tactical or civil navigation, etc. Future applications like tying together continental surveys, aircraft collision avoidance, etc., have yet to be explored in detail. This work traces the development of the Loran-C concept from its inception as a 100-kHz pulse hyperbolic navigation system to more recent times when it found a variety of applications to both timing and navigation. This work is intended to present the story of Loran-C in a readable and understandable way without resorting to the complicated mathematical formulation of the theory or detailed instrumentation aspects. Thus, the history, experimental and theoretical developments, political decisions, and field testing of the early equipment are described and the lessons learned can certainly be a guide for modern development of the system in all its detailed applications.

Key words: Cyclan; Cytac; Loran; Loran-C; low frequency, navigation; pulse propagation; radio positioning; time dissemination; time transfer system.

FOREWORD

This document was written while the author was associated with the Institute for Telecommunication Sciences, Office of Telecommunications, Department of Commerce. To the extent that the author is describing his own work and that of his associates, he is referring to work done within the National Bureau of Standards, Department of Commerce, prior to the formation of the Office of Telecommunications. Since the preparation of the text was supported by the Office of Telecommunications, it was submitted for publication within that organization under the title, "The Development of Loran-C". The consensus of reviewers and Office of Telecommuniations administrators was that it would be more appropriate for the book to be published by the National Bureau of Standards, the organization responsible for the contributions to Loran-C.

Bob Doherty of the Office of Telecommunications approached me with the suggestion that NBS should complete the work on the manuscript within the framework of a contract to provide information on time and frequency subject to the Air Force Communications Service. In view of the present extreme interest in the clock synchronization capabilities of Loran-C, it was obvious that the document would be a valuable output of the project. Portions of the section on Loran-C timing were expanded, but otherwise the author's comments and opinions are presented in their original form.

A further word needs to be said about Bob Doherty, for without his efforts it is doubtful that this volume would ever have reached publication. Bob has been deeply involved in the propagation aspects of Loran-C since the Cytac field tests in 1954, and has made valuable contributions in that regard. Since Mr. Hefley's retirement, Bob has coordinated efforts to bring this book to a state of readiness for publication, including working with reviewers. Ralph Johler of the Office of Telecommunications acted as the principal reviewer of the manuscript.

Work in the last stages of completion of the manuscript was conducted under the sponsorship of the Directorate of Communications Engineering, COMSEC/Data Systems Division, Air Force Communications Service.

L. E. Gatterer,
National Bureau of Standards
June 2, 1972

Loran-C development is traced from its inception to present day Loran-C (a 100-kHz pulse hyperbolic navigation system). This writing describes the system development and many of the propagation findings in a very readable and understandable way. This should be of great value to those not concerned with complex propagation theory, detailed mathematical formulations, or involved instrumentation aspects. Propagation research necessary to further improve the system is also outlined in the text.

Although I have not been involved with the historical evolution of this system nearly as long as the author, I have been closely related to propagation aspects of Loran-C since the Cytac field tests in 1954. It was interesting to read about the history, experimental and scientific inputs, and political decisions that influenced the development before that time. For the period following the 1954 field tests, reading the book was like reliving many interesting experiences. Equipment descriptions contained herein are primarily for historical background and consequently do not cover recent equipment developments in the late 60's and early 70's.

Robert H. Doherty
Office of Telecommunications
July 1, 1971

PREFACE

Present-day loran, more precisely, Loran-C*, is the result of more than 25 years of system development. The need for a long-range, high-accuracy radio navigation system was critical from the beginning of WWII. Conventional methods of navigation at that time were virtually useless for convoys and aircraft on anti-submarine patrol in the North Atlantic during fog and foul weather.

The first and most widely known loran system used the frequency band just below 2 MHz. For all practical purposes, the first system was useful over sea water only due to the high rate of attenuation of the 2-MHz signal over land. At that time, however, the pressing need was for navigation at sea and the system satisfied that need very well. For many years it was called "Standard Loran" but is now designated "Loran-A".

A comprehensive treatment of the loran development up to the end of WWII is given by Pierce, McKenzie and Woodward in "Radiation Laboratory Series", vol. 2, published in 1948. A condensed account of the wartime system development and some of the postwar refinements is given by Sandretto in his book, "Electronic Avigation Engineering", published in 1958.

The merit of the wartime system is evidenced by the fact that it is still in service in many areas. Of course numerous improvements have been made but the system we know today as Loran-A is, in all major respects, identical to the one which was first flight-tested in 1942. By the end of WWII, over 70 transmitting stations were in operation providing navigational coverage over nearly one-third of the earth's surface. Approximately 75,000 receiving equipments had been built and delivered by several manufacturers, and the Hydrographic Office had prepared 2.25 million loran charts.

* The term Loran-C has several different established usage forms (Loran-C, Loran C, loran C, LORAN C, LORAN C, LORAN-C, etc.) but the form used in this publication adheres to that classically used by the U.S. Coast Guard. This was done since the the Coast Guard originated the terms Loran-A, Loran-B, Loran-C, Loran-D, etc., in contrast to the term loran which was an acronym standing for long range navigation. The term loran is designated entirely in lower case by established procedure similar to the common usage of the similar acronym radar. In keeping with the Coast Guard policy, all other specifically named systems (i.e., Cytac, Cyclan, LF Loran, etc.) the first letter of the name is capitalized.

Toward the end of WWII, military requirements demanded navigational coverage over land and at greater ranges than previously required. Those requirements were not satisfied until long after the cessation of hostilities but, broadly speaking, those requirements initiated a series of developments which finally produced Loran-C, a 100-kHz pulse navigation system.

Loran, as most readers know, is a pulsed hyperbolic system. Its most distinguishing feature is that by use of pulses, the groundwave and skywave components can be separated at the receiver. High accuracy is achieved since phase interference caused by mixing of the different modes of propagation in the media does not occur.

The short pulses require considerable bandwidth, but, by the use of timesharing techniques, a great number of transmitters can operate at the same frequency. Consequently, considered from the standpoint of coverage area per unit of spectral width required, the loran systems make efficient use of the spectrum.

During WWII there were no technical problems in transmitting and receiving pulses of about 40 μs duration at 2 MHz and the necessary spectrum was available. Pulses of that duration were short enough to clearly resolve the desirable stable groundwave from the more variable first-hop skywave. When the need for overland coverage arose, the only choice for obtaining similarly stable propagation was to use a very much lower frequency to avoid the high rate of groundwave attenuation with distance. But short pulses and low frequencies tend to be incompatible and finding a satisfactory solution to the problems dictated by these conflicting requirements was no simple matter.

Several writers have published reports on loran and related subjects. Many of these reports treat specific topics in depth. The intent in this publication is to relate in chronological sequency the author's view of the significant aspects of the various developments and test programs which have resulted in Loran-C. While Loran-C is a very practical and workable system, it would be misleading to imply that all the problems involved in its operation have been solved. A great deal more groundwave propagation research is needed to improve the predictability of the system coordinates and to define the range of temporal variations. Proper cycle identification near maximum range has always been the weakest measurement in the system. Improvements in this area could extend the range and usefulness of the system.

THE DEVELOPMENT OF LORAN-C NAVIGATION AND TIMING

Gifford Hefley*

1. INTRODUCTION

The loran and loran-type (pulse) systems are in the broad category of hyperbolic radio navigation systems. There are also several CW hyperbolic systems. All are based on the principle of transmitting synchronized signals from two or more pairs of stations but at present, only Loran-C provides both high accuracy and relatively long range. Hyperbolas (geometric) are lines defined by the loci of points having a constant difference in distance from the pairs of stations. Similarly, hyperbolic (radio) lines of position are defined by the loci of points at which the difference in arrival time of the synchronized signals is constant.

The hyperbolas generated by two pairs of stations form a grid. The position of an observer can, therefore, be established by making two time-difference measurements. Since the hyperbolic lines extend outward on either side of a station pair, lines associated with two pairs of stations will cross on both sides of the station pairs. Therefore, two locations will usually exist which satisfy the measurements, but any ambiguity is of little or no practical concern because the locations are so widely separated. A location or fix determined by three independent time-difference measurements is unambiguous.

The radio hyperbolas differ somewhat, but importantly, from the geometric hyperbolas. The velocity of radio waves is influenced by the physical characteristics of the propagation media. Consequently, the radio hyperbolas are distorted if the propagation paths are dissimilar. To a good approximation, sea-water paths may be considered to be identical for groundwave propagation but land paths, or mixed paths, differ widely. If all the parameters are known accurately, the hyperbolic grid can be computed rather precisely, but such is rarely the case. When land is involved in the propagation paths, the computed grid must be adjusted or corrected by making appropriate calibration measurements if maximum accuracy is to be derived from the system due to lack of prior knowledge of the velocity of propagation.

The radio hyperbolic grid is often printed as an overlay on conventional navigation charts. Such charts are suitable for most purposes and especially for air navigation. For surface navigation, when maximum accuracy is desired, and for calibration, tables of the system coordinates are used. The hyperbolic coordinates are tabulated at intervals of latitude and longitude which are suitable for linear interpolation. The tables are rather voluminous but are easy to use at surface-vessel speeds because there is ample time to plot fixes in the conventional manner. In some specialized applications, especially where high speed is involved, Loran-C and Loran-D are used in conjunction with computers to relate the system coordinates to geographic position. With the advent of space technology and low-cost computers, this approach is becoming common.

The loran-pulsed systems differ from other hyperbolic systems, particularly from the CW systems, in many ways. Two major and important differences are that loran operates in the time domain while the other systems operate in the frequency domain and do

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not resolve the propagation time modes. A wide bandwidth is mandatory to separate the groundwave from the skywaves. Pulse modulation has proved to be the most feasible method of achieving that separation. By using pulses, a large number of transmitters timeshare the same frequency interval within the spectrum. In contrast, CW transmitters must use different frequencies. Even with no modulation, a small but finite spectrum interval is required to avoid interference between adjacent frequency assignments. The total spectrum requirement for high-power transmitters tends to be proportional to the number of transmitters. Low-power CW transmitters for short-range coverage (Decca* system for example) can operate on the same frequencies provided the individual systems are separated by great distances. But the shorter the range, the greater the number of transmitters that must be used to provide coverage for a specified area.

A few of the generalized comparisons between the pulse and CW systems are listed below:

1. The loran systems, especially Loran-C, provide greater accuracy to the limit of their groundwave range than CW systems whenever skywave signals are present.
2. CW systems (Omega* for example) at VLF, can provide much greater range than Loran-C groundwaves. Available data are insufficient to compare Loran-C skywave performance with the performance of a VLF CW system.
3. Any comparison of the spectrum requirements of loran C and CW systems tends to be misleading because of the inherent differences in range and accuracy characteristics of the systems.
4. The pulse characteristics needed in loran dictate the spectrum requirement. Efficiency of the spectrum usage depends primarily on the number of stations operating and the corresponding coverage area.

To synchronize the transmission from two or more loran stations, one functions in the capacity of a MASTER while the others operate as SLAVES. Originally, the master was freerunning and the slaves servoed their frequency to the master. Normally the slaves are now controlled by atomic standards so all stations can free run. The signals transmitted by the slaves are identical to those of the master but are maintained in a constant time relationship relative to the master signals. In loran-A, the pulse envelope only is used. In Loran-C and Loran-D, the pulse envelope and the carrier phase are maintained in constant relationship with the master signals and are used at the receiver to obtain measurements to a small fraction of one cycle.

The technique of accomplishing the synchronization is as follows:

1. The master signal is received at the slave.
2. A very precisely generated time interval of arbitrary length is initiated upon reception of the master signal.
3. At the end of the interval the slave signal is transmitted. The time interval is called the "Coding Delay".*
4. The actual time of transmission of the slave signal is controlled to maintain relationship with the master signal either through servo control or with atomic standards.

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* See Glossary.

By transmitting the master and slave signals sequentially rather than simultaneously, and selecting the proper coding delays at the slaves, the master signal always arrives first regardless of the location of the receiver. In that way, possible ambiguities are avoided.

The different pairs of chains of stations are identified by transmitting the pulses at different repetition rates (see sec. 7). Each pair of Loran-A stations uses a different repetition rate. The Loran-C and Loran-D stations, however, use a slightly different scheme. In each chain, the master and two or three slaves, which form two or three pairs of stations, all transmit on the *same* repetition rate. In the latter case, the coding delays of the slaves are chosen so that all the signals from the chain arrive at any location in the same sequence. Correspondingly, the pulse-repetition period is chosen so as to be commensurate with the transmission times from the master to the slaves plus all the coding delays.

The choice of sites for transmitters for any long-range system is determined primarily by geographic and political considerations in relationship to the areas where navigational coverage is desired. Because of the range of Loran-C, there is a relatively wide choice of sites for that system, but due to geographical constraints alone, ideal transmitter configurations are in some cases virtually impossible. The most efficient configuration is to locate transmitters on the corners of a square, but, in actual situations, shorelines and islands usually provide the most practical sites for the areas where navigational coverage is desired.

The accuracy of Loran-C or any hyperbolic system cannot be described by a single number because of the geometric considerations in the navigation grid. The accuracy with which a time difference can be measured of course, deteriorates somewhat with adverse signal-to-noise ratios. More importantly, the spacing increases between the hyperbolic lines of position with increasing distance away from the transmitters due to geometry. At the same time, with most station configurations, the angle of intersection between lines of position decreases. Toward maximum range, the fix accuracy of Loran-C is determined mainly by geometric factors not by the small loss of precision in the time-difference measurements. Several examples are given in section 5.

The merits of all electronic systems must be viewed and weighed against their shortcomings. Loran-C, on the credit side, provides better accuracy (tens of meters) at greater ranges (1000 to 2000 km) than any other radio navigation or timing system yet developed. It also can and does provide coverage over a substantial fraction of the earth's surface at the expense of only 20 kHz of the radio spectrum. On the noncredit side, the useful range of the groundwave signal at 100 kHz which practical transmitters can radiate virtually excludes some areas of the world from prime coverage.

Loran-C is not the ultimate fulfillment of all navigational needs, but neither is any other system. Detailed information on loran equipment is most readily available from the principal manufacturers, Sperry, ITT, Collins, and more recently, Liftcom, Teledyne, Epsco, and Decca. Inquiries on loran operation, the availability of charts and tables and timing should be addressed to the Department of Transportation, U.S. Coast Guard. Questions on timing may also be addressed to the U.S. Naval Observatory. Questions relating to the propagation of loran signals should be addressed to the Institute for Telecommunication Sciences of the Office of Telecommunications in the Department of Commerce.

The above sources of information are given because several of the documents listed in the References and Bibliography have not been published in the open literature and are not conveniently available, if at all.

2. EARLY DEVELOPMENT OF LORAN AND GEE

Some of the highlights of the wartime loran developments described by Pierce, et al.(1948), are summarized here.

The first known practical application of position finding with a hyperbolic system was in WWI when enemy guns were located by measuring the difference in arrival time of the sound reports at three listening posts. In that case, the listening posts defined the foci of the hyperbolas while in a loran system the transmitters define the foci.

The possibility of devising a pulsed radio navigation system was foreseen by Alfred L. Loomis of the Microwave Committee and was formally proposed by him in October 1940. The Microwave Committee was a group composed of representatives from the Massachusetts Institute of Technology (MIT), government and industry who were concerned with military radio applications. The proposal was accepted, and the system concept gained momentum rapidly. By early spring of 1941, a small fulltime group headed by Melville Eastham at the MIT Radiation Laboratory had been formed to pursue the development of a system which later became known as loran.

An interesting coincidence is that the same system possibility was also foreseen by Robert J. Dippy in Britain and that an almost identical development effort was underway there at the same time under his direction. The British system was called "Gee".

From the summer of 1942 on, the two developments were very closely coordinated. The principles of the two systems were essentially identical, but the intended applications were quite different. Consequently, there were many differences in detail, the greatest of which were frequency and baseline length.

Gee had the purpose of providing accurate navigation to a distance of about 300 mi for high-flying aircraft on bombing missions over the European mainland. Gee did not have the requirement to provide coverage on or near the surface at long range and, therefore, did not require a long baseline. In contrast, the objective of loran was to supply navigation coverage to as great a distance as possible for surface vessels and low-flying aircraft on antisubmarine patrol. In view of these different system requirements, line-of-sight frequencies in the HF and VHF bands were ideal for Gee because short pulses (6 μs) could be transmitted easily and it was easy to change frequency to avoid enemy jamming. On the other hand, surface coverage dictated a much lower frequency for loran. The band which was chosen just below 2 MHz was not necessarily optimum, but it was available, and it did provide substantial groundwave range over sea water. Initially, overland coverage by loran was not considered to be important.

The development of the loran transmitting, synchronizing and receiving equipment proceeded smoothly. The first transmitters were designed for 100-kW peak pulse power and by June 1942, had been installed at Montauk Point, Long Island, New York, and Fenwick Island, Delaware, for initial system testing. The two stations, of course, provided only one set of position lines (hyperbolas), but by checking the stability of the lines it was possible to estimate how the entire system would work. During the same month a receiver was flown on a Navy blimp from Lakehurst, New Jersey, and shortly thereafter, another receiver was installed aboard the U.S.S. Manasquan for extended long-range observations.

The results of these tests were so encouraging that the Army and the Navy took immediate action to install the loran system in the northwest Atlantic from Fenwick Island to Cape Farewell, Greenland. By the fall of 1943, the loran transmitters or chains had been extended to Iceland, the Faroes, and the Hebrides. Other chains in the United States and in the Pacific were in various stages of planning and installation. Expansion of the system continued on an accelerated scale until the end of the war.

As early as the summer of 1942, it was seen that many aircraft would need both the loran and Gee systems but usually not at the same time. Loran would be needed for flying across the North Atlantic , and Gee would be needed after the aircraft arrived in Britain. Accordingly, the loran receivers were made physically interchangeable with the Gee receivers and were designed in such a way that they could be operated directly from the electrical systems in both British and American aircraft.

Loran and Gee, however, did not furnish all the navigation facility that was needed in the European theater of operations. The nighttime skywave loran signals could be received at distances great enough to reach deep into Europe , but the spacing and crossing angles of the hyperbolic lines of position were not satisfactory for a good fix accuracy. A means of overcoming the difficulty was proposed by J. A. Pierce. Having observed the stability of the first-hop skywave (E layer reflection), he suggested using that mode of propagation to synchronize the transmitters. While the skywave could be used only at night, the baselines could be increased to about 1400 miles, and the system could be used overland. The longer baselines would greatly improve the geometry of the loran grid in the areas where coverage was needed.

In the spring of 1943, Pierce assumed leadership of the Loran Operational Research Group. This group was primarily concerned with skywave propagation of the loran signals. In April 1943, Pierce and others carried out the experiment of having the Fenwick Island station synchronize on the first-hop skywave signal from Bona Vista, Newfoundland, 1100 nmi distant. This simple test showed a probable error in the line of position of only 0.5 nmi.

In the early fall of the same year, more extensive skywave-synchronized loran (SS Loran) testing was accomplished. Transmitters were installed at Gooseberry Falls, Minnesota, and Key West, Florida, to form pairs with the East Brewster, Massachusetts, Montauk Point stations, respectively. The long east-west and north-south baselines provided a grid having favorable geometry over a large part of the eastern half of the country. Army (AAF), Navy, and RAF planes navigating only by SS Loran made exhaustive accuracy tests. The average error of hundreds of navigational fixes was between 1 and 2 miles over the entire service area.

The AAF, the Navy, and the RAF all concurred that the skywave-synchronized system had great operational value. The system was installed as quickly as possible in the European theater. Its first operational use was in October 1944.

Both groundwave-synchronized loran (generally called Standard Loran) and SS Loran were used extensively in the Pacific. Owing to the vast ocean expanses and the fact that so many islands and land areas were occupied by the enemy, the installation of loran in the Pacific occurred under quite different circumstances than prevailed in the North Atlantic. In general, however, installations were made as soon as possible. Air-transportable transmitters had been developed mainly for use in the Pacific. Without them, installations could have been much slower and more difficult.

Loran was very useful in the Pacific, but it would not satisfy some very important navational requirements.

A system having longer range and longer baselines was needed to provide coverage in the vicinity of Japan and on to China. Also, 24-hour overland coverage was especially needed in Southeast Asia for our transport aircraft flying the "Hump" route. These requirements brought about a reconsideration of the frequency that should be used.

It was evident that a much lower frequency would have to be used to reduce the groundwave attenuation rate overland. But changing to a low frequency would not be a simple matter. In the original concept of the system it was generally thought that 1 MHz would be about the lowest frequency which would be suitable for pulse transmissions of this type. To obtain efficient radiation at low frequencies would require large costly antennas and so much bandwidth would be required to transmit pulses short enough to separate the groundwave from the skywave that a serious interference problem would result. The short pulses would further complicate the antenna problem because the antenna would have to have a low "Q" for the pulses to rise rapidly. A low Q would require more radiation resistance and hence, a still larger and more costly structure. Compromise was inevitable.

It was considered impractical at low frequencies to attempt to transmit short pulses similar to those used at 2 MHz. Instead, it was decided to increase the pulse length to around 300 μs, which would require a bandwidth of only 8 to 10 kHz, and to lower the carrier frequency to the LF band. The longer pulse and narrower bandwidth would combine the groundwaves and skywaves into a composite pulse instead of separating them. The hope was that the composite pulses could be matched in the same way as practiced with standard loran.

Logically enough, the low frequency version of the system was called LF Loran. As soon as the basic design considerations had been determined, the Radiation Laboratory, on virtually an emergency basis, undertook to build an experimental low frequency system. Transmission tests were started in August 1944 on 170 kHz. The frequency was later changed to 180 kHz. Standard loran transmitter components were used or modified wherever possible to minimize the amount of new design work and construction. For receiving, simple converters were built which could be used with the standard loran receivers. By the spring of 1945, the new system was ready for testing.

3. LOW-FREQUENCY LORAN, CYCLAN AND WHYN

In early 1945 the need for longer-range radio navigation facilities in the western Pacific and Southeast Asia was becoming increasingly urgent. Testing the new LF Loran system proceeded with a remarkable degree of speed and efficiency.

Immediately upon completion, the experimental transmitters were installed at sites near Key Largo, Florida, Cape Fear, North Carolina, and Brewster, Massachusetts, in order to test the system before putting it into operational use. These tests were quite comparable to the tests that were made with SS Loran before it was used operationally. The low-frequency tests, however, were even more comprehensive and involved a special antenna problem. Conventional tower antennas, tall enough to provide efficient radiation at 180 kHz, were not available, and to construct such antennas would have taken a great deal of time. As a time- and money-saving expedient, barrage balloons were used to support 1300-ft wire antennas.

A well-organized monitoring and system-evaluation program, headed by key members of the Operational Research Staff (ORS) and the Communications Liaison Branch of the Office of the Chief Signal Officer (Operational Research Staff, 1946), was in motion when the transmitters came on the air in April 1945.

The purpose of the test program was to determine the technical characteristics of the system in sufficient detail to predict the performance of any similar system installed elsewhere in a different configuration. It was equally the purpose of the program to develop methods to determine the merits of any proposed LF Loran system relative to other navigation systems.

The operation of the transmitters was supervised by the Radiation Laboratory. Most of the monitoring and data collection was done by the Signal Corps personnel. Some monitoring at several widely separated points, however, was also done by the Radiation Laboratory. Figure 3.1 shows the transmitter locations, the principal monitoring sites, and test-flight routes.

The Cape Fear station served as a double master to provide two pairs of stations. In contrast to typical standard loran pairs , which would normally use different specific rates. both LF pairs were operated on the same repetition rate. With all the pulses synchronized, the two slaves could also be used as a pair to provide a third line of position. Any one of the three available time differences obviously could be derived from the other two, but they could all be measured separately.

In figure 3.2, the transmission time is indicated by T + t (T is the primary transmission time and t is the secondary-phase correction) with subscripts to identify the different propagation paths. Random variations in transmission time are represented by a,b,c,d, and e. If there were no measurement error, the time difference (TD) at the receiver would be:

$$TD_y = T_{my} + t_{my} + a + T_{yr} + t_{yr} + b - [T_{mr} + t_{mr} + c] \, , \tag{1}$$

$$TD_x = T_{mx} + t_{mx} + e + T_{xr} + t_{xr} + d - [T_{mr} + t_{mr} + c] \, , \tag{2}$$

$$TD_{yx} = T_{my} + t_{my} + a + T_{yr} + t_{yr} + b - [T_{mx} + t_{mx} + e + T_{xr} + t_{xr} + d] \, . \tag{3}$$

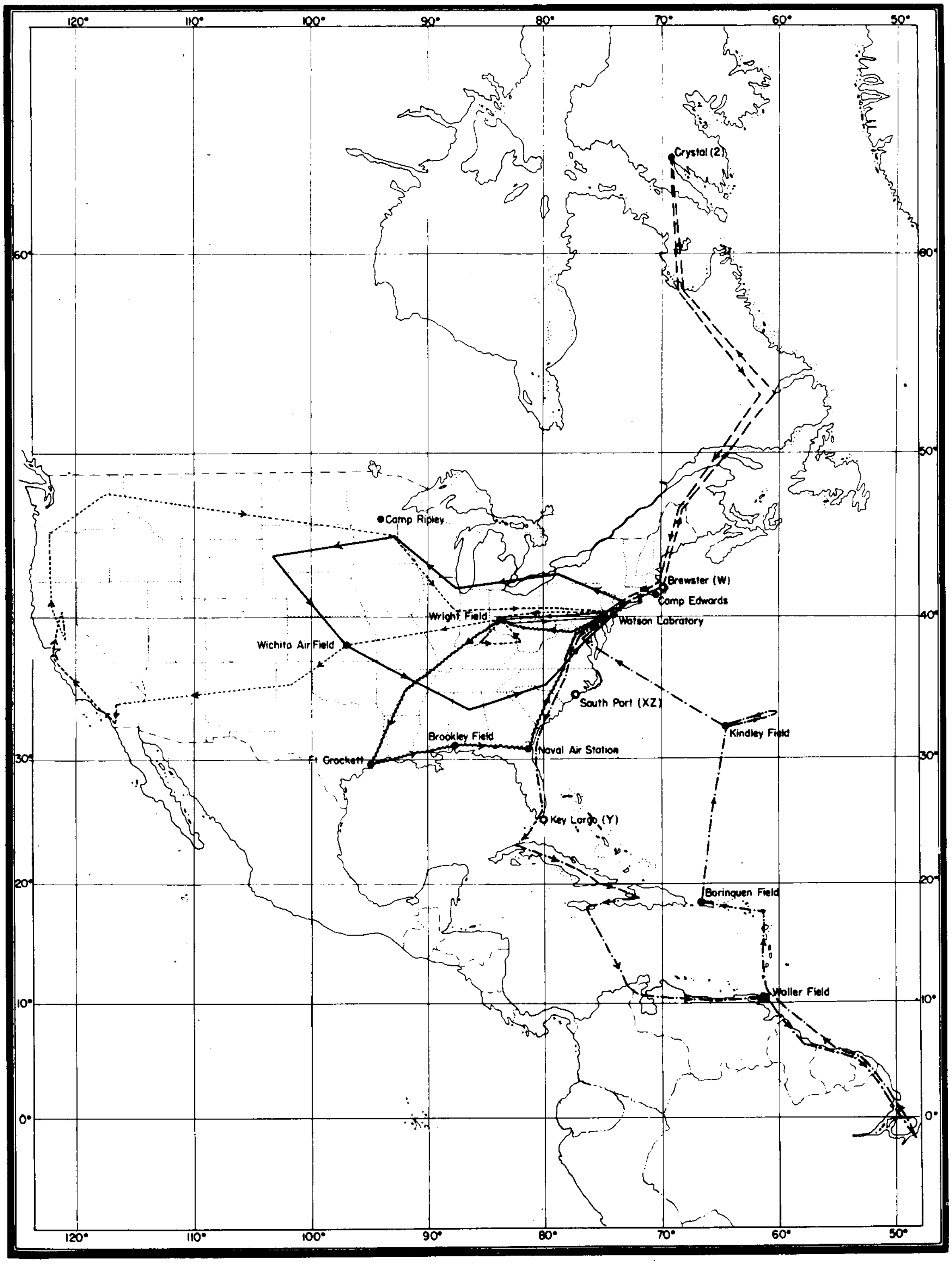

Figure 3.1. LF loran monitoring sites and test-flight routes (Signal Corps).

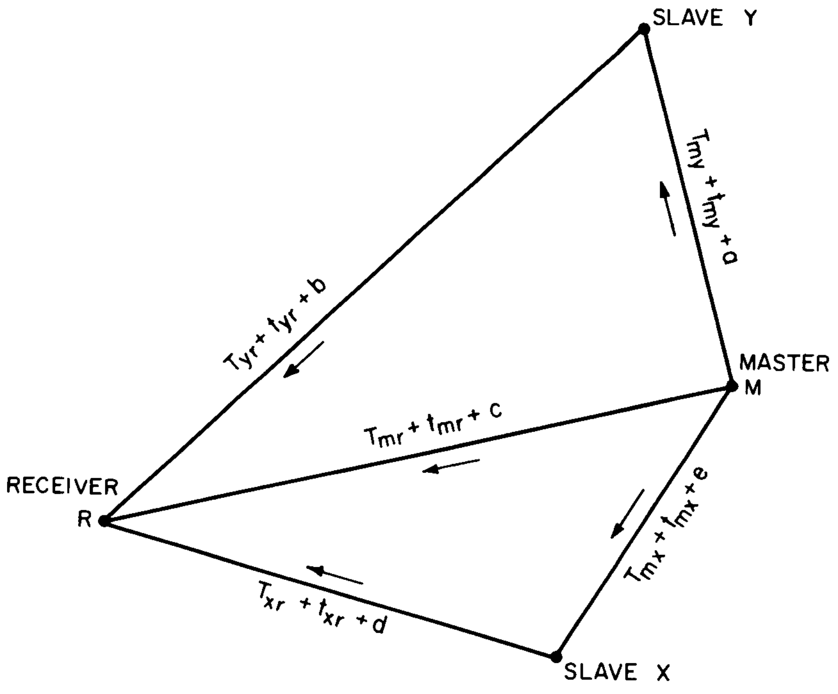

Figure 3.2 Loran triad geometry.

Note that the third time difference, TD_{yx}, in (3) is identical to the difference between the first two, (1) and (2). However, measurements always have some error and in this case it was possible to evaluate the error made by the receiver operator simply by comparing the measured values of (3) and the difference between (1) and (2). The coding delays are omitted for simplicity.

It is interesting to note that this basic formulation was defined late in 1945 (Operational Research Staff, 1946). The T's were defined as the calculated groundwave transmission time and the t's as the systematic propagation delays. At that time, the groundwave transmission time was arrived at merely by dividing the distance by the velocity of a radio wave in air. That is precisely what is now treated as the primary wave-transmission time. No one at the time was explicitly conscious of the secondary phase correction even though Norton (1941), who was largely responsible for the above formulation, had published a paper describing the secondary correction in considerable detail. In LF Loran, since the groundwave and the first- and second-hop skywaves were not clearly separated, the observed systematic propagation delays (t) were governed largely by the relative amplitude and time of arrival of the component waves. The much smaller secondary groundwave phase correction escaped notice.

The monitoring program included fixed receiving stations at Wright Field, Ohio; Watson Laboratories, Red Bank, New Jersey; Wichita, Kansas; Camp Ripley, Minnesota; Fort Crockett, Texas; and Crystal 2, Baffin Island. A B-17 aircraft fitted with LF Loran receiving equipment was used for airborne measurements and short-term measurements while on the ground at a number of locations including: Borinquin Field, P.R.;

Trinidad, BWI; Batista, Camaquey, and Guantanamo Bay, Cuba; Port au Prince, Haiti; Vernam Field, Jamaica; Maracaibo and La Guarira, Venezuela; Belem, Brazil; Paramaribo, Dutch Guiana; and Antigua, BWI.

Both time-difference and field-strength measurements were made at all the monitoring stations.

Atmospheric-noise measurements were made at Wright Field and Fort Crockett. The measured atmospheric noise levels were generally consistent with the predicted worldwide levels of atmospheric noise which were available at that time.

Estimates of system reliability were made on the basis of expected signal field strength and expected noise, using the monitoring station data to determine the probability that a time-difference measurement could be made in a given signal-noise situation. Contours of constant reliability (probability of getting a fix) were computed for day and night, summer and winter conditions. Similar contours were also computed for other transmitter powers.

The accuracy of the system was evaluated by analyzing statistically the time-difference errors recorded at the monitoring stations.. The observed errors were attributable to three principal sources:

a. Operator error (random error in matching the pulses),
b. Random propagation variations,
c. Systematic propagation delays.

At short distances from a transmitter, the received pulse is practically all groundwave but at greater distances (500-1000 miles), the skywaves become dominant and at distances beyond about 1000 miles, the pulse is nearly all skywave. The transition from groundwave to skywave with distance is relatively smooth, on the average, and the time-difference measurements differ from the computed groundwave values in accordance with the additional transmission time required for the signal to travel via the ionosphere. This is shown in figure 3.3.

The fix accuracy can be improved by taking the systematic delay corrections into account but substantial random errors remain because the ionosphere is not constant and individual readings may differ considerably from the average. The fix errors observed at the Camp Ripley and Wright Field monitoring stations are shown in figures 3.4 and 3.5. The value of using the corrections is clear but the remaining random errors are large. Typically, the fix errors at night were much greater than during the day. Figures 3.6 and 3.7 illustrate the day-night comparison.

The signals could be received over a vast area but the experimental system provided useful navigation coverage over only a very small portion of that region. Using a fix error of 5 miles as a criterion to define the useful coverage area, it was estimated that the daytime coverage was 20,300 sq. miles and the nighttime coverage only 6400 sq. miles. The lack of repeatability was the result of two basic considerations: system geometry and the time-difference errors already described. The geometric problem was, of course, clearly understood at the time, but several years passed before the groundwave-skywave problem was understood well enough to build a high-accuracy system.

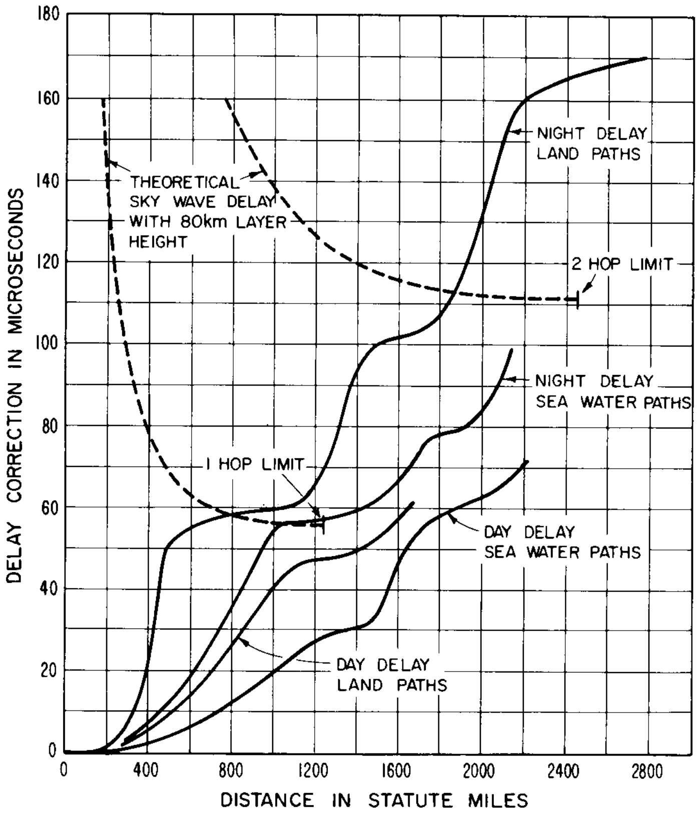

Figure 3.3. Average transmission delay corrections for LF Loran (Signal Corps).

The ideal station configuration to provide maximum coverage with a specified accuracy is to locate the transmitters of nominal 90-kW peak pulse power, as used in the experimental system, in the square configuration (700 miles on a side), could provide 5-mile accuracy over an area of 877,000 sq. miles during the day and 670,000 sq. miles at night. By increasing the size of the square to 1000 miles on a side, the day and night coverage areas would be 1,790,000 and 1,370,000 sq. miles, respectively. The virtue of the square configuration is that the lines of position intersect nearly at right angles over a maximum area (see fig. 3.8). In practice, there are many restrictions on transmitter sites but in any event, it is clear that sites should be chosen insofar as possible so that the lines of position intersect at favorable angles in the desired coverage area. When the time-difference readings are subject to large variations, useful coverage can be obtained only by optimizing the geometric considerations as was done with SS Loran.

Technically, it was a near-fatal mistake to reduce the bandwidth of the system so much that the groundwave was not clearly differentiated from the skywaves. It was hoped that the composite pulses could be matched in the same manner that had proven so successful with standard loran. But mutual interference among the groundwave and the first two skywave reflections severely distorted the leading edge of the pulses and the peak of the pulse was subject to shifts of 50 μs or more. The operator was constantly confronted

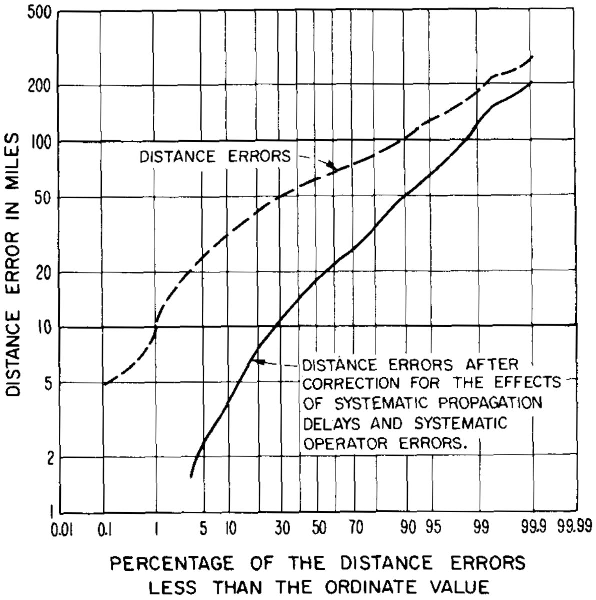

Figure 3.4. Camp Ripley data (Signal Corps).

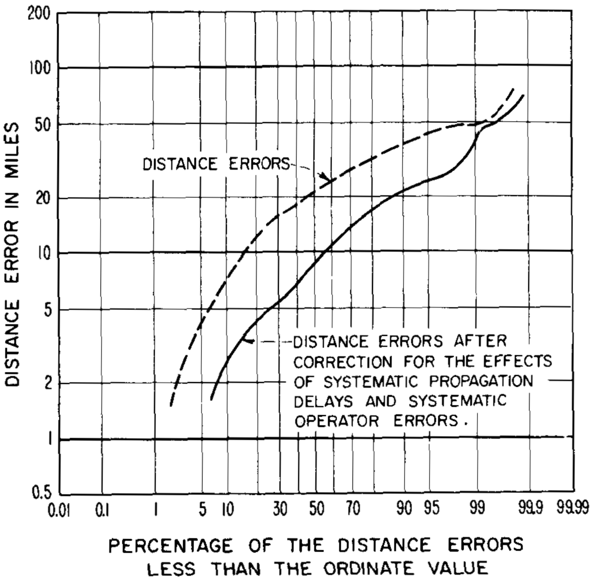

Figure 3.5. Wright Field data (Signal Corps).

with the question of how to match the pulses. The matter was made even worse because the relatively narrow bandwidth (about 8 kHz initially) of the receiver tended to smooth and stretch the leading edge of the pulses. Frequently matches would appear to be good when, in fact, they were quite erroneous.

There was no really correct way to match the pulses, but two techniques of some merit did evolve from practice. One was to match the slopes of the first part of the leading

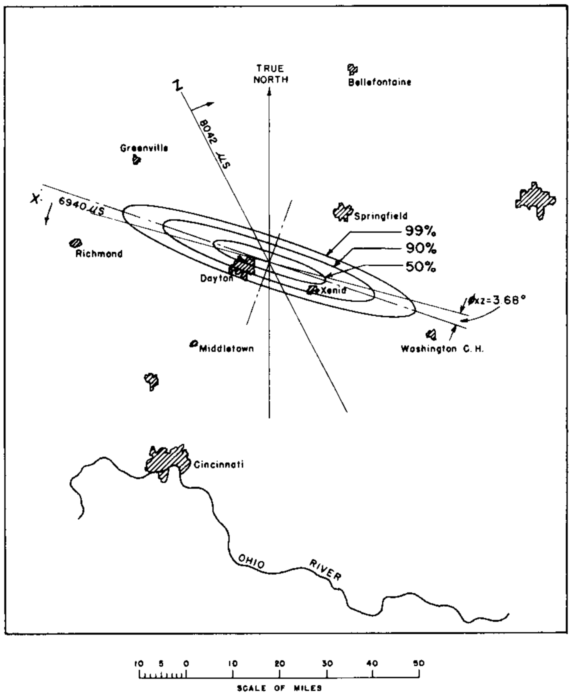

Figure 3.6. Distribution of daytime errors, Wright Field (Signal Corps).

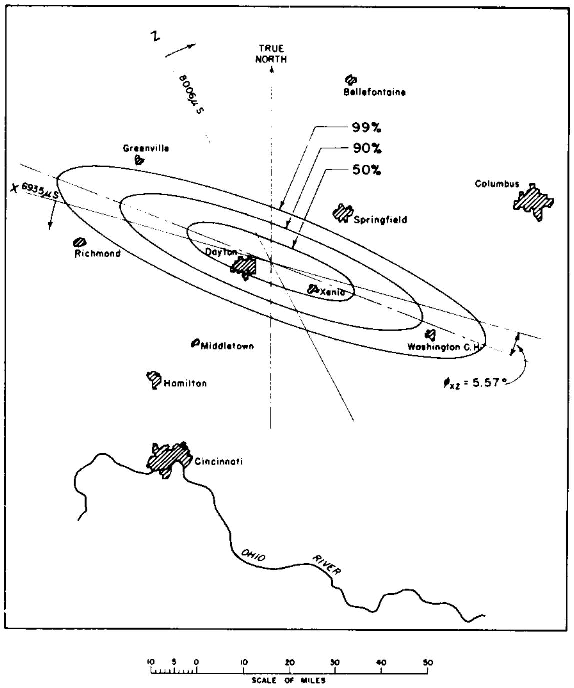

Figure 3.7. Distribution of nighttime errors, Wright Field (Signal Corps).

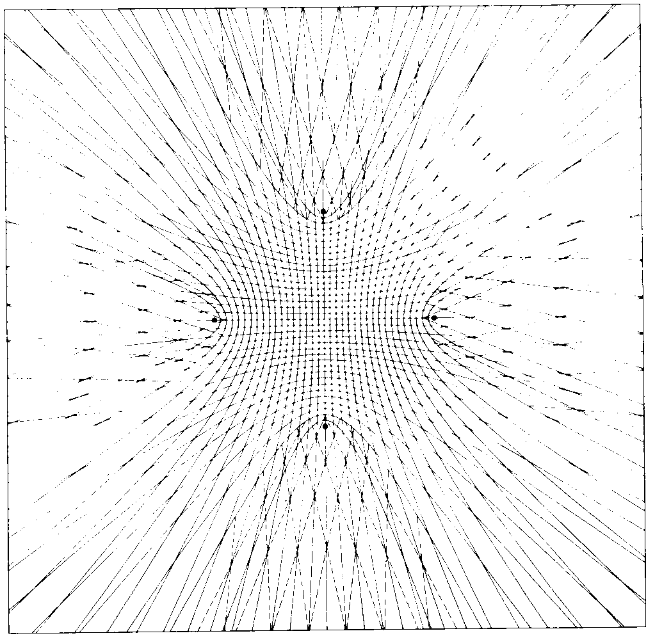

Figure 3.8. Loran grid for square configuration of transmitters (Signal Corps).

edge. The other was to use the maximum receiver gain that noise would permit in order to find the earliest detectable pulse energy. In the latter case, the first portion of the leading edge of the pulses would appear as vertical lines on the oscilloscope. Both techniques had the advantage of avoiding the peak of the pulse which was contaminated by skywaves, but neither provided any guarantee of a correct or repeatable reading.

In the ORS analysis of the data (Operational Research Staff, 1946), the measurement errors (operator errors) were computed from the three time-difference readings as described in page 5. The standard deviations of the time-difference readings were also computed. In these computations, it was assumed there was no variation in the slave-transmitter synchronization. The assumption was justified as there was good evidence that the transmitters were synchronized on the groundwave and the synchronization tolerance was held to less than 3 µs. Variations in the time-difference readings were presumed to be due to actual variations in the transmission time from the transmitters to the receiver plus measurement error. The computed measurement errors would be completely independent of propagation variations if it had been possible to measure the three time-differences simultaneously. Actually, the readings in most cases were taken within a period of 5 min or less. Since LF propagation changes are generally rather slow, the lack of simultaneity in the measurements probably had little if any effect on the computed values.

The standard deviations of the measurement errors and of the time-difference readings are listed in table 3.1. A glance at the measurement or operator error columns (σ_E) quickly shows the seriousness of the pulse-matching problem.

Table 3.1. Standard deviation of measurement errors and time differences - µs.

Monitoring Station	Day				Night			
	σ_E	σ_X	σ_Y	σ_Z	σ_E	σ_X	σ_Y	σ_Z
Wright Field, Ohio	12.6	11.6	18.8	20.1	18.1	23.7	26.9	27.5
Watson Laboratory, New Jersey	20.6	19.0	29.0	26.2	22.3	29.9	29.9	33.8
Camp Ripley, Minnesota	15.4	12.9	12.8	11.0	16.0	18.7	27.3	24.0
Fort Crockett, Texas	21.5	19.8	21.5	19.7	20.3	36.8	43.0	22.4
Mobile, Alabama	14.2	19.8	36.5	11.4	27.3	45.0	49.4	37.8
Borinquen Field, Puerto Rico	18.4	26.8	17.8	14.2	14.4	12.8	22.3	15.1
Trinidad	14.2	12.5	10.9	13.4	25.3	22.6	24.4	20.4
Batista, Cuba	50.9	15.2	30.9	25.1	34.4	16.4	15.4	2.6
Guantanamo, Cuba	13.5	29.4	30.3	11.7	---	---	---	---
Vernam Field, Jamaica	14.1	21.6	16.4	12.3	13.4	8.7	26.0	16.0
La Guaira, Venequela	21.3	21.1	25.6	15.1	27.7	35.9	18.7	15.0

The test program was stopped abruptly with the termination of the war. Even though the immediate need for the system vanished, it was fortunate that funds were available to complete the data analysis. While the experimental system was far from perfect, a great deal was learned about low-frequency navigation systems. There was time to think about other applications, both civil and military.

Shortly after the war, Operation Musk-Ox was planned. This was a Canadian Army exercise involving the cross-country movement of personnel and a variety of vehicles near the north magnetic pole in wintertime. Supplies for the ground party would be air-dropped by the RCAF. Navigation, however, particularly in bad weather, would present problems in a region where the magnetic compass was of greatly reduced value.

As a joint undertaking by the U.S. and Canadian Governments, it was decided to move the LF Loran stations to new locations where optimum coverage would be provided for supplying the ground party. Responsibility for moving and reinstalling the system was assigned to the Air Materiel Command of the Army Air Forces. Transmitter sites at Gimli, Manitoba, Hamlin, Saskatchewan, and Dawson Creek, British Columbia, were selected, and the reinstallation was accomplished during January and February, 1946.

The use of LF Loran in Operation Musk-Ox was largely of an operational nature but efforts were made to obtain the propagation data and to further evaluate the system. Ground-monitoring stations were established at Churchill, Yellow Knife, Baker Lake, Norman Wells, and Portage La Prairie, Gloucester, Edmonton, and Fairbanks.

After Operation Musk-Ox was completed in the early summer of 1946, the LF Loran system was kept in service until September, 1947, for extended testing. The extended program was called Operation Musk Calf and was sponsored jointly by the U.S. Air Force, the Royal Canadian Air Force, the Royal Canadian Navy, and the Royal Canadian Corps of Signals.

The performance of the system was entirely consistent with the estimates made in the ORS-P-23 report based on the earlier east-coast tests. Extensive experience in using the system was gained. By present-day standards the accuracy was not good but, in general, pilots and navigators were pleased with the system.

A personal experience of the author may illustrate in part why a great many looked upon LF Loran with favor. On a night flight from Hamlin, Saskatchewan, to Gimli, Manitoba in winter, we encountered bad weather. Everything was normal until we realized we were lost. By that time it was night and it was snowing. LF Loran equipment was aboard, but we were not in a region where good fix accuracy was provided. Only one line of position was good. Lt. Commander L.C. Read (navigator) was able to get a reasonably good radio DF bearing on a broadcast station while I was keeping track of the LF Loran line of position. We finally obtained a fix of sorts and found we were off course about 60 mi north of our destination. The rest of the flight was uneventful. In situations like that, 1 mi or 5-mi accuracy was largely an academic matter. The important point was that we established our position well enough to reach our destination safely.

On many other occasions, where aircraft were flying in the service area in good weather to check fix accuracy, the results were quite good. There were errors, of course, but at 20,000 or 30,000-ft altitude, an error of 5 mi or so did not seem very significant.

Qualitatively, the accuracy obtained on flights seemed to be better than would be expected from the ground-monitoring data. However, monitoring on the ground and using the system for navigation are quite different. In the air, the objective is to establish the position and track of the aircraft. The navigator can disregard "wild" readings and average the rest in plotting the course.

There was clear and definite need for a long-range navigation facility in the far north beyond the coverage area of the Musk Ox-Musk Calf chain. "Operation Beetle" was initiated by the U.S. Air Force to provide coverage in the Arctic for training, photographic, and weather missions. This project called for the installation of a complete operational LF Loran chain with transmitters to be located at Skull Cliff, Alaska, Kittigazuit and Cambridge Bay, Northwest Territories, and control-monitoring stations at Barter Island and Saw Mill Bay. In contrast to the experimental chain, 625-ft self-supporting steel towers would replace the balloon-supported antennas, and all new transmitting equipment designed for operational use would be built. Actual planning started in February 1947 when the Commanding General (Watson Laboratories, AMC, 1948) was given the responsibility for establishing the chain. It was hoped to complete the installation by October 1st of the same year. Two of the three transmitting stations, however, were not finished until the summer of 1948.

Planning of the project appears in retrospect to have been too hasty. Procurement of materials and the logistics of the operation did not fit together efficiently. Excessive costs and delays resulted before the installation was finally completed.

A major cost item was the erection of the 625-ft towers. The installations were unique in that the foundations were set in permafrost. At Cambridge Bay, special refrigeration equipment had to be used to prevent the heat of the setting concrete from causing excessive melting and settling. Even without special problems, the cost of construction at isolated arctic bases is very great.

One single mistake of blunder proportions caused the failure of the system. The groundwave signal was too weak to synchronize the Cambridge Bay slave, and the Skull Cliff slave could be synchronized only with the aid of a control-monitor station near the midpoint of the baseline (Barter Island). The location of the baselines over permafrost had not been taken into account. In all fairness it must be pointed out that LF propagation was not understood as well then as now so the mistake should not be viewed too harshly from a technical standpoint. Perhaps the program should be criticized more for not using corrective measures such as increasing the transmitter power and/or lowering the frequency.

The receiver bandwidth had been increased from 8 kHz to 20 kHz. This will be discussed in some detail later. The wider bandwidth, which responded to more noise, was attributed in part to the synchronization difficulties.

A limited number of field-strength measurements (Pickard and Burns, Inc., Final Engrg. Report, 1950) were made in the vicinity of both the Skull Cliff and the Kittigazuit stations. Reduced to a distance of 1 mi, the measurements gave field-strength values of 1.8 and .2 V/m, respectively. It is quite probable that the ground system at Kittigazuit was inadequate, and evidently the radiated power was reduced to about half the normal value. The lower power of the master station in combination with the attenuation over the longer path to the Cambridge Bay slave (612 nmi) made it impossible to achieve satisfactory synchronization. Even with the aid of the control-monitor station at Saw Mill Bay, proper system operation proved to be virtually impossible. Efforts to synchronize the Cambridge Bay slave were abandoned early in 1949 and the entire program was terminated in February 1950. That was the end of LF Loran as a system.

During these programs, some experimentation was performed to develop receivers that would provide more accurate time-difference readings. These efforts, while they did not result in immediate success, marked the beginning of a succession of technical developments that eventually led to the measurement techniques used in the present-day Loran-C system. The most noteworthy of these experimental efforts was increasing the receiver bandwidth from 8 kHz to 20 kHz and matching the rf cycles instead of the pulse envelopes.

The greater bandwidth was needed to avoid distorting the leading edge of the pulse. It was hoped that the beginning or first rf cycle in the pulse envelope could be seen on the oscilloscope of the navigation receivers. The increased measurement precision that could be achieved by matchng cycles instead of pulse envelopes is self-evident.

The experiment was nearly successful. Unfortunately, noise prevented reliable identification of the beginning of the pulse. Consequently, the time-difference readings were distributed in groups at intervals of 1 cycle. The spread of the groups was about the same as the spread in the conventional envelope readings, so most engineers at that time were quick to conclude that there was no merit in cycle matching. That conclusion is documented by the following paragraphs that are quoted from the final engineering report on LF Loran (Beetle) by the engineering firm of Pickard and Burns (Pickard and Burns, Inc., 1950):

> In the technique of cycle matching, the unrectified radio-frequency of intermediate frequency, signals are displayed on the oscilloscope and cycles of the master signal are superimposed on cycles of the slave signal. It is an intriguing trick of instrumentation. Ideally the signals could be held in synchronism with a precision of a fraction of a cycle (5.5 micro-seconds). Actually it is impossible to identify cycles at these frequencies with a reasonable bandwidth. Because of the uncertainty of selecting cycles the technique is misleading. It leads the operator to believe he is maintaining precise synchronism when actually he may be holding the wrong cycle and would do better to match the leading edges of the rectified signals.
>
> The practice of cycle matching has influenced the choice of bandwidth and the design of equipment for three long and expensive programs. Now at last it has been abandoned as impractical.

Based on the conclusions in the preceding two paragraphs, Pickard and Burns (Pickard and Burns, Inc., 1950) made the following recommendations in regard to groundwaves, skywaves, and bandwidth:

> We have concluded that Low Frequency Loran is a system of composite groundwave and skywave pulses and that its range is too short. Since the original reason for choosing the wide bandwidth, the resolution of groundwaves and skywaves no longer applies, the range can now be increased by decreasing the bandwidth. If for instance, the bandwidth were reduced from 20 to 5 kHz we might expect the transmitted power and the sensitivity of the airborne receiving system to be increased by a factor of two ...

Pickard and Burns further recommended using a lower frequency such as 100 kHz. The merits of the lower frequency for increased range were obvious, but the question of cycle identification was not an obvious matter at that time. Experienced engineers working in the field of LF radio navigation were divided into essentially three groups on the issue of cycle identification. Some elaboration on this point is important because resolution of the matter largely determined the further development of LF pulse navigation systems.

The three groups were made up of those who (1) were convinced that cycle identification was possible, (2) believed that cycle identification was not possible, and (3) had no strong convictions one way or the other. The author is identified with the first group and while in Edmonton, Alberta, with the "B-29 group" during the Musk-Ox operation (winter, 1946-47), proposed that the leading edge of the pulse could be frequency-modulated to mark or identify any particular cycle. Briefly, the proposed scheme was that by shifting the carrier frequency up and down on alternate pulses, an oscilloscope display would show the traces of 1 cycle superimposed, while the traces of the other cycles would be separated. The idea was never tried, and it is doubtful if any of the correspondence on the subject is still in existence. In the light of present knowledge, it is clear that the proposed method of cycle identification was sound in principal but it gained no favor at that time.

Shortly after WW II, military requirements for a precision, long-range bombing system were emerging. The development of such a system hinged on the development of a navigation or guidance system which could provide the required accuracy, range, and reliability. The possibility of perfecting techniques for cycle identification and cycle matching offered the greatest hope for meeting the requirements.

In 1946, the Rome Air Development Center placed two development contracts for the purpose of achieving a low-frequency system that would provide the navigation or guidance component of the bombing system. The objectives of the two developments were identical but the proposed instrumentation techniques were quite different. One contract was with Sperry Gyroscope Co., for a pulse system (Cyclan), and the other was with Sylvania for an FM system (Whyn). The two systems were entirely competitive and it was understood that the one demonstrating the greater feasibility would be selected, assuming, of course, that minimum requirements could be met.

Both systems were far more advanced than LF Loran in that cross-correlation detection techniques were used and completely automatic receiver operation would be contemplated. Like loran, both systems used the same concepts of master and slave synchronization. In contrast to LF Loran, both systems were predicated on separating the groundwave from the skywave at the receiver using only the groundwave for time-difference measurements in order to achieve high accuracy. To accomplish the groundwave-skywave separation, both systems used substantially greater bandwidth than LF Loran. The radically different viewpoint on bandwidth from that held during the LF Loran development was defended on the basis of military requirements. It was realized that groundwaves and skywaves could not be separated by any means other than using an appropriately wide bandwidth. Just how much bandwidth would be needed was not too well understood.

The Cyclan system used two sets of pulses which rose to full amplitude in about 50 to 60 μs or approximately 2-1/2 times faster than the LF Loran pulses. One set was centered on 180 kHz and the other on 200 kHz. (The latter frequency was changed to 160 kHz to reduce interference to other radio systems.) Each set of pulses occupied a spectral width of approximately 20 kHz so the system required a total bandwidth of 40 kHz. The pulse-envelope delay and relative phase measurements were made on both sets of pulses. The only justification for the second set of pulses was that it was estimated that the envelope time-difference measurement would not be accurate enough to identify the "correct" or corresponding rf cycles of the pulses. By using two phase-locked frequencies, the longer period or a cycle of the difference frequency (20 kHz) could be resolved and, in turn, the relative phase of corresponding cycles in either set of pulses could be determined without ambiguity.

The Whyn system, from an instrumentation standpoint, had very little in common with Cyclan, and initially appeared to be capable of performing the required functions with better spectrum economy. It was claimed that by virtue of the FM approach to the problem, much higher average power could be transmitted than would be possible with the pulse system. During the course of development, however, the spectrum requirements had to be revised upward to achieve the necessary range and separation of groundwaves and skywaves. In this connection, the transmissions were described as "frequency modulated" with a "shaped spectrum". In reality, the transmissions evolved into frequency modulated, long pulses. Finally, it was generally agreed that, in principle, the system requirements could be met by either Cyclan or Whyn and that, ultimately, the power and bandwidth would be about the same in either case. As a practical matter, however, there was one major difference between the two systems. The Whyn system presented what appeared to be almost insurmountable difficulties in maintaining the necessary phase stability of the sidebands. Sideband stability was no problem in the pulse system.

Development of the experimental Cyclan system took about 4 years. Field tests were made during the period from October 1950 to June 1951. Development of the Whyn system was finally abandoned in 1952 without attempting any field tests.

The Cyclan field tests were carried out on the west coast where two 650-ft vertical antennas belonging to Mackay Radio were available for the transmitters. One was located at Palo Alto, California, and the other at Hillsboro, Oregon. For economy, only one pair of stations was used. Only one experimental receiver was built and it was installed in a van so it could be moved conveniently to a number of locations (see fig. 3.9). For the test program, three sets of loran-receiving equipment were extensively modified and installed in fixed locations for monitoring and to assist in the operation of the transmitters. These equipments had conventional oscilloscope displays and, consequently, the accuracy of the time-difference measurements was limited. They were, however, quite useful for detecting trouble at the transmitters. One set was installed at Medford, Oregon, near the center of the baseline and the other two sets were installed on the baseline extensions. These installations, however, were not made at the beginning of the test program. The need for the monitors was not clearly seen until shortly after the tests were started.

The services of the Sierra Electronic Co., of San Carlos, California, were engaged to install and operate the system under the supervision of Sperry engineers. The

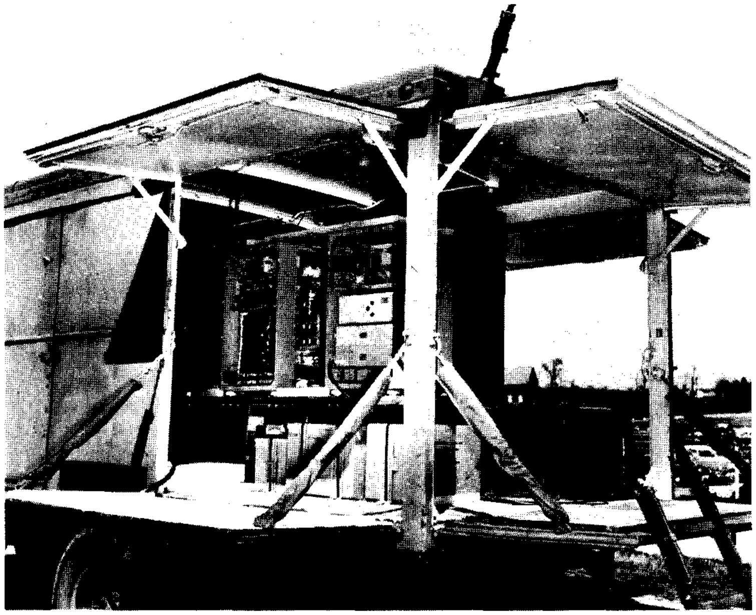

Figure 3.9 Cyclan mobile receiver.

Central Radio Propagation Laboratory (CRPL) of the National Bureau of Standards (NBS) had the responsibility of evaluating the system tests and analyzing the data from a radio propagation standpoint (Hefley, 1953).

The Cyclan instrumentation was quite complex. There were many adjustment problems and component failures, but in view of the new and intricate circuits and circuit functions, such difficulties were understandable. The primary objective was to demonstrate the principles of the system and in this regard, the Cyclan development was highly significant.

The fast-rising pulses (as compared to those used in LF Loran) in combination with sampling gates which operated on the leading edges, made it possible to measure the phase and evelope time differences on the groundwave only. The first measurements were made on the slave baseline extension near Hillsboro, Oregon. In spite of some equipment troubles when the system was functioning properly, the phase readings showed a stability that was about 100 times better than the LF Loran envelope time-difference measurements. The effectiveness of the cross-correlation phase detector in operating on a weak signal in the presence of noise was nothing short of remarkable at that time. Initially, a conventional diode detector was used in connection with the envelope time-difference measurements. During the tests it was replaced with a correlation detector, but even the diode detector performed with a fair degree of satisfaction. The envelope measurements were subject to several microseconds of variations, but most of the time the excursions were less than ± 2.5 μs which was adequate to avoid cycle ambiguity.

The results of the slave baseline extension measurements are shown in figure 3.10. The data for curve 1 were obtained by operating the equipment while driving the van slowly along a highway which crossed the baseline extension at approximately 90°. The data for curve 2 were obtained by monitoring at four locations as shown. It was not feasible to

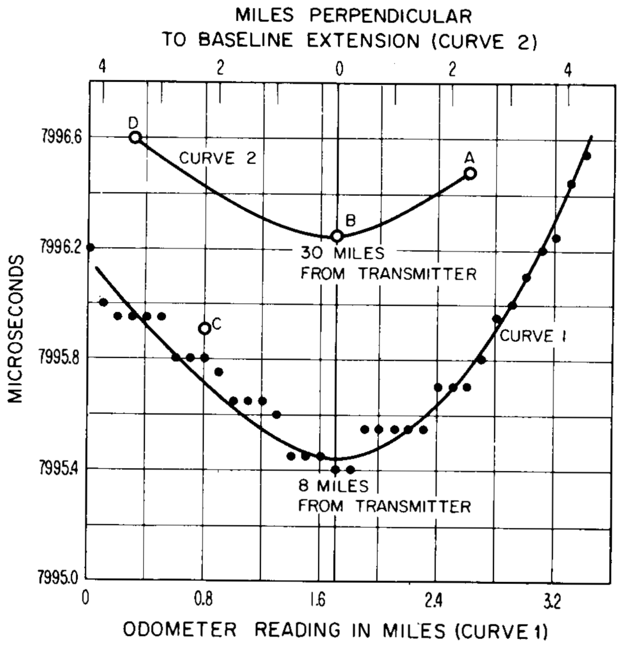

Figure 3.10. Cyclan baseline extension data.

make measurements while in motion in that area. In the data analysis, it was presumed that the measurements at location C were in error. Consequently, they were disregarded in drawing a smooth curve through A, B, and D. As can be seen in section 9, the two sets of measurements in figure 3.10 are in reasonably good agreement with the theory and with other measurements made much later.

The first fixed monitoring station was installed at Medford shortly after the slave baseline extension measurements were completed. The next major step in the test program was to measure the roundtrip transmission time over the baseline. The van stopped at Medford enroute to the master station at Palo Alto. The time-difference readings obtained with the two sets of equipment compared quite well. While the measuring accuracy of the equipment at the fixed station was only about ± 0.5 μs, it was evident that there were no gross discrepancies between the readings of the two receivers.

The measured roundtrip times at two locations, about 1 mi apart, and on the master baseline extension were 13980.81 and 13980.76 μs. The computed value (without corrections) for both locations was 13972.40 μs. The difference of 0.05 μs between the measured values could have been attributed to a number of causes , but such a small discrepancy was close tc the overall accuracy of the experimental system. The measured values could be either averaged or simply rounded to 13980.8 μs.

The significant fact is that the actual transmission time was 8.6 μs greater than the computed time for a radio wave traveling the same distance in air, and about 3.0 to 3.5 μs greater than could be explained by plane-earth propagation theory. The measurement accurac was ample to show that more realistic propagation theory would be required to predict the time-difference readings. Conversely, it became evident that measurement techniques which were precise enough to reveal deficiencies in the available propagation theory could be used to advantage in revising and improving the theory.

A more adequate theory would have to take into account such parameters as the curvature of the earth, mountains, and variable or mixed conductivity along the propagation path. It was also obvious that a great deal of time would be required to develop such a theory. However, an encouraging observation was that the phase of the groundwave was very stable and apparently not subject to diurnal or other variations. That is, the time-difference readings had a high degree of repeatability , and that was an essential consideration in a practical navigation system. Without precise prediction of the navigation grid, a stable system could still be calibrated.

During the remainder of the test program, the baseline extension monitors were installed and time-difference measurements were made primarily at Los Banos, California, and Reno, Nevada. The results obtained at Los Banos were of interest because the combination of a weak slave signal and local interference prevented proper groundwave synchronization. The phase sampling gates were picking up some skywave signal. Since the skywave is variable, the standard deviation of the phase readings during the day was about 4 times greater than normal and nearly 15 times greater at night. The skywave contamination of the phase measurements had the further degrading effect of causing serious cycle ambiguity. It was not possible to analyze the contamination effects on the two frequencies separately, but it was obvious that complete groundwave and skywave separation was mandatory.

A further ramification of using two pulse frequencies is that any difference in dispersion of the groundwave signals would also tend to cause cycle ambiguity. The problem has never been evaluated quantitatively in a rigorous way because the two-frequency system was abandoned in favor of a single frequency pulse. The field measurements seemed to indicate that significant differential dispersion might be present, but equipment troubles and adjustment errors were such that any actual effects were probably overshadowed.

The monitoring at Reno was started in February 1951, but the entire system by that time was so urgently in need of maintenance work it was scarcely feasible to continue trying to gather data without making the necessary repairs.

So few hours of good data had been obtained that a thorough system overhaul was deemed advisable in order to have greater confidence in the test results. Accordingly, a subcontract with the firm of Jansky and Bailey was negotiated for the necessary maintenance work and for operation of the experimental system to obtain 100 hours of useful data. It was agreed by all concerned that the additional data should be taken at Reno, both for economy and to provide as much information as possible on the long-term stability of the groundwave phase-difference readings.

The Jansky and Bailey subcontract was accomplished without any serious problems. The additional data actually did not reveal anything new, but a further demonstration of the stability of the groundwave phase was most valuable.

The good results that had been obtained were most encouraging. The troubles pertained largely to the equipment itself with little or no reflection on the principles of the system except for the obvious fact that greater simplicity would be highly desirable.

Before the end of the tests, the frequency band of 90 to 110 kHz had been firmly established by international agreement for experimental navigation use (see sec. 6 for further information). The use of 160 and 180 kHz, in fact, the entire spectrum from 150 to 190 kHz, became increasingly difficult to justify even for the most compelling reasons. The phase stability of the LF groundwave provided the incentive to develop a high accuracy, long-range system, but the need to conserve spectrum and to move to a lower frequency effectively terminated the development of Cyclan as a system.

Military system requirements, meanwhile, became more clearly defined and confidence grew that a much simpler, single-frequency system operating at 100 kHz could be devised. As a logical consequence of the knowledge gained from Cyclan, the development of a simpler system that would meet requirements and be more compatible with other systems was proposed and undertaken by Sperry. The new development was given the code name "Cytac".

4. CYTAC DEVELOPMENT AND PRELIMINARY TESTS

Cytac was to be an all-weather, long-range, ground-based, tactical bombing system. The development was sponsored by the Rome Air Development Center (RADC). The Sperry Gyroscope Company was the prime contractor, with NBS providing advisory information on pertinent aspects of low-frequency propagation.

Development of Cytac was started in 1952, but, before proceeding with the technical description, the unexpected turn of events that occurred in 1954 will be mentioned briefly. During the quite successful field testing of the system, the development program was cancelled by the Air Force. It is emphasized that the cancellation in no way related to the performance of the system but was based on a planning decision not to pursue further development of land-based bombing systems. Officially, the Air Force had no interest in developing the navigation portion of the system as an end in itself, and it was fortunate that the field tests were allowed to continue to the extent possible with the funds that had been committed.

Returning to the chronological sequence (1952), Cytac was considered as a weapon system that would ultimately have the capability to automatically bomb a number of preselected targets. To accomplish this objective, a special-purpose digital computer was to be used to guide the aircraft to the bomb-release points using navigational information from the Cytac receiver and other inputs from various aircraft instruments all in combination with preprogrammed target and ballistic data. At the time such a system was a rather ambitious undertaking.

Devising fully reliable instrumentation was a major challenge in itself, but the radio considerations posed a still greater challenge. At least there were many unknowns in the radio area. The phase stability of the groundwave observations during the Cyclan tests, more than anything else, inspired confidence that range and accuracy could be achieved. The goal was 1000 ft at 1000 miles. But, however stable the groundwave phase might be, there were many other problems to be solved.

The two-frequency scheme used in Cyclan was not only complex and cumbersome, but the nominal 40-kHz bandwidth was difficult to justify even for military purposes. A single-frequency system was a matter of practical necessity. Furthermore, through international agreement (see sec. 6), the 90-110 kHz band was allocated for experimental navigation use.

The fact that any further system development would have to be located in the vicinity of 100 kHz was viewed with mixed reactions. An efficient antenna for radiating a broadband pulse would be an economic problem, but at the same time, the lower groundwave attenuation rate was quite attractive. But perhaps the most compelling consideration was that the longer period of the lower carrier frequency would make cycle identification easier. The author had proposed a cycle identification technique in 1949 and had another technique that also appeared to be sound. With confidence that obvious technical problems could be solved, the development was undertaken with the basic understanding that certain crucial system functions should be proved by demonstration before funding the entire system development.

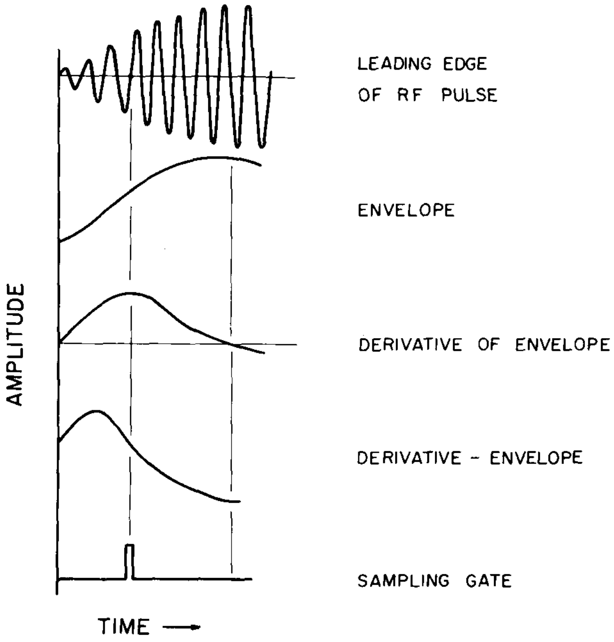

Figure 4.1. Sperry technique for marking a point on the Loran-C pulse.

The success or failure of the proposed system hinged largely on whether or not cycle ambiguity could be resolved using a single frequency and without exceeding the available spectrum. Regardless of the rest of the instrumentation, without the navigation function, there would be no system to test.

The cycle identification scheme proposed and developed by Sperry consisted essentially of marking a point on the leading edge of the pulse envelope by subtracting the envelope waveform from its derivative (see fig. 4.1). The axis crossing of the resultant waveform provided a point that was independent of envelope amplitude. By sampling the resultant waveform with a narrow gate in the vicinity of the axis crossing, an error voltage could be derived to provide servo-control of the position of the sampling gate. By performing the same operation on both master and slave pulses, the envelope time difference was simply the time interval between the sampling gates.

The relative phase between two rf signals was measured by sampling the output of a phase detector with similar gates whose position was controlled by the envelope sampling gates. The error voltage derived from the master phase samples was used to shift the phase of the reference voltage to maintain a quadrature-phase relationship with the incoming signals and thus establish phase-lock. The error voltage from the slave phase samples was used to operate a second phase shifter to indicate relative phase.

It is to be noted in this scheme, that the axis crossing the envelope minus its derivative can be placed anywhere along the leading edge of the pulse by appropriate choice of circuit constants. Two principal and opposing considerations not only determine the optimum location of the axis crossing, but the maximum practical pulse-rise time also. The sampling point must be placed early enough to avoid the first skywave reflection and also at a point where the groundwave amplitude is as great as possible to make effective use of the transmitted power. Consequently, the pulse-rise time and the bandwidth are loosely defined because power and bandwidth can be traded to some extent. In practice, however, the opportunity to trade is limited by the lack of available spectrum in one direction and by excessive waste of power in the other.

The carrier-phase and pulse-envelope measurements were designed to be entirely independent except they were made at the same point on the pulse. To avoid cycle ambiguity, the envelopt time-difference measurement must have an accuracy of ± 1/2 rf cycle or better. There was little doubt that such a figure could be met from an instrumentation standpoint but it was somewhat uncertain how much the carrier cycles would shift relative to the pulse envelope as the signal was propagated. This latter point was one of the major questions to be resolved before proceeding with full-scale development of the system.

The author's approach to the cycle-resolution problem (frequently called the "NBS pulse") was much simpler to instrument, but it was intended primarily for oscilloscope presentation rather than automatic circuit functions. It used amplitude modulation and a modified pulse repetition period to produce a pattern as shown in figure 4.2 when the signals were viewed on an oscilloscope. Instead of the usual uniform repetition period, every other period was shortened by exactly one or two whole cycles. The long and short periods defined pairs of pulses, and their amplitudes were adjusted so that two positive half-cycle peaks along the leading edge were superimposed.

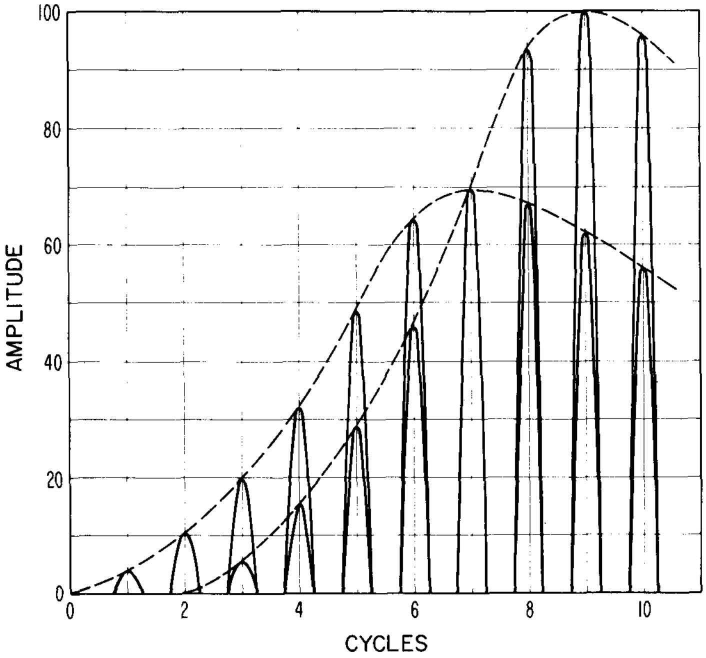

Figure 4.2. NBS pulse scheme.

This scheme was field-tested in 1952 for the purpose of obtaining specific data as soon as possible that, hopefully, would show the feasibility of cycle identification. A loran transmitter installed at the RADC experimental site near Forestport, New York, had been modified for 100-kHz transmissions. The 1200-ft base insulated antenna, originally constructed for general purpose use, provided good radiation efficiency. The circuit functions needed to modify the repetition period were simply and easily "patched in" for the tests.

The receiving equipment consisted essentially of a laboratory-built TRF wideband 100-kHz amplifier and a Navy model DAS-4 loran indicator. The equipment was installed in a trailer for convenience and mobility.

Observations were made at a number of sites within a radius of approximately 100 miles of the transmitter. In all cases the cycle identification was entirely clear. There was no noticeable change in pulse shape nor was there any tendency for the superimposed cycle peaks to separate. Figure 4.3 is typical of the waveforms that were observed on the oscilloscope. The monitoring locations are shown in figure 4.4.

The principal criticism to be made of the tests is that additional observations were not made at much greater distances. Signal-to-noise ratios would have permitted going to distances of 500 to 600 miles or more. Nevertheless, it was conclusively demonstrated that the concept of visual cycle identification was valid to a distance of at least 100 miles and it was anticipated that the same would probably be true at greater distances. Those results provided a tangible measure of assurance that the single frequency was sound.

It was proposed by the Bureau of Standards that somewhat shorter skywave delays might be encountered at 100 kHz than at the higher frequencies. In view of the fact that the skywave delay was known to be a critical parameter, the Bureau undertook to measure the delay as well as possible with available equipment.

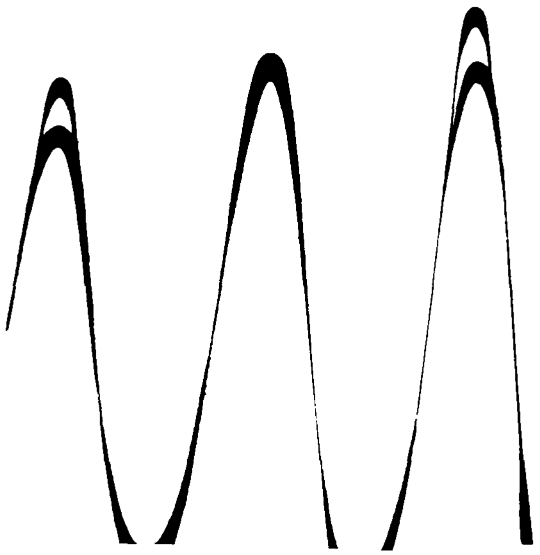

Figure 4.3. Scope photograph of NBS pulse.

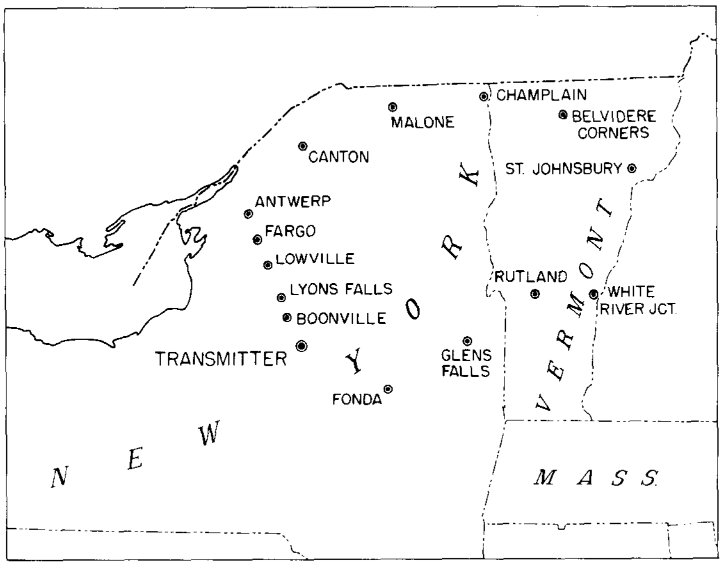

Figure 4.4. NBS pulse-monitoring locations.

Pulses having a rise time of about 60 μs and a peak power of the order of 200 kW could have been transmitted from Forestport but available receiving equipment limited the data-taking to viewing the signals on an oscilloscope. By virtue of the fairly high radiated power, the beginning of the pulse could be observed with reasonable certainty to distances of 400 to 500 miles. It was well known that the exact beginning of the skywave part of the pulse is generally not obvious on an oscilloscope especially in daytime. The skywave and groundwave components of the pulse blend smoothly until the skywave part reaches sufficient amplitude to produce noticeable distortion in the resultant pulse.

To overcome this difficulty, the leading edge of the pulse was carefully traced on a piece of transparent paper over the face of the oscilloscope. Tracings were made at intervals of several minutes to find slow changes in the ionosphere. Typical results are shown in figure 4.5.

Observations were made in Michigan and northern Ohio. In spite of the relatively crude measurement techniques, the data were surprisingly consistent and indicated a daytime virtual reflection height in the vicinity of 70 km and about 85 km at night. The 70-km figure was lower than most people expected , but it was fortunate that the pulse-rise-time requirements were recognized at an early date in the system development. On the basis of a 70-km virtual height, it was originally estimated that the first-hop skywave delay at 1000 to 1200 miles would be only 25 to 30 μs depending on the conductivity of the path. More refined calculations on digital computers have later shown 35 to 40 μsec are the true delays.

The Rome Air Development Center engaged the services of SRI (Stanford Research. Institute) to study the problem of radiating a pulse that would meet system requirements without exceeding the available spectrum. The Forestport transmitter was used for most of the experimental transmissions for propagation measurements.

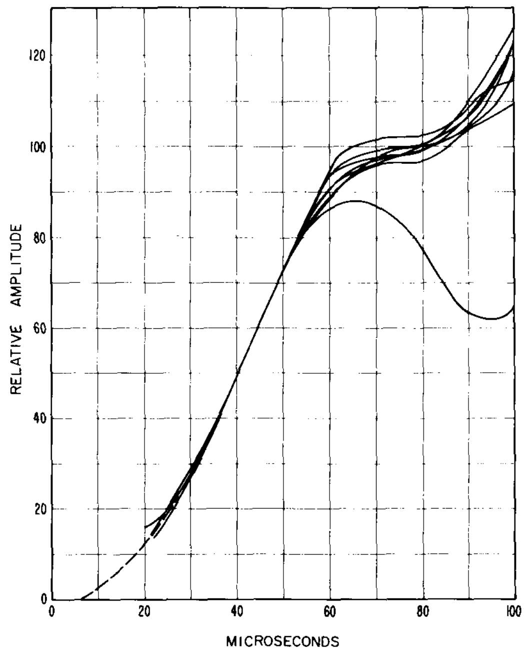

Figure 4.5. Pulse envelope tracings.

During the summer of 1953, a pulse that reached full amplitude in 3 cycles (30 μs) was transmitted. The spectrum of that pulse exceeded the 20 kHz-wide navigation band by approximately 10 kHz , but the short rise time made it possible to verify the earlier skywave delay measurements.

The first major phase of the Cytac development program was to investigate the following critical system considerations by test: (a) cycle ambiguity, and (b) groundwave range and stability.

Minimum instrumentation to make these tests was completed by Sperry in the spring of 1953. The receiving equipment, including the addition of an atmospheric noise receiver, was installed in a van for field testing during June, July, and August. Sites were chosen along a general east-west line from Michigan to Montana (Johler et al. 1954).

Sperry operated their equipment while the Bureau of Standards made supplementary measurements of field strength, skywave delay and noise. SRI continued their work on antenna matching and pulse shaping.

For the sake of both time and economy, the Forestport transmitter was used to simulate a pair of transmitters. This represented a partial compromise in the testing since only one propagation path at a time could be used, while an actual pair of separated transmitters would obviously involve two different propagation paths at the same time. It could be reasoned, however, that if no cycle ambiguity was found over a number of individual paths, none should be expected that would be using two paths at a time.

The field tests produced four results of major significance:

1. The much-feared problem of cycle ambiguity was not encountered in any serious degree. The envelope time-difference readings were quite stable, and the difference between the envelope and carrier-phase readings rarely exceeded the critical value of 5 μs or one-half cycle of the carrier even at signal-to-atmospheric-noise ratios of the order of -35 dB. The deviation of the envelope-to-cycle reading which was not exceeded 90 percent of the time at all sites is shown as a function of signal-to-noise ratio in figure 4.6.
2. The skywave time-delay measurements not only confirmed the delay estimates based on the 1952 observations but showed that beyond the limiting geometrical-optical distance of about 1200 miles, the delay (first hop) was either constant or nearly so. The interpolated value of the first-hop skywaves relative to groundwaves at distances beyond 1200 miles was determined to be 26 μs. It was also found that the first-hop skywave field strength did not diminish rapidly beyond the limiting optical distance as had been expected. In figure 4.7, the measured field strengths are compared with the values expected on the basis of geometrical-optical theory. The measured groundwave values are plotted also but are not compared with computed values because the conductivity was not known accurately enough for such a comparison to be meaningful. The geometry of each of the skywave paths is shown in figure 4.8.
3. The range of 1800 miles at which the groundwave was received and the adverse signal-to-noise ratios with which the coherent detection techniques could cope for resolving cycle ambiguity clearly established that a 1000-mile system could have a very high degree of reliability. A radiated peak-pulse power of approximately 220 kW and only a single pulse per repetition period (conventional loran practice) were used

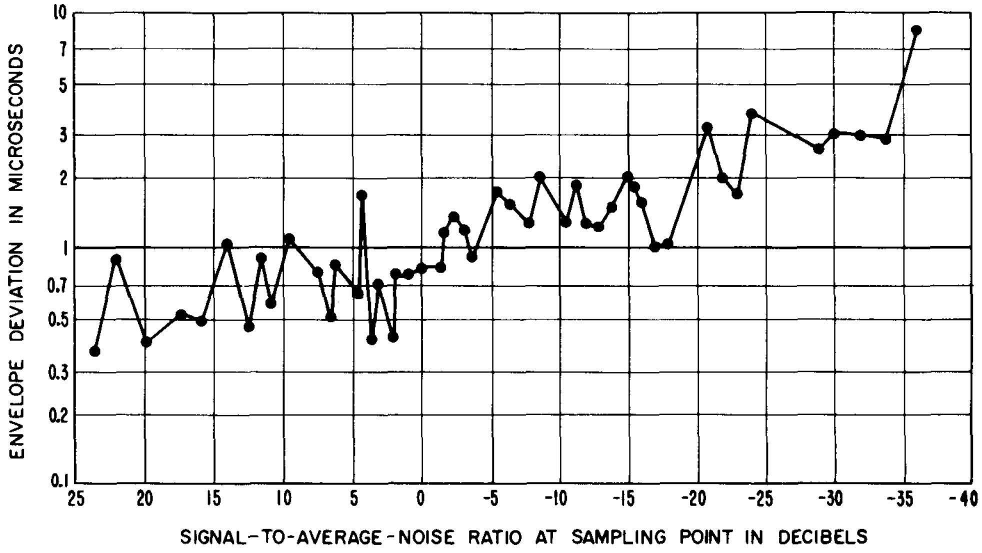

Figure 4.6. Cytac envelope deviations ordinate value not exceeded 90 percent of time.

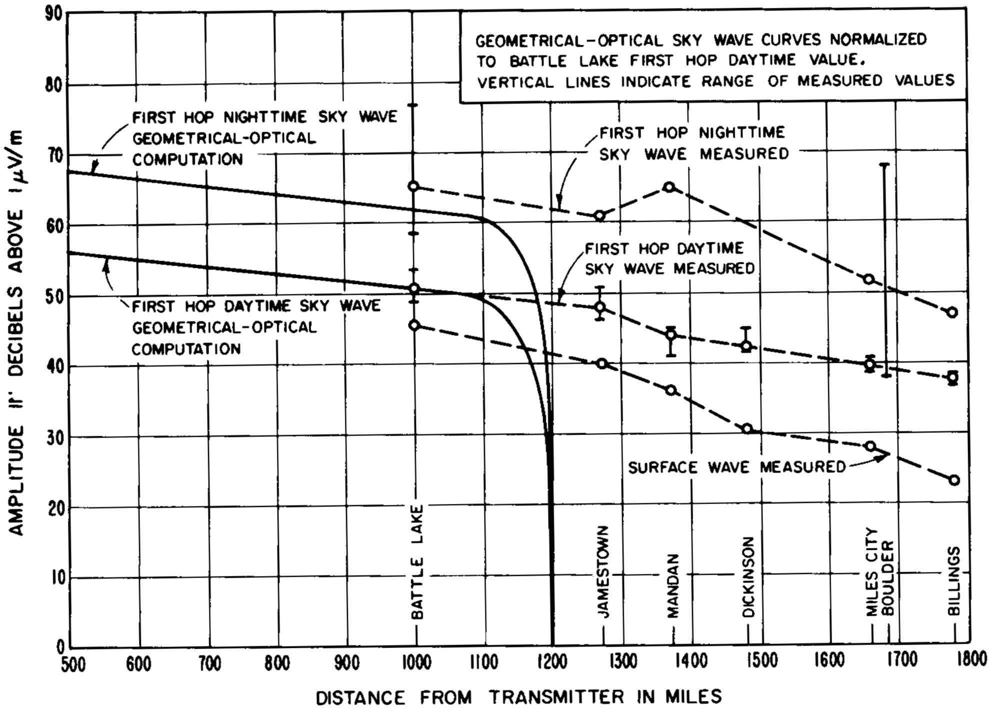

Figure 4.7. Cytac ground- and skywave measurements.

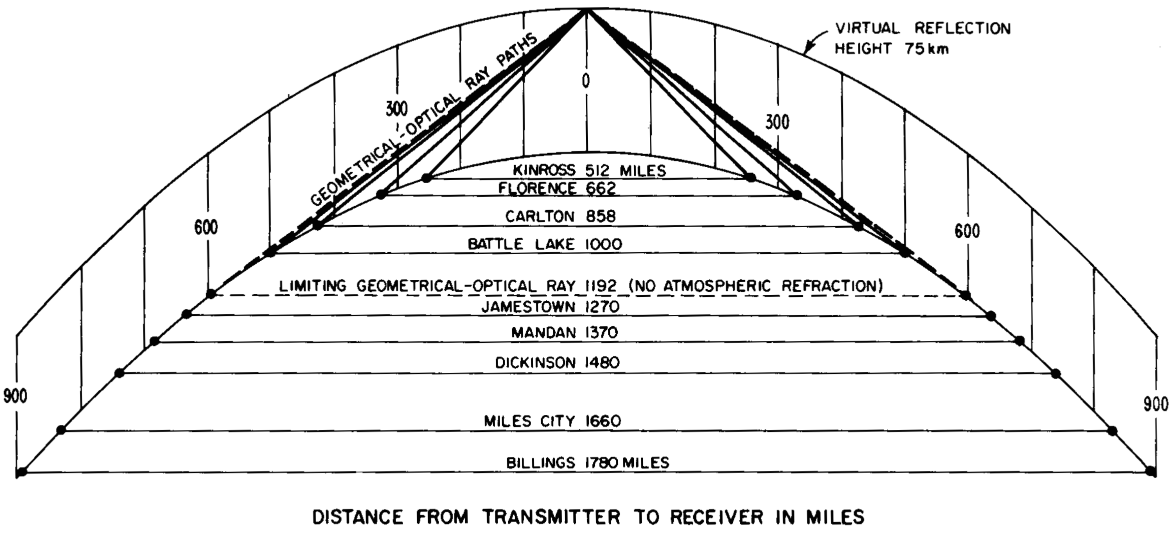

Figure 4.8. Geometric representation of skywave paths.

in the 1953 tests. If required, the peak power could be substantially increased and the average power could be increased by using a group of closely spaced pulses instead of a single pulse each repetition period.

4. By an ingenious scheme of synchronous switching, the zero drift in the servos, which had plagued Cyclan, was completely eliminated. Improvements in component quality and simplifications resulting from the use of a single frequency all combined to make the experimental equipment reasonably reliable in its operation. At best, Cytac would still be a complex system but hope for ultimately achieving adequate reliability became more realistic.

The completion of the preliminary field tests with clearly satisfactory results in regard to the points about which there had been justifiable skepticism, cleared the way to proceed with the development of the complete system. A system for military use, however, would involve problems that were taken into account in the preliminary tests. Enemy jamming could be assumed, and, unfortunately, the signal as used in the tests could be rendered useless by a simple CW emission on the same frequency.

To cope with the jamming problem, two entirely new concepts in loran signal format and signal processing were devised. Multiple pulsing, as already indicated, was used to increase the average power, but, more importantly, the multiple pulses made possible a scheme of phase coding that would reject synchronous jamming signals. A spacing of 1200 μs between pulses in a group of eight was somewhat arbitrarily chosen to allow time enough for the skywave reflections from a preceding pulse to arrive before transmitting the next pulse. The phase of each pulse was shifted in a fixed sequence. The shifts were exact multiples of 45°. The phase of the reference signal in the receiver was shifted in the same sequence so an interfering coherent CW signal would appear as noise in the detector output while the desired signal would be received normally.

The phase-shift sequence or code was made different for the master and slave stations to provide a means of signal identification and to facilitate automatic search. The master signal was further identified by transmitting an extra pulse in each group. The ninth pulse, however, was not included in the phase coding, but it served the very practical purpose of quick visual signal identification.

The basic principles of coherent detection will not be elaborated here, but some special comments may be in order regarding atmospheric noise, the wideband circuits, and the pulse-sampling techniques. At low frequencies in a band 20 kHz wide, atmospheric noise tends to have the characteristics of spikes or impulses rather than white noise. This is especially true when there are thunderstorms within a range of several hundred miles. The impulses are, of course, the radiated energy from individual lightning strokes. The impulses, or simply sferics, range in duration from several microseconds upwards but few exceed a millisecond. When a sferic and a Loran-C pulse arrive simultaneously, the receiver is frequently saturated and that particular pulse is obliterated. The output of the sampling gate is at maximum level with equal probability of being either positive or negative. When averaged, the positive and negative samples soon average to zero.

Under such receiving conditions, the loss of even a large percentage of the loran pulses has surprisingly small effect on the accuracy of the phase and envelope measurements.

As long as some of the pulses arrive "between the sferics" and compete only with the relatively quiet background noise, quite satisfactory measurements can be made. Contrasting the sferics with the relatively quiet background is accurate enough for describing the characteristics of noise that is typically received, but the background is, in reality, distant sferics from virtually all parts of the world where there are thunderstorms. The total number of lightning flashes taking place is so great that the very distant sferics overlap and resemble white noise. The characteristics of received atmospheric noise vary widely from time to time and place to place. The high-amplitude noise bursts which make up most of the total atmospheric noise power cause far less interference to the system than the same noise power in the form of white noise.

There is no adopted measure of atmospheric noise that adequately defines its interference value to a low-frequency pulse system. For that reason, data describing system performance in terms of signal-to-average or rms noise-ratio are not entirely consistent. Several years after the original development, it was shown by NBS (unreported formally) that noise-limited signal samples could easily be eliminated from the input to the post-detection filter. By accepting only "good" samples, an appreciable improvement in the stability of the phase and envelope readings can be achieved. There is evidently no simple way to describe the interference value of atmospheric noise.

5. CYTAC FIELD TESTS

5.1. General Description of Test Program

The preliminary tests in 1953 left little doubt that the system was sound in principle but whether or not it would actually yield the nominal 1000-ft accuracy at 1000 miles had to be demonstrated.

A test program was planned that, it was hoped, would provide conclusive answers on the feasibility of the system for bombing purposes. The principal participants in the program were the Air Force, NBS, Sperry Gyroscope Co., and the Stanford Research Institute (SRI). The Air Force provided overall guidance in planning. The primary role of NBS was in the area of radio propagation and data analysis (Linfield et al. 1957), while SRI was responsible for evaluating the susceptibility of the system to jamming. Sperry was responsible for carrying out the test program.

The airborne portion of Cytac consisted of two major components -- the navigation system and the bombing computer. While the test program envisioned testing the entire system ultimately, the immediate objectives were confined almost exclusively to testing the navigation system. The computer involved instrumentation only, but in contrast, the navigation system depended on several aspects of propagation that were not completely understood and, under any circumstances, would limit system performance.

Knowledge of groundwave phase corrections was somewhat limited at that time, but the Cyclan tests showed that propagation over different types of terrain could result in serious fix errors unless all factors were taken properly into account.

In those tests, no diurnal or other time variations of the groundwave phase were found but, on the other hand, there were no long-term measurements to establish the point conclusively. Also, the Cytac system involved propagation paths twice as long as those in the Cyclan tests. The preliminary Cytac tests used a single transmitter, and even though the paths were long, the stability of the groundwave still had not been proved to the satisfaction of all.

Another possible pitfall was the possibility of cycle ambiguity at the greater distances. Cycle identification at ranges up to about 100 miles had been demonstrated by NBS in 1952 and the technique for marking a point on the pulse envelope (developed by Sperry) by subtracting the derivative of the envelope from the undifferentiated envelopes was used in the preliminary tests in 1953. While there did not appear to be any serious shift of the cycles relative to the envelope, the tests were not absolutely conclusive on this point. At that time, the dispersion or change in shape of the pulse as a function of distance and conductivity had not been evaluated, but it was realized that the upper and lower sidebands extending to approximately 110 and 90 kHz would be attenuated differently. Some change in pulse shape was expected.

The limited measurements were ample to warrant confidence that there would not be a cycle ambiguity problem at short range and perhaps not at long range. But the long-range measurements in 1953 used a common path for the simulated master and slave signals. Different paths might introduce trouble. In any event, it was reasoned that even if there should be considerable shift of the cycles relative to the envelope, the shift would be somewhat similar in both master and slave signals and that would tend to minimize the problem.

The stability of the groundwave phase that had been observed in the Cyclan tests created a great deal of optimism about the performance that could be expected from Cytac, but nothing short of a full-scale test of the system could provide direct answers to the many crucial questions.

Transmitters were installed at Carolina Beach, North Carolina, Carabelle, Florida, and Forestport, New York. Vertical top-loaded antennas were used. The Forestport station was installed at the Air Force experimental transmitter site where a 1200-ft base-insulated antenna was available. The other two stations used 650-ft base-insulated self-supporting towers.

Despite the difference in antenna heights, the pulses were very similar in shape. All the transmitters were alike , but the greater efficiency of the taller antenna provided a radiated signal of 220 kW (peak-pulse power) while only 50 to 60 kW could be radiated from the other antennas. The stations were operated as a triplet with Carolina Beach serving as the master.

A total of seven receivers were built for the test program. Five were intended for ground monitoring only and were of standard rack and panel construction. The other two were packaged for airborne use.

The test program was scheduled for 1 year to obtain data on any seasonal variations in the propagation that might be found and to allow enough time to make the many measurements necessary with the limited number of receivers.

To determine whether or not long-term variations or trends in the time-difference readings would be found would require measurements at one or more fixed locations for the duration of the program. It was further reasoned that the long-term measurements should include as wide a variety of propagation paths as possible. It was agreed that three of the receivers should be used for fixed-station monitoring.

One receiver was located at a site about 50 miles west of the master transmitter to provide an approximate check on the round-trip time measurements made at the master and to monitor the overall stability of the system. Such a check was considered worthwhile because of the inherent problems in making precise time-difference measurements at a transmitter. A site in the prime part of the service area near South Webster, Ohio, was selected for the second receiver and the third was located near Clarksdale, Mississippi, toward the fringe of the service area.

The remaining two ground-monitoring receivers (GMR's) were installed in vans so short-term measurements could be made at a wide variety of locations and distances.

The selection of monitoring sites that would satisfy the requirements for the test program was a task in itself. Most of the site selection was done in advance since it was obvious that an excessive amount of operating time would be lost if sites had to be found during the program. It was also desirable to select the sites in advance so the time-difference computations could be made before making measurements.

It was assumed that an ideal site should be on flat homogeneous ground where there were no trees or other obstructions. In addition, precise geographic coordinates were specifically required.

In order to satisfy the latter requirement, sites were chosen at or near first-order triangulation stations. The other requirements, however, were more difficult to satisfy. Practical rules of thumb had to be adopted regarding trees, overhead wires and the like. In the Cyclan tests it was found that standing waves induced in overhead wires greatly affected the em field at very short distances but the effect was quite localized. It was assumed that if there were no trees or wires within 100 yards of the receiver, the site would be satisfactory.

The 26 sites (see table 5.1) were selected in advance and most of them are identified by the name of the triangulation station.

During the test program, extensive use was made of topographic maps for both ground and airborne measurements. In most cases, coordinates could be scaled with satisfactory accuracy.

Regular operation of the transmitters started in September, 1954, and was continued through the middle of October, 1955. The operating schedule, however, was not on a 24-hr basis but enough measurements to suffice were obtained at all hours of the day. The system was not operated continuously for economic reasons. From a technical standpoint, the intermittent schedule was not fully satisfactory because of the time required for the transmitters to warm up and otherwise settle down to steady-state operation after each off-period.

Since the phase-coding function of the system was classified, there was reluctance to transmit the coded signals. It was assumed that the coding would have no bearing on the test results so the decision not to reveal any more of the system characteristics than necessary during the tests appeared entirely logical. Phase coding was designed to minimize the effects of synchronous jamming but no one realized until late in the program that multiple-hop skywave reflections were, in fact, causing a significant amount of self-jamming. The 1200-μs spacing between individual pulses in the groups of

Table 5.1. Cytac Test-Site Locations.

1. Bedford, Pennsylvania
2. Brownsville, Texas
3. Canaday, Georgia
4. Cat Point, Florida
5. Chester, Georgia
6. Clementine, Missouri
7. Cumby, Texas
8. Diamond, Kentucky
9. E. Martello, Florida
10. Evensville, Tennessee
11. Forman, Arkansas
12. Gavin, Mississippi
13. Goose, Indiana
14. Irvin, Louisiana
15. Max Patch, North Carolina
16. Meserve, Maine
17. Prospect, Pennsylvania
18. Punta Rassa, Florida
19. Rena Lara, Mississippi
20. Rodgers, North Carolina
21. Roe, Ohio
22. Smith Louisiana
23. Smith Center, Kansas
24. Wilson, Florida
25. Wolverhill, Virginia
26. Yerkes, Wisconsin

eight was thought to be large enough to avoid skywave interference among the pulses. Rather accidentally it was discovered that the higher order hops were interfering, but unfortunately that discovery was almost too late. After some persuasion, phase coding was used during the last two months of operation. The result was that only two months of really good data were obtained.

While the measurements made with the GMR's were an entirely necessary part of the program, the results of those measurements did not necessarily reveal how accurately an aircraft could be guided to a predetermined bomb-release point.

The GMR's were built for fixed operation so there was no need for rate servos. Also, long time constants were used to reduce the effects of noise.

In the dynamic situation of drawing information from the signals to provide guidance for an aircraft, time constants and signal-to-noise ratio are items of major importance. Time constants must be long enough to provide satisfactory smoothing of the time-difference readings, but they must also be short enough to respond to the changing readings as the aircraft moves across the hyperbolic grid. Rate servos can update the readings to the approximate position of the aircraft when flying a straight course, but during maneuvers or any change in course, additional information must be drawn from the signals. In this situation, the signal-to-noise ratio is the principal factor that ultimately governs the difference between the indicated position of the aircraft and its actual position.

Ultimately, it was recognized that acceleration information would probably have to be obtained from inertial devices in order to insure the required accuracy. The immediate test objectives, however, were confined to the radio system only. Refinements could be added if necessary.

Two independent methods of correlating the aircraft's position with the Cytac grid were devised. One consisted of using a vertical camera on a gyro-stabilized mount to photograph identifiable objects on the ground whose Cytac coordinates were known. At the instant a picture was taken, the Cytac coordinates, as measured in the aircraft, were recorded. The other method consisted of plotting the aircraft's track as observed with a vertical camera obscura (24-inch focal length lens) that was mounted immediately beside one of the GMR's. An autopilot coupler was used with the airborne receiver to hold the aircraft on the same line of position as measured by the GMR. By flying first one line of position and then the other, a fix could be established by the intersection of the two tracks. At altitudes from about 1000 ft up, it was quite easy to follow the image of the aircraft with a pencil as it moved across a calibrated chart used with the camera obscura.

Both methods were quite accurate and entirely adequate for the purpose. The camera obscura, however, did have one distinct advantage. The results of each test could be communicated immediately by radio to the aircraft. When it was necessary to repeat a run, and it frequently was, it could be done immediately.

A variation of the first method, combined with the autopilot coupler, was used quite successfully to determine how accurately the aircraft could be guided to any specified set of target coordinates. In these tests the aircraft was flown automatically on one line of position and the vertical camera was triggered by the other line or time-difference reading.

5.2. Summary of Field Measurements

The location of the transmitters and the hyperbolic grid of the system are shown in figure 5.1. The sites and area where measurements were made are shown in figure 5.2. The following representative and significant data are presented and discussed (Linfield et al. 1957).

5.2.1. Baseline Extension Measurements

The first measurements were made in the Forestport baseline extension region to determine the coding delay. The measurement and analysis technique used was similar to, and identical in principle to, that described in section 9. Both airborne and ground measurements were made. Figure 5.3 is a map of the Forestport baseline extension region showing where the measurements were made.

The available roads crossed the extension obliquely rather than at right angles. The oblique-crossing data were entirely valid but more computation was required in the analysis. The distance from the Forestport transmitter to the various crossings is shown in the following tabulation.

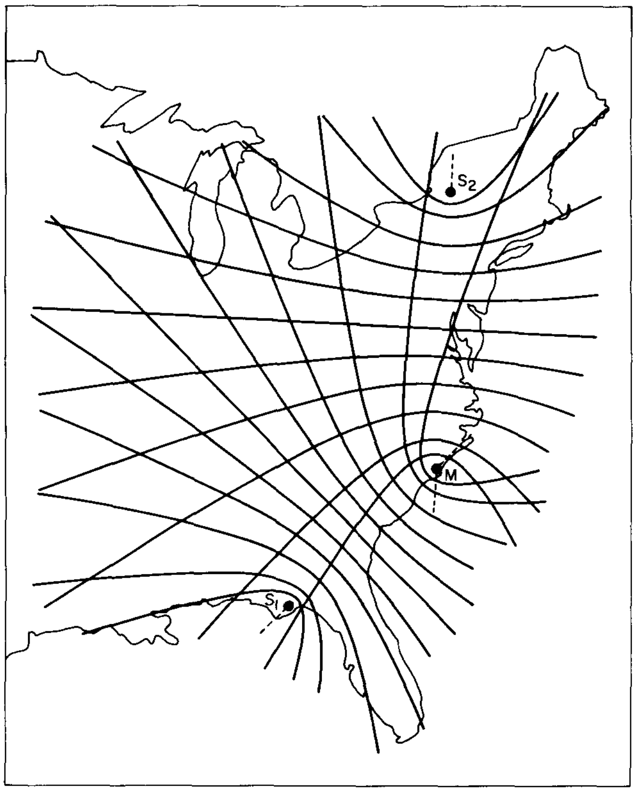

Figure 5.1. Cytac transmitters and grid.

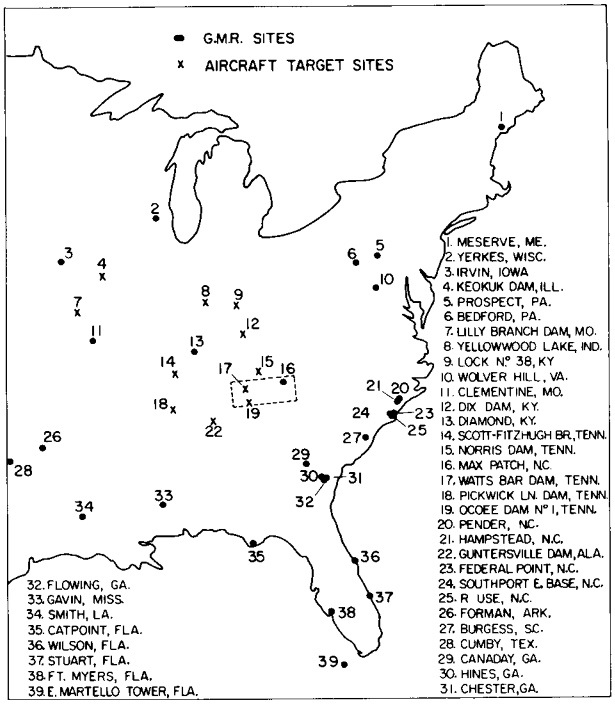

Figure 5.2. Cytac monitoring sites.

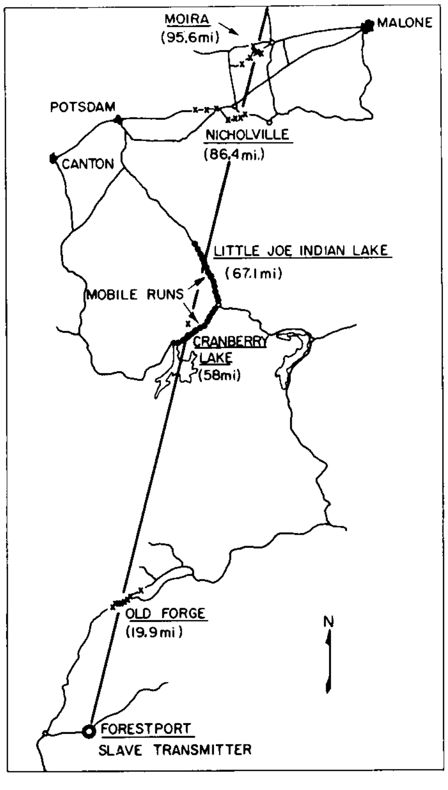

Figure 5.3. Forestport (S_2) baseline extension.

1.	Old Forge	19.9	statute miles
2.	Cranberry Lake	58.0	"
3.	Little Joe Indian	67.1	"
4.	Nicholville	86.4	"
5.	Moira	95.6	"

The time-difference reading was monitored at a point close to the extension near Cranberry Lake for a total of 34 hours. At each of the other sites, approximately 2 hours of data were obtained. In addition to monitoring at the different sites, mobile runs were made at Cranberry Lake and Little Joe Indian. Since the GMR's did not have rate servos, the speed of the van was kept very low.

Three sets of time-difference curves based on NBS Circular 573 (Johler et al., 1956) were computed for each of the crossings (conductivities of 0.0005, 0.001 and 0.005 mhos/m) were used. The measured values, plotted to the best scale, were superimposed on the computed curves for the best overall fit. The measurements matched the curves for 0.001 mhos/m quite well as can be seen in figures 5.4 and 5.5. The same data are used in both figures. In figure 5.5, however, all the data are used (with appropriate adjustments for those measurements slightly off the extension) to obtain a more reliable average. The coding delay was found by subtracting the no-coding-delay-crossing values from the corresponding measured time differences. For example:

At Cranberry Lake	
Measured time difference	31107.56 μs
No-coding-delay-time difference	1.60
Coding delay	31105.96 μs

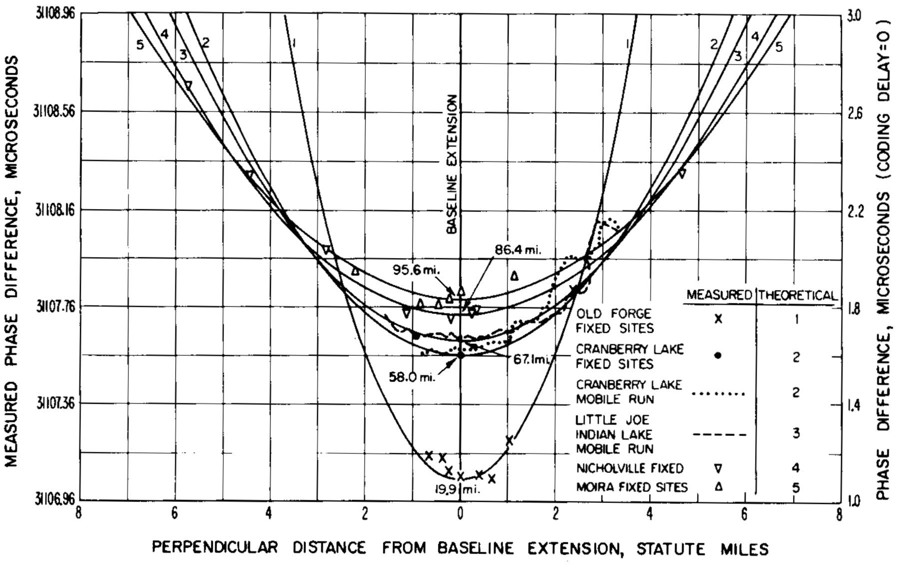

Figure 5.4. Forestport measurements. Smooth curves are for σ = 0.001.

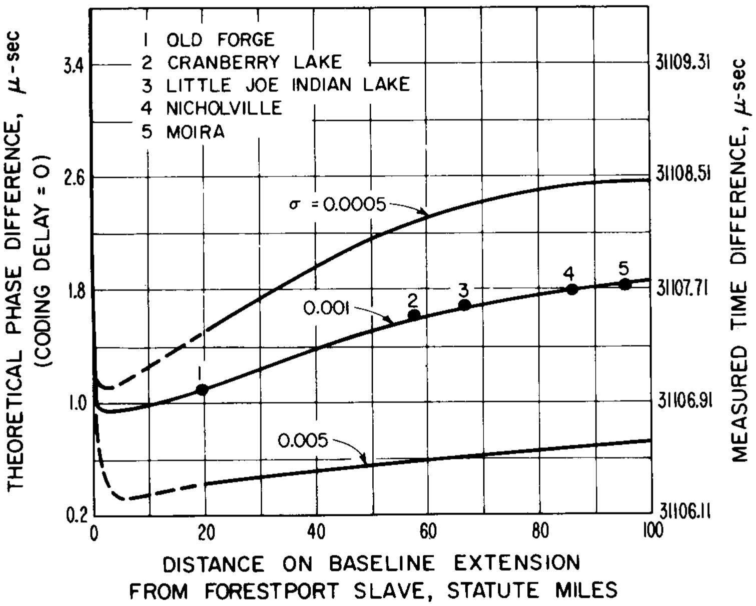

Figure 5.5. Forestport measurements.

The other three baseline extensions were over sea water so those readings were determined quite easily with the airborne receiver. Note in figure 9.2 (page 127) the secondary correction over sea water in the range of 30 to 100 km is quite small and changes slowly. The exact distance from the transmitter at which the crossings were made was not critical.

The measured coding delay of the Carabelle slave was 13808.00 μs and the transmission times over the two baselines were:

Master to Forestport	3576.71 μs
Master to Carabelle	2602.79 μs

These values are one half the round-trip transmission time measured on the master baseline extensions.

5.2.2. Random Errors

Table 5.2 shows the date of operation, the number of hours of observations and the number of individual time-difference (phase and envelope) readings recorded by the ground-monitor receivers at 26 different sites. The readings were continuously recorded on Esterline Angus charts. The charts were scaled at 2.5-min intervals to obtain individual readings.

Both random and systematic errors in the time-difference readings were found at all the monitoring sites. The mean reading at a site may properly be considered to be the correct reading, while the deviation of individual readings from that value represents the random or unpredictable error which is inherent in the system. Figures 5.6 through 5.10 show the cumulative distributions of random errors at five representative sites.

Table 5.2. Periods of observation.

Site No.	Site	Period Covered		Hours of Observation	Number of Observations
		From	Thru		
1.	Bedford, Pa.	10/28/54	10/29/54	51.8	1243
2.	Brownsville, Tex.	2/7/55	4/12/55	97.9	2349
3.	Canaday, Ga.	12/16/54	12/17/54	14.2	341
4.	Cat Pt., Fla.	1/26/55	1/26/55	9.3	223
5.	Chester, Ga.	12/29/54	12/31/54	15.6	374
6.	Clementine, Mo.	12/6/54	12/10/54	52.0	1248
7.	Cumby, Tex	2/4/55	2/4/55	6.8	163
8.	Diamond, Ky.	12/13/54	12/17/54	5.2	124
9.	E. Martello, Fla.	1/13/55	1/14/55	8.0	192
10.	Evensville, Tenn.	11/29/54	12/3/54	57.8	1387
11.	Forman, Ark.	2/2/55	2/3/55	8.0	192
12.	Gavin, Miss.	1/27/55	1/28/55	7.8	187
13.	Goose, Ind.	11/8/54	11/12/54	51.2	1229
14.	Irvin, Ia.	11/23/54	11/24/54	21.8	523
15.	Max Patch, N.C.	11/18/54	11/19/54	27.2	653
16.	Meserve, Me.	10/5/54	10/15/54	91.8	2203
17.	Prospect, Pa.	10/25/54	10/27/54	17.1	410
18.	Punta Rassa, Fla.	1/17/55	1/18/55	7.1	170
19.	Rena, Miss.	11/1/54	10/7/55	800 (206)	4944
20.	Rodgers, N.C.	11/1/54	9/12/55	750 (244)	5856
21.	Roe, Ohio	11/1/54	2/11/55	200 (26)	624
22.	Smith, La.	1/31/55	2/1/55	8.7	208
23.	Smith Center, Kansas	11/29/54	12/3/54	30.4	729
24.	Wilson, Fla.	1/6/55	1/12/55	33.9	814
25.	Wolverhill, Va.	10/28/54	10/29/54	16.4	394
26.	Yerkes, Wis.	11/15/54	11/19/54	45.9	1102

These errors are attributable to noise, instrumentation, and propagation. Since phase coding was not used when these measurements were made, it may be possible that multiple-hop skywave interference contributed to these errors. (Multiple-hop skywave interference will be discussed later in this section.)

Most of the errors appear to be normally distributed. Both noise and skywave interference will produce that type of distribution. Some of the errors, however, appear to have a different origin. Note the S_2 readings in figure 5.6. The abrupt changes at both ends of the distribution indicate errors of a non-random nature. The actual reason for those errors is not known but it is a reasonable guess that changes in the coding delay or envelope-cycle relationship occurred for brief periods of time.

The geometry of the hyperbolic grid and the variability of the time-difference readings combine to cause the fix errors to be distributed in the form of an ellipse. The error ellipses containing 50 percent of the fixes at the above five sites are shown in figures 5.11 through 5.15. For comparison, the circular-error probability (CEP) for 50 percent of the fixes is also shown. The major and minor semi-axes of the ellipses (50 percent of fixes) at 22 of the sites are tabulated in table 5.3.

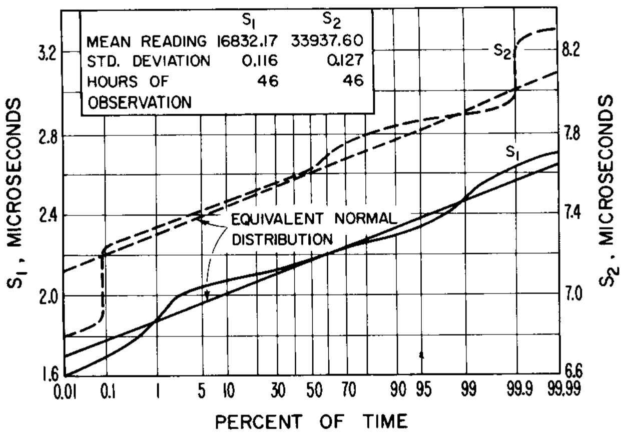

Figure 5.6. Readings at Williams Bay, Wisconsin.

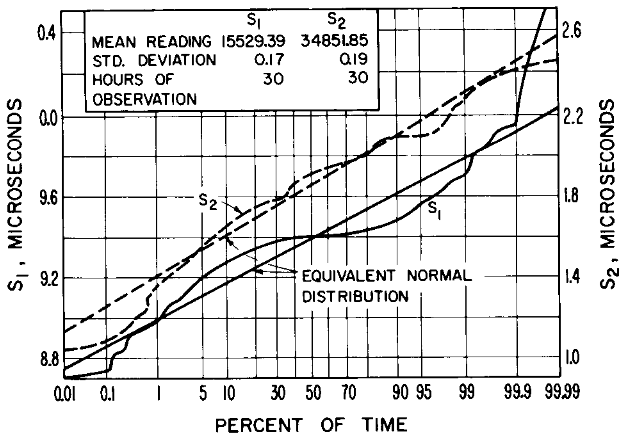

Figure 5.7. Reading at Smith Center, Kansas.

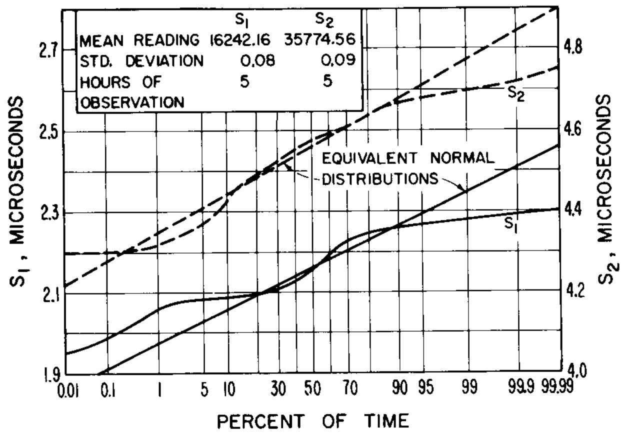

Figure 5.8. Readings at Drakesboro, Kentucky

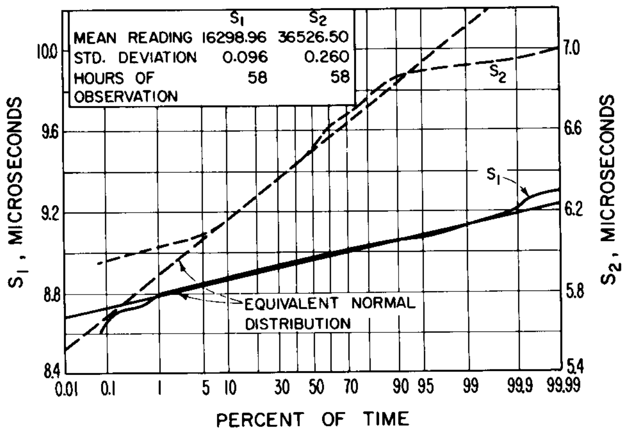

Figure 5.9. Readings at Dayton, Tennessee.

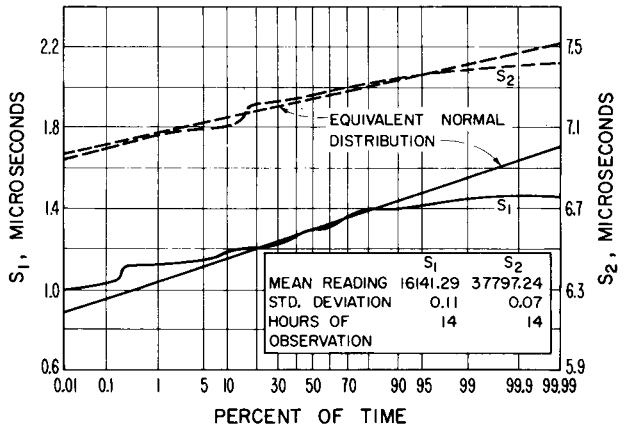

Figure 5.10. Readings at Twin City, Georgia.

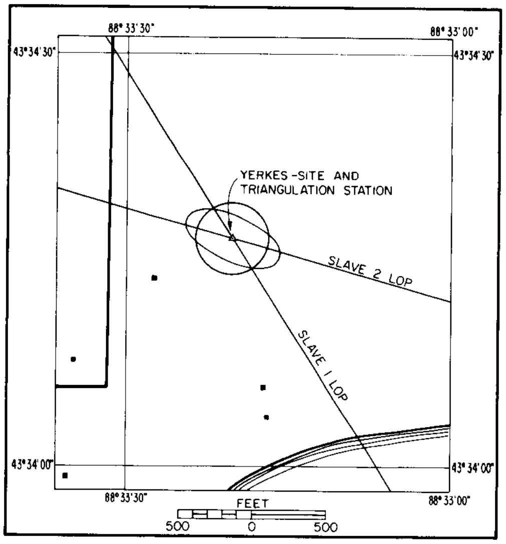

Figure 5.11. Circular and elliptical distribution of errors, 50% of fixes. Williams Bay, Wisconsin.

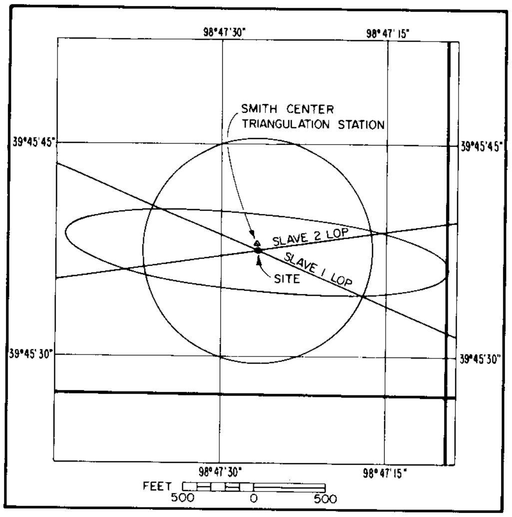

Figure 5.12. Circular and elliptical distribution of errors, 50% of fixes. Smith Center, Kansas.

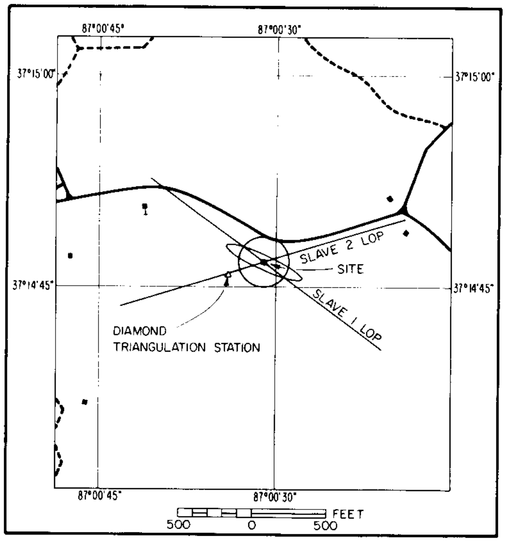

Figure 5.13. Circular and elliptical distribution of errors, 50% of fixes. Drakesboro, Kentucky.

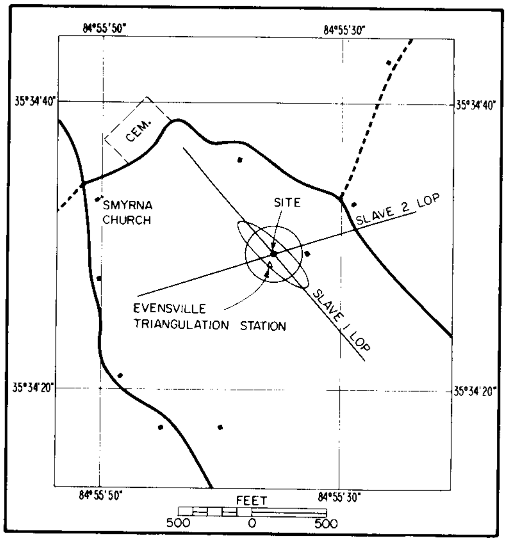

Figure 5.14. Circular and elliptical distribution of errors, 50% of fixes. Dayton, Tennessee.

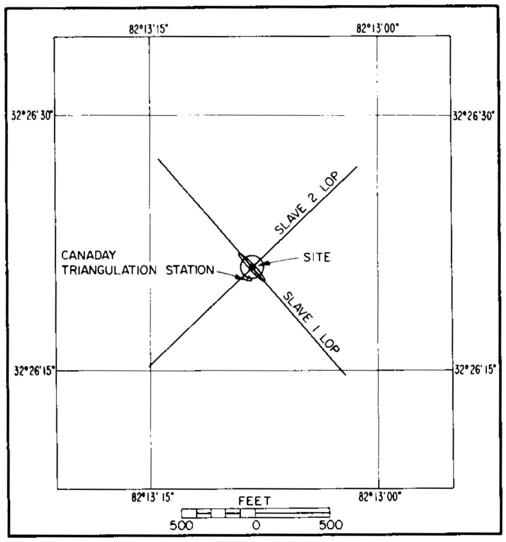

Figure 5.15. Circular and elliptical distribution of errors, 50% of fixes. Twin City, Georgia.

Table 5.3. Major and Minor Semi-Axis of 50-Percent Error Elipses

	Major Semi-axis (ft)	Minor Semi-axis (ft)
1. Bedford, Pennsylvania	240	31
2. Canaday, Georgia	120	65
3. Cat Point, Florida	4072	254
4. Chester, Georgia	378	49
5. Clementine, Missouri	840	173
6. Cumby, Texas	773	73
7. Diamond, Kentucky	289	52
8. Evensville, Tennessee	334	84
9. Forman, Arkansas	941	90
10. Gavin, Mississippi	742	124
11. Goose, Indiana	186	85
12. Irvin, Iowa	588	112
13. Max Patch, North Carolina	100	80
14. Prospect, Pennsylvania	223	29
15. Punta Rassa, Florida	2157	63
16. Rena Lara, Mississippi	1370	207
17. Rodgers, North Carolina	345	106
18. Roe, Ohio	108	51
19. Smith Center, Kansas	1384	287
20. Wilson, Florida	3481	120
21. Wolverhill, Virginia	345	30
22. Yerkes, Wisconsin	347	159

5.2.3. Systematic Errors

The difference between computed and measured time differences can be treated as a systematic error. The major source of systematic errors is inaccuracy in computing the transmission time of the signals. Errors in either distance or the velocity of propagation or both, affect the computation but in these tests, significant distance errors were eliminated by using sites whose coordinates were established by first-order triangulation. To a good approximation, all the systematic errors can be attributed to the physical characteristics of the ground over which the signals were propagated.

The distances from the transmitters to each of the sites were computed by the method given by Clarke (1880). The propagation times were computed in accordance with NBS Circular 573 (Johler et al. 1956), "Phase of the low radio frequency ground wave". Secondary corrections for paths of mixed conductivity were computed by a method given by Millington (Millington and Isted, 1950). The majority of the conductivity data available was in the form of a conductivity map of the U.S. (Fine, 1954). This map, however, is based on the attenuation of standard broadcast signals , and little hope was held that it would be meaningful at 100 kHz.

Since the conductivity cannot be determined from individual time-difference measurements alone (except in the case of the round-trip time between transmitters and as described in sec. 9), and because the conductivity data were of such a dubious nature, a great deal of trial-and-error procedure was necessary to correlate the measurements with the computations.

It was found that secondary-phase corrections based on a conductivity of 0.005 mhos/m gave the smallest (nearly 0) average systematic error. Corrections based on the FCC map reduced the error in slightly over one third of the cases but increased the error in the others (see table 5.4).

It was thought that paths involving mountainous terrain might require larger phase corrections than would be indicated by the conductivity alone. The elevation profiles of several paths were plotted but there was no obvious correlation between the topographic features and the time-difference readings.

At the 26 monitoring sites, the systematic error (based on 0.005 mhos/m) was less than 1 μs in 72 percent of the lines of position. Since the errors were small in most cases, linear interpolations of the errors between the sites were made in order to construct contours of constant error (see figs. 5.16 and 5.17).

5.2.4. Flight Tests (Random and Systematic Errors)

The interpretation of the data given below is essentially the interpretation made during and immediately after the tests. A recent review of the test results strongly suggests that in and over mountainous terrain, unexpected scatter fields contributed inaccuracies that were blamed on noise, improper adjustment of autopilot coupling, etc. There was a tendency for the aircraft to fly an oscillatory track, especially at Dayton, Tennessee, and the reason was thought to be improper autopilot coupling adjustment. It now seems more probable that distortion of the grid by scatter fields is the correct explanation of the results (see sec. 9).

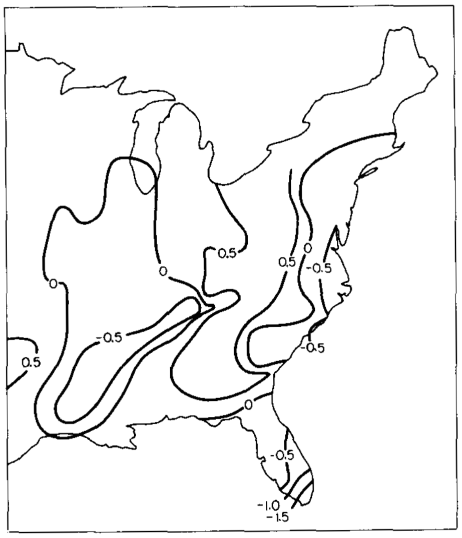

Figure 5.16. Contours of constant time-difference corrections (S_1).

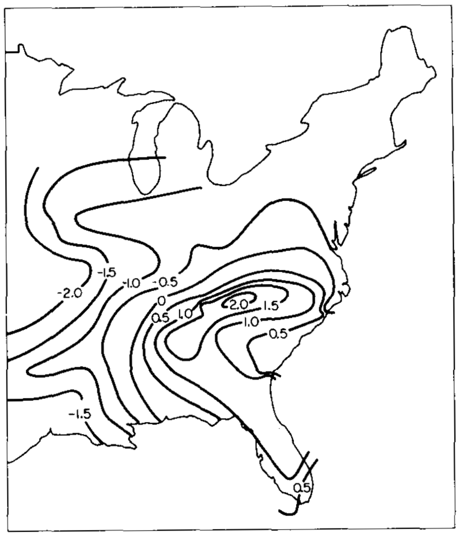

Figure 5.17. Contours of constant time-difference correction (S_2).

Table 5.4. Cytac Errors Based on Conductivity Corrections.

	Site	Errors in μs					
		No Correction		0.005 mhos/m		Millington-FCC Map	
		S_1	S_2	S_1	S_2	S_1	S_2
1.	Bedford, Pennsylvania	+3.80	-0.99	+1.30	-0.09	+0.22	+0.26
2.	Brownsville, Texas	-3.32		-1.25			
3.	Canaday, Georgia	-0.35	+4.58	-0.05	+0.38	-0.82	-0.52
4.	Cat. Point, Florida	-3.20	+4.80	-0.01	+0.65		
5.	Chester, Georgia	+0.62	+5.24	+0.32	+0.14		
6.	Clementine, Missouri	-1.14	-1.88	-0.04	-2.88		
7.	Cumby, Texas	-1.70	+0.66	+0.80	-1.19		
8.	Diamond, Kentucky	-0.13	+0.47	-0.07	-0.95	+0.55	+0.35
9.	E. Martello, Florida	-0.85	+5.45	-1.08	-0.03	-0.40	-1.37
10.	Evensville, Tennessee	-0.86	+3.02	-0.76	+0.78		
11.	Forman, Arkansas	-1.82	+0.68	+0.48	-1.37		
12.	Gavin, Mississippi	-2.67	+3.52	+0.43	+0.07	+0.04	-0.81
13.	Goose, Indiana	+1.39	-1.94	+0.29	-1.04	-0.28	+0.76
14.	Irvin, Iowa	-0.20	-1.68	+0.28	-1.58		
15.	Max Patch, North Carolina	+1.34	+4.74	+0.50	+2.24	-0.29	+2.50
16.	Meserve, Maine		-0.47		-0.07		+1.82
17.	Prospect, Pennsylvania	+2.55	-1.63	-0.15	-0.43	-0.78	+0.39
18.	Punta Rassa, Florida	-1.27	+5.87	+0.02	+0.02	+0.73	+0.05
19.	Rena Lara, Louisiana	-2.03	+1.93	-0.10	-0.47	-0.45	-0.46
20.	Rodgers, North Carolina	+3.35	+5.43	+0.35	+1.01	-0.82	-0.80
21.	Roe, Ohio	+2.02	+0.04	+0.48	-1.20		
22.	Smith, Louisiana	-3.96	+1.32	-0.81	-1.59	-0.86	-1.52
23.	Smith Center, Kansas	-1.70	-2.02	-0.60	-2.22		
24.	Wilson, Florida	+0.90	+5.79	-0.51	+0.89	-1.46	-0.43
25.	Wolverhill, Virginia	+3.50	-0.33	+0.63	-0.33		
26.	Yerkes, Wisconsin	+0.37	-2.23	-0.13	-1.33		

Random errors can be removed from the GMR data by long-term averaging as has been done above in order to study the systematic errors. Random errors in data taken in flight can be minimized but not removed entirely, while the systematic errors can be effectively removed. The technique described earlier of flying over a GMR using the same lines of position indicated by the GMR provided a means of evaluating directly the accuracy with which an aircraft could be guided to known coordinates.

Periodically, during these tests, the GMR and airborne receiver (EAR) readings were compared by bringing the GMR to a conveniently located airport where th equipments could be operated at the same place. In most instances, both receivers gave the same readings, but in some cases they differed by as much as 0.2 to 0.3 μs. The reason for the different readings could not be fully determined with the test equipment available in the field, but when differences were found, attempts were made to take them into account in the data analysis.

Sites for these tests were chosen so the propagation paths included mountains, smooth terrain, and sea water, in various combinations. The sites were located near Dayton, Tennessee, Twin City, Georgia, Savannah, Georgia, Titusville, Florida, and Fort Meyers, Florida. It was suspected that mountainous regions might involve complicated corrections and that shorelines might cause phase perturbations which would affect the guidance accuracy.

The site at Dayton, Tennessee was chosen because of its proximity to the mountains. The path to the master station crossed the mountains within a few miles from the receiver and it was thought the effective path length might be shorter at altitude because the "ray path" between the aircraft and the transmitter would be a smoother arc than that defined by the elevation profile of the terrain. (This subject is discussed further in sec. 9.) The paths to the slave stations were somewhat similar, but the distance from the receiver to the mountains was greater. Several flights over the GMR were made at 2000-, 6000-, and 10,000-ft altitudes using the autopilot coupler. The track of the aircraft passed near the GMR but not precisely over it except in a few cases. The difference between the ground and airborne readings was adjusted to take the miss distance into account. The adjusted differences are plotted in figures 5.18 and 5.19. The track of the aircraft on several flights, as plotted with the camera obscura, is shown in figure 5.20.

The data seem to indicate a change in reading with altitude as would occur if the path to the master station were shortened. However, the scatter of the individual readings and the possibility that small instrumentation errors could have occurred, reduce the confidence that should be placed in the results. These flights were among the first using the autopilot coupler, and it took some time for all concerned to acquire the skill and know-how needed to carry out the measurements efficiently.

The results of the flight tests at Dayton and the other four sites are shown in tables 5.5 through 5.10. The average miss distances vary by as much as 10:1 among the sites. At least one cause for this was the autopilot coupler that was not designed to operate under adverse noise conditions. At Savannah and Titusville, the signal-to-noise ratio was excellent (M and S_1), and the accuracy of the guidance was limited mainly by the instrumentation -- not propagation. At Dayton, the signal-to-noise ratio was relatively

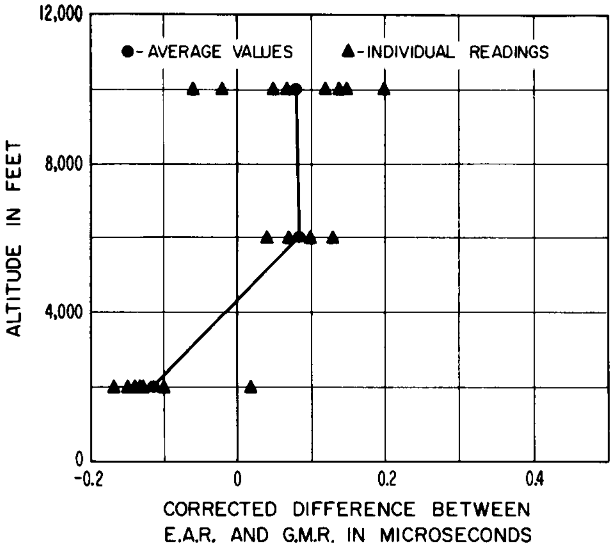

Figure 5.18. S_1 readings, Dayton, Tennessee.

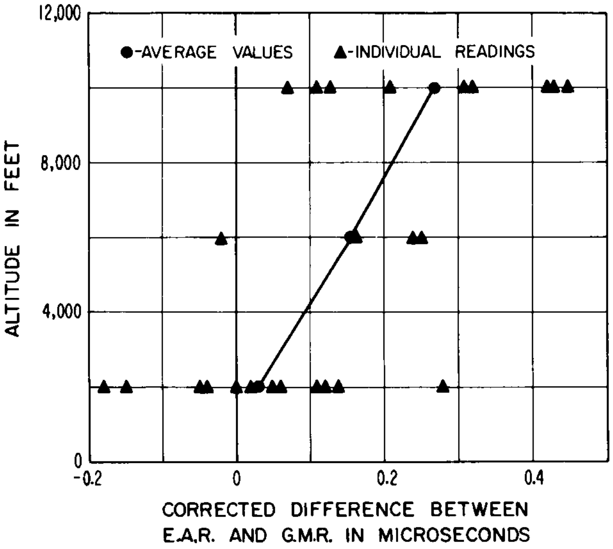

Figure 5.19. S_2 readings, Dayton, Tennessee.

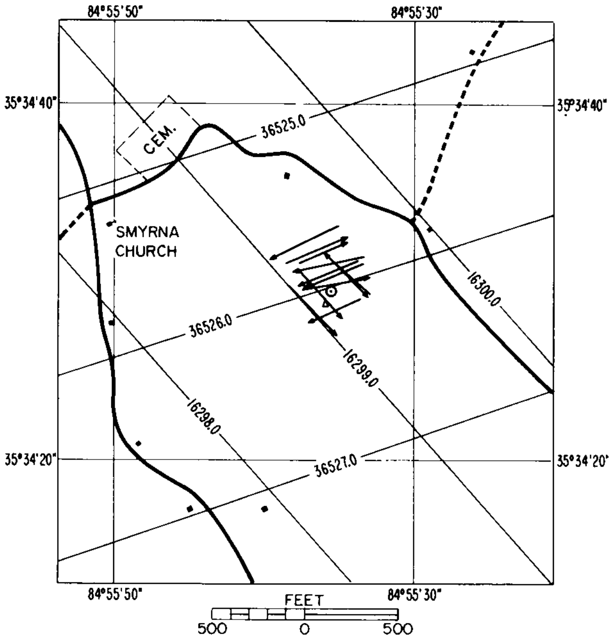

Figure 5.20. Tracks of aircraft flying over GMR, Dayton, Tennessee.

good, but evidently there were enough sferics to materially degrade the precision of the control.

The ground and airborne readings were compared after making adjustments for the miss distance as determined by both the vertical camera and the camera obscura. The absolute value of the difference is small and the algebraic average of the differences is zero or nearly so in all cases except at Dayton on the S_2 pair. The fact that the average is not zero in this case could be interpreted as evidence to support the notion that the reading changed with altitude. However, if the effective distance to the master station did become shorter with altitude, the S_1 readings should have changed also, but the algebraic average of the S_1 differences does not show such a change. It seems more probable that an instrumentation error was present in the S_2 readings.

The sites at Savannah, Titusville, Punta Rassa, and Fort Meyers were all either on or very near a shoreline. Phase perturbations at the land-sea boundaries were expected but they were either absent or so small they escaped notice. A year later (1956), such phase perturbations were clearly found with the Decca system and were reported by Pressey et al. (1956), Pressey and Ashwell (1956), and Reynolds (1953). Why the pulse system does not seem to detect the shoreline phase perturbations has not been explained.

Flying over a GMR on the same lines of position observed by the GMR demonstrated the accuracy that could be expected from the system when the target coordinates were known. In actual use of the system, target coordinates would not be known so precisely. Systematic errors could seriously degrade the accuracy even if the random errors were within acceptable limits. To test the system more realistically, 11 targets were selected that were easily identifiable from the air. Their coordinates were computed on the basis of a uniform conductivity of 0.005 mhos/m and then adjusted by applying the systematic corrections scaled from figures 5.16 and 5.17.

The aircraft was flown along one coordinate or line of position with the autopilot coupler and the vertical camera was triggered when the other target coordinate was reached. The miss distances were scaled from the photographs. Figures 5.21 and 5.22 are the photographs of the Watts Bar Dam and the Scott-Fitzhugh Bridge that were selected as targets. The computed Cytac coordinates and the aircraft positions are superimposed.

In table 5.10, the actual miss distances, the computed miss distances that would have prevailed if no systematic corrections had been used, and the distance to the nearest calibration (GMR) site are shown.

The average improvement in accuracy from the systematic corrections was entirely expected, but the deterioration of the accuracy at Yellowwood Lake Dam and Dix Dam was surprising. These targets were nearer the transmitters than the rest, with the exception of one other, so it is unlikely that noise was a controlling factor. Possible causes of the greater errors are multiple-hop skywave interference and inaccuracy in the systematic corrections used. Multiple-hop skywaves probably caused errors in the S_2 synchronization and in the time differences measured by the receivers. It is also possible that the mean values of the readings obtained at the GMR sites were subject to errors of a few tenths of a microsecond. Consequently, the systematic corrections (figs. 5.16 and 5.17) are subject to the same errors. The widely varying

Table 5.5 C-47 flights at Dayton, Tennessee (Evensville).

Distance to Transmitters in Statute Miles

M = 412.006

S_1 = 391.257

S_2 = 754.802

Microseconds difference between G M R and E A R corrected

Run No.	Altitude	LOP flown	Miss distance feet	Aerial	Photos	Camera	Obscura
				S_1	S_2	S_1	S_2
Nov. 30, 1954							
1	2,000	none	---				- .04
2	2,000	none	---				+ .12
3	2,000	none	---	- .13	+ .13	- .07	+ .11
4	2,000	S_2	245	- .10	+ .02	+ .11	.00
5	2,000	S_2	78	- .13	- .01	- .18	- .05
6	2,000	S_1	52	+ .03	+ .28	+ .02	+ .29
7	2,000	S_1	135	- .14	- .15	- .14	- .32
9	10,000	S_1	130	- .02	+ .32	- .02	- .08
10	10,000	S_1	156	+ .04	+ .11	- .06	+ .29
11	10,000	S_2	312	+ .05	+ .18	+ .03	+ .07
13	10,000	S_2	104	+ .07	+ .27	- .08	+ .27
14	10,000	---	---		+ .25	+ .25	+ .13
Dec. 3, 1954							
1	2,000	S_2	66	- .47[1]	- .19	- .61[1]	- .18
2	2,000	S_2	286	- .17	+ .06	- .25	+ .02
3	2,000	S_1	317	- .16	+ .05	- .15	+ .09
Dec. 10, 1954							
2	10,000	S_2	609[2]		+ .19		+ .21
3	10,000	S_2	54	+ .14	+ .42	+ .05	+ .45
4	10,000	S_2	350	+ .12	+ .40	- .09	+ .43
5	10,000	S_1	133	+ .15	+ .31	+ .15	- .09
6	10,000	S_1	133	+ .15	+ .42	+ .20	.00
7	6,000	S_1	88	+ .11	+ .25	+ .13	+ .19
Dec. 10, 1954							
8	6,000	S_1	20	+ .07	+ .16	+ .10	+ .16
9	6,000	S_2	115	+ .07	+ .21	- .08	+ .24
10	6,000	S_2	1052[3]	+ .04	+ .01	+ .50[3]	- .02
11	2,000	S_2	191	[4]	+ .06	[4]	+ .06
12	2,000	S_2	124	[4]	+ .14	[4]	+ .14
	Algebraic Average			- .01	+ .16	- .01	+ .10

Average Miss. Distance
Evensville, Tennessee
S_1 = 129'
S_2 = 211'

Notes:

[1] Large reading on line crossed evidently due to noise burst effecting instantaneous E.A.R. reading.

[2] Large miss distance due to too large μ sec. correction needed at 10,000'. Correction had not been applied on first runs.

[3] Large miss distance evidently due to 1 μ sec. error in setting coupler (value not used in average). Large miss distance caused error in crossing LOP.

[4] S_1 transmitter off air.

Table 5.6 C-47 flights at Twin City, Georgia (Canaday).

Distance to Transmitters in Statute Miles
M = 273.197
S_1 = 223.075
S_2 = 852.345

Microseconds difference between G M R and E A R corrected

Run No.	Altitude	LOP flown	Miss distance feet	Aerial	Photos	Camera	Obscura
				S_1	S_2	S_1	S_2
Dec. 16, 1954							
1	6,000	S_1	0	+ .09	+ .17	.00	+ .08
2	6,000	---	---	---	---	.00	- .02
3	6,000	S_1	0	- .01	+ .09	- .05	+ .09
4	6,000	S_1	0	- .11	+ .19	- .07	+ .22
5	2,000	S_1	20	- .12	+ .01	- .04	- .03
6	2,000	S_1	36	---	---	- .22	- .22
8	1,000	S_1	33	- .03	+ .09	- .02	+ .09
9	1,000	S_1	54	+ .03	+ .06	+ .02	+ .08
10	10,000	S_1	250	- .19	+ .04	+ .06	- .01
11	10,000	S_1	10	+ .07	- .02	+ .03	- .01
12	10,000	S_1	50	- .08	- .03	- .02	+ .08
13	10,000	---	---	+ .21	+ .16	- .15	+ .34
14	10,000	S_2	225^1	+ .12	- .33	.00	- .37
Dec. 16, 1954							
15	6,000	S_2	25	---^{2}	---^{2}	+ .02	+ .11
16	6,000	S_2	685^1	---^{2}	---^{2}	- .23	+ .37
17	2,000	S_2	71	---^{2}	---^{2}	- .13	- .04
	Algebraic Average			.00	+ .04	- .05	+ .05

Average Miss Distance Canaday, Georgia

S_1 = 45'
S_2 = 251'

Notes:

1. Large miss distances caused by weak and noisy S_2 signal. Coupler did not have smoothing circuits for operating on weak signal.
2. Malfunction of aerial camera.

Table 5.7 C-47 flights at Savannah, Georgia (Chester).

Distance to Transmitters in Statute Miles
M = 255.784
S_1 = 228.860
S_2 = 874.937

Microseconds difference between G M R and E A R corrected

Run No.	Altitude	LOP flown	Miss distance feet	Aerial S_1	Photos S_2	Camera S_1	Obscura S_2
Dec. 19, 1954							
2	10,000	S_1	96	+ .16	- .07	+ .10	- .06
3	10,000	S_1	25	---	---	+ .16	+ .03
4	10,000	S_1	42	+ .12	- .71[1]	+ .01	- .72[1]
5	4,000	S_1	68	+ .09	+ .12	+ .10	+ .17
6	4,000	S_1	92	+ .07	- .02	+ .06	+ .06
7	4,000	S_1	53	+ .10	+ .26	+ .14	+ .18
9	4,000	S_1	20	+ .02	+ .01	+ .01	+ .03
10	2,000	S_1	58	+ .05	- .03	+ .05	.00
11	2,000	S_1	105	+ .05	- .10	+ .11	- .09
12	2,000	S_1	0	+ .08	- .13	+ .07	- .13
13	2,000	S_1	10	+ .15	+ .03	+ .15	- .05
14	1,000	S_1	167	+ .02	- .08	+ .01	- .09
15	1,000	S_1	15	+ .06	- .06	+ .09	- .09
16	1,000	S_1	54	+ .01	+ .15	+ .00	+ .15
Dec. 31, 1954							
1	2,000	S_1	18	+ .14	+ .15	+ .12	+ .15
2	2,000	S_1	8	+ .18	+ .11	+ .22	+ .13
3	500	S_1	52	.00	+ .04	- .01	+ .02
4	500	S_1	36	+ .03	- .05	+ .03	- .05
5	500	S_1	31	- .01	- .21	- .01	- .21
6	500	S_1	14	+ .02	- .16	+ .02	- .18
7	5,000	S_1	23	- .07	+ .02	- .06	.00
8	5,000	S_1	23	- .08	- .06	- .05	- .03
9	8,000	S_1	50	- .08	+ .02	- .09	+ .02
10	8,000	S_1	7	- .05	- .14	- .04	- .14
11	3,000	S_1	40	- .19	+ .21	- .07	+ .21
12	2,000	S_1	47	- .04	+ .07	- .02	+ .08
13	2,000	S_1	129	- .04	- .02	+ .01	- .03
	Algebraic Average			+ .07	.00	+ .04	.00

Average Miss Distance
Chester, Georgia
S_1 = 48'
S_2 = not flown

Notes:

1. Large reading on line crossed evidently due to large noise burst effecting instantaneous E.A.R. reading (not used in average).

Table 5.8 C-47 flights at Titusville, Florida (Wilson).

Distance to Transmitters in Statute Miles
M = 408.048
S_1 = 249.026
S_2 =1067.180

Microsecond difference between G M R and E A R corrected

Run No.	Altitude	LOP flown	Miss distance feet	Aerial Photos		Camera Obscura	
				S_1	S_2	S_1	S_2
Jan. 7, 1955							
1	500	S_1	19	+.01	-.36	+.01	-.33
2	500	S_1	34	.00	-.01	+.02	+.03
3	1,000	S_1	8	+.03	+.02	+.04	+.06
4	1,000	S_1	6	-.04	+.03	-.04	+.07
5	2,000	S_1	42	.00	+.10	-.01	+.15
6	2,000	S_1	92	-.10	-.19	-.12	-.15
7	6,000	S_1	25	+.09	+.22	+.06	+.36
8	6,000	S_1	13	-.04	-.07	.00	-.03
9	10,000	S_1	0	+.04	-.33	+.03	-.29
10	10,000	S_1	20	.00	-.04	+.03	-.01
11	4,000	S_1	6	-.06	+.24	-.05	+.28
12	4,000	S	71	+.01	-.17	+.03	-.13
Jan. 7, 1955							
13	4,000	S_1	33	-.05	-.01	-.02	+.07
14	2,000	S_1	12	+.03	-.20	+.05	-.16
15	1,000	S_1	0	-.06	-.13	-.06	-.09
	Algebraic Average			-.01	-.06	.00	-.01

Average Miss Distance
Wilson, Florida
S_1 = 25'
S_2 = not flown

Table 5.9 C-47 flights at Ft. Myers, Florida (Punta Rassa).

Distance to Transmitters in Statute Miles

M = 576.392
S_1 = 282.096
S_2 =1232.17

Microsecond difference between G R M and E A R corrected

Run No.	Altitude	LOP flown	Miss distance feet	Aerial Photos S_1	Aerial Photos S_2	Camera Obscura S_1	Camera Obscura S_2
Jan. 18, 1955							
1	1,000	S_1	93	NO PHOTO DATA		+.07	+.15
2	1,000	S_1	132			-.17	-.14
3	1,000	S_1	142			+.03	+.02
4	1,000	S_1	0			-.11	-.28
5	500	S_1	75			-.05	+.06
6	500	S_1	65			.00	---
7	4,500	S_1	75			+.05	-.12
9	4,500	S_1	24			+.08	-.01
10	10,000	S_1	0			-.03	-.08
11	10,000	S_1	79			-.06	+.17
12	7,000	S_1	0			-.02	.00
13	3,000	S_1	38			+.06	-.17
Jan. 18, 1955							
14	3,000	S_1	10	NO PHOTO DATA		+.16	+.20
15	1,000	S_1	40			-.09	-.08
16	1,000	S_1	36			-.07	+.30
	Algebraic Average					-.01	.00

Average Miss Distance
Punta Rassa, Florida
S_1 = 51'
S_2 = not flown

Table 5.10. Miss Distances Associated with Bombing Runs.

Target	AMD*	UMD*	D-GMR*
1. Guntersville Dam Alabama	1045 702	2675	104
2. Lock 38 Kentucky	417 320 211	465	104
3. Watts Bar Dam Tennessee	324 429	1500	18
4. Yellowwood Lake Dam Indiana	1110 1270 915	500	156
5. Scott-Fitzhugh Bridge Tennessee	162 318 200	825	70
6. Dix Dam Kentucky	1080 309 680	360	109
7. Morris Dam Tennessee	522	840	55
8. Ocoee Dam No. 1 Tennessee	378 172 296	1400	31
9. Pickwick Landing Dam Tennessee	1320 1650 572	1380	139
10. Keokuk Dam Illinois	206 185	1700	87
11. Lilly Branch Dam Missouri	1010	4450	70
Average	643	1463	87

* AMD - Actual miss distance in feet.
UMD - Unadjusted miss distance in feet.
D-GMR - Distance to nearest GMR site in nautical miles.

distance between the contours shows that the systematic correction does not change linearly with distance. The monitoring sites were so far apart the contours were subject to considerable interpolation error.

If there are no other errors in the system, the accuracy should deteriorate with distance away from the GMR sites. A plot of the miss distances vs. distance from the nearest GMR site (fig. 5.23) shows a definite trend of that nature. The scattering of the points results from both random and systematic errors. The average miss distance in flying over the GMR at Dayton, Tennessee, suggests that about one third of the average miss distance in these flights was random.

With so few points and so much scattering, the straight line in figure 5.23 is only a rough estimate of the rate at which the predictable accuracy deteriorates with distance away from a monitoring or calibration site. The important point illustrated is that over land, the systematic errors are major problem and to determine accurate correction contours, a very large number of calibration points must be used.

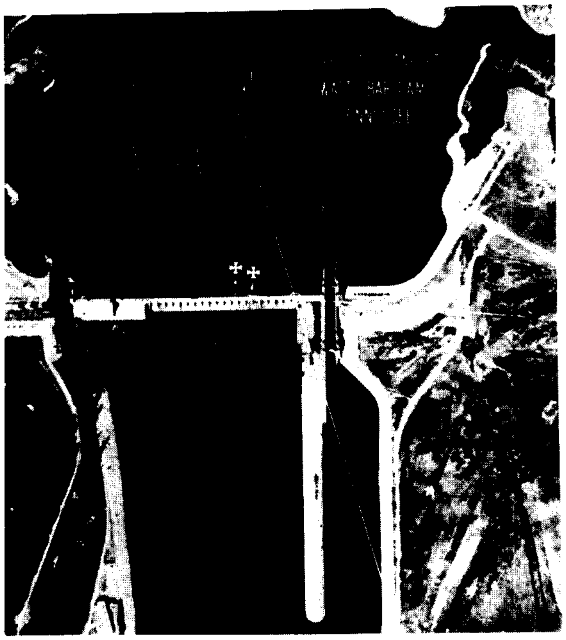

Figure 5.21. Simulated bombing runs. The unadjusted prediction shows the error that would have been made without using the correction contours.

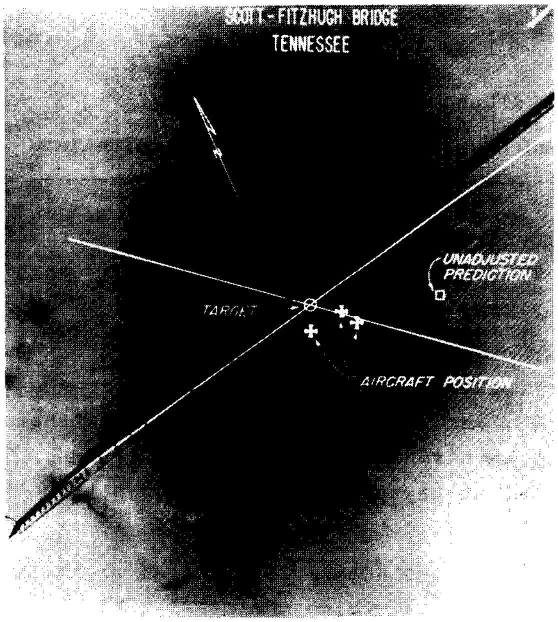

Figure 5.22. Simulated bombing runs. The unadjusted prediction shows the error that would have been made without using the correction contours.

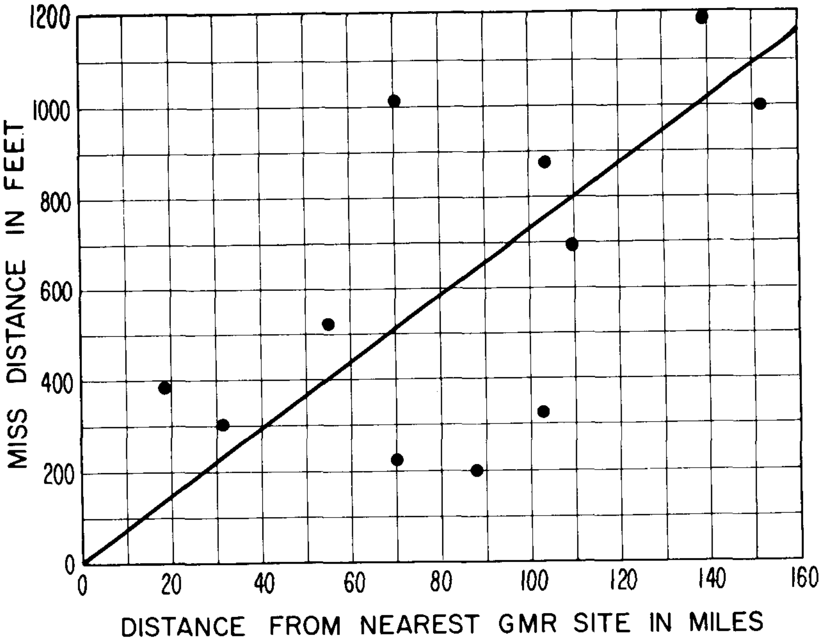

Figure 5.23. A plot of the miss distances vs. distance from the nearest GMR site.

5.3 Rate of Change of Systematic Errors

The airborne receiver and two GMR's were used to investigate the space rate of change of the systematic errors. To facilitate these tests, the hyperbolic grid was plotted on topographic maps (scale 1:24,000) of the region where measurements were planned. Positions could be scaled to an accuracy of about 50 ft, which was adequate in view of the random errors in the fixes. Most of these measurements were made in southeastern Tennessee and western North Carolina where the largest systematic corrections were found. The area is shown in figure 5.24.

In table 5.11, the sites are identified only by the topographic map where they were located. It would have been desirable to choose sites along a straight line to plot the error or correction as a function of distance, but that was not possible due to the lack of roads and the nuisance of overhead wires. In all but one instance, two or more sites were found in the area covered by each map. To arrive at a correction that would be as representative as possible for each area, the observed values at closely spaced sites were averaged.

The corrections measured by flying over the area are plotted in figure 5.25. The average values for the Goodfield, Riceville and Athens quadrangles are also plotted for comparison. The two sets of measurements do not differ grossly but they also do not show the close agreement found in flying directly over the GMR. Since phase coding was used in these later tests, multiple-hop skywave interference can be ruled out. However, coding-delay changes could have occurred during the course of the measurements. It is most probable that the differences simply indicate a rapid change in the correction with distance.

Table 5.11. Site Locations for Calibrating Flights.

Topographic Map	No. of Sites	Average	Correction
		S_1	S_2
Evensville	7	0.00	+1.50
Decatur	3	-0.20	+1.40
Goodfield	2	-0.20	+1.35
Riceville	3	+0.40	+1.20
Athens	6	+0.40	+1.50
Etowah	3	-0.05	+1.05
Benton	2	-0.16	+1.13
Oswald's Dome	2	+0.05	+1.25
Parksville	2	-0.10	+1.55
Caney Creek	1	0.00	+1.50
Persimmon Creek	8	----	-2.32

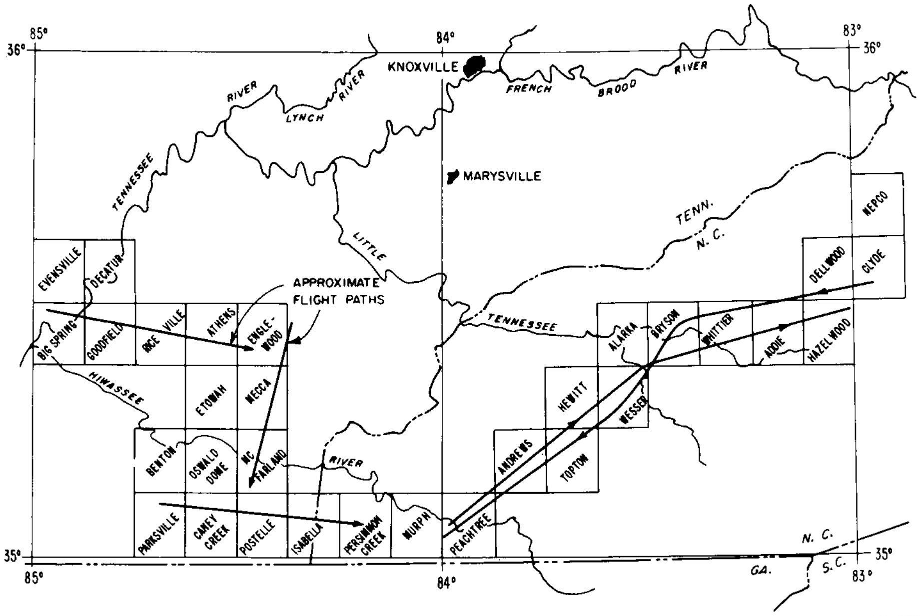

Figure 5.24. Area where systematic corrections were studied.

Similar measurements were made near Bryson City, North Carolina, where the terrain was especially rough. Two flights were made over the area while two GMR's were used to explore the nature of the corrections on the ground. The results were quite similar to those described above except the rate of correctional change was greater. The data are presented graphically in figures 5.26 through 5.29. In figures 5.26 and 5.27, the grid lines are spaced at 1-µsec intervals in both S_1 and S_2 time differences.

When the results of these flights are compared with those of flights across shorelines, there is a strong implication that the rapid changes in the corrections may be related to the roughness of the terrain. The flights over the shorelines were generally

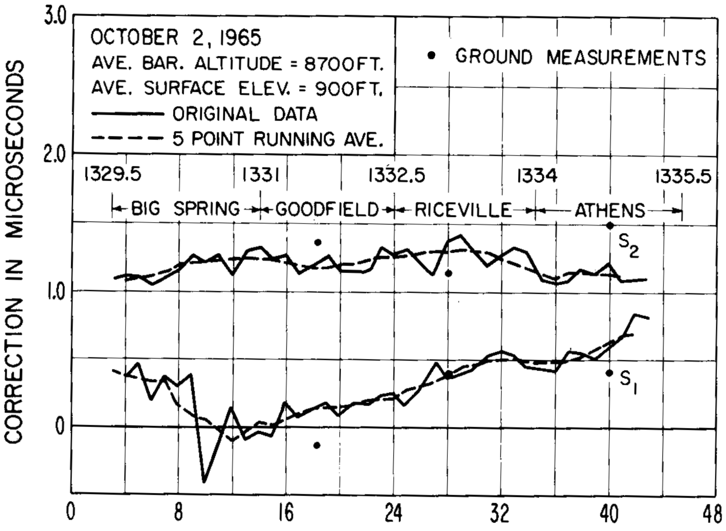

Figure 5.25. Airborne and ground measurements of systematic corrections.

in the areas of smooth transitions to sandy beaches. Subsequent flights over land-sea boundaries with abrupt transitions have shown effects similar to the irregular terrain effects. These results would suggest that if the effect is due to conductivity changes, the abruptness of the change may be more significant than the total amount of the change. On the other hand, something other than conductivity, such as reflections or diffracting effects, may account for the phase changes over rough terrain and abruptly changing seacoasts.

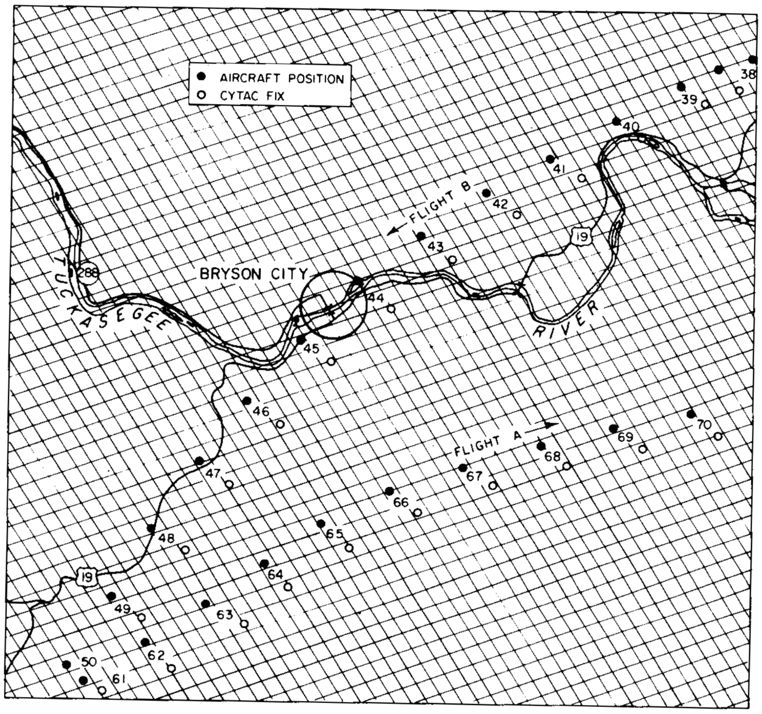

Figure 5.26. Airborne measurements of systematic errors.

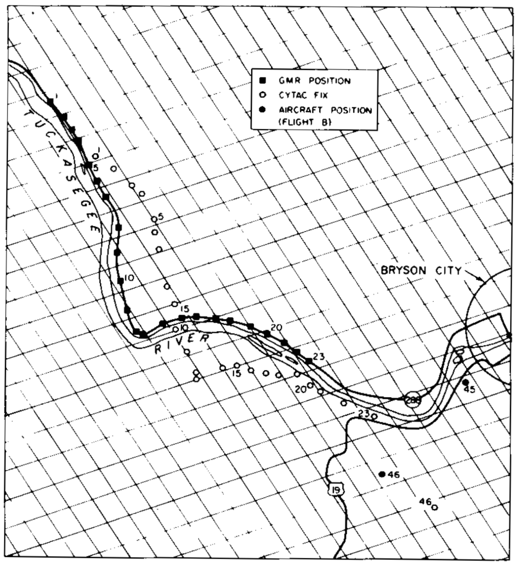

Figure 5.27. Measured systematic errors.

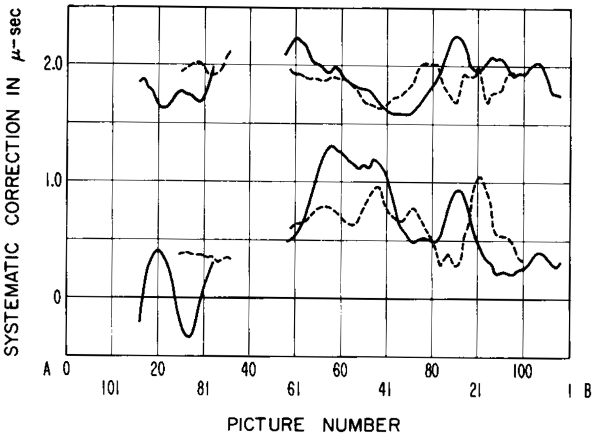

Figure 5.28. Airborne measurements of systematic corrections.
Dashed curves - flying east.
Solid curves - flying west.
(See fig. 5.26 for locations.)

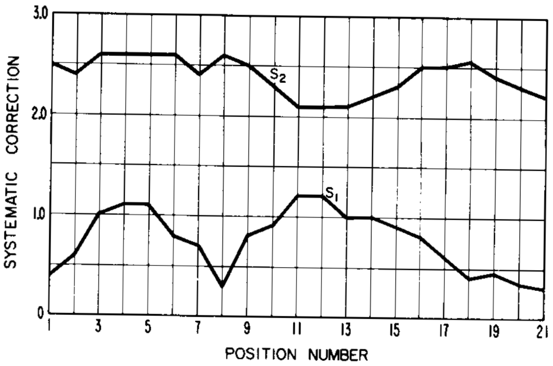

Figure 5.29. Additional systematic correction measurements near Bryson City, North Carolina.

While these phase changes are systematic in nature, i.e., non-time varying, they do not appear to have any recognizable pattern or trend. Their rate of change is so great it would be exceedingly difficult to determine precise contours of constant correction over such terrain unless a prediction theory for the effects could be implemented.

5.4 Localized Phase Errors

It was known generally that overhead wires and perhaps trees and other objects would disturb the phase readings. To have confidence that the measurements made at the various monitoring sites were not subject to errors of that sort, localized effects were investigated.

While in the Riceville, Tennessee, area, a section of U.S. Highway 11 was found suitable for these measurements. This section was 3.2 miles in length and reasonably straight so the van could be operated for monitoring purposes on the highway without creating an undue traffic hazard. Telephone lines ran parallel to the highway for about two thirds of the distance, and at one point, a power line was only a few yards away.

Measurements were made at three clear sites in the immediate region to determine the systematic corrections. Mobile measurements were made along the highway at 0.1-mile intervals. The van locations and the corresponding fixes are plotted in figure 5.30. The telephone lines were only a few yards from the highway between locations 1 and 21. From location 22 on, the lines were set back an estimated 65 yards or more. At location 26, a powerline terminated at the highway right-of-way.

It is evident that 100-kHz standing waves were induced in the telephone lines. Their influence on the receiver, however, was quite localized as shown by the disappearance of the disturbance at locations beyond 21. The powerline in this case did not seem to affect the readings.

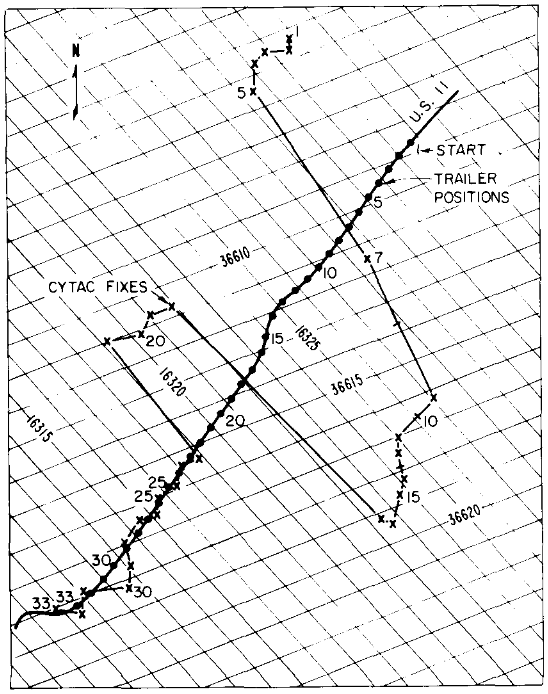

Figure 5.30. Measurements along U.S. Highway 11, near Riceville, Tennessee.

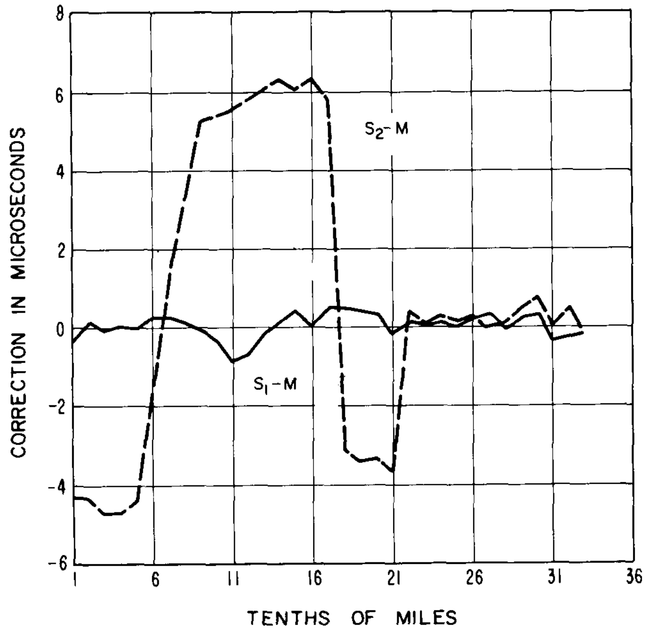

Figure 5.31. Time-difference errors from fig. 5.30.

The difference between the observed and computed time differences is plotted in figure 5.31. Most of the disturbance was associated with the S_2 (Forestport) pair only. Why only one reading should have been affected is not entirely clear.

In other similar measurements in the area, it was found that the readings were affected by large trees in the immediate vicinity of the receiver and by surface features in the terrain such as cuts and excavations associated with highway construction. All these effects, however, were highly localized. The original criterion of a 100-yard separation between receiver and the nearest overhead wires or other objects was evidently adequate.

5.5 Instrumentation Errors

Multiple-hop skywave interference may be treated as an instrumentation error in the sense that it can be removed by proper instrumentation, i.e., by the use of phase coding. An example of the time-difference readings with and without phase coding is shown in figure 5.32. As might be expected, the interference was greatest at night, but note also that the mean daytime readings with and without phase coding were different. These changes could have been due to skywave interference, changes in coding delay, seasonal changes between December 1954 and September 1955, or any combination. If simultaneous baseline-extension measurements had been made, the reason for the changes could be more definitely established.

During the time that phase coding was used, some changes in the S_1 coding delay were found. It would be a good guess that similar changes occurred at other times also. The S_1 changes were isolated by comparing simultaneous GMR readings at Rena Lara, Mississippi, Clarkton, North Carolina, Oak Ridge and Dayton, Tennessee. These readings were taken during the period September 1 to 13, 1955. The transmitters were not on a continuous schedule, and, for a variety of reasons, the GMR's were not all operating all the time.

Several short periods totaling only 13.1 hours of simultaneous readings did occur. The readings from these periods were plotted in chronological order without breaks in the time scale to indicate the interruptions in the data (see fig. 5.33).

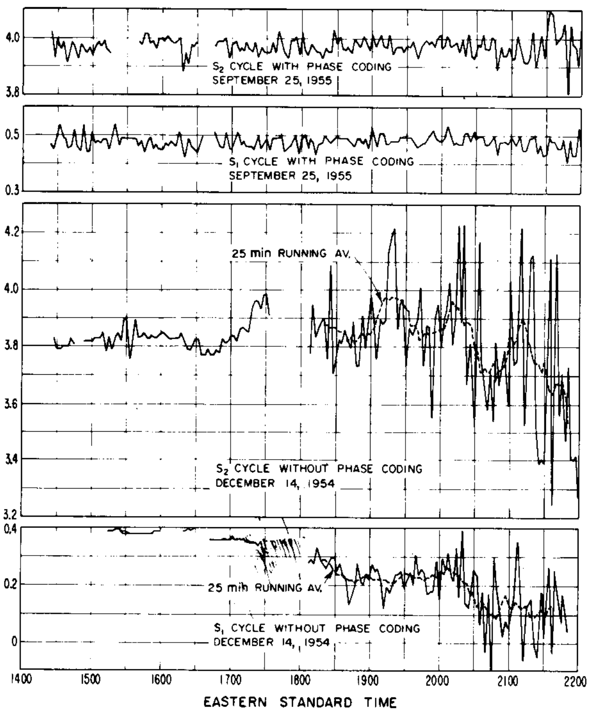

Figure 5.32. Time-difference readings with and without phase coding - Dayton, Tennessee.

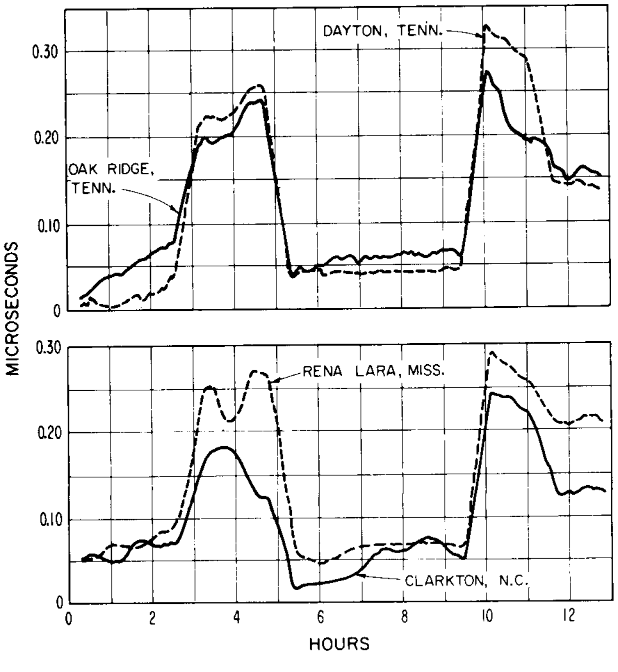

Figure 5.33. Simultaneous S_1 time-difference readings.

A change in coding delay is the only thing that could logically cause all the readings to change virtually the same amount simultaneously. The small amount by which the plots differ was probably due to noise and slightly different servo time constants in the GMR's or variations with meteorological conditions.

A limited number of flight tests were made with the bombing computer; however, "bugs" that are normally associated with initial testing of new equipment interfered considerably with the results. There were good indications that the navigation system and the computer could be made to work together as planned , but the actual data obtained were not especially significant.

5.6 Temporal Variations

A number of observed phase changes have been attributed to various weather phenomena presumably relating to changes in the index of atmospheric refraction. In a number of instances, there has appeared to be correlation and that possibility should be considered. The author also recalls that in some instances the round-trip phase measurements showed remarkable correlation with local rainfall at the slave transmitters.

Figures 5.34, 5.35, and 5.36 show phase variations whose causes were certainly rather multifold in nature. It is quite probable that multihop skywave interference was a significant contribution to the diurnal variation found in figure 5.34, but the long-term variations in figures 5.35 and 5.36 include virtually all the instrumentation errors as well as any long-term or seasonal propagation effects. All that can be concluded safely here is that the Cytac data do not clearly reveal identifiable atmospheric effects. This, however, does not mean that such effects were not present but simply that they were masked by other unrelated phase changes.

Theory indicates that the effect of the refractive index on the low-frequency propagation is two-fold. An increase in surface refractive index will increase the propagation time of the LF signals. However, an increase in surface refractive index will also increase the lapse rate (rate of decrease in refractive index with height) and this will tend to decrease the propagation time of the LF signal. A possible means for resolving the effects could be related to the fact that a surface refractive index change does not affect the signal amplitude, but a change in lapse rate does affect the amplitude of the signal One instance where the groundwave theory, as worked out by Johler, Kellar, and Walters (1956), may relate to the temporal effects is: the change in phase predicted for a given change in lapse rate is greater for a low-conductivity path than for a high-conductivity path.

It appears that atmospheric effects may indeed be quite significant in limiting the ultimate range and accuracy of the system. If it should be found that the leading edge of the groundwave pulse suffers dispersion due to the atmosphere, then the technique for marking a point in time on the pulse would yield degraded accuracy.

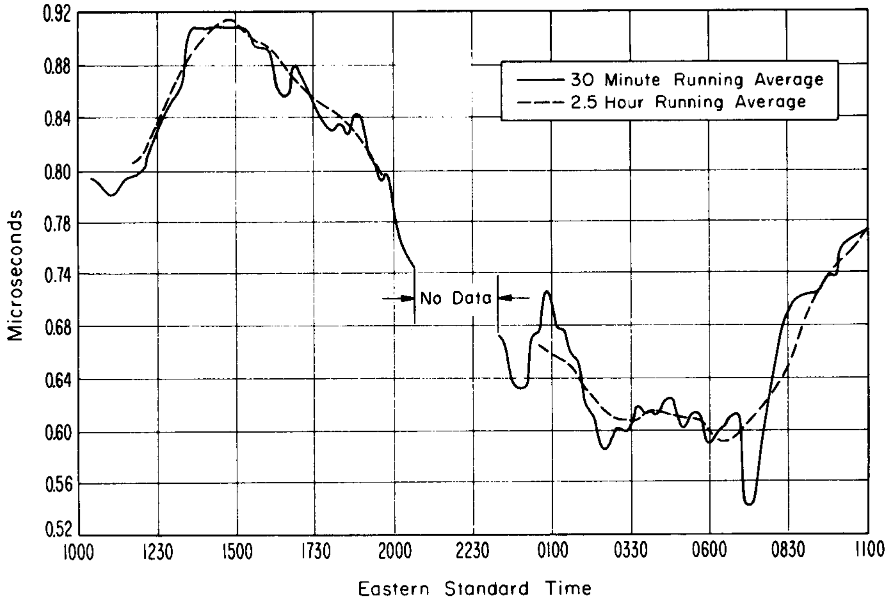

Figure 5.34. Running average of Clarkton, North Carolina S_2 time difference, November 30 to December 1, 1954.

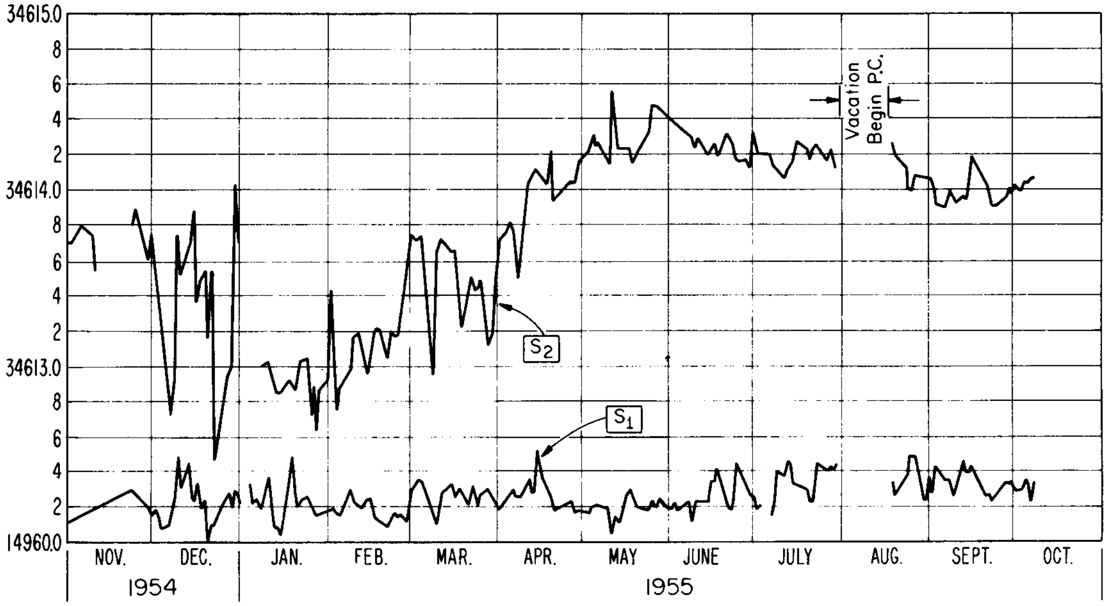

Figure 5.35. S_1 and S_2 average cycle readings at Clarksdale, Mississippi (Rena).

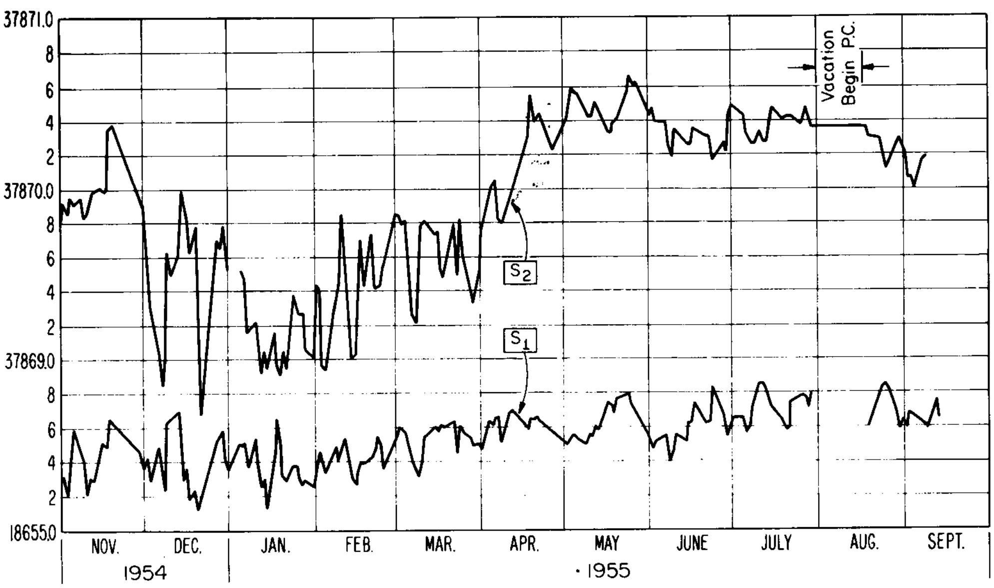

Figure 5.36. S_1 *and* S_2 *daily average cycle readings at Clarkton, North Carolina (Rodgers).*

5.7 Skywaves

The Cytac system was designed to operate within the range of groundwave reception and on groundwaves only. Nevertheless, skywave signals were of considerable interest, especially after it was discovered that the multiple-hop reflections had degraded so much of the data. A limited amount of time was devoted to skywave observations with the hope that the skywave interference problem might be better understood.

In these observations, the first through the seventh hop reflections were identified in the 1200-μs interval between the pulses. However, all the hops were not always detectable at any one site. The presence or absence of a particular hop seemed to be related to the receiving site or propagation path.

Contrary to expectations, it was found that the amplitude of the higher order reflections did not decrease in an orderly manner. In some cases, the later reflections were actually stronger than some of the preceding ones.

The daytime reflections were generally distinct and stable, whereas, at night the reflections tended to merge and were much less stable. Daytime skywave measurements made at Spring Creek, North Carolina, Woodstock, Kentucky, and at two sites near Boulder, Colorado, are summarized in table 5.12. As an interesting exercise, the virtual height of the reflecting layer was calculated using the measured delays. Simple ray paths and specular reflections were assumed. The range of daytime virtual heights (63.6 to 78.8 km) calculated in this way does not appear to be realistic. The usual stability of the first-hop skywave suggests that the actual reflection height is more nearly constant than these values indicate.

Table 5.12. Daytime skywave measurements.

Distance Statute Miles	Transmitter	Total Delay Ms	Amplitude in μv/m	Most Probable Hop	Corresponding Layer Height
		WOODSTOCK, KENTUCKY			
508	S_1	304	9.6	3rd	65.0
508		Nothing could be observed for 4th			
508	S_1	784	10.3	5th	65.5
508	S_1	1024	10.8	6th	63.6
653	S_2	285	19.2	3rd	69.5
653	S_2	505	14.4	4th	71.8
653	S_2	753	11.2	5th	71.7
653	S_2	993	9.6	6th	69.6
		SPRING CREEK, NORTH CAROLINA			
308	S_m	815	24.4	4th	68.0
308	S_m	1050	20.0	5th	64.0
420	S_1	454	-	3rd	74.2
420	S_1	752	13.2	4th	74.0
670	S_2	1083	-	6th	74.0
		BOULDER, COLORADO			
1570	S_2	32	-	1st	*
1570	S_2	448	-	5th	78.8
1570	S_2	618	-	6th	78.3
1565	S_2	34	-	1st	*
1565	S_2	298	2.0	4th	77.4
1565	S_2	440	-	5th	77.5
1560	S_m	34	-	1st	*

*Beyond geometrical-optical range.

At the time the observations and calculations were made, little thought was given to the dispersion the pulse might suffer in the reflection process and it was taken for granted the delay readings were correct. It is quite probable the pulses were so distorted after multiple reflections that the delay measurements were in error by one or more cycles. A further consideration is that the angle of incidence at which the wave impinges upon the ionosphere is a factor in the reflection process. In retrospect, the variation in virtual height calculated by such an oversimplified method is not surprising.

Attention is called to the Boulder data (table 5.12), where, at one site, the S_2 fourth-hop skywave was missing, but was present at another site only 10 miles distant.

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Conversely, the S_2 sixth hop was present at the first site but was missing at the other. Similar behavior of the higher order skywave reflections was noted earlier in the Woodstock, Kentucky area. Evidently, the propagation of some of the higher order hops is not supported over certain paths. The reasons for this are not understood. Investigation of the phenomenon might be a worthwhile research effort.

Measurements were made at Boulder, Colorado, for 1 month during the latter part of September and the first part of October, 1955. It was possible to receive the groundwave from the S_1 slave (Carabelle, Florida) only. When the receiver was synchronized on the S_1 groundwave and the first-hope skywave from the master, the variations in the skywave could be measured directly.

The transmitters were operating on a single shift, daylight schedule at that time, but on two occasions it was possible to change the schedule to include sunset. As sunset approached, both the cycle and envelope readings changed greatly, but by different amounts indicating a substantial amount of dispersion of the skywave signal (see fig. 5.37). The other readings during sunset were very similar.

During the day, the phase of the first-hop skywave was quite stable. The deviation from the mean was seldom greater than ± 0.25 μsec and never greater than ± 0.5 μsec. The envelope readings were much more variable, but there was no apparent difficulty in obtaining unambiguous readings. The observed stability of the daytime skywave clearly suggested the possibility of using it at distances beyond groundwave range, but that was outside the scope of the tests so the matter was not explored. In one other instance, similar skywave stability was noted at a site in extreme southern Louisiana. The site was inadvertantly chosen beyond the groundwave range of the Forestport

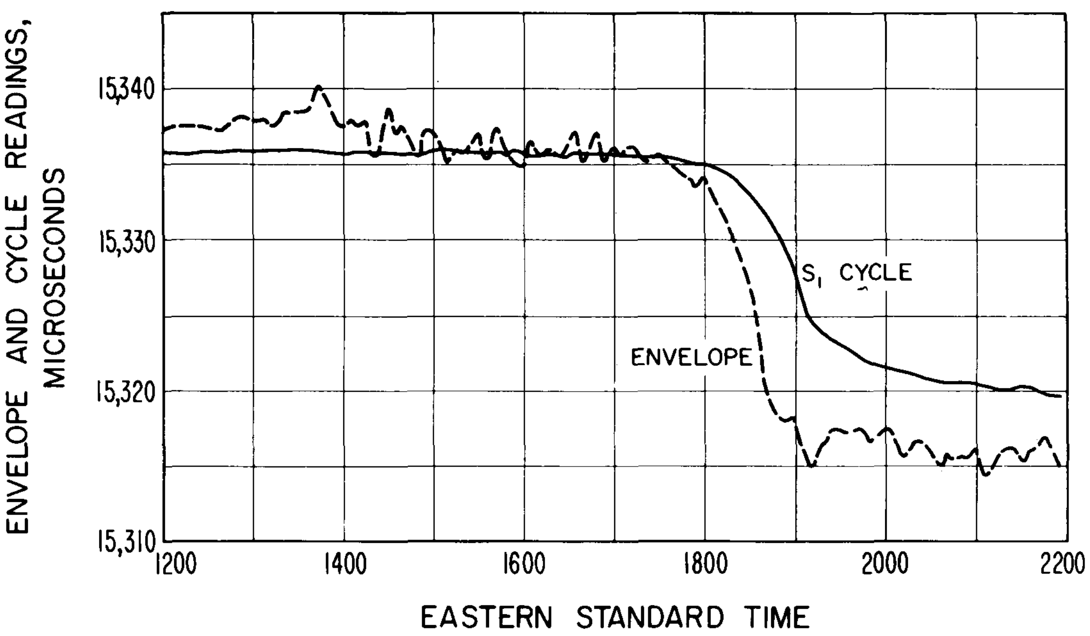

Figure 5.37. First-hop skywave measurements, Carolina Beach to Boulder.

transmitter. Few data were taken, however, and another site was chosen where the groundwave signal could be received.

5.8 Conclusions

The most significant results of the test program were:

(1) The low-frequency groundwave was found to be sufficiently phase stable and nondispersive that an envelope measurement could be used to identify the correct cycle.

(2) The instrumentation techniques used in the system were both effective and practical for separating the groundwave from the skywave.

(3) The objective of achieving 1000-ft accuracy at 1000 miles was accomplished in the ground-monitoring tests. In the flight tests, however, the maximum range attempted was only about 850 miles. The autopilot coupler did not have optimum smoothing characteristics and could not be used for automatic guidance unless a favorable signal-to-noise ratio prevailed. An improved coupler design could have extended the range , and greater transmitter power could have increased the range still further. In view of the average miss distance of 643 ft while flying over the target sites, there was no question that both range and accuracy requirements could be met or exceeded if systematic corrections were available.

From an operational standpoint, obtaining the systematic corrections would present problems because reconnaissance over enemy territory would be required. Mountainous terrain would make the problem still more difficult due to the rapid rate of change of the corrections. To insure 1000-ft accuracy, reconnaissance over the target area would be required in regions similar to western North Carolina. On the other hand, if the system were used for peacetime navigation, the systematic corrections could be measured without serious difficulty.

Although it was entirely outside the scope of the Cytac program, the possibility of using the system to distribute precise time was foreseen. To synchronize the transmissions with a master clock would, in no way, interfere with the navigation function of the system. Other clocks could be operated in conjunction with receivers and could be set in accordance with the transmission time from the transmitters to the receivers.

6. LORAN-C -- AN OPERATIONAL SYSTEM

In 1957, an operational requirement of the U.S. Navy demanded a long-range, high-accuracy radio-navigation system. The results of the Cytac tests 2 years earlier showed conclusively that the navigation portion of that system would satisfy the new requirements.

Navigational coverage in the Atlantic and other areas was needed, and there was considerable urgency to put the signals on the air as soon as possible. It was decided, therefore, to use, on an interim basis, the developmental Cytac transmitters which had been built during 1953 and 1954. The transmitter locations used in the Cytac tests, however, provided only secondary coverage over the ocean. To have more nearly optimum coverage, and to provide sea water paths for the baselines, it was necessary to move the slave stations to the Atlantic Coast. Sites at Jupiter Inlet, Florida, and Martha's Vineyard, Massachusetts, were selected. The master station was left in the same location near Carolina Beach, North Carolina. It may be noted that this station configuration was very similar to that used in 1945 for the first LF-Loran tests.

In view of the Coast Guard's long experience in loran operation, it was only natural that this system should be operated by the Coast Guard also. Even though the system development bore the name, Cytac, it was fundamentally a loran-type system. At the same time, the Coast Guard was also developing a classified version of standard loran. To more systematically identify these systems, the designations of Loran-A, Loran-B, and Loran-C were adopted for standard loran, its classified version and Cytac, respectively.

At the time Cytac or Loran-C was being converted to an operational system, it was declassified and a few simplifying technical changes were made. The rather complicated phase code used in the developmental system was changed to a sequence of 0 and 180° phase shifts. The pulse spacing within a group was changed from 1200 to 1000 μs, and the repetition rate for the first or East Coast chain was made an exact 20 pulse groups per second to be consistent with the basic scheme of loran rates.

The new slave station locations and contemplated additional installations focused attention on the requirement for a standardized and practical antenna design. The opposing considerations were the high cost of antennas tall enough (1000-1200 ft) to have good radiation efficiency, and the economy of shorter antennas that could radiate enough power to provide a satisfactory signal in the service area. In the latter case, it is implicit that the inefficiency of short antennas would have to be compensated in part by larger transmitters.

Comparison of the 1200-ft and 650-ft antennas used in the Cytac tests provided the principal basis for making a choice. With nominally the same input power, the shorter antennas radiated only about one fourth as much power as the taller one, but, from a practical standpoint, the weaker signals seemed adequate for most purposes and the cost of the taller tower was difficult to justify. Guyed, base-insulated, top-loaded, 625-ft towers were selected as the most practical compromise. The top loading consisted of 24 600-ft elements anchored at a radius of 850 ft from the base of the antenna.

Figure 6.1 shows the Martha's Vineyard station during construction. Figures 6.2 and 6.3 show the Jupiter station after completion. Figure 6.3 is a view of the power

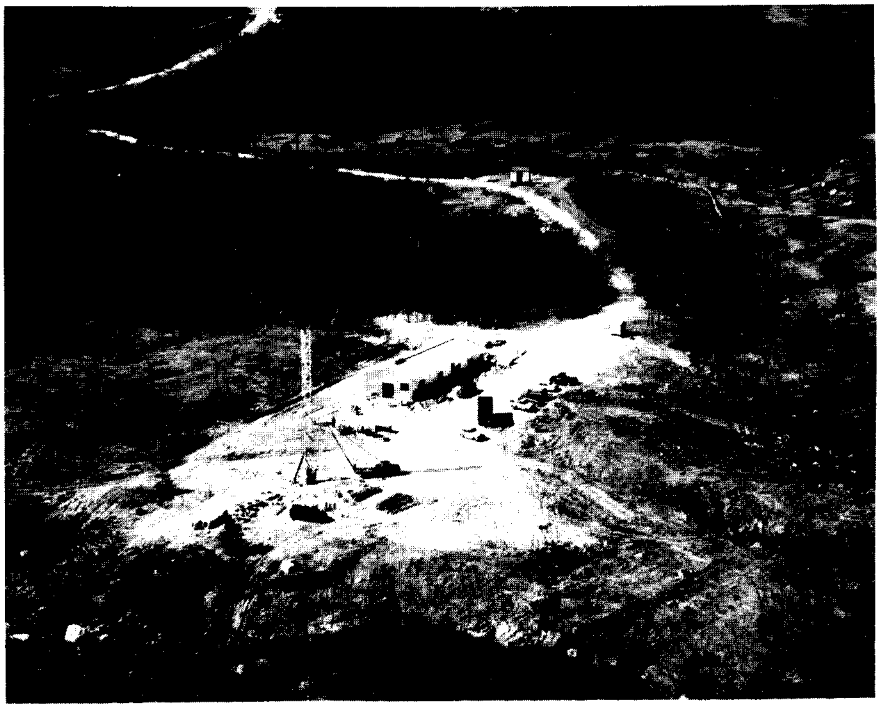

Figure 6.1. Martha's Vineyard Station during construction.

Figure 6.2 Jupiter Station after completion.

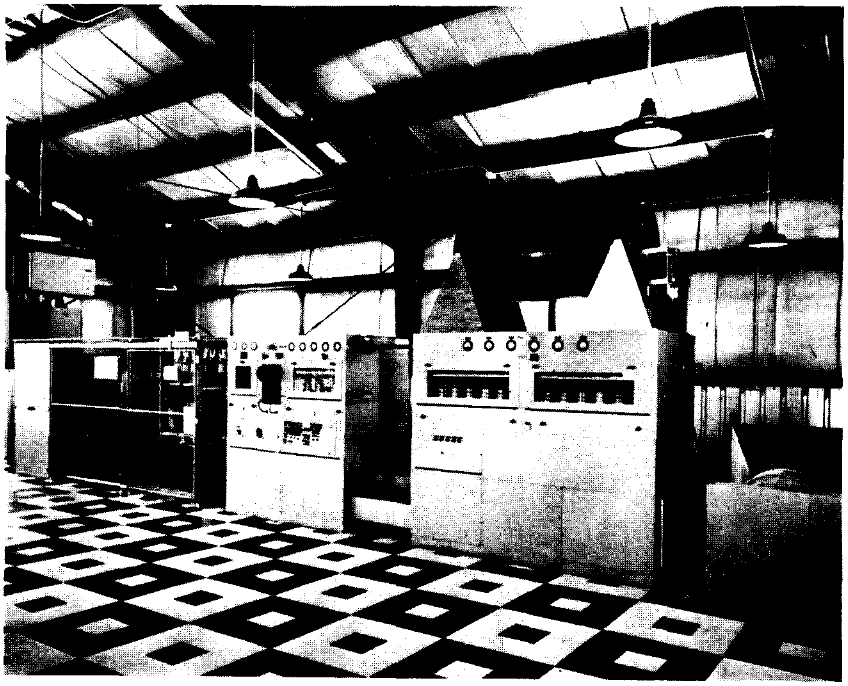

Figure 6.3. Jupiter transmitter (AN/FPN 15).

supply and final amplifier. The equipment is part of one of the original Cytac transmitters designated AN.FPN 15. The new installations were nominally the same as the Carabelle, Florida, Cytac slave, but, for a number of reasons which are not entirely clear, the initial operation of the new chain was beset with considerably more technical problems than were experienced originally.

Calibration and operation monitors were set up on both slave baseline extensions, and a third was located on Bermuda (Dickinson, 1959). The monitors proved to be quite valuable because phase drifts, especially long-term drifts, were a problem. Frequently, a slave station would have an indication of a change-in-coding delay, but the master would have no change. At other times, the monitors would note a change when there was no indication at the transmitters. Most of this type of trouble was finally traced to phase instability of the sample of the local signal that was fed to the transmitter synchronizers. The transmitted signals were not unstable, but leakage of the local signal via undesired routes to the synchronizers resulted in phase errors and false readings.

The receiving antennas were located about 1500 ft from the transmitting antennas. Initially, there was considerable difficulty with pickup of the local signal by the transmission lines from the receiving antennas to the synchronizers. Various remedies for the problem were tried. One was to move the receiving antenna to the synchronizer, thus eliminating the transmission line. There were still problems, however. With the receiving antenna under the top-loading elements of the tuned transmitting antenna, there were evidently phase shifts that could not be controlled.

After some experimenting, it was found that a more stable sample of the local signal could be obtained by placing a pickup loop near the feedline to the transmitting antenna. This arrangement was an improvement , and, for a while, pickup loops were used at all the stations. The stray pickup problems were reasonably well solved, however, and the original antenna configuration was adopted.

Obtaining a stable sample of the local signal did not solve all the drift problems, but it did bring enough consistency to the readings to make the system manageable. The overall nature of the difficulties with the new installations is described rather pointedly by the following quote from an engineering evaluation report on the system by Jansky and Bailey, Inc. (Dickinson, 1959):

> A great deal of good engineering practice is required in order to obtain stable time difference measurements in the immediate vicinity of the transmitters. This applies to the master as well as to the slaves. It should be pointed out that satisfactory monitoring at the slaves and at the master does not require absolute accuracy but does require stability. If time difference measurements are stable and dependable, the question of accuracy can be taken care of during initial system calibration.

In addition to phase-drift problems, component failures in the transmitting equipment and inadequate supporting facilities materially reduced the reliability of the system. A number of statistics describing the operation and the causes for interruption were compiled by Jansky and Bailey. Those statistics are summarized in the following two tables. Table 6.1 covers the period from February 3 to August 28, 1958, and shows the percentage of data recorded by the Bermuda monitor that was usable. The percentage of usable data corresponds very closely to the percentage of time in which properly synchronized signals were transmitted.

Table 6.1. Time and Data Percentages - Feb. 3 to Aug. 28, 1958

Percentage of Usable Data	On Percentage of Days
100	5.6
97	20
95	32
90	40
85	55
80	61
62	82
56	90
38	95

Typical causes for interruption are shown in table 6.2. The period covered in the tabulation is from June 2 to July 3, 1958. During that period, 362 interruptions were recorded in the master-station log.

The first four causes account for 60.5 percent of the total number of interruptions and clearly reflect the need for more reliable equipment for operational use.

Table 6.2. Transmitter Interruptions for Period June 2 to July 3, 1958.

Cause of Interruption	Number of Occurrences	Percent of Total
1. Transmitter power supply	64	17.7
2. Phase code errors	55	15.2
3. Divider jumps	55	15.2
4. Unexplained jumps	45	12.4
5. Inadequate communications	33	9.1
6. Commercial power failure	23	6.4
7. Operator error	20	5.5
8. Component failure	18	5.0
9. 400-cycle generator faults	11	3.0
10. Inadequate commercial power	7	1.9
11. Oscillator drift	7	1.9
12. Atmospherics	7	1.9
13. High ambient temperature	6	1.7
14. All others	11	3.1
Totals	362	100

No one can deny that the system performance was far from perfect at first, but it may be remembered that the original developmental transmitters and associated equipment were pressed into service in order to have signals on the air at the earliest possible date. Difficulties were fully anticipated. The matter of making system improvements and devising operating procedures was, in fact, a continuation of the system development. When the geographic coordinates of the new antenna sites were established, NBS undertook the task of computing a table of system coordinates. That table differed from previous loran tables in one significant respect. The secondary phase corrections, as described in Circular 573, were "built-in", when formerly, only the length of the geodetic arcs and the velocity of radio waves in air were used in the computations.

The built-in phase corrections proved to be quite satisfactory. Since then, the Hydrographic Office has computed all Loran-C charts and tables in that manner. Recently, however, it appears that some improvement in accuracy can be obtained by revising the treatment of atmospheric refraction in computing the phase corrections (sec. 9 on System Calibration).

With reasonable phase stability at the transmitters, the monitors, especially those on the slave baseline extensions, could notify the nearby slave of any needed adjustment of the coding delay to restore the proper time-difference reading at the monitor. Carrying out that procedure is merely performing the functions of a servo loop. In principle, it might seem that drifts would be relatively unimportant as long as effective control could be exercised. In practice, however, the servo control seems to be practical only when the system stability is good enough that the servo is scarcely needed. Monitoring, as an independent check on system operation is virtually indispensable, but it is fundamental that the fewer the errors to be corrected, the better the system performance. Loran-C is a very precise measuring system. Typical time differences are of the order of 5,000 to 50,000 μs measured to 1/100 μs. When the entire system is functioning properly, the confidence level of the reading is about 0.04 or 0.03 μs, depending, of course, on signal-to-noise ratio and integration time.

Despite instrumentation problems, it was possible, with the aid of the monitors, to maintain reasonably stable system coordinates. Figure 6.4 shows the fixes recorded by the Bermuda monitor from September 1, 1957, to August 28, 1958, as reported by Jansky and Bailey. These fixes are based on 8-hour averages of the time-difference reading. With such long averaging periods, it may be assumed that virtually all random noise was removed from the data. The scattering of the fixes certainly reflects the phase drifts or synchronization errors already discussed.

Figure 6.5 shows the fixes obtained by averaging the readings over 15-min periods for about a day and a half (1630 September 4 to 0700 September 6, 1957). Variations such as these were, of course, largely averaged out in figure 6.4, but even 15 min is long enough to remove most of the effects of atmospheric noise. It is assumed that these variations were caused by more or less random synchronization errors. Such an explanation is plausible inasmuch as the data sample was taken shortly after regular operation was started and technical problems were numerous at that time.

As previously discussed, phase changes have been attributed to various weather phenomena, supposedly relating to changes in the index of atmospheric refraction. Jansky and Bailey, however, could find no evidence of seasonal variations in phase in the Bermuda data. This may not be too surprising since all paths involved were over sea water and any effect on them would be minimal.

In evaluating the performance of the system, Jansky and Bailey, Inc. reported on the rather extensive flight tests made during the spring and summer of 1958. The purpose of these tests was to determine the useful groundwave range over sea water and to explore the feasibility of using skywaves beyond groundwave range. Two sets of flights were made: the first, in March and April, and the second, in June and July. In the first set, measurements were made in Bermuda, Puerto Rico, Trinidad, and Brazil. The second set of flights included measurements of interfering signals in the North Atlantic and Mediterranean areas where additional chains were being planned.

In probing the extent of the groundwave coverage, two techniques were used. One was to fly away from the transmitters until the receiver could no longer hold synchronization, and the other was to approach the stations and find the maximum range at which the signals could be acquired. As might be expected, the signals could be tracked to somewhat greater distances than the maximum distance at which synchronization could be established.

The receivers used in these tests (SPN-28's) did not have an automatic search facility for signal acquisition; therefore, it was necessary to have signals that could be seen above the noise on the test oscilloscope in order to position the sampling gates. Flying toward the transmitters in daytime, it was found that the maximum range was about 1500 nmi. No measurement of noise level was reported other than the appearance of the signals on the oscilloscope. The groundwave was described as "invisible" but the skywave could be seen from all three stations so it was possible to position the sampling gates closely enough for the servos to find the proper groundwave lock-on point.

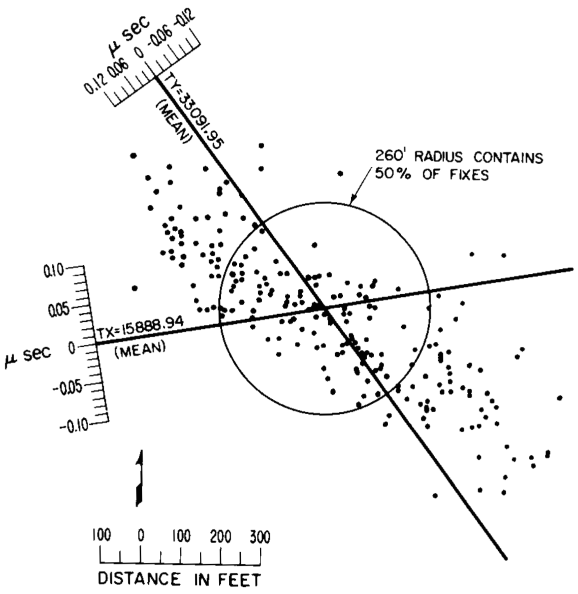

Figure 6.4. Bermuda fixes - September, 1957 to August 1958, 8-hour averages. (Jansky & Bailey).

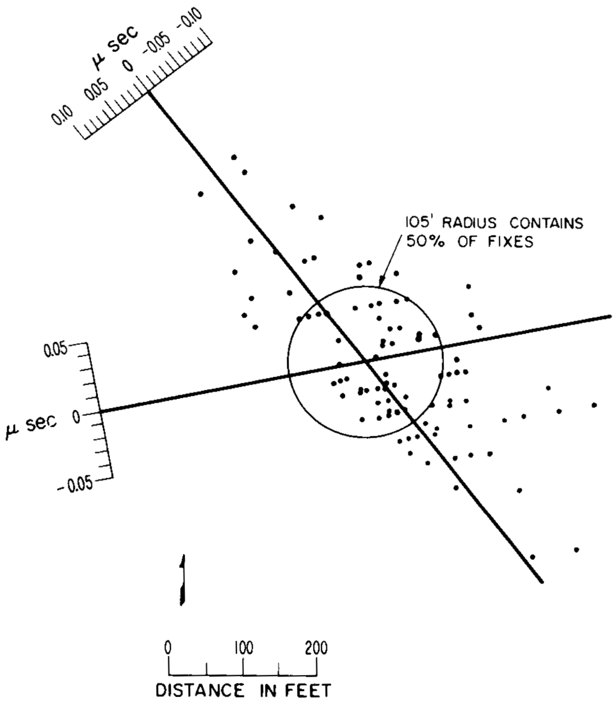

Figure 6.5. Bermuda fixes - September 4-6, 1957, 15-min averages (Jansky & Bailey).

It was further reported that it was possible to determine if the receiver was actually synchronized on groundwaves by two methods. First, the measured-field strengths agreed well with expected values, and second, the time interval between the arrival of the first two detectable signals (groundwave and first-hop skywave) was consistent with other measurements of the first-hop skywave delay. Comparison of the Loran-C fixes with the actual position of the aircraft could not be made over the ocean as there was no independent means of establishing position with appropriate accuracy.

Other than Bermuda and the Bahama Islands, there is no land in the principal service area where fix accuracy can be conveniently checked. Several fixes were taken on a flight July 9, 1958, over three points in the vicinity of the Little Bahama Banks. With the aid of a vertically stabilized drift site, the aircraft was flown over the known points. The accuracy of the aircraft's position was estimated to be better than 10 ft. The time-difference readings were recorded when passing directly over the points. The passes were made at an altitude of 1300 ft and at an average ground speed of 120 knots. The fixes are plotted in figures 6.6, 6.7, and 6.8.

Averaging of these readings was performed only by receiver time constants. The individual fix errors are considerably larger than the actual error in position that would be expected in navigating with the system. In practice, the navigator would draw a smooth track through a number of fixes. The average error shown in the figures is probably the better measure of system performance.

It is noted that the average errors are similar in magnitude and are in approximately the same direction. It is possible that they are attributable to a systematic propagation effect, but it is equally possible that the synchronization of one or both slaves was slightly in error.

The problems with component failures and phase drifts that plagued the early operation of the system were gradually worked out. A major improvement was made in 1962 when the original experimental transmitters (AN/FPN-15's) were replaced with entirely new equipment designated AN/FPN-42's. The new transmitters, in addition to being more stable and reliable, provided a signal of nominal 290-kW peak pulse power in contrast to only 50 to 60 kW delivered by the AN/FPN-15's. Actually, the AN/FPN-42's were the third generation of transmitters. They were preceded by the AN/FPN-39's, which were similar and has an output power of about 250 kW. All the powers given above refer to radiated power with the 625-ft antennas.

During the interim, the Martha's Vineyard station was moved to Nantucket to combine the installation with that of an existing Loran-A transmitter. The new location increased the baseline length somewhat and, of course, necessitated new computation of grid, but otherwise, the move was not technically significant.

The Coast Guard did not consider the East Coast chain in "operational" status until the new transmitters were installed and appropriate calibration and accuracy checks had been made. Table 6.3 summarizes the comparison of measured time differences with the predicted readings at a number of sites (USCG EE Rpt. L-33, app. 1962).

The time-difference errors could, of course, be converted to fix errors, but several of the sites are poorly situated for fixes. It is pointed out that the propagation paths contain varying amounts of land and uncertainties in the ground conductivity contribute to the prediction errors. In a stable system, systematic or prediction errors can be

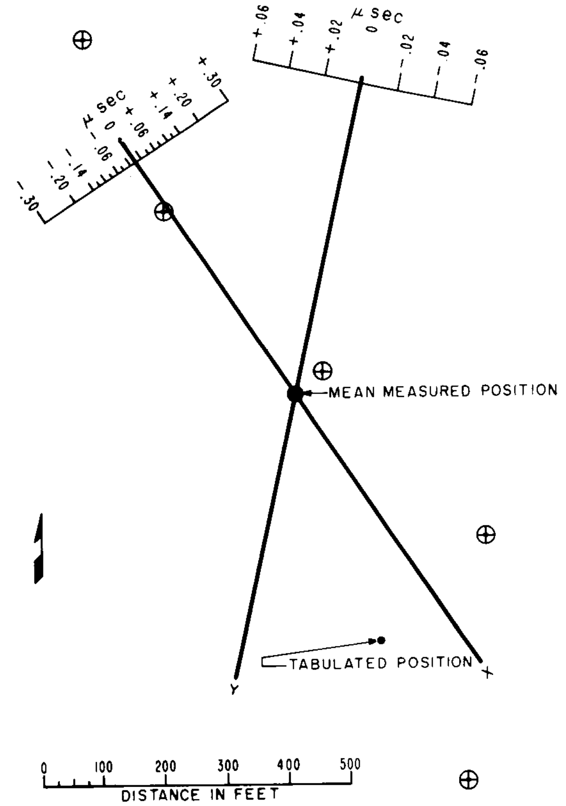

Figure 6.6. Airborne fixes, Little Sale Cay (Jansky & Bailey).

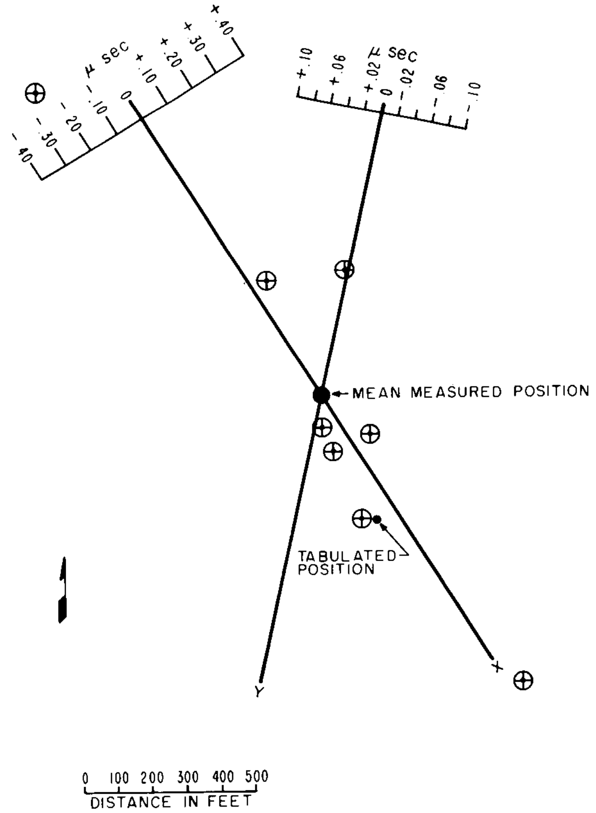

Figure 6.7. Airborne fixes, Bassett Cove (Jansky & Bailey).

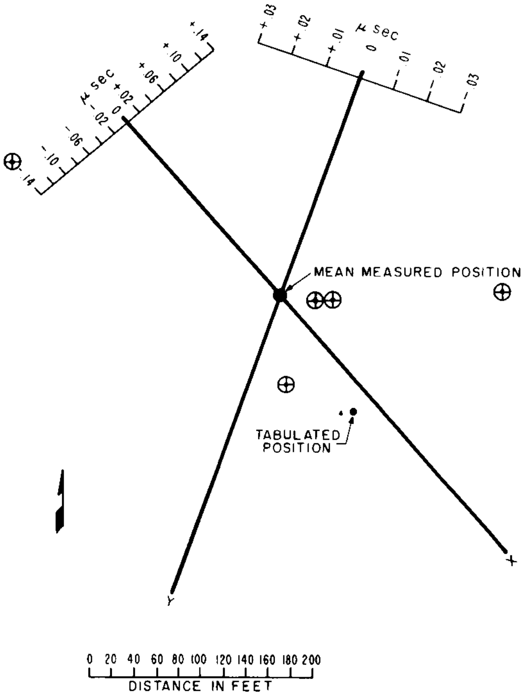

Figure 6.8. Airborne fixes, Walker Cay (Jansky & Bailey).

Table 6.3. Measured vs. Predicted TDs.

Site	Prediction Error	
	Xµs	Yµs
Otis AFB, Mass.	-0.30	+0.05
Suffolk AFB, N.Y.	-0.50	+0.05
Atlantic City, N.Y.	-0.00	+0.10
Wildwood, N.J.	-0.38	+0.01
Salsbury, Md.	-0.01	-0.14
Elizabeth City, N.J.	-0.14	+0.04
Cherry Pt., N.C.	+0.13	+0.04
Beaufort, N.C.	+0.32	+0.35
Brunswick, Ga.	-0.03	+0.04
Jacksonville, Fla.	-0.05	+0.04
St. Petersburg, Fla.	-0.11	-0.02
Kindley AFB, Bermuda	-0.04	-0.08
Monitoring Site, Bermuda	+0.03	-0.24
Eleuthera, BWI	-0.06	-0.30
Mayaguaua, BWI	+0.17	-0.28
San Juan, P.R.	-0.09	+0.07

calibrated out with a fair degree of satisfaction, especially if the errors are small. Inland calibration measurements were not made, but it was presumed that much larger prediction errors than those shown in table 6.3 would be found. Since most of the propagation is over sea water, however, it is clear that the predicted readings are quite accurate and, if needed, measured corrections can be used near shorelines and islands.

Plans to install other chains were started essentially at the beginning of the Loran-C program. Nothing could be done immediately, however, as considerable time was required to develop and manufacture new equipment and also to negotiate with other governments for transmitter sites. Table 6.4 lists the present operational chains.

The locations of all the stations presently in operation are shown in figure 6.9. The performance of the East Coast chain since June, 1962, is typical of all the chains. However, the vast differences in the geographical locations of the chains, the distances between available transmitter sites, and other physical factors made it expedient to modify some of the installations. To insure adequate signals over some of the baselines, more radiated power was necessary. By increasing the antenna height from 625 ft to 1300 ft, the radiation efficiency was increased by about 4 to 1 to provide a signal of 1.2-MW peak pulse power with the AN/FPN-42 transmitters. The fourth generation of transmitters, the AN/FPN-45's used with the 1300-ft antennas, deliver a signal of approximately 4 MW. Refer to table 6.4 for the power of the different stations. The Southeast Asia chain, with its short baselines and strict tolerance allowances, is reported to be the most stable overland chain to date.

The Mediterranean chain differs from most of the others in that more land is involved in the propagation paths. While the land does not influence the reliability or

Table 6.4. Present Operational Loran-C Chains.

Chain	Rate*	Master	Slaves			
			W	X	Y	Z
North Pacific	SL-2	Pribilof Island		Sitkinak	Attu	Pt. Clarence 1 Mw
*East Coast	SS-7	Cape Fear N.C.	Jupiter, Florida	Cape Race, Nwfld. 4 Mw	Nantucket Mass.	Dana, Indiana
Central Pacific	SH-4	Johnston Island		Hawaii Island	Kure Island	
Mediterranean	SL-1	Catanzaro, Italy		Wadi Mitrathin, Libya	Kargaburnu, Turkey	Estartit, Spain
North Atlantic	SL-7	Angissoq, Greenland 1.2 Mw	Sandur Iceland 4 Mw	Eides, Faeroe Islands		Cape Race, Newfoundland 4 Mw
Norwegian Sea	SL-3	Eides, Faeroe Islands	Sylt, Germany	Bo, Norway	Sandur, Iceland 3 Mw	Jan Mayen
Northwest Pacific	SS-3	Iwo Jima 4 Mw	Marcus Island 4 Mw	Hokkaido, Japan 600 kW	Okinawa	Yap 4.0 Mw
Southeast Asia	SH-3	Sattahip, Thailand		Lampong Thailand	ConSon So.Vietnam	Tan My, So.Vietnam

Nominal radiated peak pulse power is 250 kW-400 kW except as indicated.

* See Table 7.2.

** The Cape Race, Newfoundland station was synchronized with the East Coast chain in 1965. The additional station made it necessary to change to a lower rate (SL-0). The rate was later changed to SS-7 to avoid interference problems.

repeatability, it makes the grid more difficult to predict, and more systematic corrections and calibration are necessary.

The station on Jan Mayen Island is shown in a panoramic view in figure 6.10. It is reminiscent of the Beetle LF Loran installations, but, in this case, the obvious difficulties of installing and operating an isolated station in the far north were overcome.

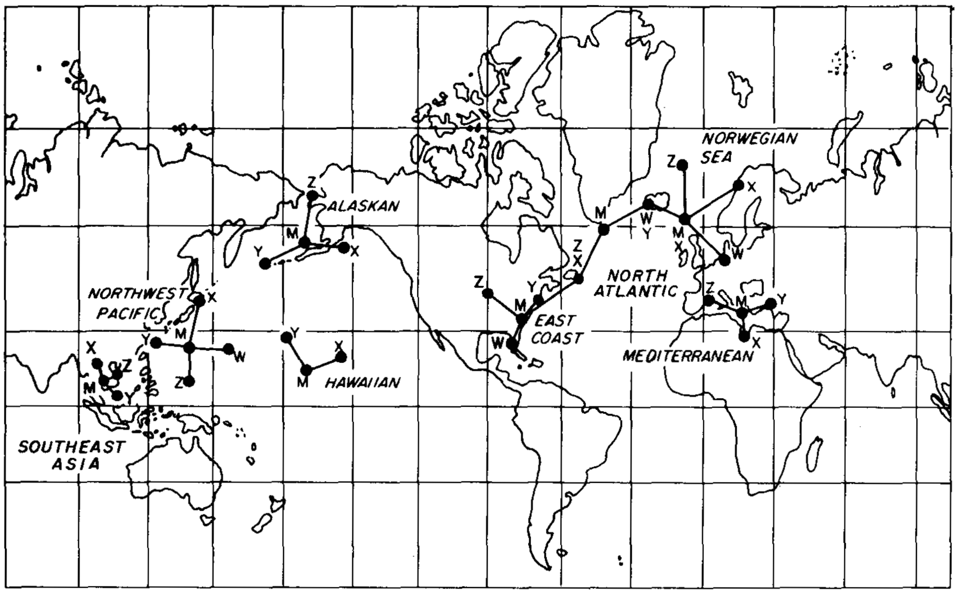

Figure 6.9. Loran-C Chains.

Figure 6.10. Jan Mayen Island station.

On one or two occasions, transmitting antennas have been lost in hurricanes and regrettably, the 1300-ft tower at the Iwo Jima station failed mechanically, resulting in the loss of two lives. Despite a few major catastrophies, which seem to have been beyond human control, the overall system reliability has become nearly perfect. It is questionable whether a percentage figure should be quoted, but, at the hazard of some inaccuracy, 99 percent is a reasonable and, perhaps, conservative estimate.

In addition to the purely technical considerations describing the performance of Loran-C, it is most important to view the system in the perspective of established goals and requirements for navigation systems. It is also important to recognize the spectrum requirements of the system in relation to internationally agreed-upon frequency assignments for other radio services (Jansky and Bailey, 1962).

It is prevalent among all users of navigation systems to visualize the attributes of the "ideal" navigation system and attempt to define its performance specifications. Obviously, there is no ideal system, and "idealized" performance specifications vary widely depending on the needs and interests of individual users. Universal agreement on performance requirements is further impeded by different countries who have their vested interests in nearly every aspect of the situation ranging from economic matters to prestige. Even on a perfectly objective basis, it would be difficult to specify an ideal navigation system that would efficiently satisfy the needs of surface vessels and high-speed aircraft.

Nevertheless, some concensus has been reached that a long-range navigational aid should (the following quotation ending on page 86 is taken from a report by Jansky and Bailey, 1962):

1. Be suitable for implementation and use in any area of the world during day and night, in all seasons, over extensive sea areas, and in all kinds of weather.
2. Provide omnidirectional navigational data that are free from operationally significant ambiguities within the area of intended coverage of at least 95% of the time.
3. Be freely available to all who wish to use it.
4. Serve an unlimited number of users in a manner compatible with the performance characteristics of their vessels.
5. Provide fail-safe indication of system malfunctions.
6. Be compatible with the currently effective Radio Regulations.

With respect to the required position-fixing accuracy, the report of Special Committee 3 of the RTCM states:

> In the ocean areas, a position fixing system with an accuracy of 5 miles or one percent of the distance from danger, whichever is the lesser, is required. With respect to aviation requirements, the report of Special Committee 67 of the RTCA states: 'As an immediate goal, fix errors in 95% of the readings up to 2000 nautical miles from the most remote station contributing to the fix shall be less than ± 5 nautical miles or ± 1% of the distance, whichever is greater.'

The International Meeting on Radio Aids to Marine Navigation (IMRAMN) put forth the following table of navigational requirements:

Ranges	Functions	Distance (n.mi.) to Nearest Source of Danger	Accuracy	Time Available to Establish Position
Long	Transocean Navigation	More than 50	± 1%	15 min
Medium	Aid to approaching land, to coasting and general port approach	50-3	1/2 n.mi. to 200 meters	5-1/2 min
Short	Aids to harbors and entrances	Less than 3	± 50 meters	Immediate

ICAO has stated (ICAO Document 7625) that, irrespective of time or weather, a range of the order of 1500 miles is desirable. The accuracy must be such that the position-fixing error will not exceed 10 miles on at least 95 percent of the occasions. The U.S. statement on aviation operational requirements is contained in the Air Coordinating Committee Paper ACC/9.1, May 27, 1957. In this paper it is stated that the accuracy should be within ± 3 miles 95% of the time. Committee Paper ACC 58/9.1 should be referred to for complete details on aviation operational requirements.

The basic policies of the U.S. with respect to long distance aids to navigation are given in Air Coordinating Committee document 58/12.1E dated December 30, 1959. They are:

1. To promote as a continuing goal, national and international standardization of a single type of ground-based, long distance radio aid to navigation suited to the needs of all users (air, surface and sub-surface). In the meantime, to standardize on the minimum number of types of aids necessary to meet the requirements of the various users.
2. To recognize the complimentary relationship between ground-based short distance and long distance and self-contained aids in the system of navigation and traffic control.
3. To promote the scientific and technical evaluation of all aids, domestic and foreign, and support the development and operational evaluation of those which are economically feasible and potentially capable of meeting recognized operational requirements. The U.S. will not advocate or accept any standard which would entail any monopolistic or exclusive advantage to any one country or to any one business enterprise or group of enterprises.
4. To encourage and promote the international exchange of technical information concerning long distance aids to navigation.
5. To support and promote national and international standardization of the essential characteristics of test standards for the standardized aid.

6. To exercise sound planning in facility implementation and development in the interest of frequency conservation, overall economies, and avoidance of unnecessary duplication.

7. To install aids to meet the requirements of the various users, as far as practicable, until a standard aid is accepted and implemented. The current types of long distance ground-based radio aids to navigation upon which present plans will be based are: Loran-A, Loran-C, non-directional beacons, and Consol.

8. To support and promote the international adoption and implementation of such aids or systems of aids which more adequately meet requirements of users and which can be technically, operationally and economically justified until a single national and international ground-based long distance radio navigation aid is accepted and implemented.

> Statutory responsibility for maritime navigational aids is covered by Section 81 of Title 14, United States Code. Under this regulation, the U.S. Coast Guard is responsible for the establishment, maintenance, and operation of maritime navigational aids required by the Armed Forces and U.S. commerce. Pursuant to this statutory authority, the U.S. Coast Guard has adopted Loran-C as a standard element in the U.S. system of radio aids to maritime navigation.

Since pulse transmissions are used in all the loran systems, some interference to other services in the crowded radio spectrum has been inevitable. Relatively few problems have arisen in North America, but, in other parts of the world, international agreements on spectrum usage have been difficult to achieve. In a report for the Coast Guard, Jansky and Bailey (Jansky and Bailey, 1962) have summarized the "Regulatory History of Loran." The remainder of section 6 is also quoted from that report with minor corrections for technical accuracy and consistency.

REGULATORY HISTORY OF LORAN

General

> Loran-A was brought to full operational status during a period which required that virtually all other considerations be subordinated to the basic objective of providing the Allied Armed Forces with the best and most reliable long range radio navigational aid that the state-of-the-art would allow. The decision as to the general portion of the radio spectrum in which loran transmitters would operate was based on the results of propagation experiments. Basic loran system parameters, such as, radiated power, pulse width, pulse rise time, repetition frequency, etc., were established almost exclusively on the basis of the effect each would have on over-all system performance. During this period, little consideration was given to minimizing the radio frequency bandwidth occupied by the loran emissions or to the effect these emissions might have on other users of the spectrum.
>
> With the cessation of hostilities, it became apparent that a radio navigation system originally developed solely to meet the urgent requirements of a global war could very effectively serve peace time navigational needs. The decision was made, therefore, which called for the continued use of loran. For the first time, there arose the aspect of loran as one of an ever-growing number of telecommunication services that must be accommodated in a finite radio frequency spectrum. The task of bringing loran operations into conformity with international regulations began.

In order to appreciate the magnitude of this task, it is necessary to review briefly the international regulatory background against which the loran system developed.

Status of Loran-A Under the Cairo Regulations (1938)

The International Radio Regulations (Cairo, 1938), which were 'in effect' during the period of loran development made no provision for the operation of a relatively broad-band radio navigation service in frequency bands suitable for loran. When it became known from propagation studies that a frequency band of the order of 2 Mc/s was near optimum for loran (as then conceived), the U.S. War Communication Board through the Interdepartment Radio Advisory Committee (IRAC) assigned three frequencies (1750, 1850 and 1950 kc/s) to the system. Nationally, the band 1700-2000 kc/s was allocated to the Amateur Service which was suspended in this country during the war. Internationally, the band was principally used for small-boat radiotelephone communications and for short-range fixed operations; both of which had been sharply curtailed in most areas during the war. During its early years, Loran-A enjoyed fairly wide and relatively clear radio frequency channels.

At the end of World War II, the majority of the international radio services which transmitted on frequencies in or near the loran frequency band began to go back into operation. Unfortunately, this caused serious interference problems in certain areas. This interference was due mainly to the continued service of wartime developed loran transmitters which radiated a broad radio frequency spectrum. The problem was further complicated by the unfavorable frequency and geographical juxtaposition of a high powered, pulsed radio navigation system (i.e., loran) and a low powered, ship/shore radiotelephone service by the general public.

Author's note: Also, to avoid interference to loran, on the basis of a request from the U.S. Coast Guard, the F.C.C. amended its rules after WWII so as to greatly restrict U.S. amateur radio operations in the 1800-2000 kHz band.

Subsequently, it was found possible through the application of technical and operational measures either to eliminate or to reduce the loran interference to tolerable levels in most cases. The initial impression concerning pulsed systems by these interference problems lingers to this day and has had a significant bearing on the obtaining of suitable frequency allocations for loran at subsequent international conferences.

Loran and the Atlantic City Radio Regulations (1947)

At the Atlantic City Conference in 1947, the United States proposed world-wide allocation of the band 1800-2000 kc/s for Standard Loran. Largely, as a result of the interference problems previously mentioned, this proposal met with determined and effective opposition from a number of European Delegations. With respect to the European area (ITU Region 1), a compromise was finally reached which allocated the band 1605-2000 kc/s to the fixed and mobile services and provided for continued operation of the European loran stations then in existence. In other areas of the world, Standard Loran System was given 'priority status' in the band 1800-2000 kc/s.

On the basis of experience with LF Loran and other systems, the United States delegation to the Atlantic City Conferences also proposed that a 'segment of the frequency band 200-280 kc/s be allocated on a world-wide basis for the ultimate long distance navigational aid.'

This proposal was not acceptable to the European Administrations, due largely to opposition in behalf of the Broadcasting Service. When it became apparent that the original U.S. proposal would not be accepted and that no similar proposal involving frequencies between 155 and 1560 kc/s would be acceptable, the situation was reviewed and the band 90-110 kc/s was selected as the best compromise between the conflicting technical and operational considerations involved. The modified United States proposal was conditionally accepted by the Conference and the band 90-110 kc/s was allocated to the (a) fixed, (b) maritime mobile, and (c) radio navigation services. The manner in which provision for the development of a new world-wide service was made in a band which was authorized for world-wide use by other services is most interesting. This was set forth in the following footnote (112) to the Allocation Table.

> 'The development of long distance radio navigation is authorized in this band which will become exclusively allocated wholly or in part for the use of any such system as soon as it is internationally adopted. Other considerations being equal, preference should be given to the system requiring the minimum bandwidth for world-wide service and causing the least harmful interference to other services.
>
> 'If a pulse radio navigation system is employed, the pulse emissions nevertheless must be confined within the band, and must not cause harmful interference outside the band to stations operating in accordance with the Regulations.
>
> 'During the experimental period prior to the international adoption of any long distance radio navigation system in this band, the rights of existing stations operating in this band will continue to be recognized.'

The influence of the interference problems involving Loran-A, previously mentioned, is clearly seen in the first and second paragraphs of the footnote.

Effect of Action by the Provisional Frequency Board (PFB) and the Extraordinary Administrative Radio Conference (EARC) on Loran-C

In accordance with the decision of the Atlantic City Radio Conference (1947) to draw up a new International Frequency List in the bands between 10 kc/s and 30 Mc/s, seven international conferences were held during the period 1948-1951. The task of drawing up a draft 'Frequency Allotment Plan' for the bands between 14 kc/s and 150 kc/s was given to the Provisional Frequency Board (PFB) which met in Geneva from January 1948 to February 1950. On 31 January 1950, the PFB adopted a 'draft world-wide plan of frequency assignments to fixed and coast stations in the band 14-150 kc/s.' As in the case of many other frequency bands, the Board found that the spectrum space available was insufficient to accommodate all the stated frequency requirements of the various administrations. In an effort to meet some of these requirements, the Board was forced to adopt very narrow channel spacing; i.e., in the vicinity of 100 kc/s, a spacing of only 350 cps was provided between adjacent assignable frequencies. Thus, 58 assignable frequencies were available between 90-110 kc/s (89.75-90.1, 90.45. . . . 109.7 - 110.05, etc.) and the Board made 158 discrete assignments on these frequencies to the fixed and maritime mobile stations of 51 separate administrations.

The Extraordinary Administrative Radio Conference convened in Geneva in 1951 for the purpose of developing a procedure whereby the Atlantic City Table of Frequency Allocations would be brought into force. Among other things, the EARC adopted the Draft Frequency List for the band 14-150 kc/s prepared by the PFB thereby giving International Registration Status to the approximately 160 frequency assignments made by the Board in the band 90-110 kc/s. Under the Atlantic City Regulations, a frequency assignment with Registration Status 'shall have the right to international protection from harmful interference.'

U.S. Proposal to the Geneva Radio Conference (1959)

The Loran-C system was brought to operational status during the period 1952-1956. The first operational chain was installed along the east coast of the United States in 1957. Subsequently, Loran-C chains were constructed in the Eastern Mediterranean Sea and in the Northeast Atlantic. In view of the rapid expansion taking place, the United States Delegation to the Geneva Radio Conference (1959) proposed that the frequency band 90-110 kc/s be allocated on a world-wide basis to the radio navigation service. For a number of technical, political, and economic reasons this proposal was unacceptable to a few administrations and it was necessary again to seek a compromise. After lengthy considerations of the matter, it was agreed that the basic allocation of the band to fixed, maritime mobile, and radio navigation services remain unchanged. In ITU Region 2, (North and South America) the Radio Navigation Service was designated the 'primary service'. In ITU Regions 1 and 3 the three services have equal rights.

The International and National Regulatory Status of Loran-C (1962)

Introduction

In this section, the Loran-C system is examined with respect to:

1. Its international and national regulatory status as a specific type of one of these general services authorized to operate in the frequency band 90-110 kc/s.
2. Its status as a basic policy of the United States with respect to long distance aids to navigation.
3. Its status as a basic component in the United states system of radio aids to maritime navigation.

International Regulatory Considerations

The frequency allocation table of Article 5 of Geneva (1959) Radio Regulations for the frequency band 90-110 kc/s is shown in Table 6.5.

With reference to Regulation 166, it should be noted that the language shown is that appearing in the document signed by the United States Delegation in Geneva in December 1959. In the final printed version of the Radio Regulations (the so-called 'green book'), the word 'agreement' has been substituted for the word 'arrangement' in the last and in the next-to-last sentence. A few words concerning this point appear to be in order.

In consideration of the safety of life aspect involved, the U.S. Delegation at the Geneva Conference took the position that the radio navigation service should either have 'exclusive' or 'primary service' status in a band. In general, this concept was supported by the majority of the delegation. However, due to the large number of existing fixed and maritime mobile operations in the bands between 70 and 130 kc/s and the fact that this agreement on a 'single system of radio navigation' had not been reached, a majority of the delegations representing Region 1 and Region 3 was unwilling to give the radio navigation service either exclusive or 'primary service' status in the band 90-110 kc/s. Nevertheless, in recognition of the safety aspect involved, it was agreed that the operation of specific radio navigation should be subject to arrangement between administrations involved and that having been established, pursuant to such arrangements, these radio navigation stations should be protected from harmful interference. The arrangements envisaged by the U.S. participants were bi-lateral understandings at the technical level similar to those under which provision had been made for operation of the then existing European Loran-C stations and the Canadian Decca chains.

To avoid confusion with the formal ITU mechanism known as a 'special agreement' which is defined in the Telecommunications Convention and for which special procedures are prescribed in the Radio Regulations, the word 'arrangement' was selected by the drafters of Regulations 164 and 166. Subsequent to the signing of the 'white document,' a special editorial committee appointed by the conference retained the word 'arrangement' in Regulation 164 which provides for radio navigation in Region 2 in the bands 70-90 kc/s and 110-130 kc/s but substituted the word 'agreement' for the word 'arrangement' in Regulation 166. It was not the intent of the Editorial Committee to change the meaning of a regulation; therefore, it has been assumed that the two words are synonymous. From the foregoing, the basic regulatory status of Loran-C operation in the band 90-110 kc/s in various areas of the world may be summarized as follows:

1. In ITU Region 2 the radio navigation service is the primary service. Therefore, Loran-C operations are entitled to protection from harmful interference from the other authorized services (fixed and maritime mobile).

2. In ITU Regions 1 and 3, the frequency band is equally shared by stations of the fixed, maritime mobile, and radio navigation services (the order of listing is alphabetical and does not indicate relative priority). However, Footnote 166 is applicable to the entire band 90-110 kc/s and stipulates that 'in these regions during the period prior to the international adoption of any long distance radio navigation system, the operation of specific radio navigation stations shall be subject to agreements between administrations whose services may be affected.'

In addition to the general requirement (Article 47 of the Convention), that 'all stations must be established and operated in such a manner as not to result in harmful interference to the radio services of other administrations,' Footnote 166 imposes an additional requirement on pulse system operation in the band 90-110 kc/s by stipulating that 'emissions from transmitters of such systems must be confined within the band and shall not cause harmful interference to stations outside the band.' The phrase 'emissions must be confined within the band' must be reasonably interpreted to mean that not more than one per cent of the total energy

> radiated shall be outside the band 90-110 kc/s. That is, the 'occupied bandwidth' as defined by the Radio Regulations shall not exceed 20 kc/s since a strict literal interpretation of this phrase would, per se, preclude the operation of any pulse system in the band. On the other hand, the phrase 'shall not cause harmful interference outside the band ...' clearly imposes a limitation on pulse systems over and above that imposed by the definitions from the Radio Regulations, Geneva, 1959, Article 1, Section III, Technical Characteristics, have been extracted and are given below.
>
> > 85-Assigned Frequency: The centre of the frequency band assigned to a station.
> >
> > 89-Assigned Frequency Band: The frequency band the centre of which coincides with the frequency assigned to the station and the width of which equals the necessary bandwidth plus twice the absolute value of the frequency tolerance.
> >
> > 90-Occupied Bandwidth: For a given class of emission, the minimum value of the occupied bandwidth sufficient to ensure the transmission of information at the rate and with the quality required for the system employed, under specified conditions. Emissions useful for the good functioning of the receiving equipment as, for example, the emission corresponding to the carrier or reduced carrier systems, shall be included in the necessary bandwidth.
>
> Under the U.S. Communications Act of 1934, radio communication stations operated by agencies of the federal government are excluded from the licensing authority of the Federal Communications Commission (FCC). The regulation of federal government radio communication facilities is the responsibility of the President. By Executive Order, the President has directed that frequency assignments and basic regulations governing federal government radio communication facilities shall be made in his behalf by the Interdepartment Radio Advisory Committee (IRAC). In accordance with this directive, all operating U.S. Loran-C stations have been duly authorized by the Interdepartment Radio Advisory Committee to operate in the frequency band 90-110 kc/s. All other U.S. operations in this band are on a secondary basis.

Since 1962, the date of Jansky and Bailey's report, no significant regulatory changes have been made. It is interesting to note that the guideline of keeping 99 percent of the radiated power within the 90- to 110-kHz band has, to some extent, resulted in a power bandwidth trade-off. Increasing the length of the pulse also increases the percentage of power within the band, which is a way of satisfying the regulation, but, otherwise, is of not value to the system. As a result of these considerations, both longer pulse-rise times and higher peak-pulse powers are used in the operational system, than were used in the early tests.

Notch filters are used in order to cope with the problem of having cw signals within the passband of the Loran-C receiver. Most receivers include two such filters. Ordinarily, the filters are used only when necessary as they distort the shape of the pulses to some extent and may lead to small inaccuracies in the time-difference readings.

Table 6.5, which further defines the frequency allocations, is also quoted from Jansky and Bailey (1962). The future of the Loran-C development will probably be influenced by the Department of Transportation National Plan for Navigation (1970).

Table 6.5. Frequency Allocations to Services

REGION 1

90-110
FIXED
MARITIME MOBILE 158
RADIO NAVIGATION
163 166 167

REGION 2

RADIO NAVIGATION
Fixed
Maritime Mobile 158
166 167

REGION 3

90-110
FIXED
MARITIME MOBILE 158
RADIO NAVIGATION
166 167

NOTE: Primary services in capital letters.

163) In Albania, Bulgaria, Hungary, Poland, Roumania, Czechoslovakia, and the USSR, the band 80-150 kc/s is allocated on a secondary basis to the aeronautical and land mobile services while within and between these countries these services shall have equal right to operate.

166) The development and operation of long distance radio navigation systems are authorized in this band, which will become exclusively allocated, wholly or in part, to the radio navigation service for the use of any one such system as soon as it is internationally adopted. Other considerations being equal, preference should be given to the system requiring the minimum bandwidth for world-wide service and causing the least harmful interference to the other services. If a pulse radio navigation system is employed, the pulse emissions shall nevetheless be confined within the band 90-110 kc/s and shall not cause harmful interference outside the band to stations operating in accordance with the Regulations. In Regions 1 and 3, during the period prior to the international adoption of any long distance radio navigation system, the operation of specific radio navigation whose services, operating in accordance with the Table, may be affected. Once established under such arrangements, radio navigation stations shall be protected from harmful interference.

7. LORAN-C TIMING

7.1 Background

Loran-C could have been used for time dissemination from the very beginning, but that use of the system did not develop until about 15 years later. Broadly speaking, the development effort in loran-type systems was directed toward achieving the greatest possible navigational accuracy at the greatest possible range. The basic considerations were to relate time and distance to the velocity of propagation, and to develop appropriate measurement techniques. While navigation was the sole motivation for the effort, it is a fair guess that is the objective had been to develop a timing system, a fundamentally similar system would have resulted.

7.2 Time and Distance

It is characteristic of electromagnetic radiation to travel at the same velocity at all times in a homogeneous medium. If a periodic signal is maintained phase-coherent with a reference clock, and if this signal is received from time to time by an observer whose position remains fixed with respect to the transmitter, the indicated time difference between the reference clock and the observer's clock will remain constant, provided the observer's clock is running at the same rate as the reference clock. The accuracy of the observer's measurement of time difference is limited by his knowledge of the distance between the transmitter and receiver, the radio refractive index at all points along the path, and the propagation delay of his receiving equipment to the signal. The resolution of the measurement is limited by the uncertainty associated with his knowledge of the same parameters.

Time, as normally used for navigation functions, relates to the position of the earth in the solar system and is measured in units related to the rotation of the earth. For many other applications, however, a more uniform time scale is needed that does not vary with changes in the earth's rotation rate. For these needs, atomic time scales have been developed that accumulate cycles of a well-defined frequency characteristic of atomic cesium-133. Since 1967, the scale unit, the second, has been defined in terms of cesium by international agreement. A compromise time scale called UTC (Universal Time Coordinated) is now used widely throught the world. This scale is based on the atomic second as defined by cesium. It incorporates occasional steps (1 per year) of exactly 1 sec to keep UTC within 0.7 sec of the UT-1 earth-based scale needed for navigation.

In either case, the units of time are based on periodic phenomena. The characteristic unit of time of a clock is determined by measuring the elapsed time between two successive periodic events, e.g., positive going zero crossings of a sine wave, or sunrises. A detailed discussion of time and its determination are beyond the scope of this writing. We add only that a time scale consists of a systematic assignment of "dates" to periodic events, and that the "accuracy" of a clock refers to the time difference between that clock and some other clock designated as the "master" or "standard" for that particular time scale.

To explain the distribution of the time scale by Loran-C, it is convenient to visualize a Loran-C transmitter as the clock which defines the time scale, and then let the transmission be such that a tagged point on a pulse occurs precisely at the beginning of established intervals on the time scale. The obvious way to accomplish and maintain the relationship shown in figure 7.1 is to obtain all the frequencies used in the Loran-C transmitter from the oscillator that drives the clock.

The Loran-C transmissions are timed by aligning the format with the UTC time scale. The format does not contain a simple once-per-second pulse train that is convenient for timing use, but there is a periodic coincidence between the loran pulse train and a once-per-second pulse train. Coincidence tables are provided by the U.S. Naval Observatory for each loran chain, making it possible for users to identify the coincidence pulses and thus obtain time.

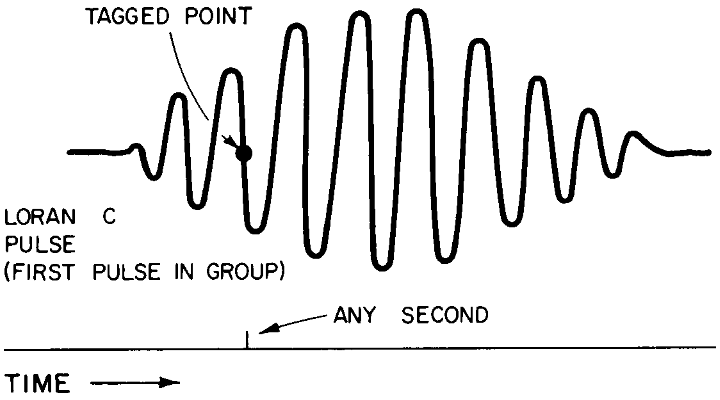

Figure 7.1. Time-scale distribution by Loran-C transmitter.

When the tagged point is seen by an observer at a distance from the transmitter, the point on the time scale which it represents has passed because time has elapsed not only during the propagation of the signal to the observer, but also during propagation through the receiver. Time, as it appears to the observer is, therefore, always slow. To set a clock correctly, it must be advanced relative to the received signal by an amount depending on the distance from the transmitter and the characteristics of the individual receiving equipment.

The transmission time to the observer can be calculated and the time required to propagate through the receiver can be measured. The proper clock setting can be illustrated by the following example. Assume that the observer is 1000 nmi from the transmitter and the transmission time has been computed as accurately as possible:

Transmission time	6176.3 μs
Receiver delay	25.0
	6201.3 μs

The clock should be set to read .0062013 sec when the tagged point, which corresponds to the beginning of a second, appears at the receiver output.

The above discussion assumed an observer in a fixed location making time-difference measurements between received time signals and his own clock. Such an observer could make beneficial comparisons even though he might not have confidence in his knowledge of the travel time of the radio wave, for he could compare the rate of his clock to the rate of the Loran-C clock. He could calibrate his clock by carrying a portable clock to the Loran-C clock, and in so doing he would also be calibrating the travel time of the radio wave. He would then be in a position to make accurate time as well as rate comparisons in the future.

The fact that an observer in a fixed location can make beneficial comparisons without knowledge of the radio path leads to important opportunities for making time comparisons between two fixed locations both of which receive a particular radio transmission having identifiable time marks. If the two stations can occasionally measure time difference between a particular received time mark and their own clocks, they can determine the differences in the rates between each clock and the clock at the Loran-C transmitter and thence the rate difference between their two clocks. A portable clock carried once between the two clocks would permit future time-difference comparisons. In summary, a clock may be set to the accuracy with which the propagation delay from the transmitter to the receiver can be predicted. But if predicting the propagation delay is not convenient, clock comparisons can be made using methods described above.

These applications of radio transmissions for time difference and clock rate comparisons are not unique to Loran-C, but that system is particularly useful because of the existence of many powerful Loran transmitters around the world, the stable propagation characteristic of the 100-kHz groundwave, and the suitability of the Loran-C format.

7.3 Evolution of Timing Requirements

For years, time signals have been broadcast by WWV and similar stations in several countries. The variability of ionospheric propagation at HF introduces errors of a few milliseconds, but that matters little to many users.

VLF transmission of time signals offers little improvement in timing accuracy because of the very slow rising pulses. The much greater stability of VLF propagation, however, has made it possible to compare frequency standards with a high degree of precision, and, consequently, to compare the clock rates. But the accuracy with which widely separated clocks could be set to agree is still limited to about a millisecond, unless specific techniques such as those involving closely spaced multiple frequencies are used.

As early as 1955, during the Cytac field tests, some experimentation was done by Sperry to investigate the feasibility of using long-range inverse hyperbolic techniques for radio location. Since the Cytac system was operating on the test program for an extended period of time, good time synchronization was available. In fact, if Cytac had not been in existence, the thought of an inverse, long-range hyperbolic experiment probably would not have occurred.

In the initial experiments, a bare minimum of clock instrumentation was used. At that time there was little or no thought of timing-system requirements, at least not from a systems point of view, but the basic ideas and techniques for a precise timing system were being generated and tested. Two years later, beginning in 1957 and extending into 1958, NBS developed highly specialized instrumentation for high-speed recording of the time of arrival of transient signals (Hefley et al. 1960). While this instrumentation did not involve any new principles, it did involve new combinations of measuring and recording techniques that later aided the development of a Loran-C timing system. The principal features of that instrumentation were an unambiguous binary time readout and a high-speed framing camera to record the time and other data.

In 1958, Sperry carried out further radio location experiments using one of the Cytac transmitters and the ground-monitoring receivers for the basic time synchronization system. There was no way to check the correctness of the timing except by the accuracy with which a signal source could be located. The results were rather good, but actually inconclusive in a strict sense in regard to proof-of-timing accuracy. It was evident that other errors could have masked any inaccuracy in the timing.

All these time-synchronization applications were for military purposes and, at that time, Cytac was still partially classified. Consequently, there was very little dissemination of the newly acquired technology in the field of precise timing. Also, military uses were specific and did not contemplate a timing system for general purpose use.

The development of techniques for using Loran-C as an unclassified, general-purpose timing system began in 1959, when the Air Force Eastern GEEIA Region sought the assistance of NBS to develop an improved timing system for the Atlantic Missile Range (AMR). However, the idea of using Loran-C for that purpose had been suggested informally by NBS at least a year earlier. The suggestion did not draw much response initially, and it is reasonable to assume that the idea was not immediately accepted for two basic reasons. First, there were very few people at that time who had even heard of Loran-C, and still fewer who had any technical understanding of the system. Second, the timing accuracy which Loran-C could provide was at least 1000 times greater than that of the existing timing system. If only a percentage improvement had been offered, the proposal probably would have gained more rapid acceptance. The transition from milliseconds to microseconds was a big step -- almost too big.

There were several rather compelling reasons for proposing Loran-C for AMR timing. The East Coast chain was in continuous service and provided adequate coverage. No other long-range system could offer comparable accuracy. While the accuracy of Loran-C was much greater than the range required at that time, it seemed a virtual certainty that new system developments would soon make use of the accuracy that could be provided.

A wide variety of observations were made in the AMR testing. Nearly all data were recorded as a function of time. The time base was in the form of a time code suitable for the particular recording. The codes were distributed from Central Control to observing stations on the mainland by hard wire and to the down-range stations by submarine cable. Such a distribution system was satisfactory as long as a high degree of timing accuracy was not required. Gradually it became evident that the hard-wire system was not entirely adequate for existing needs, and it was anticipated that it would be even less adequate in the future.

For range-timing purposes, a clock was needed that could be operated intermittently. In contrast to maintaining one or more oscillators as a time or frequency standard, operational requirements called for a clock in the form of the typical "black box" that could be turned on, set, used for a few hours, and then put back on the shelf for the next missile flight. Such a requirement virtually ruled out the use of all radio systems except Loran-C. Loran-C, being primarily a groundwave system and not subject to diurnal effects, was rather ideal for the purpose. A further important consideration was that, due to synchronization techniques inherent in the system, relatively inexpensive oscillators could be used. That is, a cheap oscillator synchronized with or slave to the carrier frequency of the master transmitter could drive a clock with the same accuracy as the master itself.

Another attribute of Loran-C for timing was that, by virtue of the slaving technique, and using the groundwave only, no clock could gain or lose with respect to any other clock in the system. In contrast, independent clocks always gain or lose in accordance with the accuracy and stability of the frequency sources from which they are operated. Presumably, atomic standards define an exact frequency, but, in practice, small variations are always present. Two clocks operating on separate atomic standards could drift apart as much as a few microseconds in a week. The relative gain or loss between two clocks running at different rates is shown in figure 7.2. It is immediately apparent that when agreement among clocks is important, use of the slaving technique is a definite necessity.

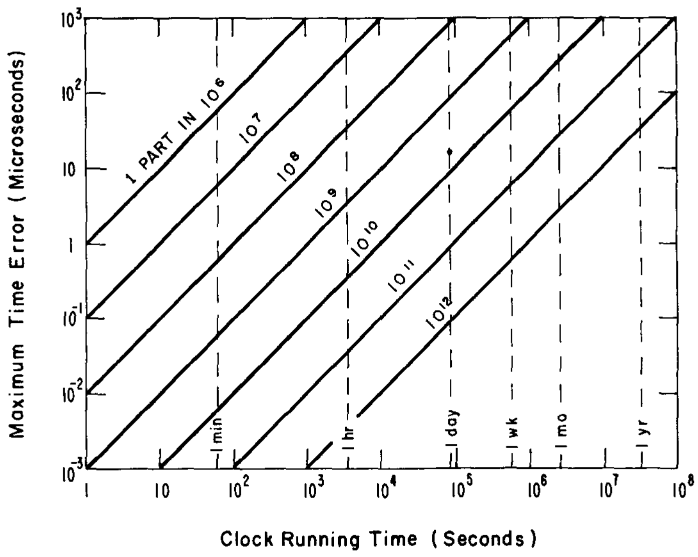

Figure 7.2. Relative gain or loss of independent clocks as a function of clock-frequency error.

7.4 The Loran-C Clock

7.4.1 General

The term, "Loran-C Clock" (Doherty et al. 1961b), refers to a group of electronic devices assembled together and interrelated in such a way that time, as derived from Loran-C signals, is displayed in a conventional manner. Two developmental clocks built for demonstration at the AMR consisted of the following major components:

(a) Loran-C timing receiver,
(b) local oscillator and phase-lock servo,
(c) divider chain,
(d) readout register and display,
(e) power supplies and test oscilloscope,
(f) WWV receiver.

One of the clocks is shown in figure 7.3.

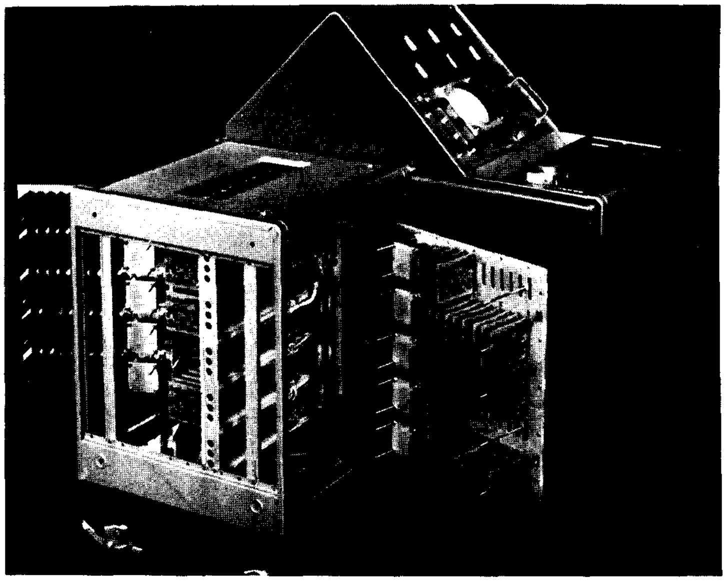

Figure 7.3. Loran-C Clock.

7.5 Timing Receiver

A conventional navigation receiver, with appropriate modifications, can be used for timing, however, many of the functions that are necessary in a navigation receiver are not needed for timing. It was much more practical and economical to have a receiver designed specifically for the special purpose. In a timing receiver, synchronization with only one transmitter at a time is needed, therefore, two of the three sets of phase and envelope servos were deleted. Since the timing receiver was intended for fixed operation only, the rate servos were also deleted.

Some features needed in a timing receiver that were not included in a navigation receiver were:

(a) provision to select either master or slave-phase code,
(b) a meter indicator (with output connectors for a recorder) to show the amplitude of the desired rf cycle,
(c) a separate, manually adjustable phase shifter for fine setting of the clock,
(d) temperature compensation to prevent phase drift.

Detailed specifications for a Loran-C timing receiver were written by NBS and an order for four receivers was placed on competitive bid. Sperry Gyroscope Co. was the successful bidder. In 1962, more complete timing-receiver specifications were developed jointly by NBS, the Naval Observatory, and the AMR. These specifications were distributed as an NBS report (Lidkea et al. 1962).

7.6. Divider Chain and Clock Readout

The local oscillator and phase servo loop in the timing receiver were entirely equivalent in principle to those used in navigation receivers but differed considerably in detail in order to provide the desired input to the clock-divider chain. In this case, the phase shifting was accomplished at 500 kHz and a second phase shifter was driven mechanically in parallel with the synchronizing shifter in the servo loop. The mechanical drive to the second shifter included a slip-clutch and a manual shaft adjustment. The output of the second shifter was fed to a 1-MHz pulse generator. The 1-MHz pulses were the input to the divider chain. The purpose of the slip-clutch and the manual shaft adjustment was to make provision for fine setting of the clock without disturbing the phase-lock on the Loran-C signal.

The divider chain consisted of 15 trochoidal beam-switching tubes operating as decimal counters. A particular merit of the beam-switching tubes was that the carry-time through the entire divider was less than 1 μs. Thus, all 15 dividers representing time up to hundreds of days were in a brief steady state every microsecond and could be read out unambiguously.

To insure an unambiguous readout from any read command (random or synchronous), the command was used to select one of the 1-MHz pulses. From that pulse, a new and slightly delayed read command was generated. The new read command was adjusted in time to occur during the steady-state condition of the dividers.

The time readout was stored and displayed in conventional digital form for the operator. For normal running, the read commands were taken from any source including the 1-sec divider on either clock, but for setting, the commands were taken from the timing receiver. A trigger generated at the tagged point on the first pulse following the second was the read command. When the clock was read out at 1-sec intervals, the decimal fraction of seconds did not change. Therefore, the operator had a steady display to observe and could advance or retard the clock until the correct reading for his station location appeared.

7.7. Identification of Larger Units of Time

The East Coast chain did not use any additional modulation to identify seconds, minutes, etc., at the time the clocks were built and tested. In fact, the chain was not actually transmitting time in a strict sense, that is, no effort was made at the master transmitter to relate any of the pulse groups to time. The transmissions were essentially in the category of frequency or time interval, but that was immaterial for test purposes. Larger units of time than the 50-msec repetition period were identifiable since Loran-C and WWV could be synchronized. The WWV second pulses could then be used to identify the on-time pulse groups (see fig. 7.4).

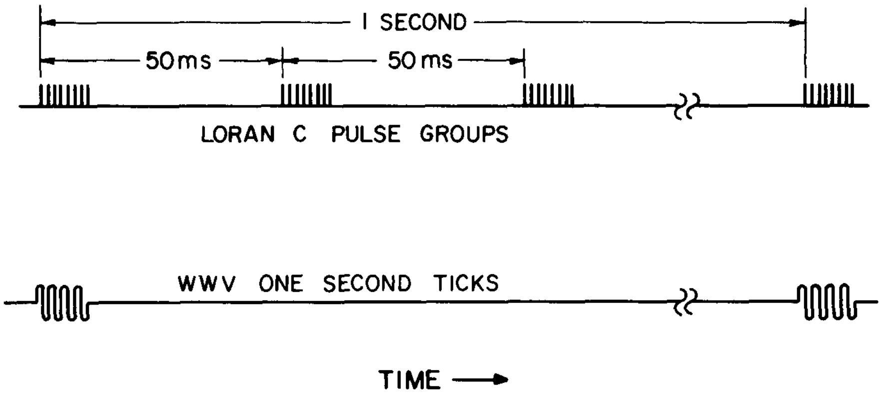

Figure 7.4 Pulse group to time relationship.

7.8. UHF Time-Distribution System

Each instrument requiring time could be supplied by its own Loran-C clock and time-code generator, but that was quite expensive and generally undesirable because of the quantity of equipment and personnel required to operate it. Typically, most of the instrumentation for missile observations at each of the different AMR stations was installed in a relatively small area. The most efficient scheme that could be visualized to distribute time locally was to use a single Loran-C clock in combination with a UHF transmitter to reach the terminal instruments. As a corollary to the clock development, an experimental UHF time-distribution system was also developed (Davis and Doherty, 1960).

The objective in the UHF time-distribution system development was to test the feasibility of the concept -- not to build prototype hardware. A frequency assignment at 1.75 GHz was obtained for use in Florida. A pulse transmitter and a receiver of simple design were built from WWII surplus components. The transmitting antenna was omni-directional and a corner reflector was used with the receiving antenna. The peak pulse power was about 200 W, which provided a good signal at line-of-sight distance up to approximately 40 miles.

The time-code generator was highly unconventional. Codes in their usual rectangular waveform were not generated at the clock, but information was taken from the clock and encoded into a pulse-time format for transmission. At the receiver, the signal was decoded and converted into the various IRIG and AMR codes. These codes ranged from 1 ppm to 1000 pps.

The circuits for decoding and generating each time code were packaged in plug-in units. This arrangement made it possible to select only the code or codes actually needed at each terminal equipment.

In relaying time via a UHF link, additional corrections must be made to take into account all the distances and delays through the equipment if the full accuracy of the clock is needed. In many instances, however, especially with the slower time codes, the transmission time through the UHF system could be neglected. Similarly, noncritical timing requirements could be satisfied by local hard-wire distribution from the UHF receiver.

7.9. AMR Timing Tests

Testing and demonstration of the use of Loran-C for timing on the AMR was an obvious climax of the Loran-C clock development. During the summer of 1960, plans and a firm schedule were worked out to take the clocks and the UHF distribution system to the Cape in October. After a few days of testing at the Cape, the equipment would be airlifted to the downrange stations for realistic trial under actual operating conditions. The plans included a commitment for a C-124 aircraft and crew, authorizations for foreign travel, and other important details.

Early in September, it became apparent that a serious problem was imminent in the well-laid plans. The timing receivers would not be delivered on schedule. A decision had to be made on the question of postponing the tests or obtaining other receivers that could be used to keep the schedule. At the sponsor's insistence, it was decided that available navigation receivers could be modified to achieve the test objectives on schedule.

That course of action seemed quite sound, but Loran-C receivers were scarce, and the timing tests did not have the priority to commandeer equipment in use by other services. The only available receivers were two early models of the SPN-28, which had been used for various experimental purposes. The performance of those receivers by that time was not good. The greatest difficulties were that the internal noise level was high and a variety of instabilities resulted in an excessive amount of maintenance. The deficiencies of those individual receivers were not fully appreciated until the tests were underway. At that point, however, there was little choice but to continue the testing effort as long as data of any value could be obtained.

The principal points to be demonstrated in the tests were the accuracy with which a clock could be set, using both groundwaves and skywaves, and the feasibility of the UHF time-distribution system.

The demonstration of clock-setting accuracy is a subject which requires further explanation than has been given thus far. Fundamentally, Loran-C provides only the technique for marking the instant a specified point on a radio signal arrives. The proper clock setting depends on the transmission time of the signal which is not measured by Loran-C. The transmission time must be determined by means external to the system, i.e., by calculation. Since Loran-C does not measure transmission time, the system itself cannot be used to furnish direct proof that a clock setting is correct. However, a synchronized pair of transmitters and two Loran-C clocks can be used to provide indirect proof.

For example: in referring to figure 7.5, assume both clocks have been set in accordance with the procedure given earlier: one clock using the master as a reference and the other clock the slave. The transmission times, T_S and T_m, are the only pertinent quantities that are subject to error. All other quantities, including the baseline transmission time, T_b, can be measured. If both clocks are correctly set, they must indicate the same time. The possibility that both could indicate the same time and be incorrectly set is very remote, and that possibility approaches nil as repeatability in all cases is demonstrated.

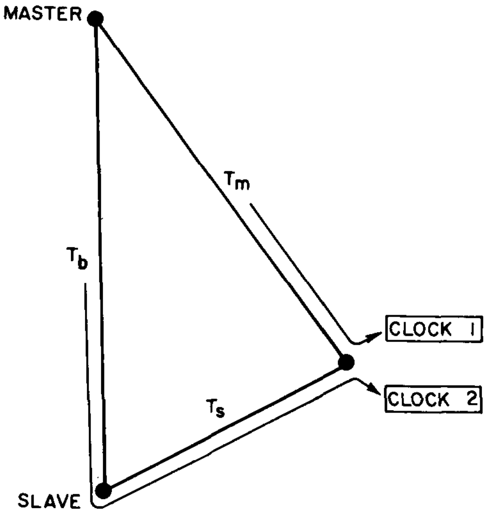

Figure 7.5 Synchronization of two clocks to check propagation.

In the AMR tests, there were no independent means available to check clock-setting accuracy so the scheme described in the foregoing example was used. The two clocks were operated independently of each other except that the receivers used the same antenna and preamplifier. The 1-sec pulses from each clock were used as read commands to the other clock. Correct setting was evidenced by the decimal fraction of seconds reading zero on both clocks. Since the clocks were designed to read to the nearest whole microsecond, a random discrepancy of 1 μs between readings also gave a valid indication of correct setting.

The results obtained at the different sites are shown in table 7.1 (Doherty et al. 1961a). The designation M for master and X, Y, Z for the first, second, and third slaves, respectively, is used. The stations used for setting the clocks are indicated by M-Y, or X-Y, etc. In some cases, both clocks were set by the same station as a further check of receiver performance.

While at the Cape, the UHF time-distribution system was demonstrated. The transmitting antenna was temporarily installed on top of the Central Control building. The signals were received at various instrumentation sites on the Cape. The slower codes were recorded with a Sanborn recorder while the higher speed codes were observed with an oscilloscope. No difficulties were encountered.

7.10. Monitoring and Steering

Since the timing receivers could not be delivered in time for the AMR tests, there was no urgent need for the contractor to complete them in minimum time. In fact, the contractor was urged to take enough time to be certain that the receivers were as nearly perfect as possible. They were delivered in January, 1961. After the frustrating experience with the SPN-28's, it was a pleasure to use the new receivers. Only a few minor items required correction after delivery. These receivers were probably the best that had been built up to that time, with respect to dynamic range, drift and noise figure. As a result of the new receivers, the groundwave signal from all three stations of the East Coast chain could be detected in Boulder, Colorado. The clocks were set up at the Table Mesa receiving site for extended monitoring.

Meanwhile, interest in Loran-C timing was growing, especially at the missile ranges and at the Naval Observatory. Arrangements were made to demonstrate the clocks to the Telecommunications Working Group (TCWG) of the Inter-Range Instrumentation Group (IRIG) at Boulder in the spring of 1961. Later the same year, the Naval Observatory began controlling or steering the frequency of the Loran-C master station.

At the Observatory, the Loran-C signal (groundwave) was compared with atomic standards. Corrections were then sent to the transmitter when a specified amount of drift had accumulated. Initially, it was not feasible to steer to precise tolerances because the quartz oscillators (a group of three) used at the transmitter did not have adequate stability. Before steering was started, the monitoring at Boulder, with the U.S.A. frequency standard as a reference, quickly revealed a diurnal frequency variation, which, when integrated, amounted to a time excursion of approximately 60 μs. At first, it was thought the skywave signal was being measured but the shape of the curve was not typical of skywave diurnal changes and the time excursion was too great. Finally, the trouble was traced to temperature sensitivity of the oscillators at the transmitter. The shape of the curve simply reflected the daily temperature variation in the oscillator room.

Better temperature regulation greatly improved the oscillator stability, but practical steering within close limits was not achieved until several months later when the quartz oscillators were replaced with a rubidium oscillator having a nominal stability of 1 part in 10^{10}.

To facilitate comparison of the Loran-C signals at Boulder with the NBS frequency and time standard, a microwave link was installed between the Table Mesa receiving site and the Radio Building. Standard frequency and time ticks (read commands) were transmitted to the Loran-C clock. The data were transmitted back to the Radio Building and automatically recorded on punch cards.

Table 7.1. Results of the AMR Tests.

Station Transmitters	Distances (miles) to Transmitters	Average Error in μsec	Max. Error in μsec
Jupiter, Florida			
M-X	500-2	1	1
M-M		0	--
X-X		0	--
Cape Kennedy			
M-X	430-90	1	2
M-M		0	--
X-X		1	--
Grand Bahama Islands			
M-X	510-110	1	2
M-Y	510-1100	1	--
X-Y	110-1100	1	2
*X-Y (night)		27	49
X-X		1	2
Y-Y		1	--
Grand Turk Island			
M-X	960-680	7	9
X-X		3	9
X-Z**	680-1230	1	--
Ramey AFB, Puerto Rico			
M-X	1260-1010	7	7
X-X		10	13
Mayaguiz, Puerto Rico			
M-X	1280-1030	41.5	51
X-X		19	45
Antigua, BWI (Site 1)			
M-X	1530-1350	5	9
X-X		10	19
M-M		27	62
Antigua, BWI (Site 2)			
M-X	1530-1350	52	59
X-X		44	--
M-M		27	62

* Presumably due to the higher nighttime noise level, groundwave synchronization could not be maintained. The average error of 27 μs is probably a measure of the skywave delay.

** The Z slave is an experimental station located at Wildwood, New Jersey. Its radiated power was about four times greater than M, X, or Y.

Table 7.1. Results of the AMR Tests (cont'd).

Station Transmitters	Distances (miles) to Transmitters	Average Error in µsec	Max. Error in µsec
Canary Islands (Mediterranean Chain)			
M-X	1990-2040	25	28
M-Y	1990-3230	55	71
X-Y	2040-3230	5	9
Lages AFB, Azores			
M-X (Med.)	2340-2620	8	22
X-X (Med.)		12	25
M-Y (N. Atlantic)	1830-1810	71	71
M-X (E.C.)	2820-3140	3	--
Y-X (E.C.)	2300-3140	62	--
Ascension Island (night)			
M-X	5040-5000	18	58
Z-X	5020-5000	11	42

Notes:

1. Due to set noise and/or external noise, the Y slave (Martha's Vineyard) could not be received reliably at either Jupiter or Cape Kennedy. The tests made with X-X and M-M showed that the receivers performed reasonably well with strong signals. The clock-setting accuracy was within 1 µsec as expected.
2. The groundwave from Y could not be received at Grand Turk Island and, in view of the large M-X errors, it is probable that the groundwave from M was nearly lost in the noise.
3. Groundwave synchronization could not be maintained at either site in Puerto Rico. The large errors with X-X indicate that the two receivers were not locking on the same part of the pulse.
4. The results at Antigua were entirely comparable to those in Puerto Rico.
5. The large errors on M-X and M-Y at the Canary Islands were probably attributable to different skywave hops being used by the receivers. Signals from the Faroe Islands and Bø, Norway stations of the North Atlantic chain were seen on the scope but were too weak for measurement purposes.
6. Signals from the East Coast, the North Atlantic, and Mediterranean Chains were all visible at night in the Azores. The measurement results at Lages were not significantly different from those obtained at Ascension and the Canaries.
7. No M-M measurements were made at Ascension Island since one of the receivers would not lock on M. At a distance of 5000 miles, the difference between the readings of the two clocks is not necessarily the actual error in clock setting. The actual error could be larger if the incorrect skywave hop were assumed.
8. At Johannesburg, S.A., night signals from the M,X, and Y stations of the Mediterranean chain and the X slave of the East Coast chain were received. The Z slave of the Mediterranean chain was not in operation at that time. The signals could be seen clearly on the oscilloscope, but no measurements of consequence were obtained. Normally, signals that are clearly visible above the noise are more than adequate for good measurements. It was not established whether the trouble was with the receivers or the skywave signals. The only worthwhile result of the Johannesburg trip was to find that the skywave signal from Jupiter could be received at a distance of nearly 8,000 miles.

The monitoring at Boulder and steering by the Naval Observatory amounted to a rather valuable experiment. The most significant aspect was that, as the frequency stability of the master station was improved and as experience was gained, it became evident that the transmissions could be both controlled and monitored to microsecond accuracy or better. In the actual experiment, drifts of several microseconds were allowed to accumulate, but they were measured both at Boulder and at the Observatory. The tolerance placed on the permissible drift was essentially an arbitrary choice, or an administrative matter, not a technical limitation. It was shown that ultimately, the time transmissions could be controlled to agree with a master clock as precisely as a slave station maintains synchronism with its master.

7.11. Timing with Specific Repetition Rates

The periods of all the "basic" loran repetition rates are submultiples of 1, 2, or 3 sec. Clock-setting information is, therefore, conveniently available at those intervals. These periods are also exact submultiples of minutes, hours, and days. The clock-setting procedure described earlier can be carried out quite simply.

Use of the specific rates for timing is somewhat more complicated because they are not conveniently related to seconds, minutes, hours, or days. The periods of all the loran rates are shown in table 7.2.

Table 7.2. Loran Repetition Rate Periods.

Specific Rate	Repetition Period in μs					
	SS	SL	SH	S	L	H
0*	100000	80000	60000	50000	40000	30000
1	99900	79900	59900	49900	39900	29900
2	99800	79800	59800	49800	39800	29800
3	99700	79700	59700	49700	39700	29700
4	99600	79600	59600	49600	39600	29600
5	99500	79500	59500	49500	39500	29500
6	99400	79400	59400	49400	39400	29400
7	99300	79300	59300	49300	39300	29300

* The "0" specific rates are called BASIC RATES.

Since all the periods are multiples of 100 μs, a pulse group will be transmitted eventually on a whole second as shown in table 7.3. There is no completely simple way to set a clock from timing information in that form. While it can be done quite rigorously by rather eleaborate procedures and, at the same time, take full advantage of the coherent detection techniques, simpler approaches have been sought.

The Coast Guard proposed adding 1-sec pulses to the transmission of all the Loran-C chains. The 1-sec pulses were added for a time to the East Coast master station for evaluation. Single pulses were transmitted 2 msec ahead of the pulse

Table 7.3. Intervals in seconds at which pulse groups coincide with whole seconds.

Specific Rate	SS	SL	SH	S	L	H
0	1	2	3	1	1	3
1	999	799	599	499	399	299
2	499	399	299	249	199	149
3	997	797	597	497	397	297
4	249	199	149	124	99	74
5	199	159	119	99	79	59
6	497	397	297	247	197	147
7	993	793	593	493	393	293

groups which occurred on the whole second. Automatic instrumentation using time of coincidence dual-divider circuitry has been developed by Austron for the 1-sec pulses for use with their timing receiver. Oscilloscope presentation only was formerly used. When the signals could be seen fairly well above the noise, there was no difficulty in identifying the whole-second pulse groups. However, since the East Coast chain used a basic rate of 20 pps*, the oscilloscope pattern was steady. Such was not the case with the switch to the specific rates and a considerably better signal-to-noise ratio is required to identify the infrequently occurring "on-time" pulse groups.

In regions where the signals from several transmitters can be received, confusion could arise in correctly identifying the different 1-sec pulses. In principle, the different pulses could be coded for identification purposes, but, in view of the tiny fraction of the total radiated power they contain, practical limitations would surely be encountered. The 1-sec pulses may be very useful where strong signals are available, but it seems probable that more complex techniques may be required eventually.

Prior knowledge of the approximate time can be assumed since the principal role of Loran-C in timing is to provide high accuracy that is not otherwise possible. For example, let us assume that a correctly set clock exists at the master transmitter of a chain which operates on the SH-4 rate. It is shown in table 7.3 that a pulse group is transmitted on the whole second every **149** sec. An arbitrary relationship between the 149-sec interval and the time of day must be established; therefore, let the beginning of a day and the beginning of a 149-sec interval coincide. Pulse groups on the whole second will then be transmitted at 149 sec, 298 sec, 447 sec, etc. A clock may be set with these transmissions by using the following procedure:

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* changed to SLO in 1965, and to SL7 in 1968.

1. Compute the Loran-C transmission time from transmitter to clock as in earlier example.
2. Determine the approximate time (within a few milliseconds) by WWV or similar means.
3. Set Loran-C clock to the approximate time.
4. Read the clock out at the end of the next 149-sec interval. (The readout signal must be taken from the Loran-C timing receiver.)
5. The difference between the actual clock reading and the computed reading is the amount by which the clock must be advanced or retarded for correct setting.

The above setting procedure is applicable for all specific rates, but one further problem remains. Since none of the intervals, such as 149 sec, is an integral submultiple of a day (86,400 sec), a second arbitrary choice in procedure must be made at the beginning of the second and subsequent days. On the SH-4 rate, for example, the end of the last full interval of 149 sec in the first day falls at 86,271 sec. The next interval ends at 86,420 sec, or 20 sec after the beginning of the second day. If operation is continued without interruption, a new table of intervals or ephemeris must be made for each day. As an alternative, it might be more practical to reset the clock at the beginning of each day and avoid the problem of a continually changing ephemeris. The only objection to that procedure would be that navigation receivers would be briefly thrown out of synchronization. Timing receivers would also have to be resynchronized, but the clocks would not need to be interrupted.

8. LORAN-C SKYWAVES

The stability of the daytime skywave observed during the Cytac tests in 1954-1955 clearly suggested that the system might be used with that mode of propagation at distances beyond groundwave range. However, in the Cytac test program, there were neither time nor funds to follow up the possibility that became evident during the tests.

Early in 1956, the Coast Guard became interested in the possibilities of using Cytac for navigation. The groundwave performance of the system had already been demonstrated well enough that no serious questions remained, but the possility of using skywave at much greater range was very tantalizing. Inasmuch as the Cytac transmitting stations had been secured at the end of the test program with all the equipment in operating condition, and, since all the receivers were still available, a modest skywave measurement program seemed clearly in order.

Arrangements were made with Sperry by the U.S. Coast Guard to operate the system and to install one of the experimental airborne receivers aboard the USCGC Androscoggin. Separate arrangements were made with NBS to plan the measurement program and to collect and analyze the data. A trip of approximately 1 month was decided upon with stops of about 2 days each at several Caribbean ports, thence, through the Panama Canal and south along the west coast of South America. The principal reason for planning the trip in that manner was that the groundwave signal from the Carabelle, Florida, slave station would be available as a reference at several of the planned stops. At the same time, the distance to the other two stations would be, in most cases, either beyond groundwave range or, at least, great enough that the skywave would be much larger than the groundwave.

Installation of this receiver aboard the Androscoggin was performed at Miami Beach, Florida, during the first part of April, 1956. The trip started immediately upon completion of the installation.

The significant data obtained on the trip is summarized in table 8.1, in which the following symbols are used:

M -- Master station, Caroline Beach, North Carolina
X -- Carabelle, Florida, slave
Y -- Forestport, New York, slave.

The letter or number following the station code indicates the mode of propagation. For example, X-G means groundwave from Carabelle, and Y-3 is the third-hop skywave from Forestport, New York.

The column marked "Delay" shows the difference between the average reading and the computed groundwave time difference.

In the preliminary measurements made in 1953, it was found that the daytime skywave delay was either constant or nearly so at distances beyond approximately 1200 miles, i.e., the distance at which ray paths from a 70-km ionosphere are tangent to the earth. Over land paths, using a pulse that rose to full amplitude in 3 cycles, the measurements of the skywave delay indicated a value of 26 μs was correct at these ranges. The delays of 29.9 and 30.0 μs, measured in British Honduras and Nicaragua,

Table 8.1. Measurements Made on Caribbean Trip.

Xmtrs. and Mode	Distance in Nautical Miles		Day or Night	Delay μs	Standard Deviation in μs
		Belize, British Honduras			
X-G, Y-G	770	1693	D	- 0.4	0.94
X-G, Y-1	"	"	D	+29.9	1.01
X-G, Y-1	"	"	N	+43.1	1.22
X-G, Y-3	"	"	D	+102.8	0.54
X-G, Y-2	"	"	N	+103.9	1.46
X-G, Y-4	"	"	N	+267.7	0.90
		Kingston, Jamaica			
M-G, X-G	965	832	D	- 0.7	0.55
X-G, Y-G	832	2069	N	+ 0.3	0.37
M-G, Y-G	965	2069	D	+ 1.0	0.36
		Puerto Cahezas, Nicaragua			
X-G, Y-G	953	1813	D	- 2.2	1.23
X-G, Y-1	"	"	D	+30.0	1.44
X-G, Y-1	"	"	N	+49.7	1.23
X-G, Y-3	"	"	D	+211.4	1 02
M-G, X-G	1235	953	N	- 1.9	0.25
		Buenaventura, Columbia			
M-G, X-G	1804	1612	D	- 2.6	0.59
M-1, X-1	"	"	N	- 2.1	0.41
M-1, Y-1	1804	2369	N	0.0	0.94
M-G, Y-2	"	"	D	+37.5	1.86
M-G, Y-3	"	"	D	+105.3	0.91
M-1, Y-4	"	"	D	+222.7	1.31
X-G, Y-4	1612	2369	D	+235.9	1.01
		Guayaquil, Ecuador			
M-1, X-1	2174	1931	N	- 1.98	0.30
M-1, Y-2	2174	2748	N	+56.6	0.53
M-1, X-1	2174	1931	D	- 0.5	1.81

respectively, were in excellent agreement with the earlier value of 26 μs, when the differences in groundwave phase corrections for land and sea are taken into account. The nighttime values of 43.1 and 49.7 μs, however, are not readily explanable. The standard deviations do not suggest that an average difference of 6.5 μs could be attributed to random measurement error. If the effective height of the nighttime ionosphere changed enough between the times of observation to account for the difference, which is probably the explanation, then it would seem desirable, for navigation purposes, to use the same skywave hop from both stations -- not one groundwave and one skywave.

While each set of skywave measurements covered only a short period of time, the standard deviations in all cases were relatively small and certainly small enough to suggest that useful fix accuracy could be obtained. The crossing angles of the lines of position were not favorable for fixes, but on several occasions, while underway, the lines of position were quite stable both day and night as might be expected from the standard deviations of the readings taken in port. At distances beyond 1200 miles, when using pairs of skywaves (first or second hops depending on the distance), the time differences were in quite good agreement with the computed groundwave values. Such agreement was expected, because, at those distances, the delay had previously been essentially constant and, therefore, the same delay would be added to each signal. It is pointed out, however, that while underway, and not having the benefit of exact position information, identification of the hops was more difficult than when in port.

On one occasion, while steaming south at night along the west coast of Columbia, and essentially parallel to the lines of position, there was a good opportunity to check the accuracy of the skywave readings. As an experiment, the bridge was advised of our distance from the shore, according to Cytac. The actual distance measured by radar was requested. The discrepancy was shocking and there were some rather disparaging remarks about the electronic navigation system. A few minutes later from the bridge -- "My God, you are right!", or words to that effect. The radar operator found he had been mistaking the reflection from the mountains several miles inland for the shoreline. The Cytac line of position was requested for the remainder of the night.

Despite some uncertainties about the cycle ambiguity, and proper identification of the number of hops, all who were immediately concerned felt quite encouraged about the potential use of skywaves.

The Jansky and Bailey evaluation of measurements made in 1958 (Dickinson, 1959), on the usefulness of skywaves at distances beyond groundwave range, was generally favorable but included some important reservations. Some difficulty had been experienced with cycle ambiguity, and it was realized that there might be a problem in correctly identifying the different skywave hops. As in earlier measurements, these extended over periods of only a few days at each site and did not warrant conclusions on long-term stability or predictability of the skywave.

The most encouraging aspect of the skywave data was the phase stability, except, of course, during sunrise and sunset. The Jansky and Bailey measurements were in good agreement on phase stability with those made by NBS in 1956 (see tables 8.1 and 8.2), however, they differed by approximately 10 μs on the daytime first-hop skywave delay at great distances (compare tables 8.1 and 8.3). Jansky and Bailey reported that the SPN-28 receiver did give trouble at time with cycle ambiguity due to malfunctioning, but they believed that the equipment was working properly when the data shown in the tables were recorded. There is good evidence to indicate that the performance of the Cytac receiver (EAR), which was used in 1956, was substantially better than that of the SPN-28. For example, the groundwave was received with the Cytac receiver at distances up to nearly 2000 nmi, while in most cases, the SPN-28's performance was quite poor beyond 1000 miles and 1500 miles was the maximum groundwave range reported. However, the skywave signal has a different dispersion characteristic than the groundwave signal, so the SPN-28 may have been tracking the correct cycle while the Cytac receiver was tracking the wrong cycle. Somewhat different rf filter characteristics in the two receivers could account for greater sensitivity and a tendency to lock on the wrong cycle in the earlier receiver.

Table 8.2. Time Difference Measurements (Jansky and Bailey Measurements).

Receiver Location	No. Hops	Distance Nautical Miles	Xmtrs.	Mean Measured TD-Computed Gnd Wave +D	95% of TD Reading Within	No. of Readings	Readings EST	Date 1958	Uncertainty of receiver Location in Miles
Newfound-land	1	1340	M-Y	- 0.3	± 0.4	20	2030-0030	6/17,18	0
	1	1730	M-X	+ 0.1	± 0.9	29	1945-0145	6/17,18	0
Puerto Rico	1	1129	M-X	+ 0.75	± 1.2	34	2000-0500	3/29,30	± 0.11
	1	1390	M-Y	- 0.85	± 0.1	10	0545-0800	3/29	± 0.12
	1	1390	M-Y	0	± 0.45	39	2000-0430	3/29,30	± 0.12
Trinidad	1	1445	M-X	- 0.9	± 0.5	15	1130-1500	3/31	± 0.25
	1	1445	M-X	- 0.28	± 0.72	36	2000-0500	3/31:4/1	± 0.25
	1	1906	M-Y	- 0.5	± 0.7	16	1130-1500	3/31	± 0.29
	1	1906	M-Y	- 0.2	± 0.8	32	2000-0430	3/31:4/1	± 0.29
	1	1906	M-Y	+ 0.2	± 0.7	11	1930-2145	4/1	± 0.29
	1	1445	M-X	- 0.9	± 0.8	14	1215-1615	4/7	± 0.25
Belem, Brazil	2	2692	M-X	+ 0.5	± 1.6	28	2130-0430	4/2,3	± 1.03
	2	2692	M-X	- 0.2	± 0.3	11	0130-0400	4/3	± 1.03
	2	2830	M-Y	+ 5.0	± 1.0	29	2130-0430	4/2,3	± 1.32
Natal, Brazil	3	3402	M-X	+ 2.9	± 1.2	19	2115-0215	4/5,6	± 0.89
	3	3435	M-Y	- 1.45	± 0.7	10	0054-0330	4/6	± 1.16

Table 8.3. Summary of Measured Skywave Corrections (Jansky and Bailey Measurements).

Receiver Location	Xmtr. and No. Hops		Distance Naut. Mi.		Sky-wave Correction	Date 1958	Time EST
Bermuda	M-G	X-1	665	856	- 37.2	3/23	0820
	M-G	X-1	"	"	- 37.4	3/23	0845
	M-G	X-1	"	"	- 37.2	3/23	0900
	"	"	"	"	- 59.4	3/24	2124
	"	"	"	"	- 59.4	"	2125
	"	"	"	"	- 58.8	3/25	0106
	"	"	"	"	- 59.0	"	0115
	"	"	"	"	- 60.2	"	0222
	"	"	"	"	- 60.6	"	0235
	"	"	"	"	- 61.2	"	0400
	"	"	"	"	- 59.0	"	2351
	"	"	"	"	- 59.2	"	2353
	"	"	"	"	- 59.2	3/26	0000
	"	"	"	"	- 58.8	"	0006
	M-1	Y-G	665	614	+ 51.3	"	0530
	"	"	"	"	+ 51.5	"	0545
Puerto Rico	M-1	X-G	1129	928	+ 37.5	3/29	0605
	"	"	"	"	+ 37.1	"	0615
	"	"	"	"	+ 37.2	"	0630
	"	"	"	"	+ 37.3	"	0645
	"	"	"	"	+ 37.2	"	0700
	M-G	Y-1	1129	1391	- 39.5	3/30	1615
	"	"	"	"	- 40.3	"	1625
	"	"	"	"	- 39.1	"	1640
Newfoundland	M-G	X-1	1340	1730	- 38.7	6/18	0847
	"	"	"	"	- 39.1	"	0857
	"	"	"	"	- 38.7	"	0907
	"	"	"	"	- 38.4	"	0930
	"	"	"	"	- 39.1	"	0955
	"	"	"	"	- 38.6	"	1000
	"	"	"	"	- 38.6	"	1005
	"	"	"	"	- 39.4	"	1019
	"	"	"	"	- 37.3	"	1030
	"	"	"	"	- 37.3	"	1045
	"	"	"	"	- 38.2	"	1100
	"	"	"	"	- 39.2	"	1112
	"	"	"	"	- 38.4	"	1120
	"	"	"	"	- 38.8	"	1150
Trinidad	M-1	X-G	1673	1445	+ 57.2	3/30	2245
	M-1	Y-2	1673	1906	- 64.4	"	"
	"	"	"	"	- 65.1	3/31	0000
Natal, Brazil	M-3	Y-2	3402	3435	+ 61.3	4/5	2142
	"	"	"	"	+ 60.8	"	2148
	"	"	"	"	+ 59.8	"	2220
	"	"	"	"	+ 59.6	"	2231
	"	"	"	"	+ 59.4	"	2245
	"	"	"	"	+ 58.2	"	2300
	"	"	"	"	+ 59.0	"	2322
	"	"	"	"	+ 56.8	"	2349
	"	"	"	"	+ 56.8	4/6	0000
	"	"	"	"	+ 55.0	"	0025
	"	"	"	"	+ 55.8	"	0033
	"	"	"	"	+ 57.6	"	0230
	"	"	"	"	+ 58.1	"	0237
	"	"	"	"	+ 57.1	"	0245
	"	"	"	"	+ 57.5	"	0300
	"	"	"	"	+ 57.2	"	0315
	"	"	"	"	+ 60.9	"	0330
	M-2	Y-3	3402	3435	- 61.6	"	2155

In measuring skywaves with the Cytac receiver, it was noted that the discrepancy would frequently exceed ± 5 μs for short periods. Most of the time, however, the discrepancy was within normal limits, and it was assumed that those readings were correct. Jansky and Bailey made the same assumption in analyzing their data. Thus far there is no clear explanation of the disagreement between the two sets of measurements but the suggested explanation is a 1-cycle error in the earlier measurements. Further evidence for this conclusion is that current skywave delay measurements at Boulder do not agree with the earlier measurements. The daytime first-hop delay at Boulder from the East Coast stations appears now to be about 35 μs. That value is in very good agreement with Jansky and Bailey's measurements of 38 to 40 μs over sea water paths. Also, more recent theoretical calculations (Johler, 1962) show that 35 to 40 μsec is the proper asymptotic delay for a 70-km layer height. The earlier calculations did not properly account for the skywave delays due to diffraction near the region of tangency.

In all skywave measurements, and especially at night, the discrepancy* is variable with time. That variation may provide a clue to the explanation of some of the apparent inconsistencies in the skywave data. In the process of reflection from the ionosphere, the pulse suffers dispersion to a greater or lesser extent, depending on the time-varying characteristics of the ionosphere. When the pulse shape is changed and when the phase relationship of the cycles to the pulse envelope is changed too, the measurement technique, which is "built in" to a Loran-C receiver, is no longer valid. The receiver is designed to operate on a particular pulse; and especially on two identical pulses. Whether or not an incorrect reading occurs depends on how much the pulses have been modified. The fact that the discrepancy is variable shows the pulse shape does change; therefore, the assumption made earlier that the reading obtained most of the time was correct, perhaps should not be defended. The time-difference measurements between corresponding skywave reflections certainly provided ample reason for enthusiasm, but the repeatability of those measurements provided no proof or guarantee that both master and slave pulses were not similarly distorted. Pulse distortion could easily have been present with little or no error resulting in the time-difference readings. Using one groundwave signal and one skywave signal to measure the skywave delay, however, can result in errors if the received pulses are dissimilar. It is felt that the inconsistencies in the data are probably attributable to such causes.

In a report on the East Coast chain, Jansky and Bailey (1962) stated that the skywave accuracy was better than 5 μs, 95 percent of the time, except during sunset and sunrise. At the same time, they emphasized the need to correctly identify the mode of propagation or hop to avoid gross errors.

When going away from the transmitters, a skillful operator should be able to switch to the first-hop skywave upon reaching the limit of detectability of the groundwave. Experience has shown that this can be done quite well at slow speeds. At aircraft speeds, the problem is fundamentally more difficult because information must be obtained from the signals at a faster rate. Also, at a higher speed, there is

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* See Glossary.

less opportunity to compare the newly acquired skywave reading or position with a dead-reckoning position based on the last groundwave reading. Under such conditions, further confusion can arise in distinguishing between the first- and second-hop skywaves.

When approaching the transmitters from beyond groundwave range, the problem of identifying the mode of propagation is considerably more difficult. In this situation, it must be assumed that the position is not known precisely, therefore, the operator does not necessarily have an opportunity to select the mode of propagation which will yield a fix that agrees with his position.

In the various skywave navigation tests that have been made using the East Coast chain, the results have been surprisingly good, but in all cases, the operators have had considerable knowledge of propagation. If the operators did not have that knowledge, it is a safe bet that the reported skywave performance of the system would have been much less satisfactory.

A great deal of long-term skywave monitoring of the East Coast signals has been done at Boulder for purposes of detecting ionospheric disturbances. Other long-term monitoring has been done at the Attu and Sitkinak slave stations of the Aleutian chain. A limited amount of monitoring has been done at the Kure and Hawaii stations of the Central Pacific chain. In more recent years, long-term monitoring has been done in all chains except the Mediterranean chains.

The long-term monitoring has been quite valuable in that a much better understanding has been gained of the behavior of the 100-kHz skywave signals. The data have probably created more questions than they have answered, but, at least, some observational facts are clear.

Except for the unresolved question of the earlier measurements of the first-hop delay using the East Coast signals, the long-term data are consistent with the earlier measurements, and, in addition, reveal phase and amplitude perturbations caused by solar flares. Data from the Pacific and the Aleutian stations show the effects of solar flares, but also indicate that the characteristics of the lower ionosphere vary substantially with geographic location and season. Other data from the Pacific, to be discussed shortly, add confusion to the problem of interpreting the observations.

The paths over which most of the skywave measurements have been made are shown in figure 8.1. Long-term measurements at Boulder, using signals from the East Coast chain, and the earlier measurements in 1956 in Central America (Doherty, 1962), have shown that the skywave delay (first hop) usually increases abruptly by about 20 μs at sunset then decreases at sunrise. During the day, the average phase variations are less than ± 1 μs, and less than ± 4 μs at night. These limits, however, may be exceeded during certain disturbed ionospheric conditions. Typical diurnal amplitude variations are of the order of 20 dB. Both day and night amplitudes are variable, with the largest variations at sunset and sunrise (see fig. 8.2). Additional phase and amplitude measurements are shown in figure 8.3. Curiously enough, most amplitude variations throughout the day and night are seldom accompanied by correlative phase shifts. However, effects associated with solar flares and high-altitude

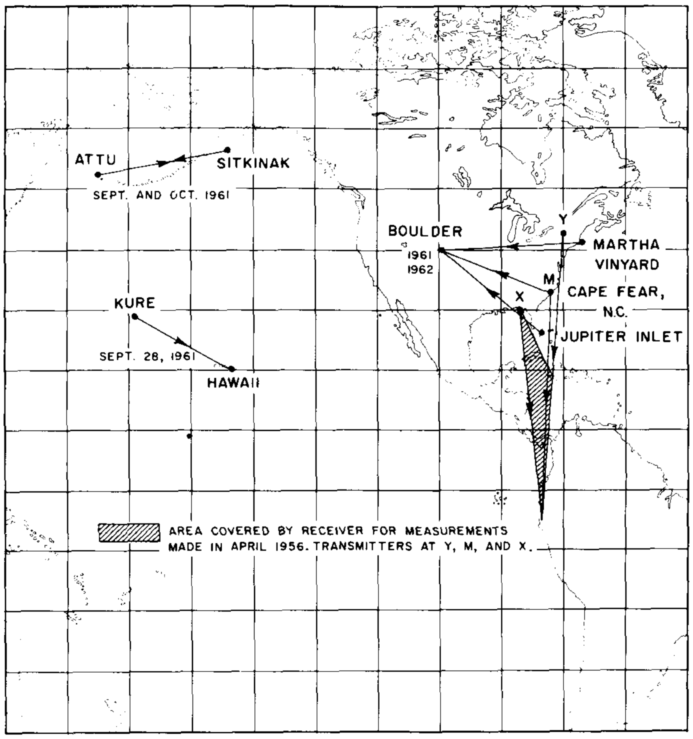

Figure 8.1. Regions where the majority of skywave measurements have been made.

nuclear detonations are notable exceptions. It has also been observed that the higher order hops are subject to large amplitude variations, but the amplitude variations of any one hop seem to be independent of, or at least, show no obvious correlation with the amplitude variations of the other hops.

Doherty (1962) proposed, and Johler and Harper (1962) have shown, theoretically, that a sparsely ionized region below the D layer could produce considerable attenuation without appreciable phase shift. If it is assumed that such a sparsely ionized region is time-variable, such a mechanism could explain both the day and night amplitude variations that are not accompanied by phase shifts.

The 1956 measurements showed that, at a given distance, the skywave field strength was greater from the more southern transmitters, both day and night. The location of the transmitters and the observation sites were substantially in a north-south configuration. The transmitter locations were at 43°, 34°, and 30° north latitude, and observations were made over the range from 30° north to 3° south latitude.

Measurements at Boulder also showed stronger skywave signals from the more southern transmitters. Signals from the mid-latitude and northern transmitters were roughly 6 and 12 dB weaker, respectively, than those from the southern transmitter. It seems evident that the characteristics of the D region are latitude-dependent.

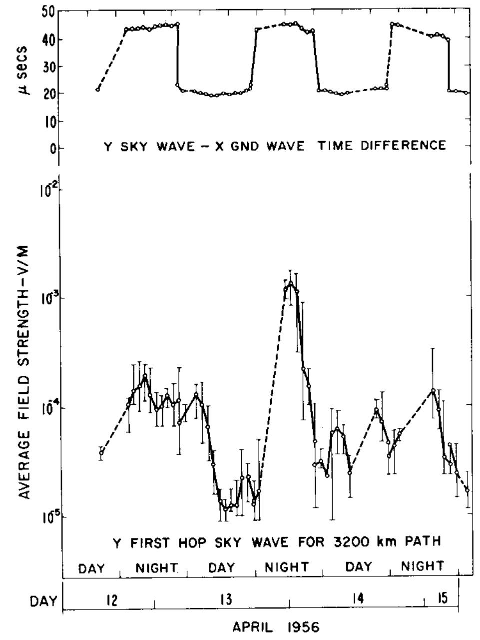

Figure 8.2. Phase and amplitude of the Loran-C skywave recorded on a north-south path.

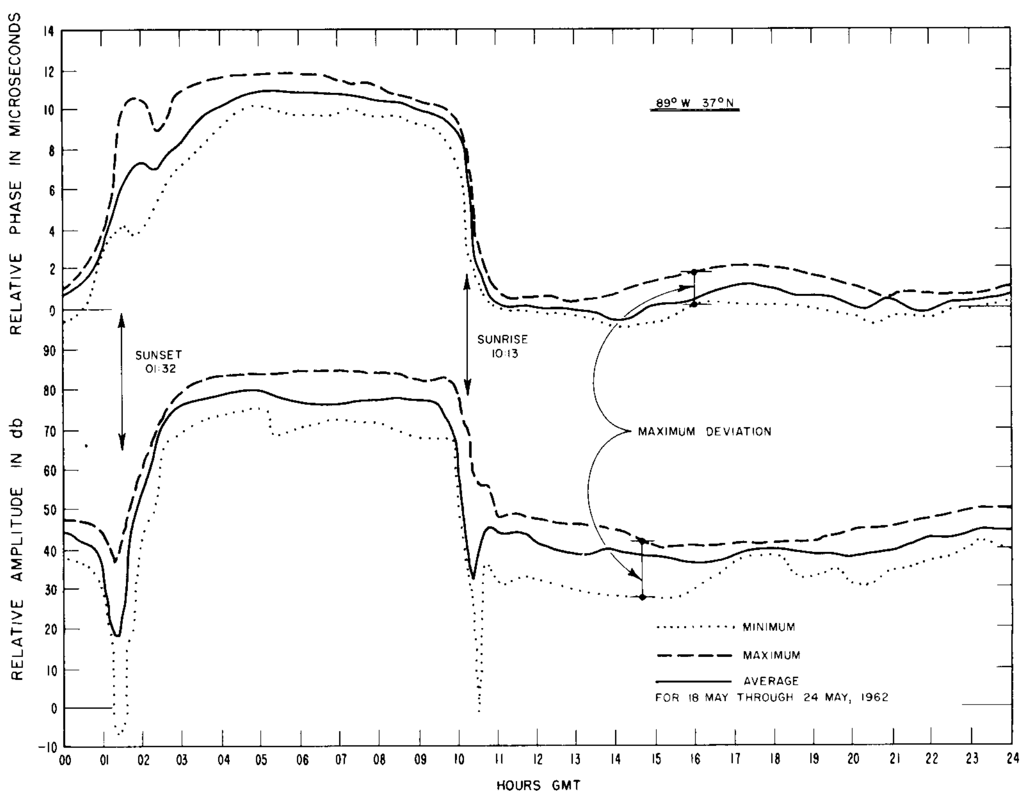

Figure 8.3. First-hop skywave from Carolina Beach, North Carolina to Boulder, Colorado.

If appropriate attributes were assigned to the presumed sparsely ionized region below the D layer, the amplitude-latitude dependence could probably be explained. Doherty (1962) proposed that such a region could be created by particle bombardment. Some evidence to support such a proposal may be found by observing the effects of solar flares as shown in figures 8.4 to 8.7. Solar flares can produce either phase advance or retardation and amplitude increase or decrease at LF. The mechanisms involved are quite complex , and interpretation of data is somewhat speculative.

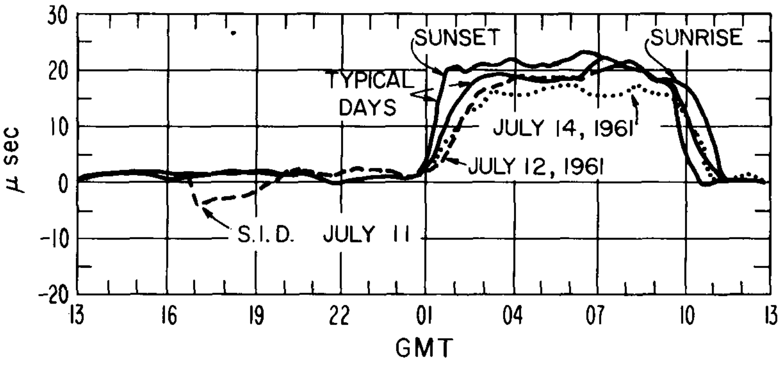

Figure 8.4. First-hop skywave from Carolina Beach, North Carolina, to Boulder, Colorado.

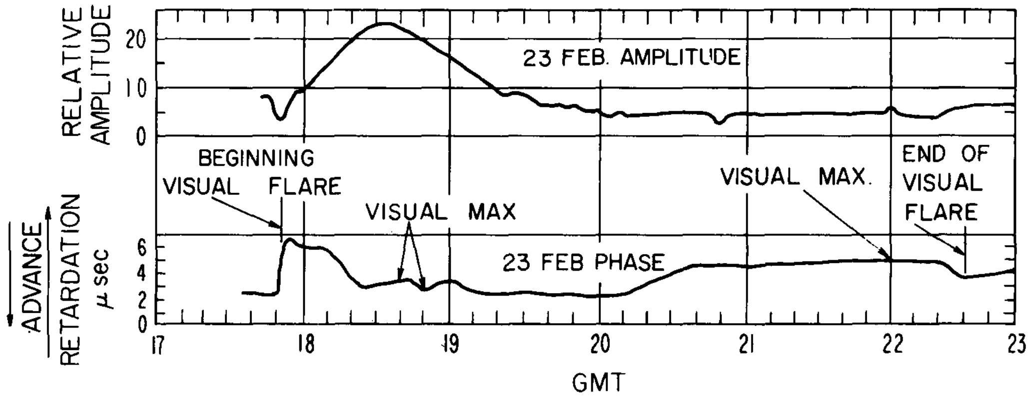

Figure 8.5. First-hop skywave from Carolina Beach, North Carolina, to Boulder, Colorado.

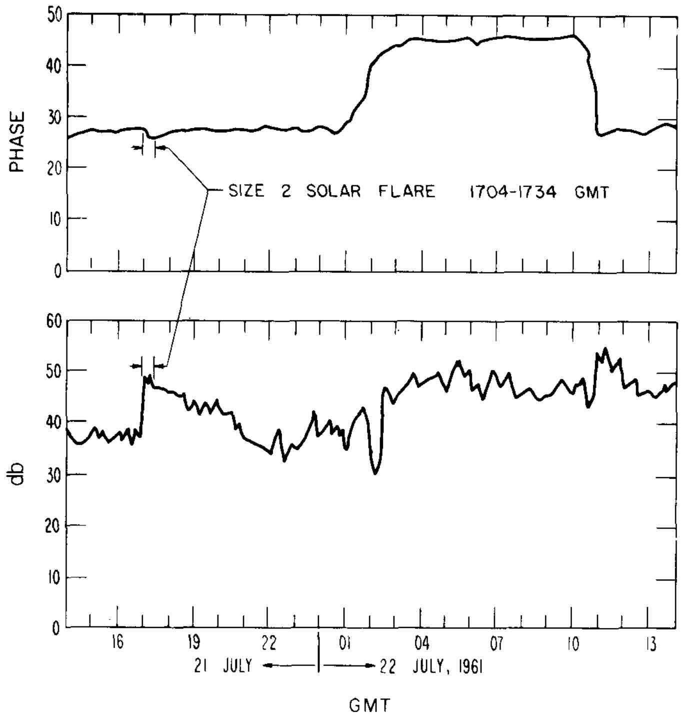

Figure 8.6. First-hop skywave from Carolina Beach, North Carolina, to Boulder, Colorado.

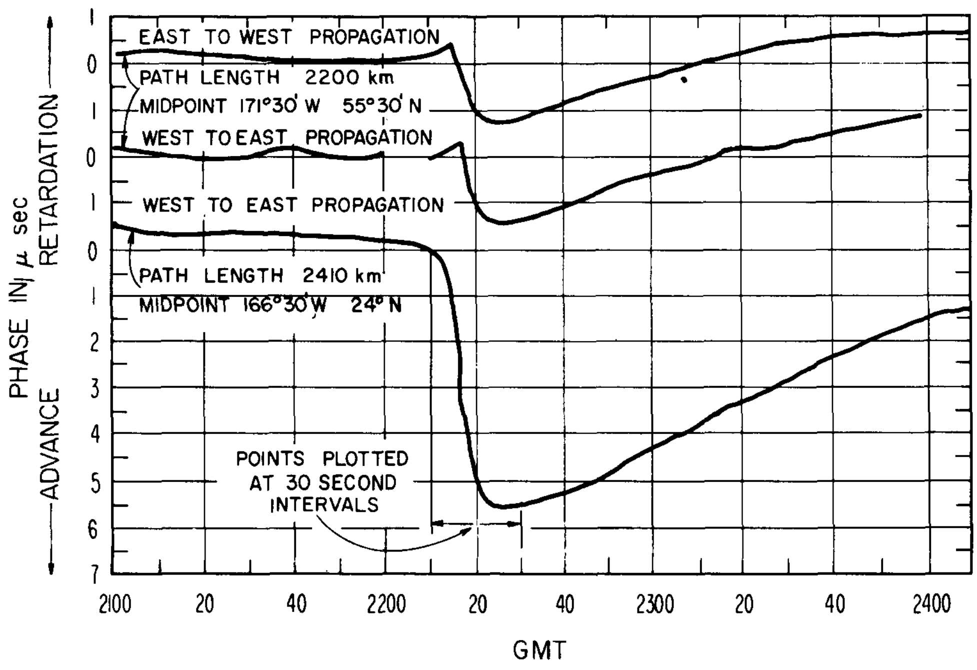

Figure 8.7. Solar event of September 28, 1961.

Quantitative data on east-west versus west-east propagation is entirely too inadequate to attempt an analysis of the subject. General impressions are, however, that skywave propagation from west to east is better than in the reverse direction. The greatest distance over which the reception of Loran-C skywave signal has been reported is approximately 8000 miles, which was from Jupiter, Florida, to Johannesburg, South Africa, during the Loran-C timing tests (Doherty et al. 1961a). It may be noted that the distances from Johannesburg to all three of the East Coast transmitters are nearly the same, but only the southernmost transmitter could be received. The influence of the earth's magnetic field on the ionosphere (Johler and Harper, 1962) very probably accounts for the observations, but uncertainties about the electron density make it difficult to draw positive conclusions.

To further investigate the feasibility of using skywaves for navigation, the Coast Guard, with some technical assistance from CRPL, set up a fixed monitoring station at Wake Island. The site was chosen because of its location relative to the stations in the Central Pacific chain (SH-4). One of the stations was within groundwave range. The other two were sufficiently distant that the skywave would predominate. The stations were located at Johnson Island, Upola Point, Hawaii, and Kure Island, and at distances of 1518, 2436, and 1139 statute miles, respectively, from the monitoring site. Monitoring was started in October, 1963.

One of the major objectives of this monitoring effort was to obtain long-term observations with the navigation application in mind since it was felt that the previous skywave measurements were too few, or oriented too much toward academic studies, to warrant prediction of system performance. The entire instrumentation for the monitoring was much more elaborate than that used in any of the previous measurement efforts. Two SPN-30 receivers were modified for use with an external local oscillator , and provision was made to record the AGC and envelope-error voltages of all channels in addition to the envelope and cycle readings. The outputs were recorded on punched paper tape, on printed paper tape, and on analog strip charts.

The overall arrangement was fine in principle, but maintaining the equipment proved to be a nearly impossible task. The SPN-30 receivers and the local oscillator functioned well enough, but the recording equipment was a perpetual headache. As a result, little useful information was obtained. After 10 months, the monitoring was discontinued.

Despite the loss of data, there were enough "good" measurements to show that the behavior of the system with skywaves in this situation was markedly different from that observed using the East Coast chain. In this context, the term "good measurement" is used only to indicate that the equipment appeared to be functioning in the manner in which it was designed to operate. Figures 8.8 to 8.12 show the readings obtained on six different days during the period from November, 1963 to July, 1964 (Haidle and Washburn, 1965).

These results are so radically different from those previously discussed that the author tends to feel the data may be invalid, but the facts do not completely justify such an assumption. There is no obvious explanation for the extreme scattering of the data except that there was evidently little or no tendency for the envelope

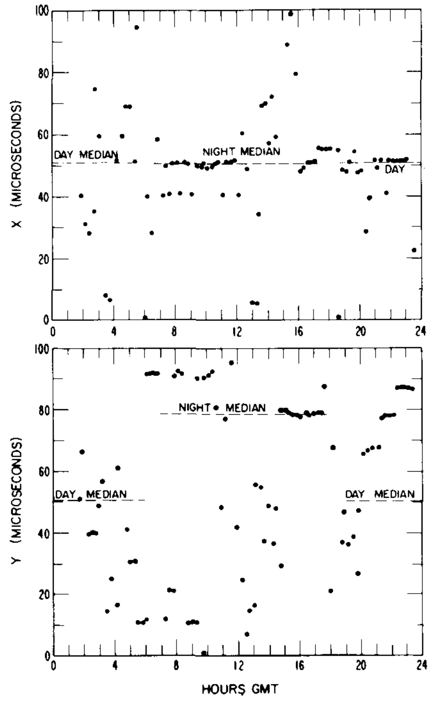

Figure 8.8. Wake Island, Nov. 1, 1963.

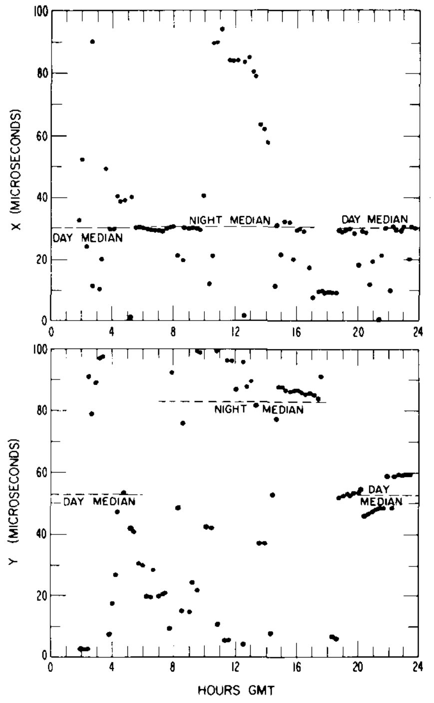

Figure 8.9. Wake Island, Nov. 8, 1963.

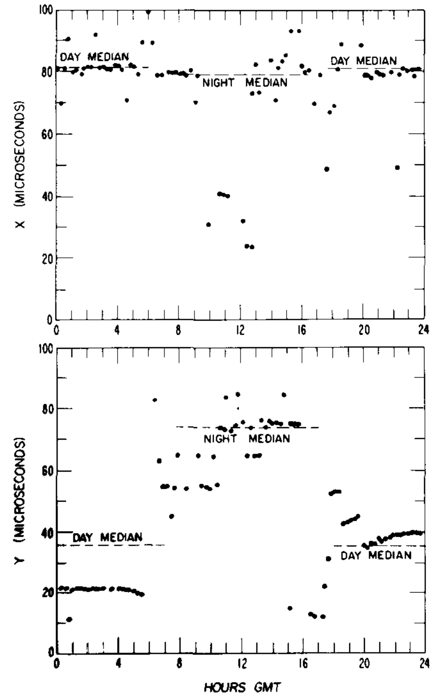

Figure 8.10. Wake Island, May 1, 1964.

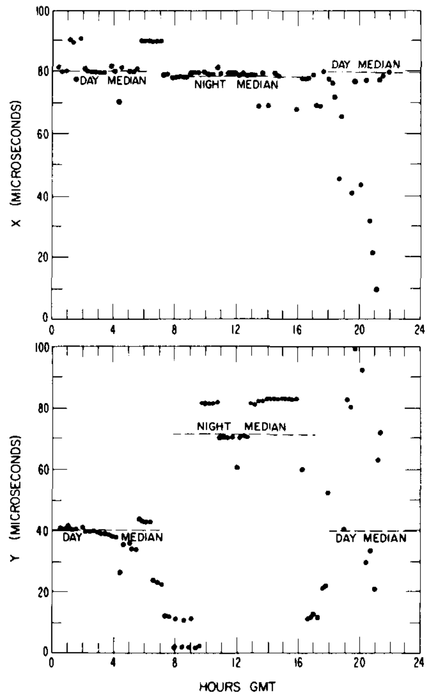

Figure 8.11. Wake Island, May 2, 1964.

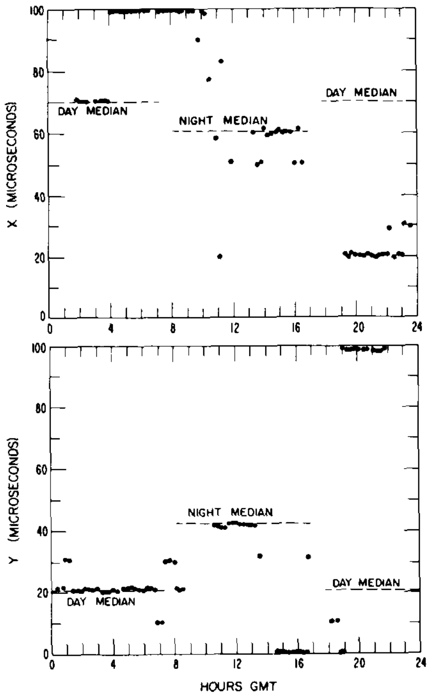

Figure 8.12. Wake Island, July 10, 1964

circuits to select any particular point on the skywave pulse. Whether the circuits were malfunctioning or improperly adjusted, or the pulse was severely dispersed is not known to the author. There is no logical explanation for the diurnal behavior of the median values of the X-pair readings. It seems futile to attempt to draw meaningful conclusions from these data or any of the data from Wake Island.

It can be shown that most of the scatter in this data is in increment full cycles. If increment full-cycle corrections are made on all the data points, phase stabilities similar to those reported for other measurements can be obtained. The envelope circuitry of the SPN-30 receivers may have been upset by skywave dispersion and skywave-groundwave mixing. The conclusion of the report, that accurate Loran-C skywave navigation is not feasible with the instrumentation and operator techniques used during the experiment, is undoubtedly true. There is a strong indication from the nature of the data, however, that with only minor changes in operator procedures, skywave navigation would indeed be practical. Since effective use of Loran-C skywave signals can expand the service area of a Loran-C chain by a significant amount, further work along these lines would be justified.

The main reason for including the Wake Island data in this report is because other skywave data from the Central Pacific chain show different diurnal behavior of the lower ionosphere than is observed at Boulder from the East Coast. For example, the diurnal pattern of the delay change is almost sinusoidal and deep fades frequently occur for solar zenith angles of less than 70° (Doherty, 1968). Without resorting to speculation, there is no completely satisfactory explanation to date of the skywave observations in that region.

In summary, the Loran-C skywave observations have provided some basis for estimating system performance in certain areas, but the characteristics of the lower D region evidently vary a great deal geographically. Until the characteristics of the D region are better understood, general prediction of system performance with skywaves is largely a matter of guesswork.

9. CALIBRATION OF A LORAN-C SYSTEM

The transmission time of a radio wave is a measure of the distance over which it travels. The velocity of light is fundamental in this relationship, but the influence of the physical characteristics of the propagation path and measurement techniques is the principal consideration here.

In low-frequency groundwave propagation, the most satisfactory measure of distance between two points seems to be the length of the geodetic arc which joins them. It is possible that some adjustment or correction might be desirable if very high elevations are involved, but that situation has not been explored thoroughly enough to justify conclusions at this time.

Somewhat erroneously, the groundwave has been visualized as propagating literally along the surface of the ground. That notion would suggest that the proper distance would be measured along the surface, which, of course, would be slightly longer than the geodetic arc if the path crossed hills and valleys. There is no experimental evidence to support that notion, at least not at low frequencies.

The factor that has the greatest effect on the transmission time, other than distance, is the conductivity of the propagation path. The effect of the dielectric constant is calculable but is of only very minor practical importance at low frequencies. The phase of the low-frequency groundwave has been evaluated by Johler et al. (1956) in NBS Circular 573. This publication has served as the basis for virtually all Loran-C phase calculations even though only a smooth, homogeneous earth is considered. An extension of the theory defined by Millington and Isted (1950 in field-strength predictions, and elaborated by Pressey and Ashwell (1956), is in general use to compute the phase over paths of mixed conductivity.

The available theory is not adequate to predict the phase accurately over mountainous terrain. Presumably, topographic features in combination with nonuniform conductivity are responsible for the prediction errors. The intent here is to show how available theory can be applied in actual situations and to describe measurement procedures that can be used to supplement the theory. Finally, new measuring techniques are proposed with a view toward a better understanding of the problem of propagation over land.

The time difference in microseconds, measured by a receiver, can be represented by the following expression:

$$T = \frac{10^6}{2\pi f} [k(D_{ms} + D_{sr} - D_{mr}) + \phi_{ms} + \phi_{sr} - \phi_{mr} \mp \alpha_m \mp \alpha_s] + CD,$$

where

$k = \frac{2\pi f}{C} E$,
f = frequency in Hz/sec,
C = velocity of light in vacuum (299792.5 km/sec),
E = effective index of atmospheric refraction,
ϕ = secondary phase correction based on smooth spherical earth,
D = distance (geodetic),
α = additional phase correction not defined in the idealized calculation of ϕ,
CD = coding delay.

The subscripts ms, sr, and mr, identify the paths from master to slave, slave to receiver, and master to receiver, respectively. The subscripts m and s identify the master and slave signals. This equation is based on the theory given in NBS Circular 573 (Johler, et al., 1956), but the α corrections have been added to allow additional path parameters that are not considered in the Circular.

While the groundwave propagation theory has not been developed completely enough to treat all propagation paths quantitatively and precisely, there is no doubt that the basic theory is sound. When actual propagation paths closely approximate the idealizations made in developing the theory, there are no problems. Difficulties arise only when the physical properties of actual paths differ markedly from the simplified models that we are now obliged to use for computation.

Some general discussion may help to better visualize the influence of the propagation medium on the phase of the low-frequency groundwave. It seems self-evident that a wavelength of 3 km (100 kHz) cannot "see" fine-grain structure in the medium. In this case, "fine grain" implies dimensions of the order of a wavelength and smaller. For instance, the conductivity of land varies appreciably from place to place within small areas as shown by typical probe measurements. Furthermore, the conductivity varies greatly with depth from place to place, especially within the first few feet from the surface. These variations seem to depend, in a rather complicated way, on the type of soil, its chemical composition, and moisture content. But, regardless of what causes the variations, we are led to the conclusion that the conductivity influence on a long wave must be represented by some sort of average or effective value for a region whose dimensions are greater than 1 wavelength. Possibly 10 wavelengths would be a realistic estimate of an area size where conductivity changes could be identified.

Similarly, it is to be noted that the index of atmospheric refraction substantially changes in the vertical direction within distances much less than a wavelength at 100 kHz. Typical lapse rates are of the order of 40-N units/km. Substantial changes occur also in both the surface value of the index and the lapse rate from time to time and place to place.

Referring to NBS Circular 573 (Johler et al. 1956), it is noted that an average value of 1.000338 for the surface index, and a lapse rate corresponding to 4/3 earth radius are suggested. If actual values of index and lapse are substituted, measurable changes (order of 0.1 μs) in time difference are predicted for some locations (see sec.6, USCG EE Rept., 1962). Such changes apparently occur mainly over very low conductivity paths. In areas where they have not been observed, they may have been obscured by other factors. One study (Sperry Rand Corp., 1969) suggests measurable effects over sea-water paths. Observations under more carefully controlled conditions are needed, but most data thus far seem to indicate that frequently the phase is either independent, or nearly so, of variations in the refractive index. The effects that have been observed are generally smaller than secondary factor effects predicted for conductivity variations. Recently, in an attempt to explain this apparent phenomenon, the manner in which the refractive index was used in NBS Circular 573 was reviewed by Johler and the author, resulting in the following conclusions.

First, it is noted that as the surface index increases, the primary wave is retarded, thus increasing what we may call, the primary phase correction. At the same time, an increase in the surface index normally results in an increased lapse rate, which, in turn, increases the effective radius of the earth and reduces the secondary phase correction (ϕ). If the phase is independent of changes in the refraction index, as some of the data indicate, then the changes in the primary and secondary phase corrections must be nearly equal in absolute magnitude at these locations. In order to satisfy this condition, a value of the index must be used which is smaller than the surface value, and the effective earth-radius factor must be reduced from 4/3 to a value near unity, but this condition is also dependent on the conductivity of the path involved.

This conclusion is entirely consistent with the axiomatic assumption that a long wavelength cannot "see" fine-grain detail in the structure of the medium. In this case, however, it appears that the 100-kHz wavelength only partially "sees" the lapse rate and an effective value should be substituted for the surface index. Comprehensive computer analysis of data gathered over many different paths for long periods of time should be capable of yielding the best surface refractive index and effective earth radius to best fit all conditions for 100-kHz propagation. Such an analysis could be undertaken using existing Coast Guard monitoring data.

It would be ideal if the navigation grid could be calculated or predicted precisely, but in practice there are always uncertainties. The ideal situation is very nearly realized when the service area is over sea water as the conductivity is uniform and any refractive index effects are minimized. The transmitter sites are on land, however, usually on or near shorelines, which introduce a sharp discontinuity on conductivity. Even in a nearly ideal situation, measurable and unpredictable phase effects may be present. When the service area is over land, the problem is much more complicated and some form of calibration is necessary.

It has been learned from experience that one of the most reliable ways to maintain the calibration of a system is to monitor the time differences at a convenient location in the service area. If a change in the time-differences reading is noted, the monitor station notifies the slave concerned and requests an adjustment which will restore the time difference to its original value. This is not calibration, but it is a practical and effective technique for maintaining stability. During calibration, it is especially desirable to have one or more monitor receivers in operation to detect any phase shifts which might otherwise go unnoticed or be misinterpreted.

The most important part of the calibration is to measure the time differences on the baseline extensions to determine the round-trip transmission time and the coding delay. When the extensions are over sea water, the procedure is relatively simple because the conductivity of sea water is known. When they are over land, the conductivity is an additional unknown which must also be evaluated.

In the case of an overland baseline extension, calibration can be a very complex and difficult problem if the terrain in the extension area is not reasonably smooth with uniform conductivity. Measurements must be made at a minimum of two locations on the extension to obtain enough information to determine all the unknowns. Furthermore, the locations must be far enough apart to clearly show a difference in reading.

The secondary phase correction (ϕ) is shown as a function of distance in figures 9.1 and 9.2 and parametric plots are given to facilitate scaling. Figure 9.3 shows a plot of the rate of change of the secondary correction at a great distance (where it is nearly linear) as a function of conductivity. This curve and the curves shown in figure 9.2 are particularly useful in analyzing baseline extension data.

If there were no secondary phase corrections, the time-difference readings would be constant anywhere on the extensions. On a slave extension, the time difference would be precisely the coding delay, and on the master extension it would be the round-trip time plus the coding delay. However, the extension readings involve the difference between the phase correction to the signal from the near transmitter and that portion of the correction to the distant signal which is contributed by the path from the near transmitter to the receiver. The reading on the slave extension is not affected by the correction applicable to the master signal in traversing the baseline, but the master extension reading includes the baseline correction to both signals.

From figures 9.1 and 9.2, it can be seen that the phase correction reaches a minimum within the first 30 km for all conductivities. If the extension is over sea water, the measurement can be made almost anywhere beyond 30 km from the near station (see fig. 9.2) because the minimum is broad and, therefore, the exact distance from the transmitter is not critical. Over land, the measurement nearest a transmitter should not necessarily be made at the minimum correction. If the distance to the near transmitter is too short, the amplitude ratio of the signals may exceed the design capability of the receiver and thus introduce a phase error. Furthermore, on the assumption that the conductivity is unknown, the distance should be great enough to be sure the measurement is made somewhat beyond the minimum value of the correction. A further, but perhaps less critical, consideration is that the measurements should be made far enough from the transmitter to avoid any possible spurious local-phase effects that might be caused by slightly mismatched transmission lines, the antenna coupler, or other circuits carrying high rf currents or voltages. The measurements should always be made at locations which are free from trees, overhead wires, etc., and on reasonably smooth terrain. The best practice is to take readings either continuously while crossing the extension (perpendicularly) or at a number of closely spaced locations, then plot the data and draw a smooth curve through the points to establish the minimum or maximum readings.

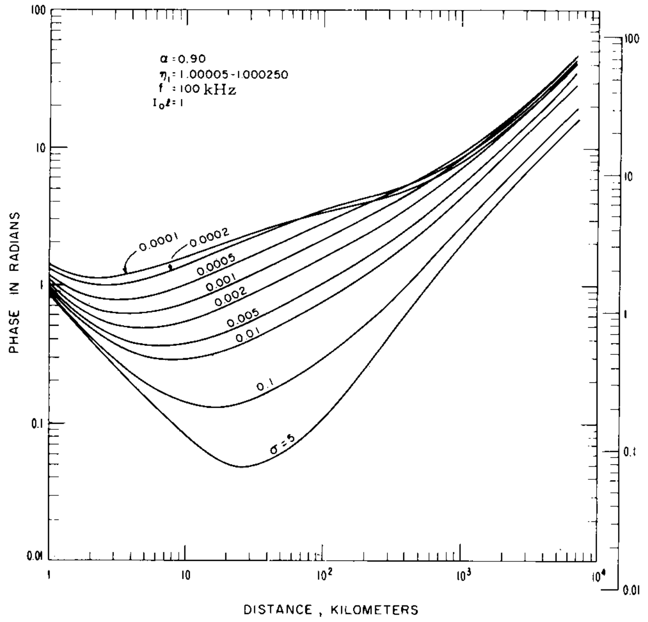

Figure 9.1. Secondary-phase corrections as a function of distance parametric in conductivity.

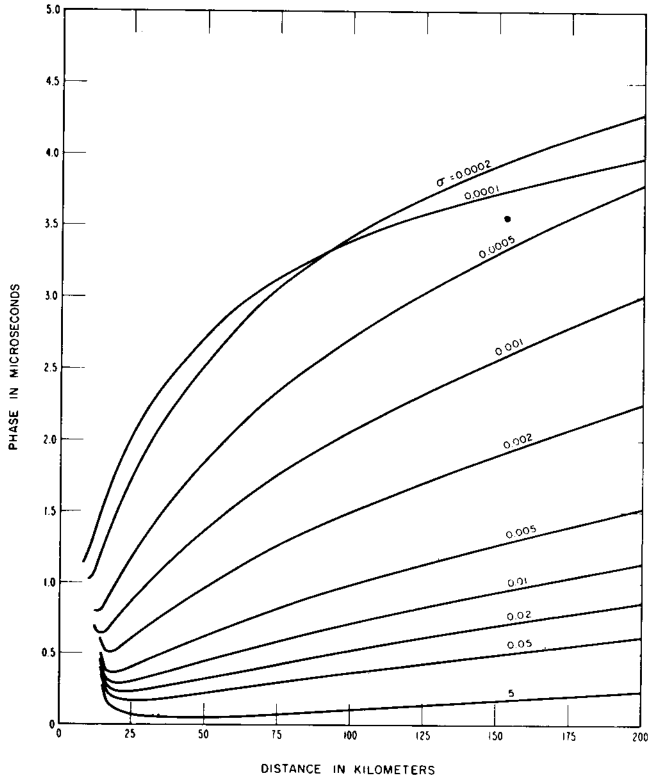

Figure 9.2. Secondary-phase corrections as a function of distance parametric in conductivity.

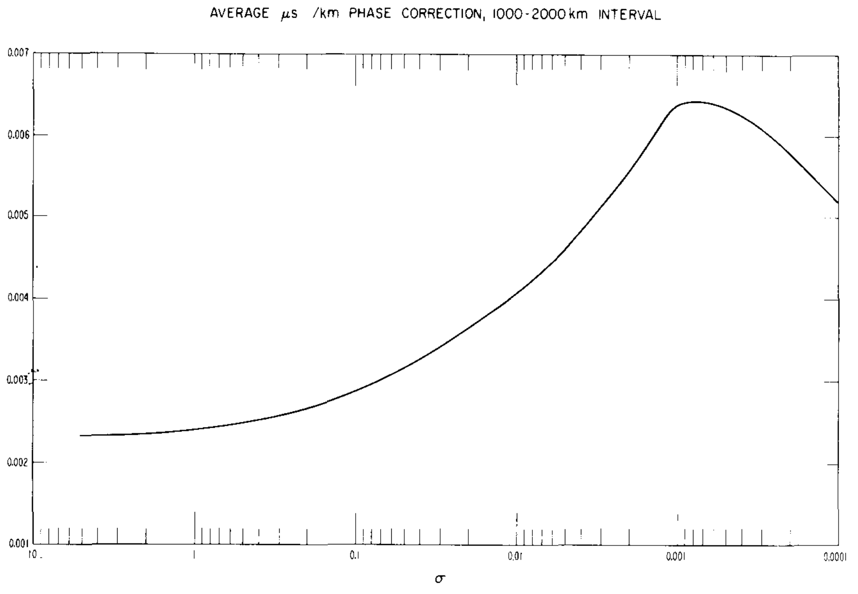

Figure 9.3. Rate of change of secondary correction at a great distance as a function of conductivity.

If the terrain is such that measurements cannot be made on the ground, airborne measurements must be made. Problems, such as lack of good sites and accessibility, are effectively solved by operating from an aircraft but other problems may be introduced. Baseline-extension measurements should be made with the greatest possible care and accuracy. Trouble may be encountered in obtaining a valid maximum or minimum reading if the speed of the aircraft and the response characteristics of the phase servos are not compatible with the rate of change of the phase difference. Aircraft speed is not a problem in the service area because the rates of change of phase are relatively constant and are compensated by the rate servos. Crossing an extension near a transmitter, however, involves a fairly rapid change in rate with attendant opportunity for error in reading.

When the extension measurements have been made and the distances to the transmitters determined, the data can be analyzed graphically with adequate precision. Referring to figure 9.2, scale and difference the values of ϕ for an appropriate range of conductivities at the distances from the near transmitter where the measurements were made. Now find the corresponding changes in ϕ for the distant signal over the distance interval. The difference between these differences can be plotted as a function of conductivity as shown in figure 9.4. For the sake of an example, distances of 30 and 100 km are arbitrarily chosen. The conductivity which would produce the measured difference in baseline extension readings can be seen immediately from such a graph. The example curve (fig. 9.4) also gives a good idea of the relationship between the accuracy of the conductivity determination and the accuracy of the phase difference measurements.

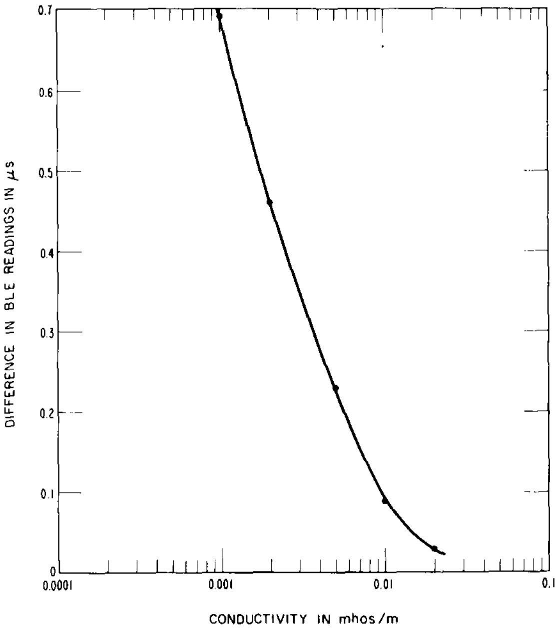

Figure 9.4. Example plot of readings taken at 30 and 100 km from near transmitter.

If the measurements are on the slave baseline extension, the coding delay can be found by applying the appropriate phase corrections from figure 9.2 using the conductivity just determined. Similarly, the round-trip time can be determined from the master extension readings.

The difference between the round-trip time and the time that would be required for the signal to travel in air over the same distance can be interpreted as the secondary-phase correction. If the baseline does not involve significant topographic features and, assuming of course, that confidence can be placed in the baseline extension readings, such an interpretation is reasonable. However, if the physical characteristics of the path deviate substantially from the assumptions made in applying smooth spherical-earth propagation theory, then it must be recognized that other factors could also contribute to the measured round-trip time. At present there is no established technique by which the true origin of measured phase corrections can be positively established.

In predicting the lines of position over land, it is generally considered that the greatest accuracy will be obtained when the best known values of conductivity are used. But the big problem is that reliable values of conductivity are seldom known. There is little that can be done by present practices other than to assume average values based on acquired knowledge for computational purposes. If no conductivity information is available, the round-trip time measurements for a land path may be helpful in arriving at a reasonable estimate of an average value.

Referring to the Cytac test results, it can be seen that one practical way to improve the accuracy of the lines of position is to measure the time differences at a number of places in the service area and then construct contours of constant correction. One advantage of this approach is that, as additional measurements are made, the correction contours can be updated until eventually the full accuracy of the system can be realized. On the other hand, it has the disadvantage that the correction contours apply to one system installation only and are of little or no value in predicting the accuracy of a similar system elsewhere.

An alternative system for utilizing measured data is to predict a number of measured points in a relatively small area on the basis of separate propagation velocities to the three transmitters. These propagation velocities can be selected to fit reasonable conductivity values. Then, by using computer techniques to minimize errors for a number of points, a best fit can be obtained by incrementally adjusting the three conductivities (i.e., propagation velocities to the transmitters). The conductivity values deduced for one local can be used as a starting point for adjacent locals and eventually the entire service area of the system can be mapped in best-fit conductivity values for predicting Loran-C time differences.

Service area calibration, or any kind of accuracy check at sea, is difficult to accomplish. For such a check to be meaningful, the position of the receiver must be established accurately by independent means. No other long-range radio position-fixing system provides comparable accuracy, and ordinary celestial navigation fixes are entirely too coarse to be useful. Even conveniently situated islands do not necessarily provide satisfactory reference points. Unless the position of the islands has been carefully established and related to the triangulation system containing the transmitters, test results are apt to be inconclusive.

To derive maximum usefulness from Loran-C, especially over land, more experimental research on groundwave propagation is needed to predict the grid more accurately. The needed research can now be done because of the vast improvements in oscillator stability that have been made since the Cytac tests. The oscillators used in Cytac had a stability of only 1 part in 10^8, compared to the present portable cesium-beam, battery-operated oscillators that are now available. According to data published by Hewlett-Packard (Bocily, 1965), their stability, even under flight conditons, rivals that of the primary standards. By using highly stable oscillators at the master transmitter, and in a specially equipped aircraft, one-way transmission-time measurements can be made. More description will follow shortly, but the important aspect of the one-way measurement is that the effect on the phase of different path parameters can be studied in detail. As an extra bonus, the additional independent measurement would make it possible to compute the transmission times from the slaves to the receiver from the time-difference measurements.

The essence of the oscillator stability requirement is that the transmitter and airborne oscillators must maintain the same frequency within sufficiently close limits so that the cumulative, relative phase drift will be negligible during the time the measurements are made. For practical measurements, the cumulative phase drift should be held to about 0.1 μs (preferably less) over a period of 2 to 4 hours. Accuracy of

0.1 μs would be sufficient to provide quite useful data and typical measurement flights would generally not require more than about 4 hours. By substituting a precision oscillator for the oscillator normally used in a navigation receiver, and by making provision to record the master phase servo relative to the standard, the transmission time of the master signal between two points can be measured independently of, and without interference to, the normal functions of the receiver.

As mentioned earlier, certain cautions must be observed in making ordinary time-difference measurements in an aircraft. The addition of a precision oscillator to the airborne equipment would introduce additional reasons for exercising care. Also, to make effective use of the phase-measuring possibilities a precision oscillator would provide, certain auxiliary equipment would be most useful and perhaps necessary. The following is an estimate of the problems and limitations to the measurement procedures that could be used.

The ideal operating environment normally associated with frequency standards cannot be duplicated in an aircraft. The nearest approach to that environment which is generally available is provided by commercial jet aircraft. For passenger comfort, temperature variations are limited to a few degrees and noise and vibration are minimized. Pressure variations are also minimized. In good flying weather, inertial forces are small but they cannot be eliminated. Oscillators with well-designed solid-state circuitry and excellent crystal ovens also seem to perform quite well in this sort of environment as evidenced by several experiments carried out by the Radio Standards Laboratory of NBS. In these experiments, portable clocks were "hand-carried" on commercial airlines several times with no obvious degradation of oscillator performance. How satisfactorily precision phase measurements can be made in the air has yet to be demonstrated, but the outlook is very favorable. Furthermore, oscillator performance can be evaluated by repeated measurements.

A vertical camera on a gyro-stabilized mount equivalent to that used in the Cytac test would be essential to establish the precise location of the aircraft for correlation with the phase-difference readings when other precise location methods are not possible. For some measurements it would be most desirable to maintain a constant phase-difference reading in order to minimize errors that could be introduced by the finite response time of the servos. A further consideration is the near impossibility of "hand-flying" an aircraft accurately along a constant phase-difference course. For that reason, it is necessary to provide a coupling device to feed phase information to the autopilot in such a way that the aircraft can be guided automatically along an arbitrary constant phase-difference course. An elementary coupler of this nature was used in the Cytac tests with good results. The same basic idea could be used in combination with the stable oscillators and vertical camera to map contours of constant phase around the master transmitter. The absolute value of the phase can be determined by correlating the phase contour map with the baseline extension measurements.

A typical master station location, the baseline extensions, and contours of constant phase are illustrated in figure 9.5. It is assumed that the area is accurately mapped to an appropriate scale so the vertical photographs can be correlated with land marks and topographic features. An important aspect of flying the contours of

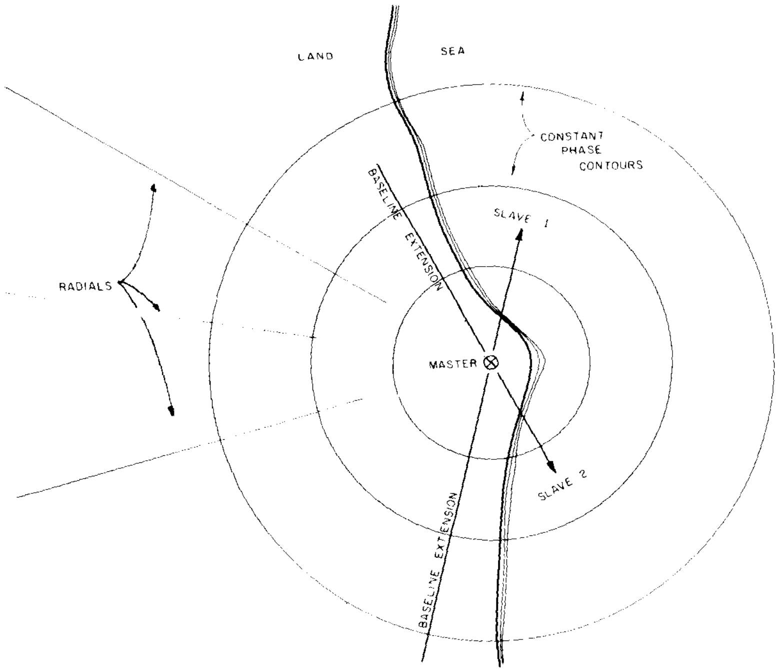

Figure 9.5. Typical master station location.

constant phase is that the oscillator performance can be evaluated quantitatively by making two or more circuits of the same contour. If there is no oscillator drift, the aircraft should retrace its track rather precisely. If there is drift, the track will be a spiral, either inward or outward, depending on the direction of the drift. The magnitude of the drift can be calculated simply from the data.

It is to be pointed out, however, that the above assumes that the master phase information is translated perfectly into aircraft position. In practice, some noise is always introduced in the translation process. For example, wind can cause some noise, and less than critical damping in the autopilot and coupler servo systems will cause the aircraft to fly a slightly oscillatory course about the actual phase contour. Experience with the autopilot coupler during the Cytac tests indicated that no serious trouble should be expected but improper adjustments cannot be tolerated.

Since the master phase servo is basically a synchronizing device, any arbitrary point of phase lock must be related to the total phase by external means. Flying across the baseline extensions on a constant phase contour, at or near a point where delay measurements have been made, would provide a unique opportunity to establish that relationship. Once established, the contours would represent not only constant phase, but constant total phase or transmission.

If the aircraft is flown at a constant speed, directly toward or away from a transmitter, the rate of change of phase relative to that transmitter is maximum and constant except for the influence of the secondary corrections. When the rate of change of phase is constant, or very nearly so, the rate servos' function should be nearly perfect.

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In this situation, the phase-difference readings should be nearly as accurate as when flying a constant phase contour. Care must be taken to avoid the possibility of errors when relating the master phase reading to a known position near the constant phase contours. For that reason, the most conservative procedure would be to fly directly toward the station long enough for the master servos to reach a steady-state condition before reaching the region calibrated with the constant phase contours. After a correlation between the master phase reading and a calibrated point is established, the aircraft may be maneuvered as desired to take up another course, provided synchronization is not lost.

In general, any straight-line course could be flown, but, until oscillator drift has been proved not to be a limiting factor, it is assumed that flights should be planned to obtain propagation data over as large an area as possible in minimum time. Radial flights from the master transmitter with return to the initial calibration point would best serve that purpose. Returning via the same route would show the repeatability of the readings and would also provide a direct measure of the average oscillator drift.

A baseline involving mixed conductivity, part land and part sea water, for example, offers a unique opportunity to make measurements that would show conclusively whether the secondary correction is the same in both directions over the same path. If the method of treating the secondary phase correction over mixed conductivity paths, proposed by Millington (generally called Millington's Method), is correct, measurements should at least show general agreement with the theory. To the author's knowledge, Millington's Method has not been completely checked experimentally.

Propagation over rough terrain of mixed conductivity is a very real and practical problem; however, at present, there is no recognized formal method of predicting either the amplitude or phase of a radio wave in that very ordinary situation. For years it has been well known that the performance of radio systems is generally less satisfactory in mountains than elsewhere, but little has been done toward coming to grips with the problem because of its complexity.

Loran-C, in combination with stable oscillators, offers a new approach to phase measurements that has promise of isolating the effect of the different path parameters. The effects of conductivity and roughness may be indistinguishable; however, there is some evidence to indicate that they may be quite different. According to generally recognized groundwave theory, phase changes due to conductivity alone should be smooth and very small in terms of μs per mile.

The Cytac tests suggest that part of the effect of mountains is equivalent to introducing scatter fields. The concept of scatter fields seems necessary to explain the phase changes which were observed over distances considerably less than 1 wavelength. These variations were more or less random , as might be expected if a number of sinusoidal perturbations were combined. However, the smoothed or averaged time-difference readings showed changes with distance which were slower than should be associated with scatter fields but were more rapid than can reasonably be inferred from NBS Circular 573 (Johler et al. 1956).

The implication is that mountainous terrain involves corrections which are not implied in the groundwave theory based on a smooth earth. The nature of such corrections not taken into account in the present theory provides some suggestions for further investigation.

1. The conductivity to a depth of several feet, or even tens of feet, is significant in the propagation of the low-frequency groundwave. While it may be assumed that "fine grain" variations in conductivity are unimportant, such considerations as geologic structure and depth of water table frequently extend over many wavelengths and may constitute significant stratification of conductivity. A modification of the theory is required to describe such a situation.
2. Natural erosion tends to deposit soil from the mountain slopes in the valleys, and, in combination with the greater amounts of water in the valleys, there is a tendency toward a network of more highly conducting strips surrounding the mountains.
3. Forested regions probably present a more diffuse earth-air boundary than nonforested regions because of the conductivity of the trees. Whether this is significant at 100 kHz is not presently known but theoretical investigation of the problem appears to be in order.
4. Topographic features probably cannot be considered realistically on the basis of shape alone. Other parameters, especially conductivity and stratification, almost certainly must be treated simultaneously.

It has been cautioned that aircraft speed and servo response time are important in making phase measurements. Conversely, it is pointed out that at speeds of the order of 500 mph, the disturbances which are presumably due to scatter fields could be largely averaged out by appropriate choice of time constants and/or data processing techniques. It seems unlikely that scatter fields can be reliably predicted, but it may be possible to remove their degrading effect on system accuracy for air navigation.

The more slowly varying (with distance) corrections which also seem to be associated with mountainous terrain may be predictable, at least in part. A possible approach to the problem would be to theoretically work out the propagation over several arbitrary paths using realistic assumptions regarding conductivity and topographic features. Later, attempts should be made to predict the propagation over specific paths where measurements can be made. The eastern and east-central U.S. would be ideal for measurements, not only because of the availability of good signals but also because of the extensive topographic and geological data for that region. It is to be assumed that relating conductivity to the geology of a region would be a difficult task , but it would seem futile to attempt such research without a maximum of presumably pertinent physical data.

From a practical engineering standpoint, it would seem desirable to refine the time-difference predictions by successive approximations such as the α corrections mentioned earlier. To what extent such a procedure might be feasible is largely a matter of speculation at present. In any event, there appears to be no substitute for the combination of rigorous theoretical treatment and carefully controlled supporting experiments.

10. ACKNOWLEDGEMENTS

The author wishes to make special acknowledgement of the assistance of the following individuals and organizations for lending photographs, file copy reports, and other documents which are rare and difficult to obtain:

1. Walter N. Dean
2. R.H. Woodward
3. U.S. Coast Guard

11. GLOSSARY OF SPECIALIZED TERMS AND SYMBOLS

1. Loran and Loran-type Navigation Systems

Loran-A - Standard Loran or 2-MHz loran.

Loran-B - Similar to Loran-A with phase measuring added. Data classified.

Loran-C - 100-kHz system. Measure phase and envelope time differences.

Loran-D - A tactical version of Loran-C.

LF Loran - Similar to Loran-A but used at 180 kHz.

Cyclan - A two-frequency pulse system (160 and 180 kHz). Phase and envelope time differences were measured.

Cytac - A radio-bombing system. The navigation portion was renamed Loran-C.

2. CW Navigation Systems

Omega - A long-range VLF/cw navigation system in operational usage.

Whyn - A hyperbolic low-frequency FM/cw system developed between 1946 and 1950. This system was dropped in favor of the pulse system.

Decca - A short range LF CW hyperbolic navigation system (British). At ranges where the groundwave is very much stronger than the skywave (generally less than 200 miles), its accuracy is similar to that of Loran-C.

3. Loran-C Transmitter Designations

AN/FPN-15
AN/FPN-39
AN/FPN-42
AN/FPN-45

4. Loran-C Receiver Designations

EAR - Experimental airborne receiver (Cytac).
GMR - Ground-monitoring receiver (Cytac).
AN/SPN-28
AN/SPN-29
AN/SPN-30
LR-101
LR-201 (timing)
EECO-885 (timing)
Lorchron (timing)
Austron (timing)

5. Station Identification Symbols

M - master
X,Y,Z - slaves. (During the Cytac tests, the slaves were identified S_1 and S_2).

6. Baseline Extension (BLE) - The extension of the line (geodetic arc) joining a master and slave station.

7. Chain - A group of three or four synchronized loran transmitters which provide a navigation grid.

8. Coding Delay (CD) - The time interval between the arrival of the master signal at a slave station and the transmission of the slave signal. The word *coding* was applied to the delay inserted at the slave stations during the first use of loran to describe the scheme of changing the time-difference readings to minimize the possibility of the enemy making use of the system. The term became firmly established and has remained in use in connection with all loran systems.

9. FCC - Federal Communications Commission

10. ICAO - International Civil Aviation Organization

11. IRAC - Interdepartmental Radio Advisory Committee (U.S.)

12. IRIG - International Range Instrumentation Group

13. ITU - International Telecommunications Union

14. LOP - Line of Position

15. Loran Rates - The pulse repetition rates at which signals are transmitted. Different rates are used to distinguish one chain from another (see sec. 7).

16. Millington's Method - A procedure for computing the phase correction over paths of mixed conductivity. The correction is computed for each section of the path as described in NBS Circular 573. Computations are made, traversing the path in both directions. In general, a different value is computed for each direction. The average of the two values is used.

17. Phase Coding - A scheme of changing the phase of the pulses within a group to minimize pulse-to-pulse skywave interference and to reject synchronous interfering signals. Master and slaves use different phase codes for signal identification.

18. RTCA - Radio Technical Commission for Aeronautics (U.S.)

19. RTCM - Radio Technical Commission for Marine services (U.S.)

20. Service Area - Region where useful fixes can be obtained. The region is frequently defined by a contour which bounds an area of specified fix accuracy.

21. Skywave Delay - The time interval between the arrival of the groundwave and the various skywave reflections.

22. Total Phase - Synonomous with transmission line.

23. UT2 - A designation used to define a universal time standard.

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