WILD GOOSE ASSOCIATION
PROCEEDINGS

OF THE

FOURTH ANNUAL TECHNICAL SYMPOSIUM

AT THE

HUNT VALLEY INN, COCKEYSVILLE, MARYLAND
ON OCTOBER 16 AND 17, 1975

published by
THE WILD GOOSE ASSOCIATION
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This publication is a complete printing of the papers presented at the Fourth Annual Technical Symposium of the Wild Goose Association held at the Hunt Valley Inn at Cockeysville, Maryland on October 15, 16, and 17, 1975. Also included, as the last paper, is the award-winning paper presented by Cdr. William Roland at the Third Annual Technical Symposium in 1974.

The theme of the 1975 Technical Symposium was to show what Loran-C can do for the user. Papers were selected principally for demonstration of actual performance obtained with Loran-C or for presentation of new applications of Loran-C.

The symposium was well attended and the papers presented contain a significant amount of information about the use and potentials of the Loran-C system of navigation. This Proceedings is printed so that all those who are using, procuring or designing Loran-C equipment can profit from the efforts put into the following papers by the authors who prepared them.
A general discussion of preliminary investigation of public sector land use of Loran C generated from a series of meetings by an informal interagency group. The identification applications by agency with position fixing and tracking problems for which Loran C appears well suited. System problems which have surfaced requiring further investigation and development relating to inland applications. Planned and/or ongoing research and development projects with some detail on the New York conceptual planning project. Preliminary plan for system implementation.

The Annex to the Department of Transportation National Plan for Navigation published in the Congressional Record in July 1974 established Loran C as the government provided marine radio aids to navigation system for the coastal confluence zone. The Annex included a phaseout schedule for the existing Loran A stations in 1979 and 1980.

Historically, the scheduled phaseout of navigation systems has rarely been achieved; the normal pattern being indefinite deferment. Not surprisingly, some Loran A system users are seeking a three-five year extension of system operation basing their argument primarily on economics. They argue that their sizeable investment in existing equipment has not had time for reasonable amortization since the announcement of phaseout and that the replacement Loran C receiver cost under the circumstances is excessive.

The Department of Transportation's interest in ensuring that this scheduled phaseout is met is also economic. Loran A system operating costs are approximately $10 million a year and any extension would require considerable rehabilitation of the existing chains. At stake is a potential expenditure of between $30-$50 million for operating expenses and capital improvements if phaseout is delayed.

In analyzing the situation, it became apparent that to reach our objective of phasing out the Loran A system on schedule, the timely availability of a very low-cost receiver would be extremely helpful even if not essential. Technological advancements in the past few years have made a major reduction in price range promising with sufficient market volume. Since the marine market is relatively limited and represents only a fraction of the receiver market needed (100,000+) additional classes of users are necessary to ensure the availability of a low-cost receiver within the time frame of the scheduled phaseout of Loran A.

Ground, and to a lesser extent aviation, classes of users constitute more than an adequate potential market for this purpose. From all indications, these additional classes of users would be readily attracted to the Loran C system by superior performance and the availability of a low-cost receiver, if the planned groundwave coverage were extended over the entire continental United States. Since the coastal confluence system will provide groundwave coverage over more than 2/3 of the United States, total coverage would require only five additional stations in the mid-continent. It was concluded that the low-cost receiver and the Loran C gap-filler stations are interrelated and could be available by the 1978-79 period. Of greater importance, the analysis pointed up the enormous potential benefits to both public and private users from a common nationwide position fixing system. A rare opportunity to capitalize on the sunk costs of the maritime system by an incremental expansion of the planned coverage to provide a terrestrial navigation system.

A number of federal agencies were contacted to explore possible terrestrial position fixing requirements and the applicability of Loran C to these needs. With a few notable exceptions, the application of real-time, accurate position fixing information to agency functions is a totally new concept. Land navigation has traditionally been by visual reference points from the blazed trail of the past up to the route numbers and street names of the present. Marine and Aviation navigation lacking visual reference points, except in terminal areas, early developed the use of celestial bodies and more recently radio navigation systems for position fixing and navigation. Erroneous position information in the Marine and Aviation modes risks destruction; while on land, the major effect is loss of time and inconvenience. Motivation to seek improved land navigation must stem from an understanding of the savings in time, productivity and flexibility available from accurate position information. Visualizing the translation of real-time position information through a software system into increased productivity and effectiveness is understandably difficult for the individual agency in view of the institutionalized processes of government.

To assist in this process, an informal ad hoc group of agency representatives was formed. The exchange of information on Loran C capabilities and agency requirements has been useful in identifying potential applications. The list of applications which follows is more representative than complete since only the user agencies have been polled and their individual inputs range from sketchy to fairly comprehensive. An estimated 500,000 receivers would be required to satisfy the identified potential terrestrial applications to date.

A brief summary of agency-identified applications gives some insight as to the potential uses. Within the Department of Transportation, the Federal Highway Administration (FHWA) development efforts are for the most part geared toward implementation by the states. FHWA has used position information but their major concern is to ensure that the states have a simple and easy method of location identification. Successful highway programs require coordinated and integrated information for highway safety, highway planning and highway maintenance. The key to the integration of data gathered through these activities is the identification of the location on the roads and streets where the data observation is made.

A wide variety of systems for accident location have been developed, although none is satisfactory. Needed is a single state-wide, readily computerized system requiring a minimum level of training and with the flexibility to readily reflect road changes and upgraded data. Loran C shows great promise for these
functions with the availability of a low-cost, small-sized receiver. FHWA has identified two additions to the receiver which would greatly enhance its usefulness: (1) provision of direct reading of the coordinate display with the ability to input other data in the form of digits, letters, or symbols and (2) provision for transmission of the coordinate display to a central office by radio. Potential installations include police cars, highway maintenance vehicles, snow plows, etc. Evaluation of Lorcan C by FHWA is programmed.

The National Highway Traffic Safety Administration (NHHTSA) has several unique requirements for accurate position fixing somewhat related to those of the FHWA. The most apparent are accident detection and location for real-time response to accidents; data collection on high accident locations, and in-forcement relating to system and traffic control. The use of a common reporting format would provide a data link between the accident, citation, and location for real-time response to accidents. Present procedures for meeting NHHTSA's position fixing requirements are expensive in terms of hardware, software, or both, rely heavily upon measurements in the field for accuracy, and are linear by nature. Present procedures are not satisfactory and many states are seeking alternatives. Potential installations are the same as FHWA's plus all emergency vehicles. Evaluation of Lorcan C is programmed.

The Urban Mass Transportation Administration (UMTA) has a major ongoing project to develop, test, and evaluate an advanced Automatic Vehicle Monitoring (AVM) system. AVM represents an electronic means of ascertaining the location and status of land-based vehicles. In the case of transit vehicles, AVM is expected to result in better service to passengers, greater operational efficiency, and greater operator and passenger security. Studies estimate that AVM will increase police effectiveness up to 1/3 by permitting dispatch of the car closest to the emergency situation. Potential installations: buses, taxis, delivery service vehicles, and other vehicle fleet operations. Lorcan C is to be evaluated as one of a number of candidate location subsystems.

The Federal Aviation Administration (FAA), in view of the proposal to expand Lorcan C coverage throughout the continental United States, is evaluating the system as a supplement to the existing VOR/OMGE system. State-of-the-art receivers will be examined for performance in the mountainous areas of New England, at low altitudes offshore, and in Alaska. A program to evaluate Lorcan C for use in the domestic air traffic system is planned. The major questions to be answered are: Can the reduction in navigation performance caused by occasional transmitter failure be circumvented? Can techniques be developed to improve the aircraft noise environment? What type of signal monitoring will be needed to support widespread aviation use of Lorcan C navigation?

Although concerned primarily with the coastal areas, the Coast Guard sees benefit from inland coverage by: improved positioning in the Western Rivers, thereby decreasing buoy replacement and improving mapping and notices of channel shifts; inland search and rescue; precise time distribution; own aircraft RNAV capability; precise river navigation; redundant lines of position in coastal, Gulf and Great Lakes areas; and emergency vehicle location during flood relief. As system manager, they see an early need to develop an operating doctrine, control and monitor standards for a wide variety of users, determination of common grids and charting for the system and the development of calibration requirements and improved propagation predictability for a terrestrial Lorcan C system.

Within the Department of Agriculture, the Animal and Plant Health Inspection Service has a requirement for precise navigation of aircraft for spraying or dusting blocks of 125 to 250 thousand acres. Reciprocal flight paths 20-30 miles long with 150-200 foot spacing must be accurately flown. The present contracted navigation services are expensive and not completely satisfactory. Target insects, including fire ants, gypsy moths, grass-hoppers and range caterpillars, are geographically spread over most of the continental United States. Present funding levels are insufficient for adequate control, unless costs can be reduced. Evaluation of Lorcan C is planned.

The United States Forest Service has a need for an accurate positioning system. Forest fire control requires the capability to rapidly chart the location of spot fires or smoke; provide guidance for ground crews, smoke jumpers, and retardant aircraft in the initial attack on the fire; control air drops of supplies and tools; navigate fire patrol aircraft for mapping and reconnaissance and to navigate helicopters for rescue or evacuation operations. In addition accurate positioning is required for survey operations, including roughing in a road or timber sale, to provide location information to timber cruisers, geologists, wildlife managers in resource surveys and to increase the accuracy of aerial mapping. Similar position accuracy is required for Forest Insect and Disease Control to map insect infestations and the layout of spray blocks, to navigate spray planes, and to locate and relocate sample trees for spray assessment. Evaluation of Lorcan C is in the planning stage.

In the Department of Justice, the Law Enforcement Assistance Agency (LEAA) has identified a number of potential Lorcan C applications: To improve location accuracy for Crime Victimization Surveys conducted periodically and aligned with Census Bureau surveys; Police Vehicle Location Monitoring, for optimal use of police vehicles; Suspect Vehicle Tracking to know the location and direction of travel of a suspect vehicle; Cargo Security to track trucked cargos; high value contract and private security patrols for various routes; to Synchronize Time Clocks on patrol cars; use of the stable signal Frequency Standard to provide a natural data system as a polling signal to clock out data at specific time slots to a central computer from fixed or mobile data transmitters. These potential applications have varied accuracy requirements ranging from 50 to 500 feet. Evaluation is in the planning stage.

The Department of Commerce Census Bureau is considering the possibility of attaching specific geographic identifiers to the individual elements of the basic data files so that census data can be aggregated and tabulated for all of the
geographic combinations required by the many users. Loran C appears to have the potential for adding the needed geographic identifiers. By providing accurate location information efficiently and economically, the system would promote high productivity and greater accuracy in the Current Population Survey, the Geographic Base (DIMES) File System, and the Decennial Census of Population and Housing as well as other Bureau programs.

Evaluation is proceeding.

The Energy Research and Development Administration (ERDA) has the requirement to track truck shipments of nuclear materials throughout the United States. Loran C appears to offer the greatest economical advantages and provide the most accurate location information of all the systems studied. Use depends on the provision of adequate coverage on a timely schedule. Evaluation of the use of skywave coverage pending the availability of CONUS groundwave coverage is now underway.

The Nuclear Regulatory Commission has the same requirement as ERDA and is investigating the feasibility of Loran C in conjunction with ERDA.

The Defense Civil Preparedness Agency believes that Loran C has potential for use in the National Shelter Survey system and is monitoring developments of coverage and hardware.

A number of other agencies have expressed interest in the Loran C system for a wide variety of applications. These agencies include the Post Office, Environmental Protection Agency, Bureau of Land Management, National Park Service, Agriculture Statistical Reporting Service, Drug Enforcement Agency, National Oceanographic and Atmospheric Agency and the Soil Conservation Service. Generally, this later group of agencies are monitoring developments awaiting more positive indications that the very low cost receiver and nationwide coverage will be forthcoming.

Private sector applications of Loran C for position fixing and tracking have not been investigated except as incidental to certain public sector applications. However, it takes little imagination to foresee the private sector as potentially the major user of the system. For example, it has been estimated that in the random delivery of goods and services an accurate position fixing system could increase productivity 5% to 15% with commensurate fuel savings.

To satisfy all the requirements of the various applications identified, the position fixing system hardware would be low cost, small, light weight, with a digital readout translatable to a geographic position with repeatable accuracies of 50 to 150 feet throughout the continental United States, unaffected by weather or time of day. While undesirable, minor degradation of performance in certain types of environment would be acceptable for practically all of the applications discussed. Loran C appears to have the potential to better meet these requirements than any other known system, however, there are some uncertainties which need further investigation.

The urban canyon problem may be the most difficult to solve. Sketchy data available indicates that in urban areas generally, including downtown low rise areas such as Washington, D. C., highly repeatable accuracies are readily achieved. However, in the urban canyon areas of some major cities lined with high rise buildings, the Loran C signal may be absorbed or distorted to an unacceptable degree. Signal retransmission or reinforcement and/or data processing may be a solution. Many of the planned applications would be relatively unaffected by this phenomenon but the problem must be satisfactorily resolved for universal use of the system.

Although Loran C was highly effective for surface use in Southeast Asia, system performance throughout the United States with its wide variety of terrain, seasonal climatic changes and built up urban areas remains relatively untested. Data on the effects of these variables on overland transmission paths within the continental United States are very sparse. There are indications that some areas may be adversely affected. It is believed that variations which may occur, could be compensated for in the design of the monitor subsystem with little or no derogation of accuracy.

The different rates of investigation and development of Loran C applications by the individual agencies could lead to a number of diverse and incompatible methods for generating and handling position data. This in turn could prevent or make difficult the ready exchange of data between agencies. The present informal arrangement for exchange of information between agencies is probably inadequate to insure the desired commonality. It has been suggested that the geographical identifiers under consideration by the Bureau of Census might key the effort to achieve a high level of commonality. It has also been suggested that a Loran C project office be established in DOT to, among other functions, seek commonality.

The availability of a very low cost receiver is the necessary catalyst for widespread adoption of Loran C by the potential user agencies. It has been suggested that a federal design project to develop a modular receiver using to the extent possible LSI chips available for other purposes would insure a very low cost receiver. The modular design would have the added advantage of readily accepting a variety of add-on LSI circuitry for additional functions.

Loran C has an image problem. It has been looked at and discarded for several applications in the last few years on the basis of misinformation as to cost and off-air time. In one specific case, the decision was made on cost information several years old. In the general discussions among agencies, relatively few had heard of Loran C. Those that had pictured it as an accurate system with high receiver cost, difficult to use, and with high operating expense. One potential user had rejected the system because of the risk of off-air time of an entire chain if the master station were down. He was unaware of the advent of cesium standard in 1968 and the independent station operation thereafter and had not considered the signal redundancy available from cross chain and/or range-range operation. Despite the unscientific sampling, it appears obvious that knowledge of the existence and capabilities of Loran C is slight and where it exists often incomplete or distorted.

There is a growing number of ongoing and planned research and development projects in Loran C application. The Coast Guard is designing and
testing: a Loran C ship-guidance system, targeted for accuracies of 50 feet or better; an airborne Loran C navigator with 9 waypoints and weighing less than 12 pounds; and an ocean dumping surveillance system using a sealed recording receiver. FAA is now conducting a comparative cost analysis of Loran C, upgraded VOR/DME, and the global positioning satellite; planning a study of the use of Loran C for non-precision approaches to airports; planning development and testing of a Loran C range-finder airborne navigation system; planning to develop and test a Loran C monitor system to warn operators when the signal is inadequate; planning a study of aircraft environmental noise reduction for Loran C; and planning to evaluate a low cost airborne receiver as available. NHTSA is planning an evaluation of Loran C in an Emergency Medical Service demonstration project. UMTA is evaluating Loran C as one of a number of position fixing methods in connection with development of an automatic vehicle monitoring system (AVM). The Census Bureau has completed a preliminary evaluation of Loran C in the area of Southern Maryland with excellent results and is planning a more extensive evaluation of the use of Loran C for their purposes throughout the southeast next spring. ERDA as previously noted is evaluating Loran C for truck tracking. The Plant, Animal and Health Inspection Service and the U. S. Forest Service are investigating Loran C for precision aerial spraying.

We are especially interested in a FHWA, NHTSA, and OST jointly funded conceptual study of the use of Loran C for which New York state is the contractor. New York was chosen for two reasons, the existing Loran C coverage and more important, completion of a year long effort by the State to identify agency precise position requirements. The New York State requirements were developed by an interagency committee with representatives from 8 State agencies chaired by the traffic records office. The requirements range from highway accident location to disaster relief. An example of the need for more precise positioning common to a number of State agencies was the discovery that in some areas of the State better than 15% of emergency vehicles proceed to the wrong location. Objectives of the study are two-fold; phase one, to develop a conceptual analysis of how Loran C would be used for each requirement, and its capability and cost to meet the requirement; and phase two, the development of a feasibility and demonstration plan. The latter plan is to cover the requirements of a specific county selected on the basis of having urban and rural regions as well as a variety of terrain. The phase one conceptual plan is planned for distribution to Federal agencies, as well as State and possibly county governments nationwide. As noted earlier in the paper, the application of real-time precise position fixing information to agency functions is a revolutionary concept to most levels of government. The conceptual plan should be an effective introduction to a better understanding of the potential applications of such a system.

Current thinking is to seek funding for the mid-continent Loran C stations in FY 1977 with a total continental system operational in CY 1979. There remain a number of technical problems in the inland use of Loran C for certain specific applications which need further investigation. This might suggest deferral of the decision to proceed with a continental system until these technical problems are resolved. However from the best information available, it appears that the problem areas are due to lack of specific previous attention and that resolution entails slight technical risk. In any event, the problems only impact on a limited number of applications. Early implementation is reinforced by the enormous potential increases in productivity in both the public and private sectors inherent in the availability of an accurate CONUS position fixing system. Early availability will also tend to sooner reduce or eliminate the expenditure of federal, state and local funds for a proliferation of individual and generally inferior systems. The evaluations underway or planned by the several agencies are for the most part the development of subsystems to translate position information into an end product rather than a test of Loran C system performance. The state of the art of both the basic system and receiver technology, backed up by voluminous operating data, generates a high level of confidence that the system can perform as advertised and further supports early implementation.

The views herein expressed are those of the author and do not necessarily represent those of the Department of Transportation.
You probably wonder how a Coast Guard Officer has become involved in a Department of Transportation Highway Safety Program. In reality, highway safety is an extension of work that the Coast Guard has performed in search and rescue at sea for many years. The environment and vehicles differ, but the same basic principles apply; find the individual who needs help and get him and that help together in the shortest possible time.

The Department of Transportation's role emphasizes safety. This includes the prevention of conditions prejudicial to safety, and to taking the necessary action in developing response capabilities when preventive measures fail or do not otherwise exist. The Highway Safety Act of 1966 recognized the need to take positive action about highway safety and respond more quickly by reporting on this Act, the House Committee on public works said, "When accidents occur, it is essential that every available resource be mobilized to save lives, lessen the severity of injuries, protect property, and restore the movement of traffic. An essential part of the State Safety Program should be the development of emergency facilities systems. This will require the advice and services of experts and personnel in medicine, law, engineering, communications and law enforcement, as a minimum." The Act, administered by the National Highway Traffic Safety Administration, tasks the states to implement Highway Safety Program projects. A feasibility study based on public road mileage and state population was apportioned to the states on a formula basis necessitating location information and communication operationally. This reduction of response time, mobilization, management and coordination is the subject of this presentation. The initiative of response resources has a direct impact on the bottom line. That is, reduction of death, suffering from injuries, restoring traffic movement, and safety countermeasures. In emergency medical services or health care delivery alone, meeting a national goal of a 15-minute response time has been estimated to result in a saving of 9,000 highway crash victims from the total of over 50,000. The chain of events starts with the request for assistance still being handled primarily by the telephone. Recognizing this, the Department of Transportation has issued a policy supporting implementation of the Universal Emergency Telephone Number 911 on a nationwide basis. We are also working on a structured organized program to exploit the use of Citizens Band Radio by the motoring public, in the absence of a dedicated highway communication system, as a means by which the motorist from his vehicle can request assistance, make and receive reports relating to his safety and well-being. We have also sponsored a block frequency allocation structure for emergency medical service which permits all EMS providers to fully participate, permitting medical vehicle and interface coordination. Frequencies can be assigned on a real time basis somewhat as they are for aviation or maritime operations. Inherent in these activities is the need for central command/control and communications. There are, of course, demographic, legal, political, parochial interests and other constraints which must be considered, but the programs are moving forward on sheer logic and positive demonstration of improvement of quality of life. One of the major requirements in meeting safety responsibilities for highway safety is precise location information, not only for management of response resources, but as a management tool for program evaluation and to determine priorities for funding allocation. The answers to the questions of where am I, and where has the incident taken place are equally important to reduction of response time and an integral part of the communication system. To this end, the National Highway Traffic Safety Administration has for a number of years been monitoring technology. The problem, it appears, is not technology but rather administrative constraints. Circumstances, public attitudes, the availability of tools and other timely events have now progressed to assist in selection of technology and system implementation. The use of LORAN-C is an example where, despite competing communication means and even the opinion of many knowledgeable professional communicators who are not prone to accept or encourage the use of CB, its use by the public can no longer be ignored. Loran C is in the same category as an existing tool that can be
exploited. In this respect, location information by street names, roadside markers, routing indicators and other commonly used means has changed very little. A change may not sound very exciting. After all, emergency services are being provided now and the public has apparently been satisfied. No more; nationwide trends to implement public safety systems, highway communications, the all concept, central command/control and communications are all examples of changing attitudes, growing public awareness and demand for better services. The DOT standard making authority, not only for the highway safety program but for vehicles and in-vehicle equipment, provides a powerful means to improve the quality of life on a nationwide basis. Mediocrity in providing emergency services can no longer be accepted. The missing link in location information is now available through the use of Loran C. The use of a common reference system available on a nationwide basis can provide the capability to assist in managing and mobilizing countermeasure and response resources and for enforcement on a real time basis, and for evaluation, including the identification of high accident sites. Loran C lends itself to application of computer technology in central resource coordination communications centers. I emphasize the word common although the term universal is equally descriptive. Location of ambulances, wreckers, fire and police units and incident sites can now be precisely described in Loran coordinates. An obvious application for upgrading emergency services. Accordingly, NHTSA has entered into a contract with the state of New York to perform a conceptual analysis of the application of Loran C for highway safety. As a parallel effort we have entered into an agreement with the Transportation System Center to structure an operations analysis of the use of Loran C in the operational environment in Philadelphia. This project will equip a selected number of fire department ambulances with Loran C receivers to test and evaluate the use of Loran C. This activity, as part of the effort to develop a model urban EMS system, lends itself logically to upgrading emergency services to meet day-to-day needs and those anticipated in connection with the Bicentennial celebration, and to gain experience upon which to base national programs. I recognize there are competing systems but also the opportunity and obligation to move the program forward. This is a "here and now" opportunity to put to bed once and for all many of the questions concerning terrestrial application of Loran C. I believe that Loran C is the only viable alternate that is immediately available and that NHTSA has the obligation to move rapidly in its use for highway safety. The impact on saving lives speaks for itself. This type of industry/state/federal partnership is essential to meeting a public need that transcends all other Loran C applications. NHTSA looks forward to your advice, assistance and cooperation in making it happen.
The Accuracy of Wind Finding using the Loran C Navigation System

by

P. Ryder
U.K. Meteorological Office
London Road
Bracknell
Berks, U.K.

Abstract

A series of trials have been carried out in the United Kingdom to quantify the wind finding capabilities of some commercially available equipment designed to use the Loran C navigation system. A method of predicting wind errors at any location is developed from the trial results.

1. Introduction

The concept of wind finding by the re-transmission of VLF or LF radio navigation signals, as received at an object moving with the wind, to a data receiving/analysis centre has been well described by Beukers (1967) for example. The advantages of the technique as compared with conventional radar theodolite or radar tracking include the following:

(1) the sonde is a passive device to the navigation system and the latter is therefore non-saturable

(2) the very stable sophisticated equipment is located only at the transmitters. The sonde contains a VLF or LF receiver and a transmitter operating at say 400 MHz where the bandwidth necessary to relay the received signals is readily available. This simplicity and hence low cost is clearly of importance in throw away packages.

(3) the telemetry link between the sonde and data gathering centre demands only satisfactory transmission to preserve phase difference. In particular relative motion between the two is unimportant, and because the receiving centre is not part of the tracking co-ordinate system a stable platform and tracking antenna are not necessary.

(4) Loran C has the particular advantage of being maintained with a very low down time and is freely available for wind finding activities.

(5) Being a pulsed system, Loran C also offers the possibility of distinguishing between groundwave and skywave.

The UK Meteorological Office has been engaged for some time on research into the dynamics of weather systems on the meso-scale, (10-100 km) in an attempt to understand the atmospheric spectral gap between the forecasting scale (typically 300 km) and that of the user (1-10 km). This research involves sampling meteorological parameters, including the wind field, over a 10 km depth of atmosphere on a horizontal scale of 10's of kms. The advantages of the NAVAID concept allow several sondes to be tracked at a time and sondes to be released from, and data to be collected by, a manoeuvring aircraft. This in turn gives the potential flexibility of carrying out a measurement program over large areas of the North Atlantic (an area of great meteorological significance to the British Isles) where Loran C cover may be expected to be adequate; to be independent of a fixed ground based measurement network and hence to carry out programs at short notice.
Accordingly in 1971 it was decided to attempt to quantify the accuracy of re-transmitted Loran C for wind finding. It is important to realise that, unlike the use for navigation purposes, it is errors in the rate of change of time difference which contribute to wind finding error, not errors in the time differences themselves. Thus the relatively large body of research into the long term stability of Loran C is not directly applicable to our problem.

2. Method of analysis

It is straightforward to show that, if the baseline between two Loran C transmitters, such as the master and slave \( A \), subtends an angle \( \phi_{MA} \) at a receiver, then the line of constant time difference (line of position or LOP) bisects this angle. Additionally, the rate of change of time difference with distance moved perpendicular to the LOP is \( \frac{C}{2} \sin \frac{\phi_{MA}}{2} \), where \( C \) is the effective propagation velocity. A triad of transmitters necessary to uniquely define position generates a series of parallelograms of LOPs in the tangent plane in the vicinity of the receiver. The lengths of the sides of these

\[
\frac{T_{MA}}{C} = 2 \sin \frac{\phi_{MA}}{2} \sin \theta \quad \text{and} \quad \frac{T_{MB}}{C} = 2 \sin \frac{\phi_{MB}}{2} \sin \theta
\]

where \( 2\theta = \phi_{MA} + \phi_{MB} \) and \( T \) is the so called scale factor. For optimum geometry the \( T \) should be as close as possible to the minimum of 150 m/\( \mu \)sec. Time difference changes of \( \Delta T_{MA} \) and \( \Delta T_{MB} \) then indicate a movement of \( \Delta L_{MA} \) parallel to LOP\(_{MB} \) and a movement \( \Delta L_{MB} \) parallel to LOP\(_{MA} \). Thus specifying the new location. If this change occurs in unit time then the mean velocity vector for that unit is defined.

In practice the values of time difference constitute a time series which is smoothed by a low pass filter such as a running mean. The rate of change of the smoothed values is used to define the velocity through the use of scale factors. In static monitoring, the rates of change of the smoothed time differences constitute errors \( e_{MS} \). We define a parameter \( \sigma_{MS} \) as the root mean square value of \( e_{MS} \) over some period with a specified degree of smoothing. Then \( V_{MA} = \sqrt{\sigma_{MA}^2} \), \( \sigma_{MA} \) represents the RMS wind error parallel to LOP\(_{MB} \). Note that \( V_{MS} \) is separable into two terms, one of which, \( \sigma_{MS} \), represents the geometry of the transmitter receiver location and one of which, \( \sigma_{MS} \), is a measure of the variability of the rate of change of time difference error, filtered in some way, at the receiver. The two components, \( \sigma_{MA} \) and \( \sigma_{MB} \), added vectorially are then used to obtain an estimate of the root mean square wind speed error, \( U_{RMS} \).

3. Aims of this series of trials

As far as is known two attempts have been made to quantify the precision of wind finding by the use of Loran C, those of Acheson (1970) and Taylor (1971). The former took place in a particularly good geometrical area on the east coast of the United States of America, at Wallops Island, the latter at a poor geometrical area on the east coast of Scotland. Acheson monitored Loran C signals with a fixed receiver and used any apparent movement, implied by the varying time differences, to specify wind errors. He also made some direct comparisons with radar tracking. Taylor compared tracking by Loran C with tracking by a normal radiosonde radar of limited precision.

In this report we investigate the possibility of extending the use of Loran C wind finding to research projects designed to study the air flow in frontal systems when the divergence of the horizontal wind field provides
estimates of vertical motions. This demands RMS wind errors of 0.2 to 0.3 m/s in general. Such research projects are likely to take place to the west of the British Isles and therefore particular emphasis is placed on this region. It is clearly impractical to measure wind errors at a large number of locations to map such an area. Therefore an attempt is made to produce a model capable of predicting likely wind errors from a series of measurements made in a few locations. In Section 2 we showed that the problem is separable into one of defining the geometrical factor \( g \), which is a function only of the relative positions of the transmitters and the receiving point, and a term representing the variability of the time differences (which may be a function of location, time of day, time of year, and the period over which variability is assessed). Acheson pointed out a method of predicting wind errors based on the geometrical terms only, which involved the assumption that the variability found at Wallops Island is applicable in the area for which a prediction is required.

4. **Experimental Equipment**

A LOCATE model WL balloon tracking system manufactured by Beukers Laboratories Inc. New York, was used to monitor Loran C signals.

Basically this LOCATE system consists of Loran C and 403 MHz receivers which are capable of detecting the 100 kHz transmissions directly or as detected and relayed by a VIZ radiosonde containing a Loran C receiver and a 403 MHz transmitter. These constitute the so-called LOCAL and REMOTE modes. The pulses are displayed on a monitoring oscilloscope and after passing through a limiting amplifier they are used to phase lock internally generated 100 kHz oscillations. Locking is gated to occur only on a 30 usec wide section of the eight pulses of a standard transmission. It is normal practice to make the gate coincide with the rising portion of each pulse during the initial manual 'lock on' procedure, in an attempt to maximise groundwave contribution. The phase difference between appropriate pairs of master and slave 100 kHz oscillations then produces a voltage which is a simple function of the time difference between arrival of the original signals. There is an obvious ambiguity of integrals of 10 usec but this is unimportant for wind finding. The voltages drive a two track pen recorder, where zero and full scale output indicate zero phase difference. It is possible to compare a master and slave in different chains and slave-slave or slave-master phase differences may be generated to replace the normal master-slave difference. This is clearly equivalent to transposing the role of master and slave and permits maximum flexibility in the use of existing transmissions.

5. **Static trial at Stornoway**

The above equipment was used at Stornoway radiosonde station (58°14'N, 6°19'W) for purposes of static monitoring during 19 July to 4 August 1971. The trial consisted of almost continuous monitoring of the Loran transmission from Stornoway (master) at 58°14'00"N, 6°04'26"W and Stornoway and Sandur (slaves) at 54°47'29"N, 08°17'16"E and 64°54'12"N, 21°55'20"W respectively. This was primarily through the local receiver but several comparison trials were made with fixed VIZ radiosondes using the 403 MHz link. No significant difference in the variances was observed. A 3 second analogue smoothing was employed to limit the frequency response of the pen system. This allowed objective digitising without 'smoothing by eye' or aliasing problems. The two time differences read at 3 second intervals were smoothed by simple 5 second rectangular digital filters and RMS 1 minute components and the resultant \( V_{\text{MA}}, V_{\text{MB}} \) and \( U_{\text{RMS}} \) were then obtained. Scale factors and crossing angles \( \theta \) were calculated throughout this report by assuming a spherical earth. The values of \( U_{\text{RMS}} \) obtained in this trial are shown in figure 1(a). It is clear that there is a diurnal variation. It was decided therefore to study the daytime 'quiet' period in detail and to specify night
time results with respect to those thus obtained. The quiet period at Stornoway for this time of year was taken arbitrarily from figure 1 as between 0700 and 1000 GMT.

Much of the statistical study of the data involves the assumptions that errors are normally distributed and that time differences are not cross correlated. Therefore 300 daytime 1 minute smoothed values of $e_{MB}$ were examined using Eide-Sylt and Eide-Sandur transmissions. The data were obtained from the 3-5 minute samples. The RMS values, $\sigma_{Eide-Sylt}$ and $\sigma_{Eide-Sandur}$ were found to be 15.1 nsec/min and 29.7 nsec/min respectively with distributions which were consistent at the 95 and 99% levels respectively with the hypothesis that the $e_{WS}$ are normally distributed with standard deviations equal to the quoted RMS values. The correlation coefficients between the values of $e_{MA}$ $e_{MB}$ obtained during daytime operation were evaluated and an average value of -0.35 was obtained.

The determination of winds demands subtraction of incremental position and clearly the effects of slowly varying errors are minimised. This is high pass filtering. Very short term errors can also be removed by smoothing or low pass filtering. The full process therefore is one of band pass filtering. The data in this report have been normalised to obtain 1 minute winds with 15 sec smoothing. This is a somewhat arbitrary choice and therefore the effect of calculating winds over different periods with different degrees of smoothing was also determined from the same series of daytime measurements. The results are shown in figure 2(a).

To verify that there is no significant difference between the RMS wind errors determined through the 'LOCAL' receiver and those obtained through a static sonde, several pairs of samples were taken successively in the 'LOCAL' and 'REMOTE' modes.

The night-time data are amenable to a similar analysis to that carried out on the daytime data but from the distribution of RMS wind errors shown in figure 1(a), there is some evidence of skew rather than normal distribution. This cannot be satisfactorily defined with the limited amount of data from the 5 minute samples. Mean RMS values, $V_{MA}$ and $V_{MB}$, have been evaluated for various periods through the night but care should be taken in inferring the probability of errors of a certain magnitude occurring from these data as this implies a knowledge of the distribution. The ratio of the values of $V_{MA}$ and $V_{MB}$ obtained at night to those obtained during the daytime are shown in figure 1(b).

It is also instructive to determine the effects of different degrees of smoothing on the night-time data. From the results shown in figure 2(b) it is clear that there is an increased contribution from long period errors at night compared with the daytime, because there is less improvement in the RMS error with increasing smoothing interval at night.

Attempts were made during both day and night-time to lock onto the front of the pulse where there is the maximum probability of finding unadulterated ground wave. When the locking position and hence the 10 us gate is moved from just before the pulse peak to the front during daytime then there is no change in the mean position of the trace but its random excursions, and hence the derived RMS wind greatly increase. Eight-minute samples showed increases in $e_{WS}$ of typically a factor of 10 when front locking was used. At night-time the trace of Eide-Sandur time differences drifted in such a manner as to indicate an increasing time difference, but relaxing at the front of the pulse brought the trace back to the daytime position, again at the expense of greatly increased relatively short term excursions. The Eide-Sylt trace behaviour at night was similar to that of the
daytime with little or no long term drift apparent. Visual inspection of the pulse waveforms does provide some evidence for the more detailed mechanism behind their behaviour. Frequently at night after the gate had been locked in the normal position just in front of the peak, it would appear to move slowly through the pulse. This we believe is due to a combination of ground wave and sky waves being present within the 30 μsecond gating period and as one or other of these dominates, the locking position is pulled one way or the other. This is not at variance with the slow drift of the Ede–Sandur trace and negligible drift of that of Ede–Sylt, if the first hop sky wave dominates in the case of Sandur during the night at Stornoway and ground wave in the case of Ede and Sylt. The 10–15 μsec increase in time difference of Ede–Sandur is consistent with a 10–15 km movement upwards of the reflecting layer in the Sandur–Stornoway path. Presumably there is always some ground wave/sky wave 'confusion' within the gate at night leading to similar increase in the derived RMS wind error from both Ede–Sylt and Ede–Sandur despite the lack of a long term drift in the Ede–Sylt trace.

From the evidence of this trial at Stornoway we expect an increase over the daytime RMS errors of between a factor of 2 and 4 largely due to an increase in the relatively long period variance. Acheson's results (1970) also imply similar conclusions. He obtained a factor of 3 increase in the RMS wind error between day and night with a dependance on smoothing interval shown in figure 2(b).

5. Static trial at Bracknell

Preliminary investigation of scale factors and crossing angles indicated that the Bracknell area 51°23'N, 0°47'W is best served by the Ede master transmission and Sylt slave transmission from the SL1 chain with Estarit (42°03'46"N, 0°12'20"E) slave transmission from the SL1 chain. After modification of the equipment the maximum signal and optimum position of the Sylt transmitter was used to the best advantage by forming Sylt–Ede and Sylt–Estarit time differences. Unfortunately the observed signal to noise ratio at Bracknell for Estarit transmissions in particular and to some extent those from Ede were quite low, making the locking on procedure very difficult and occasionally impossible. The situation was somewhat improved by the use of 'notch' filters designed to remove the interfering effect of transmissions originating from Prague at 98.4 and 100.93 kHz. Trials indicated that although locking itself was made easier the filters had little effect on stability after locking.

The trials were in two parts. Firstly a static trial was undertaken, using the above stations, from 11–20 August 1971 and secondly a static trial and comparison with radar were undertaken in October–November 1971. A precision tracking radar was used which has been shown to determine winds at ranges of ∼40 Kms with ±0.2 m/s, Hardman et al (1972). In the trials after August 1971 a simple data logger was used to replace the pen recorders. This printed out the pen drive voltages at 1 second intervals. During the radar comparison trial the clock drive which initiated printing also controlled the cameras photographing the radar range, azimuth and elevation dials so that synchronised 1 second data was obtained from both systems. No use was made of analogue smoothing beyond that inherent in the LOCATE equipment. The data obtained in the August trials at Bracknell were all obtained during daytime. They were analysed in the same manner as those from the daytime Stornoway samples. The mean RMS values are listed in Table 1.

The October–November results demonstrated that the wind errors obtained during static monitoring were essentially the same as those obtained by comparison of LOCATE and radar tracking, when the radar error was negligible.
7. The prediction of wind errors

As mentioned in Section 6 it is necessary to predict values for $\sigma_{MS}$ before wind errors can be specified. From the data in Table 1 it is clear that $\sigma_{MS}$ is not constant. However it has proved possible to fit the data to a physically plausible model, which in turn predicts the Wallops Island results of Acheson, for example, quite well.

We assume that $\sigma_{MS}$ is made up of two parts: a term due to fluctuations of the master signal and a term due to the appropriate slave signal thus:

$$\sigma_{MS}^2 = \sigma_M^2 + \sigma_S^2$$

We further assume that the terms $\sigma_M$ and $\sigma_S$ are functions of the short great circle distance between the transmitter and receiver only. Clearly some dependence on signal strength must ultimately be invoked but it seems reasonable to assume that above some threshold, to be defined, the major contribution to variability is not a function of the SNR at the measuring equipment. In fact it is found that if we assume a dependence specified by $\sigma = \sigma_0 + kR^2$ where $R$ is the appropriate great circle distance then a good fit to the data obtained from the Eide-Sylt and Eide-Sandur traces at Stornoway and the Eide-Sylt trace at Bracknell is obtained with $\sigma_0 = 0.5, k = 3.3 \times 10^{-11} \mu\text{sec. sec}^{-1} \text{Km}^{-2}$ when $R$ is measured in Km. Figure 3. It is interesting that the data on the RMS position error specified by the Loran C network as obtained by Dolman (1967) at Lossiemouth is also very well represented by the relationship:

$$\sigma_{\text{position}} = K_{\text{position}} \cdot R^2$$

where

$$K_{\text{position}} = 4.9 \times 10^{-7} \mu\text{sec. Km}^{-2}$$

The value of $\sigma_{MS}$ obtained at Bracknell from Sylt-Estartit does not fit this model. However the signal received from Estartit was the weakest of those used. If it is assumed that the inverse square law satisfactorily describes the decrease of received power with increasing distance from the transmitter then $E_R = E_0/R^2$, where $E_0$ and $E_R$ are measures of the received and transmitted powers respectively. Assumed values of $1/E_0$ are listed in Table 1. We have also assumed that the Estartit signal strength at Bracknell was below the threshold described earlier and that the value of $\sigma_{MS}$ found for the Sylt-Estartit combination is greater than predicted by the simple model for this reason. The apparent Eide signal is only slightly stronger than that from Estartit and therefore it is assumed that the threshold is defined by:

$$\frac{R^2}{E_0} = \frac{1}{K_T} = 4000 \text{ Km}^2 \text{ Watt}^{-1}$$

We further assumed that when $E_R < E_T$:

$$\sigma^2 = (k_1 R^2)^2 + (k_2 \left( \frac{R^2}{E_0} - \frac{1}{E_T} \right))^2$$

where $k_2$ is defined by:

$$\sigma_{\text{Sylt-Estartit}}^2 = k_1^2 (R_{\text{Estartit}}^4 + R_{\text{Sylt}}^4) + k_2^2 \left( \frac{R_{\text{Estartit}}^2}{E_0} - 4000 \right)^2$$

i.e. $k_2 = 3.61 \times 10^{-7} \mu\text{sec sec}^{-1} \text{Km}^{-2} \text{Watt}$. 

12
The full model for $\sigma_N$ or $\sigma_S$ then becomes

$$\begin{align*}
\sigma^2 &= 3.38 \times 10^{-10} R^2 \text{ when } R^2/E_o \leq 4000 \\
\sigma^2 &= (3.38 \times 10^{-10} R^2)^2 + (3.61 \times 10^{-7} (R^2/E_o - 4000))^2 \text{ when } R^2/E_o > 4000 \\
\sigma^2_{NS} &= \sigma^2_N + \sigma^2_S
\end{align*}$$

Although the specification of the threshold is somewhat arbitrary, this model is rather insensitive to the particular value chosen until the signal strength is below that received at Bracknell from Estartit. Such signal strengths are very difficult to use in practice and therefore expected wind errors become somewhat academic.

The standard equations of spherical trigonometry and equations (1) and (3) of Section 2 and equation (4) above allow the specification of the RMS wind errors $V_{MA}$ and $V_{MB}$ parallel to the lines of position at a set of grid points for any distribution of transmitting stations. If we assume that $\pm V_{MA}$ and $\pm V_{MB}$ are the expected RMS errors then these may combine as:

$$\begin{align*}
V^2_1 &= V^2_{MA} + V^2_{MB} + 2V_{MA} V_{MB} \cos \theta \\
V^2_2 &= V^2_{MA} + V^2_{MB} - 2V_{MA} V_{MB} \cos \theta \\
\sigma^2_w &= \frac{V^2_1 + V^2_2}{2}
\end{align*}$$

The distribution of errors thus obtained are shown in figure 4 for various existing transmitters. It should be remembered that these distributions are those appropriate to daytime, for 1 minute winds after the data has been smoothed by a 15 second running mean. Results for any other time of day, or treatment of the data should be determined from these diagrams in conjunction with figures 1 and 2. In figure 5 the model has been applied to the US east coast transmitters Cape Fear, Nantucket and Dana in the Wallops Island region. The agreement between the predictions and Acheson's results is very encouraging and provides independent support for the model we have proposed. Taylor's results from Shanwell provide neither confirmation of, nor disagreement with, the model, as he determined an RMS wind difference between radar and LOCATE of 1.9 + 0.7 m/sec but the accuracy of radar was approximately + 1 m/sec at typical ranges of 20 Km. The ascents also took place close to dawn and dusk.

8. Conclusion

It appears that the model described, satisfactorily explains known observations of windfinding accuracy obtainable with the LOCATE system, when the navigation aid used is Loran C, and that useful predictions can be made. These should be treated with caution where signal strengths are low. It has not proved possible to uniquely and usefully lock onto groundwave alone even where signal strengths are high as in Stornoway and there is a significant degradation in accuracy at night using the WL system. A major potential advantage of pulsed Loran C over other hyperbolic navigation systems has not therefore been satisfactorily exploited.
On the basis of this work it was decided some three years ago to proceed with the development of a NAVAID dropsonde using Loran C for windfinding. Pre-production sondes are now being manufactured and the first full experimental program is scheduled for the late summer of 1976. Meanwhile experience with a LOCATE WL3 (a development of the WL used in the trials reported here) suggests that this latest equipment achieves errors which are similar but perhaps even slightly lower than predicted in figure 4. It also appears that the WL3 is better able to distinguish between groundwave and skywave than its predecessor. It is also interesting that in recent aircraft flights across the North Atlantic the Sylt signal to noise ratio for example showed signs of a pronounced decrease close to the predicted threshold range referred to in section 7. A report of this later work is being prepared.

Acknowledgements

We wish to thank the Oceanographic Department of the University of Southampton who kindly lent us the LOCATE equipment. We are also indebted to members of staff at the Stornoway radio sonde station and to Mr P Taylor of the University of Southampton for their assistance during the static trial. This work is published by permission of the Director-General of the Meteorological Office.

References


### TABLE 1 TRIAL STATISTICS

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### TRIAL SITE

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FIGURE 1(a) VARIATION OF THE RMS WIND ERROR AT STORNOWAY IN A SERIES OF 8 TO 10 MINUTE SAMPLES

FIGURE 1(b) DIURNAL VARIATION OF RMS WIND ERRORS NORMALISED TO DAYTIME VALUES

FIGURE 1(c) DIURNAL VARIATION OF RMS WIND ERRORS NORMALISED TO DAYTIME VALUES
Figure 2. The effect of varying the smoothing interval(s) and the period over which winds are determined \( (w) \) on the measured RMS wind error.

(a) Daytime Summer Stornoway

(b) Comparison of Day and Nighttime
Figure 3. Variation of the RMS rate of change of time difference with distance between transmitters and receiver.
FIG 5  PREDICTED RMS 1 MINUTE WIND ERRORS FOR DAYTIME
DATA SMOOOTHED BY A 15 SECOND RUNNING MEAN

MASTER  CAPE FEAR  DANA + NANTUCKET
SLAVES

DANA

CAPE FEAR

0.2 m/s

0.3 m/s

0.1 m/s

ACHESON (1970) MEASURED SIMILARLY DEFINED 1 MINUTE WINDS AT WALLOPS ISLAND OF 0.10 M/SEC
Figure 4: Predicted RMS 1 minute wind errors for daytime data smoothed by 15 second running mean.
On the Analysis and Minimization of Mutual Interference of Loran-C Chains

D. A. Feldman
P. E. Pakos
C. E. Potts
U. S. Coast Guard

Abstract - The problems of mutual interference between LORAN-C chains and chains of similar systems has become increasingly important with the actual and proposed expansion of these long and short baseline systems. A complete frequency domain mathematical treatment is presented which leads to an expression for this interference, which can be evaluated by a desktop calculator. The form of the expression is shown to provide insight into the role of repetition rate, signal shape, initial synchronization and phase code play in the resulting interference level. From this a sample algorithm is developed for selection of an optimum rate, and it is shown that with proper choice of phase code and rate, interference can be practically eliminated.

The results provide an objective basis for optimum rate selection and evaluation for planned expansion of systems both in the North American and European regions. Further, the results indicate that a change in policy may be required to take full advantage of the rate structure available, and to incorporate additional phase codes. Finally, the analytical tool developed should provide the basis for international cooperation to ensure that national systems do not interfere with one another.

I. INTRODUCTION

This paper characterizes mutual interference aspects of low frequency pulsed radionavigation systems operating on the same frequency. In particular it makes reference to the Loran-C system [1] and other recently introduced commercial systems (such as Pulse/8) which have similar characteristics. Mutual interference between Loran-C chains became evident soon after two chains began operating in proximity to one another. The effect upon the performance of receiving equipment had already been predicted [2] but the exact causes and how to deal with them were to be the subject of several later studies [3,4,5]. These studies were successful in identifying the root causes of the interference and produced various recommendations concerning ways to reduce the interference to acceptable levels. However, for reasons which were entirely sound at the time, only one of the recommendations was carried out, namely: choosing chain repetition rates which were relatively non-interfering. This technique for minimizing the mutual interference between chains has been employed ever since although experience has revealed less than optimum results. This was not unexpected, as the studies clearly indicated that rate selection is not a solution in itself. Unfortunately, the studies failed to produce a complete analysis of the problem and consequently no unique or optimum solutions were evident.

II. MATHEMATICAL DEVELOPMENT

With the advent of commercial loran systems which employ characteristics similar to the Loran-C system, the avenue was open for an enhanced mutual interference environment. These new "mini-chains" (so termed because they operate with substantially shorter baselines than a typical Loran-C chain) would in some instances be wholly within the service area of a Loran-C chain. Thus, the potential for interference to one, the other, or both is high. This high probability prompted our research into finding a mathematical model which could be used not only to predict the interference but to select chain parameters to minimize it as well. We looked into the development of a time-domain model but rejected that approach as being difficult computationally and not leading to mathematical solutions from which insight into important aspects of the problem can be obtained. We turned to the frequency domain and formulated a model which although not all encompassing comprises all of the necessary variables to yield a near-complete solution to the problem. The power of the expression developed is shown in the correlation between the mathematical predictions and actual results achieved in simulated and real-world interference tests. From the overall expression we extract and examine areas which lead to a rate optimization algorithm and an insight into the importance of the phase code structure. We show that both rate selection and phase code structure are necessary considerations for the reduction of mutual interference. Neither is sufficient on its own.

We conclude by speculating on how one might design a multi-chain system by careful selection of phase code structure and repetition rate, and the advantages to be accrued from such an approach. The impact of changing the Loran-C system parameters is considered.

The authors, officers in the U.S. Coast Guard, were attached to the staff of Commander, Coast Guard Activities, Europe during the work described. The opinions expressed are those of the authors and do not represent the official policy of the United States Coast Guard.

Fig. 1 illustrates the essential equivalency of Loran-C signal generation and cross-correlation tracking. Both processes begin with an impulse pattern incorporating the phase code structure (termed the Phase Code Function, PCF) over two Group Repetition Intervals (2GRI). This pcf(t) is then convolved with an infinite impulse series with period 2GRI, which repeats the pcf(t) every 2GRI. To generate the signal, this infinite and periodic pattern is convolved with a single rf Loran-C pulse, replicating it everywhere with proper phasing. To track this signal, the cross-correlation impulse pattern samples (multiplies) both the interfering and tracked signal. These samples are then smoothed by the low pass filter of the Phase Locked Loop (PLL), represented as convolv-

* We shall use the term Loran-C to refer to the specific signal characteristics being used but our results are applicable to any periodic signal train.
In Fig. 1 we have labeled only the PLL output error term, \( e(t) \), although a tracked signal term is also present.

This model of the mutual interference problem is accurate for an ideal linear receiver with small tracking errors, and thus is a worst case model in comparison to non-linear receiver forms. Most practical receivers with processing non-linearities will not experience the severity of interference predicted by the model. The major results, insight into structure and interference minimization, are independent of the precise applicability of the model to most actual receivers. The following assumptions are made in addition to small-signal linearity:

(i) The rf pulse can be represented as the product of a low pass envelope and single carrier, i.e. there is frequency domain symmetry about the carrier frequency or zero time domain phase modulation.

(ii) The receiver does not have an automatic gain control (AGC) that interacts with the interfering signal. Such interaction will generally make the interference errors worse than predicted by our model.

(iii) When considering different Loran-C rates (GRI) the energy in a single pulse is constant. Total waveform power is arbitrarily set equal to unity at a GRI of 0.1 second and changing the GRI to 0.05 second would double this power.

(iv) The PLL is a first order, type I servo loop.

(v) The receiver rf pre-filter need not be modeled because signal power, before or after detection, is dominated by the rapid decay of the pulse frequency transform.

(vi) The ninth pulse, occurring 2 ms after the master eight pulse group (identifying the master station) is not included for the sake of clarity in the analysis. Its inclusion has an effect as will be discussed later.

We define the following terms (lower case are time functions, upper case their Fourier Transform - except GRI):

\( e(t) \) - Error at the output of the tracking Loran-C receiver caused by interference from another Loran-C signal operating at a different GRI.

GRI - Spacing in seconds between the groups of eight Loran-C pulses from any station. A Loran rate is designated by the first four digits of the GRI in microseconds.

NI - Nearest integer, the integer result of rounding off any real number.

\( p(t) \) - Low pass pulse envelope, nominally \( t e^{-t/T_p} \).

\( pcf(t) \) - Phase Code Function, a sum of + and - impulses defining the appropriate phase code.

\[ pcf(t) = \sum_{k} \alpha_k \exp(-j\omega_k T_P (t-kT_P-GRI)) \]

where \( \alpha_k \) assumes values of \(+1 \) only.

\[ PCF(\omega) = \sum_{k} e^{-j\omega_k T_p} + e^{-j\omega_k (2\pi T_GRI)} \]

\( r(t) \) - Received interfering Loran-C waveform.

\( s(t) \) - Impulse response of the PLL servo loop

\[ s(t) = e^{-t/T_s} u_0(t) \]

\( u_0(t) \) - A single impulse or delta function at time zero.

\[ u_{-1}(t) \] - Unit step function.

\( T_p \) - Spacing of Loran-C pulses within an eight pulse group. \( T_p = 1 \) ms.

\( T_s \) - Initial synchronization time, the time delay of the receiver time origin with respect to the interfering signal time origin.

\( \gamma \) - Radian frequency, less than four times the -3 dB bandwidth of the PLL \( (S(\omega)) \).

\( \omega \) - Radian frequency

\( \omega_0 \) - Carrier, \( 2\pi \cdot 10^5 \)

\( \omega_1 \) - Discrete frequency of tracking signal

\( \omega_2 \) - Discrete frequency of interfering signal

\( \theta \) - Complementary frequency, \( 2\pi \cdot 10^3 - \omega_1 \)

\( \otimes \) - The convolution operation.

Using these definitions, Fig. 1, and the equivalence of time-convolution and frequency-multiplication, we can write the received signal transform as the product of frequency components,

\[ R(\omega, \omega_0) = PCF(\omega) \sum_{k} u_0(\omega - \frac{\pi k}{2T_p}) \]
The first term, PCF \( (\omega) \), extends over all frequency and is periodic every 1 kHz. The second is the Loran-C pulse spectral envelope, which is modulated by PCF\( (\omega) \) while the last term converts this envelope to discrete line spectra spaced 1/2 GRI Hz apart. Each Loran-C waveform at a different rate has this characteristic harmonically-related line pattern and our interference analysis will be concerned with the coincidence of these line patterns and the product of the spectral envelopes at coincidence.

In a similar fashion the receiver cross-correlation waveform spectrum is

\[
\Phi(\omega) = \text{PCF}(\omega) e^{-j\omega T_1} \sum_{n=-\infty}^{\infty} u_n(\omega - \frac{n\pi}{\text{GRI}}).
\]

The PLL error transform is

\[
E(\omega) = \left[R(\omega) \otimes X(\omega)\right] S(\omega).
\]

Most of the line spectra resulting from the interior convolution will fall well outside the bandwidth of \( S(\omega) \) and be rejected. We need concern ourselves only with those line spectra of \( R(\omega) \) and \( X(\omega) \) that fall within \( \pi \) radian frequency of each other, for these are the only convolution products appearing in \( E(\omega) \).

At a tracking line frequency of \( w_1 = w_2 \) with an interfering line at \( w_1 = w_2 + \omega \), we have line pairs with equal \( \pi \) at \( w_1 = w_2, w_1 = w_2 + \omega, w_1 = w_2 - \omega \), \( w_1 = w_2 + \omega, w_1 = w_2 - \omega \), for GRI which are at least multiples of 10\( \mu \)s. Using the fact that the Loran-C pulse transform has real part symmetry and imaginary part asymmetry about \( \omega_0 \), the convolution of (3) will produce a line at \( \pi\),

\[
E(\omega) = \sum_{n=-\infty}^{\infty} [\text{PCF}(\omega) \text{PCF}(\omega) \text{P}(\omega)] e^{j\omega T_1} \cos \omega_0 T_1
\]

We also make use of the fact that for \( T_1 \) of 1 ms PCF \( (\omega) \) is periodic every 1 kHz and hence \( \text{PCF}(\omega + n\omega) = \text{PCF}(\omega) \).

From (4) we see that for our assumed ideal rf pulse, carrier effects are entirely absorbed in the delay function \( \cos \omega_0 T_1 \) while the remaining terms are evaluated at low pass frequencies \( w_1 \) and \( w_2 \).

Since we ultimately intend to compute a Parseval power sum (root-sum-square) of all line contributions to \( E(\omega) \), we must first compute the sums of all contributions at each discrete \( \omega \). These contributions depend upon the common frequency period of the line spectra of the tracking and interfering rates. This is determined by the integer values \( m, n \), which satisfy

\[
\frac{m}{\text{GRI}} = \frac{n}{\text{GRI}}.
\]

For prime \( \text{GRI} \)s (those of greatest practical interest) which are multiples of 100\( \mu \)s, the line spectra have a common period of 5 kHz and for 10\( \mu \)s multiple, 50 kHz. For the latter case the pulse envelope-transform power \( |\text{PCF}(\omega)|^2 \) is essentially zero at 50 kHz and we can treat each \( E(\omega) \) component as existing at a discrete frequency. For the prime 100\( \mu \)s multiple case, each \( E(\omega) \) line has two components which are reflected from \( \omega_1 \) and \( -\omega_1 \) convolutions, yielding

\[
E(\omega) = \sum_{n=1}^{\infty} \frac{[\text{PCF}(\omega) \text{PCF}(\omega) \text{P}(\omega)] e^{j\omega T_1} + \text{PCF}(\omega) \text{PCF}(\omega) \text{P}(\omega) e^{-j\omega T_1}]}{\text{GRI}}.
\]

To normalize the "noise" power of the interference, we must determine the "signal" power generated by the tracked rate. We do this by setting the interfering rate equal to the tracked rate, and all convolution products occur at \( \omega = 0 \). This single line is given by

\[
E(\omega) = \sum_{n=1}^{\infty} [\text{PCF}(\omega) \text{P}(\omega)]^2 \text{Re} [\text{PCF}(\omega) \text{P}(\omega) e^{j\omega T_1}].
\]

The relative PLL error power, or the Figure of Merit \( \text{F.M.} \), for the GRI being considered is now expressed as a ratio of the "noise" power caused by the interfering signal to the detected "signal" power,

\[
\text{F.M.} = \frac{\sum_{\omega} |E(\omega)|^2}{\sum_{\omega} |E(\omega)|^2}.
\]

In computing (7) we must take note of a mathematical difficulty which arises from our approach using Fourier Transforms to represent periodic signals, namely the marginal convergence of the transform of the impulse train. We note that (7) is an approximation to a Parseval Integral which requires the squaring and integrating of impulse functions. The result of this is unbounded, just as the time impulse train itself is not square-integrable. To avoid this we can define the frequency impulse as

\[
\mu(\omega) = \begin{cases} \frac{1}{\omega} & |\omega| \leq \frac{\omega_0}{2} \\ 0 & |\omega| > \frac{\omega_0}{2} \end{cases}
\]

We choose \( \omega \) to be smaller than the minimum harmonic separation, which for prime GRI yields

\[
\omega_0 = \frac{10\text{GRI}}{10^4 \cdot \text{GRI}}.
\]

where \( n=4 \) for 100\( \mu \)s multiples and \( n=5 \) for 10\( \mu \)s multiples. The result of line convolution (i.e. using \( \gamma(w) \) in (3)) followed by the Parseval integration for any component, \( E(\omega) \) then becomes

\[
\text{F.M.} = \frac{2 \text{GRI}^2}{3 \pi \text{GRI}^2} \cos \omega_0 T_1.
\]

Combining (7), (8) and (4) for the 10\( \mu \)s multiple case we have

\[
\text{F.M.} = \frac{2 \text{GRI}^2}{3 \pi \text{GRI}^2} \cos \omega_0 T_1.
\]

and a similar expression for the 100\( \mu \)s multiple using (5) vice (4) and \( n=4 \). The practical impact of
(8) is to scale F.M. by 10 for 10μs multiple GRI
compared to 100μs multiples, which compensates for
squirting before summing line pairs as is done at
100μs (5).

The detected tracked "signal" power can be normalized
to unity at GRI = 0.1 s and we see from (9) that the
power will rise 6 dB per octave-decrease in GRI. For
example a factor of 2 decrease in GRI produces a
factor of 4 increase in 1/(GRI)² but only one-half as
many line spectra occur per unit of bandwidth (1)
and (2), the occurrence of frequency impulses. At
a given GRI, changes in interfering GRI produce a
3 dB increase in "noise" per octaves-decrease in GRI
as seen in (9), noting that squaring takes place
before summation. Thus, coherently detected track
signal power rises 3 dB/octave more than the "noise"
power of the interfering signal, as it should.

Finally, to convert F.M. to an approximate time
error in the PLL output we invoke our linear small-
signal assumption to express rms error in microsec-
onds as

\[ \sqrt{E^2(t)} = \sqrt{F.M.} \cdot \frac{d}{dω} \text{sum} \cdot 10^6 \]

\[ = \sqrt{F.M.} \cdot 0.625 \mu s, \text{rms}. \quad (10) \]

The evaluation of (9) can be accomplished with
a desktop calculator. The program searches over all
tracking harmonics out to 5 kHz* and evaluates the
closest interfering harmonic. When their difference
meets the criterion for \( δ, E(δ) \) is evaluated ((4) or
(5) as appropriate) and the \( \text{sum} \cdot 10^6 \) added to the
sumation. Bookkeeping then corrects for all of the
GRI dependent scale terms after summation. The pro-
gram typically requires 10-12 minutes to evaluate a
GRI.

III. INTERPRETATION

It is illuminating to consider the pictorial
meaning of (4) and (5), the convolution process and
choice of GRI. We consider first the terms PCF(ω),
P(ω) and \( ω_0 (ω+GRI) \). In Fig.2a we show, not to
scale, the spectral envelopes for a hypothetical case.
The interfering signal has an envelope PCF(ω)P(ω).
We have depicted large variations in PCF(ω) modulated
by a slowly decaying \( P(ω) \) function. The receiver
sampling pattern has a different PCF(ω) envelope,
representative of the actual Loran-C code. These
envelope shapes are determined by signal and PCF
characteristics and are independent of GRI. When
we convolve in time to convert \( pcf(t) \cdot p(t) \) into an
actual periodic waveform, we multiply in frequency by
an infinite line spectrum whose harmonic interval is
1/GRI. In Fig.2a we see these line spectra assuming
the spectral envelope amplitude at their frequency of
occurrence determined only by their GRI.

For the illustration, convolution will now re-
fect to low frequency each interfering spectral line
which falls within a PLL passband of a receiver.

*This bound was empirically determined. \( P(ω) \) decays
very rapidly for the \( p(t) \) pulse shape used and con-
volution products beyond 5 kHz do not significantly
affect F.M.

tracking harmonic. The amplitude after convolution
will be the product of spectral envelopes for the
respective lines and the PLL response. In Fig.2c
the convolution products for our example are seen in
relation to \( S(ω) \). Note that because the closest co-
cidence occurred near a deep PCF null, line 2
although passed unattenuated by \( S(ω) \) is considerably
smaller than convolution product 1 which falls on the
skirts of \( S(ω) \) but results from the product of the
large spectral envelopes.

![RF Spectrum](image)

![PLL Response](image)

![After Convolution](image)

Fig.2. Receiver processing.

Three actual PCF(ω) functions are plotted in
Fig.3. Both the Loran-C and commercial Pulse/8 PCFs
are actually composed of two alternating functions
according to whether the harmonic line is odd or even.
This is a detail which must be accounted for in eval-
uating F.M. but which does not affect the concepts
emphasized. The "optimum" PCF will be derived below.
We see the dramatic difference in amplitude variation
among the PCFs, a point of critical importance in
interference minimization. The essence of frequency
domain analysis of mutual interference is the evalua-
tion of these PCF(ω) functions at harmonic line co-
cidences. The essence of frequency domain minimiza-
tion of mutual interference is selecting rates to
place line coincidence at spectral amplitude minima,
or in addition, manipulating these PCF spectral am-
pitudes.

The only remaining terms in (4) and (5) are the
delay or initial synchronization factors, phase term
e^{-iωTs} and amplitude term \( \cos ωTs \). As already noted,
the absorption of all RF carrier effects in the amp-
litude scale factor \( \cos ωTs \) is a reflection of our
assumed ideal signal. With no time domain phase-
modulation and at least 10μs multiple GRI's, alignment
of the time origins to be in RF phase-quadrature at
one point in the pulse will result in quadrature
everywhere else, as shown by the \( \cos ωTs \) scale term.
All succeeding computations will be made with worst-
case phase alignment, \( \cos ωTs = 1 \). Delay effects due
to the shape of the Loran-C pulse cannot be anti-
cipated from (4). For rates which are 10μs multiples,
there are no effects because each \( E(δ) \) component is
discrete and the Parseval sum destroys harmonic phase,
For the 100 ms multiple case the effects are only manifested in the addition of the two $w_1$ and $\theta_1$ components; the subsequent power computation ignores the resultant phase. Recall that our implicit definition of “effect” is the interference to signal power ratio. The actual $e(t)$ waveform at the PLL output can change drastically due to initial synchronization and still retain the same power and hence have equal effect by our definition. Our computations show that variation in initial synchronization, $T_s$, results in less than 1 dB variation in F.M. (retaining worst case carrier alignment).

\[ |\frac{n - \text{tr}(w_1, z_{2GRIT})}{2GRIT} - \frac{\text{tr}(w_1, z_{2GRIT})}{2GRIT}| < 0.03 \text{ Hz} \]

at any value of $m$ except that near the PCF zero, $f_T$. The value of 0.03 Hz corresponds to PLL time constants in the 5-10 second category. This algorithm runs in a programmable pocket calculator and was used to generate Table I for an example rate of 9930 and Loran-C phase code, with the interfering rate using the Pulse/8 PCF.

### Table I

<table>
<thead>
<tr>
<th>PCF Zero (Hz)</th>
<th>Rates $f_T-f_I$ (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>9540</td>
</tr>
<tr>
<td>245</td>
<td>6890</td>
</tr>
<tr>
<td>256</td>
<td>None meet (iii)</td>
</tr>
<tr>
<td>498</td>
<td>9830</td>
</tr>
<tr>
<td>503</td>
<td>5660</td>
</tr>
<tr>
<td>508</td>
<td>8750</td>
</tr>
<tr>
<td>493</td>
<td>8750</td>
</tr>
<tr>
<td>488</td>
<td>9830</td>
</tr>
<tr>
<td>996</td>
<td>7460</td>
</tr>
<tr>
<td>1017</td>
<td>5260</td>
</tr>
</tbody>
</table>

The values of $f_r$ nearest PCF zeros were used, as well as $f_r$ values at one to two harmonics away from this frequency ($f_T-k/2GRIT$). Fig. 4 shows the actual value of F.M. computed from (9) and we see that most of the predicted sub-optimum rates show a substantial improvement in F.M. of -20 to -30 dB. These sub-optimum rates are those with near-coincidence at harmonic intervals beyond the zeros not tested ($f_T$) in Table I.

![Fig. 3. Phase code functions.](image)

**IV. ANALYSIS AND OPTIMIZATION**

The previous discussion has shown the dependence of mutual interference (F.M.) on the combined effects of the frequency domain PCF and pulse envelope product where the line spectra of the two rates come within a servo bandwidth of coincidence. When zeros are found in either the tracking or interfering PCF, a necessary condition for a sub-optimum choice of GRI is for the tracked signal and interfering signal is immediately obvious:

Given a tracking GRI, all interfering GRI must have near-coincidence of line spectra occurring close to the PCF zero locations.

This is a necessary condition; for sufficiency we add the requirement that the GRI, must not have other similar near-coincidence at non-zero PCF frequencies. These conditions for sub-optimum rates, given that PCF zeros exist in either the tracking or interfering signal are given algorithmically by:

i. Compute the track line nearest the PCF zero

\[ f_T = n \text{tr}(w_1, z_{2GRIT})/2GRIT. \]

ii. Select all GRI, which satisfy

\[ |f_T - \text{tr}(w_1, z_{2GRIT})/2GRIT| < 0.03 \text{ Hz} \]

iii. Reject all selected GRI, which satisfy

\[ |\frac{n - \text{tr}(w_1, z_{2GRIT})}{2GRIT} - \frac{\text{tr}(w_1, z_{2GRIT})}{2GRIT}| < 0.03 \text{ Hz} \]

A master identifier (ninth) pulse was then added to the interfering rate by changing PCF. The presence of this pulse (the remaining PCF was not changed) eliminates the PCF zeros and caused degradation in the good rates plotted in Fig. 4 of 15 dB to 3 dB depending upon the original depth. The relative effect is most pronounced on rate coincidences occurring at the zeros, with decreasing effect on those good rates whose coincidences are several harmonics beyond the zeros.

![Fig. 4. Pulse/8 versus Loran-C.](image)
For the case of both interfering and tracking rates using the Loran-C phase code, our insight into the role of PCF and line spectra coincidence tells us that dramatically improved rates probably do not exist without the large attenuation of a PCF zero at near-coincidence. Without these zeros in the PCF(\(\omega\)) functions of either rate we can only generalize the near-optimum conditions given above to require that:

1. near-coincidence should occur close to PCF(\(\omega\)) minima and this should be the minima associated with even harmonics (odd pulse PCF set).

2. a "good" rate should have few coincidences.

The F.M. for interfering Loran-C PCF against a tracking Loran-C rate of 9930 was computed for all rates which are 100\(\mu\)s multiples and plotted in Fig.5. This shows that obtainable improvement differentials are only 6 dB, maximum. Coincidence analysis of the best rates show that they occur near the 175 and 325 Hz minima (Fig.3) with one or both being even harmonic line spectra, or they occur at the 0, 250, 500 Hz secondary minima. A formal optimization algorithm is of little value in the Loran-C case since so many factors interact. However, the coincidence analysis clearly shows that the interaction of line coincidence with PCF(\(\omega\)) is the most important determinant of resultant interference. From this we may also infer that providing finer GRI adjustment via the use of 10\(\mu\)s multiple rates only offers the advantage of providing a few additional "good" rates, but not further F.M. improvement. Such GRI adjustment cannot change the fundamental obtainable range of F.M. as this is determined by the PCF(\(\omega\)) functions.

\[
\sum_{i} \alpha_i \kappa_{\omega i} + \sum_{i} \alpha_i \kappa_{\omega i} = 0 \quad (11)
\]

Imposing zero conditions on PCF(\(\omega\)) we have (recall PCF(\(\omega\)) is periodic every 1 kHz):

1. 1 kHz zeros
   \[
   \sum_{i} \alpha_i = 0 \quad (12)
   \]

2. 500 Hz zeros
   \[
   \sum_{i} (-1)^i \alpha_i = 0, \quad \sum_{i} (-1)^i \alpha_i = 0 \quad (15)
   \]

3. 250 Hz zeros
   \[
   \sum_{i} (-1)^i \alpha_i = 0, \quad \sum_{i} (-1)^i \alpha_i = 0 \quad (14)
   \]

...and similarly for the second group, \(i\) in the set (8,15). These conditions are various forms of so-called balanced codes. Note that the simple balance of (1) provides only 1kHz zeros, or few opportunities for GRI\(_1\) optimization.

Solving (13) and (14) simultaneously yields

\[
\alpha_i = -\alpha_i + \eta \quad (15)
\]

which also satisfies (12) and produces a PCF(\(\omega\)) periodic every 500 Hz. Combining (15) with (11) we have

\[
2\alpha_i (\alpha_x + \alpha_y) + 2\alpha_y (\alpha_x - \alpha_y) + 2\alpha_y (\alpha_x + \alpha_y) + \alpha_x (2\alpha_x - \alpha_y) = 0 \quad (16)
\]

We see that (16) has a number of solutions which are all permutations of \(\alpha_x = \alpha_y, \alpha_y = \alpha_x, \alpha_x = -\alpha_y, \alpha_y = -\alpha_x\). Present commercial Loran-C short baseline systems satisfy (16).

Recalling the plots of PCF(\(\omega\)) and the necessary condition for minimum mutual interference we can add a further refinement in seeking an optimum PCF by requiring the zero in PCF(\(\omega\)) to be as broad as possible. The first order expression of a broad PCF(\(\omega\)) zero is

\[
\frac{d}{d\omega} \text{PCF}(\omega) = 0 \quad \text{at } \omega = 12\times175, 12\times325, 12\times500, \ldots
\]

Evaluating PCF(\(\omega\)) = 0 at 500 Hz yields

\[
\kappa_y + \kappa_i = \kappa_y + \kappa_y, \quad \kappa_y + \kappa_x = \kappa_y + \kappa_i \quad (17)
\]

while at 250 Hz we have

\[
\kappa_i = \kappa_y, \quad \kappa_x = \kappa_y, \quad \kappa_y = \kappa_x, \quad \kappa_i = \kappa_i \quad (18)
\]

V. PCF OPTIMIZATION

The frequency domain insight into the role of PCF(\(\omega\)) zeros suggests an exploration of possible PCFs which produce these desirable conditions. The fundamental condition that a PCF must satisfy, indeed its originally perceived function, is the provision of skywave protection. An adequate degree of protection is a delay of one pulse spacing (1\(\mu\)s=1 ms) which means that the first lag auto correlation of pcf(\(t\)) must be zero.

\[
\sum_{i} \kappa_i \kappa_{\omega i} + \sum_{i} \kappa_i \kappa_{\omega i} = 0 \quad (11)
\]
Combining (17), (18) and (15) yields only one PCF, which does not satisfy (11) for skywave protection. It is not possible then to have broad zeros at 250 Hz increments. However, if we use only (17) with (16) we find an "optimum" PCF which has broad zeros at 0, 500 Hz and 1 kHz with a cusp zero at 250 and 750 Hz:

\[
\begin{align*}
& \chi' - \chi_0 = \chi_0 - \chi_0 = \chi_0 - \chi_0 = \chi_0 - \chi_0 \\
& \chi_0 = 0, \chi_0 = 0, \chi_0 = 0, \chi_0 = 0
\end{align*}
\]

The PCF(\(\omega\)) for these PCFs was plotted in Fig. 3. The autocorrelation of the optimum code has values, 1.0, -0.25, 0.0, 0.25, 0 as compared to the Loran-C PCF autocorrelation 1,0,0. Thus it surrenders total skywave protection (i.e. for delays of \(n\) pulses) for desirable interference rejection properties. The search detection properties of the "optimum" code, (19), also appear to be satisfactory offering the -0.5 value at the fourth lag for a more unique pattern than the Loran-C PCF. The actual improvement in F.M. provided by the optimum code, in conjunction with rate selection, is given below.

VI. LORAN-C SYSTEM DESIGN

It is interesting to speculate on how one might choose phase codes and rates in a multi-chain system to minimize mutual interference. Using the "optimum" PCF we must look for a sequence of rates in which as many rate neighbors as possible meet the necessary and sufficient conditions for minimum mutual interference; near-coincidence at PCF zeros with no similar coincidences elsewhere. A variation in GRI, \(x\), between chains must first satisfy

\[
\frac{m-n}{2\Delta f_0 \tau + k} \approx \frac{k}{250}, \quad \text{where} \quad \frac{m-n}{2\Delta f_0 \tau} \approx \frac{k}{250} \tag{20}
\]

for near-coincidence at the \(k\)-250 Hz zero.

Assuming that \(x\) is small, we then require for sufficiency that this coincidence is the first such coincidence, or that

\[
\frac{1}{2\Delta f_0 \tau} - \frac{1}{2\Delta f_0 \tau + k} \approx \frac{1}{10(2\Delta f_0 \tau + k/250)} \tag{21}
\]

The solutions to these equations are: \(k=4, x=0.5\) ms; \(k=2, x=1\) ms; \(k=1, x=2\) ms. Thus we can select a GRI and then vary the GRI of succeeding chains in 0.5 or 1 ms steps and each chain would then have mutual interference protection from its four closest neighbors. Roland (6) has suggested rates differences of 1 and 2 ms based on a time domain correlation analysis. Other factors need to be considered in rate selection of course. For instance, rates which are even multiples of 0.1 ms or evenly divisible by 0.5 ms are more susceptible to synchronous interference due to international frequency assignment policy.

Using the "optimum" PCF, both interfering and tracking, the relative F.M. was computed and found to be better than -60 dB for all four nearest neighbors, below the best F.M. figures for Loran-C PCFs (i.e. F.M. for both chains using "optimum" PCFs is better than -90 dB). In the West Coast Loran-C system this means that the Southern California Chain would only be sensitive to mutual interference from the Bering Sea Chain, and that the Northern U.S. and Gulf of Alaska Chains would have essentially zero mutual interference from all other West Coast Chains. This mutual interference performance is characteristic of chain sequences using 0.5 or 1 ms spacing if PCFs with zeros every 250 Hz are employed. Use of the "optimum" PCF provides 20 to 30 dB more protection due to the extended breadth of the zeros. Various other good rates are then available (e.g. see Fig.4), though not in a regular sequence, for use by mini-chains interspersed among the long-baseline Loran-C chains.

VII. CONCLUSIONS

Our work has resulted in a near-exact mathematical model for the effect of mutual interference among Loran-C chains and other similar systems; that interference caused by a station in one chain or system to a receiver tracking a signal in another chain or system. The model provides an expression for relative interference-to-signal levels for any chain rate and phase code structure. From this we can objectively compare rates and phase codes to minimize interference. The model can also be used for other linear processing structures (such as the envelope index channel) by appropriate change to signal shape, \(\Phi(t)\).

The major conclusion of the work, supporting that arrived at in different ways by others, is that both phase code structure and repetition rate must be optimized together for mutual interference elimination. A consequence of this is that commercial short-baseline Loran systems which utilize a phase code with frequency domain zeros and without a ninth pulse master identifier can operate interspersed in and without significant interference to long baseline systems users.

The insight provided by the structure of the interference expression also shows why the existing Loran-C phase code structure prevents selection of rates with minimal mutual interference. This problem is fundamental and the use of additional rates of 10 microsecond multiples or chain frequency offsets cannot significantly alleviate mutual interference. These techniques only provide additional chains with the maximum 6dB improvement reported here for Loran-C versus Loran-C.

Finally, we consider what might be achieved in mutual interference elimination for long baseline systems if both phase code and repetition rate were selectable. From our understanding of the frequency domain model of interference, we constructed an "optimum" phase code which satisfied skywave protection and automatic signal acquisition requirements. With this code, the use of rates separated in a 0.5 millisecond progression and elimination of the master ninth pulse, it is possible to construct multi-chain systems in which each chain is essentially impervious to interference from its four nearest neighbors.

The suggestion that we should consider such a major change in Loran-C signal characteristics is certainly serious. The costs would be high and immediately identifiable by every equipment supplier. The long range benefits from such a change are not presently known. The problem is in trying to anticipate the interference environment circa 1985 when the multi-chain configuration exists. By then it may be too late to take effective action due to the prohibitive costs involved. Given that the changes we suggest could substantially solve such a problem, the benefits must be weighed against the cost. We submit
that this question draws the immediate attention of both government and industry. In particular we suggest multi-chain simulation studies be conducted with different type receivers. These should cover not only steady-state tracking but also vehicle maneuvering signal acquisition, and tracking-point identification. If we ignore this potential and then conclude in 1985 that we all do have a serious problem, exploitation of the full potential of the Loran-C system will have been denied. If the change is made the tools developed here can form the basis for international cooperation aimed at reducing or eliminating mutual interference. To effect the change, there must be a consensus that the user, the supplier and the government will all benefit.

REFERENCES

VELOCITY AIDING AND ALTERNATIVES FOR LORAN-C RECEIVERS
Ed Bregstone, U.S. Coast Guard

Abstract: This paper addresses performance requirements and capabilities of a Loran-C tracking loop to be used on a moving platform typical of non-military aircraft. It is shown that such a tracking loop requires either external velocity aiding or a maximum response time of 1-2 seconds in order to meet the dynamic performance requirements. A tracking loop algorithm is proposed to permit both the fast response and requisite noise protection simultaneously in the absence of external velocity aiding. A performance example of this tracking loop algorithm is also presented.

1. Performance requirements: This paper addresses the performance requirements of general aviation and air carrier services who might consider the use of Loran-C in the enroute, terminal and (non-precision) approach phases of navigation; the accuracy requirements become more stringent with each successive phase of a flight; furthermore, aircraft typically are rather maneuverable, high-speed receiver platforms. The following assumptions apply to the aircraft of interest.

1. Airspeeds will range from approximately 50 kt for small, general aviation aircraft during an approach to approximately 500 kt for turbojet aircraft enroute.

2. Aircraft maneuvers will nominally be limited by the standard rate turn. A standard rate turn is defined to be one of 30° per second, or that which results from a 30° bank, whichever requires the lesser bank. For aircraft equipped with a flight director, the limit is 25° in lieu of 30°. Turns of more than standard rate may result in small navigational errors for no longer than 3 seconds after completion of the maneuver. (1,2)

3. In the approach regime, where highest accuracy is required, speeds will be limited to no more than 200 kt. (1)

4. Rates of climb range from 100 m/min to 1200 m/min (8-737). Rates of descent substantially in excess of 500 m/min. can be followed by no less than 2 minutes at substantially less than 500 m/min.

5. Horizontal situation indicator lags in excess of 2 seconds are unsatisfactory human engineering, and one second is a more comfortable lag.

2. Loran performance parameters:

The standard rate turn can be related to change of range to a Loran station by figure 1.

\[
\begin{align*}
& v = v_0 + \gamma (\cos wt + 0(r_1/r_0)) \\
& r = r_0 + \gamma (\cos wt) \\
& ( \text{typical, the track is far from the Loran station so the following approximation is valid})
\end{align*}
\]

(2)

(3)

(4)

(When the above approximation is not valid, then the following analysis is applicable only as a worst-case bound on receiver performance; the exact results are available from a similar analysis and series expansion for (1).)

The standard rate turn specifies the angular frequency \( \omega \) and the radius of turn \( r \) as a function of airspeed, as shown in figure 2. The Loran-C tracking loop performance is of most concern for the angular velocities and radii nominally as shown in figure 2.

We may relate Loran-C tracking range lag error to speed, and thus to amplitude and frequency of the input to the tracking loop (This input is now sinusoidal as a result of eqn.(4)). For a nominal allowable lag of 0.5 microseconds (us) in range to one station, the allowable amplitude of the system function for the tracking loop error is bounded as shown in figure 3.

In order to meet the tracking requirements (0.5 us lag at 500 kt) the loop bandwidth is bounded. For example for a second order loop, \( \frac{1}{\tau} \approx \frac{8}{\omega} \) for a 500 kt aircraft, \( \omega \approx 2 \times 10^6 \) rad/sec. 1.2 km is determined by the airspeed, so 3.5%//(500)=3% is the required bandwidth and settling time requirements on the receiver are determined principally by the maximum permissible acceleration (bank angle) rather than by airspeed, to a good approximation. The result, then, is that \( \omega \approx 18 \) sec. in order to provide proper dynamic tracking, and this corresponds to a 1-sec. lag.

For an averaging time of two seconds, we have (see a required SMR of nominally 0 dB or better (at the phase tracking sample) in order to provide 90°, one-sigma on one range. For a receiver with a front-end RF bandwidth of nominally 20 kHz, sampling at nominally 25 us (in order to avoid skywave contamination), the required SMR at the receiving antenna for the same performance becomes 8 dB (because the 25 us sample is down 8 dB from the received signal at 25 us - due to the narrow-band receiver front end(3)). This is an unreasonable requirement on groundwave signals in order to assure adequate receiver performance. Skywave signals, tracked at their peak, can provide good SMR, however, so let us examine the design and performance of a receiver which combines skywave and groundwave tracking.

The Beutler Locate system has demonstrated the capability of operation with a narrow-band filtered composite (groundwave and skywave signals mixed) processor; such a receiver has good precision and short response time and does not have the accuracy of a groundwave receiver. Consider, then, the question of how to combine the accuracy of a groundwave receiver with the fast response time and good precision of a narrow-band composite signal receiver.

The received point-in-time on the groundwave signal will be denoted by \( x_1 \); the received point-in-time on the composite signal will be denoted by \( x_2 \). Initially, consider that linear estimators of times of arrival will be used; if the noise were normal, then linear estimators would also be optimal in the minimum mean-square-error sense. By writing

\[
x_1 = (x_1 - x_2) + x_2
\]

one may choose to estimate \( x_1 - x_2 \) and \( x_2 \), separately, and then combine the estimates; \( x_2 \) will then represent principally receiver platform motion and the estimator can have high SMR and fast response time, while \( x_1 - x_2 \) will represent principally receiver internal changes and propagation changes and will thus be a very slowly varying signal which may be averaged for a long time in order to get the requisite accuracy.

3. Signal effects:

1. The skywave time of arrival varies with receiver altitude. As the receiver approaches the D-layer (ascending in altitude), the path length of the skywave signal becomes shorter, and the time of arrival consequently becomes earlier. At great distances from a transmitting station, where skywave reception provides great signal enhancement over groundwave reception, this effect is typically 5-10 us (4) for 30 km of altitude. For an aircraft with a rate of climb of 1.2 km/min, the effect of altitude-dependent changes of skywave time of arrival is minimal.
Furthermore, these effects tend to cancel in navigation by time differences (to the extent that all stations in use are at great distances from the receiver).

2. The groundwave time of arrival also varies with receiver altitude. This quantitative effect can be computed as a function of effective ground conductivity, range to the transmitting station, and height. This effect, too, is small and tends to cancel in using the different frequency-domain navigation data.

3. Local propagation effects are apparent in the groundwave signal, but become "smeared out" in reception at altitude.

4. Effective ground conductivity provides additional secondary phase corrections for the groundwave and appears to provide similar (though slightly lesser) effects for the skywave. These effects are caused largely by changes in D-layer height, absorption and reflectivity. A typical maximum "velocity" of the skywave is 1-2 us/hr (in time of arrival).

5. Sunrise/sunset effects are apparent on skywaves; these effects are caused largely by changes in skywaves resulting in velocities and accelerations sometimes having "velocities" as great as 1 us in 12 minutes (or 1/12 ns/s).

6. In addition to all of the above there is, of course, ambient noise. Hence, signal phenomena which affect groundwaves and skywaves result in velocities and accelerations which are very small compared with those of the receiver platform. Furthermore, receiver platform movements (except for height variations) generally affect skywave and groundwave phase by the same amount and in the same direction (in terms of time of arrival). It thus appears reasonable to consider differencing the times of arrival of skywave and composite wave in order to perform highly accurate determinations of time of arrival and of signal properties, while we may use the much higher SNR at the peak of the composite pulse for velocity determination.

4. Dual-loop description:

If we are justified in assuming normal noise, then a linear estimator is optimal and the use of eqn. (5) guarantees that the resultant estimator is also optimal. In mathematical terms, using the circumflex to denote an estimator, we can interpret both sides as optimal estimators or as suboptimal estimators in eqn. (6). This paper addresses suboptimal estimators.

\[ \hat{x}_1 = \frac{x_1 - x_2}{x_2} \hat{x}_2 \]  

(6)

In order that this approach be viable, there must be a correspondence between motion of the skywave and motion of the composite phase. A modified peak detector provides such a correspondence.

The dual-loop form is as follows.

1. There is a loop whose sample is selected at the peak of the composite pulse (through a narrowband filter). This phase-locked loop provides the principal determination of vehicle motion in real time, and also drives the strobe time base for the second phase-locked loop.

2. There is a second loop whose time base is derived from the first loop, and which tracks the difference between the skywave time-of-arrival and the groundwave time-of-arrival.

The requirements on the loops are as follows.

1. The composite loop is fast, with a nominal "time constant" of one second and a transient response suited to the aircraft maneuvers.

2. The groundwave loop is slow, with a nominal time constant suited to track the propagation differences between skywave and groundwave (including the receiver changes between the skywave and groundwave RF filters), the groundwave loop is not tracking only small speeds (up to 1 kt) and its bandwidth may be selected to give the desired accuracy for the low SNR groundwave. It is this loop that determines the accuracy of the receiver, and this loop's time constants can be made very long (several minutes) if desired for a special application. Note that at 70 MHz, the groundwave (skywave) and at SS0, a 79-second time constant and a first order groundwave loop yield a standard deviation of 1 us for time-of-arrival, for example, and longer averaging times could be used without seriously compromising the ability of the receiver to track motion which is quite rapid.

5. Performance gain of dual-loop receiver

The composite sample is taken through a narrowband filter (2.5 kHz is satisfactory and 5 kHz is useful) and this provides a noise advantage (over a 20 kHz filter) of 9 dB (for the 2.5 kHz filter) with respect to wideband noise, and a significantly higher advantage with respect to interference (CNI) outside of 90-110 kHz, as multipole filters can be used. In their LCR-301 receiver, LITCOM showed that, with a multipole filter, it may not be necessary to use notch filters to combat CNI. Because the peak of the narrowband signal is slightly lower than that of the wideband signal, in the absence of skywaves the incident signal is degraded by approximately 3 dB, so the processing gain overall is 20 dB (6 dB for the peak versus sampling point on the received groundwave signal, 8 dB of suppression of the groundwave sample point by the receiver's 20 kHz groundwave RF front end, plus 9 dB of noise suppression by the narrowband filter, less 3 dB of Loran signal peak suppression) on a single sample (not all of which may be realized in practice), depending on the receiver's front end characteristics in its RF filter. In the presence of skywaves which are of greater amplitude than the groundwave, this nominal 20 dB enhancement is increased by the ratio of composite amplitude to groundwave amplitude, measured at the peaks of both signals.

The groundwave sample is processed through a very slow loop (perhaps a two-minute time constant) which substantially enhances the CNI capabilities of this loop. Compared with the 3-second loop in the TDL601 (which is there requisite for tracking vehicle motion) this provides nominally 16 dB of enhancement at two minutes, together with greatly enhanced envelope detection possibilities and greatly reduced unlock probability (cycle-jump) for the loop.

6. Mathematical analysis of dual-loop:

For the purpose of computing system functions, transients, etc. the dual-loop may be represented as shown in figure 4. The symbolic representation should be used with care, as all notations and variables refer to times, and this convention can lead to confusion. The equations of the dual-loop are as follows.

\[ E_2 = (X_2 + N_2) / (s^2 + sc + c_0) \]  

(7)

\[ \hat{X}_2 = (X_2 + N_2)(sC + C_0) / (s^2 + sc + c_0) \]  

(8)

\[ \hat{Q}_2 = Q_2(sC + C_0) / (s^2 + sc + c_0) \]  

(9)

\[ E_1 = (X_1 - X_2) / (s^5 + s^4c + c_0) + N_1 s^3 + N_2 (sC + C_0) / (s^2 + sc + c_0) \]  

(10)
\[ H_1(s) = \frac{s^2 + sC_1 + C_2}{s^2 + sC_1 + C_2} \]  
\[ H_2(s) = \frac{s^2}{s^2 + sC_1 + C_2} \]  
\[ E_f = (X_f - X_{ref}) H_f(s) + X_s H_r(s) + N_f H_f(s) + N_s (\frac{s}{s^2}) H_f(s) H_r(s) \]  

Note that \( H_f(s) \) represents the error of a narrow-band loop, while \( H_r(s) \) represents the error of a wide-band loop. If the wide-band loop has a bandwidth which is substantially greater than that of \( H_f \), then we may write \( H_f H_r \approx H_f \), thus simplifying equation (13). Note, too, that the reference time (estimate of time of arrival of the groundwave) is the strobe time in the \( H_1 \) loop, and time differences are to be measured to this strobe time.

The basic advantage of the dual-loop, in terms of this symbolism, is that \( H_2 \) has a standard deviation of only one-tenth that of \( H_1 \) (in \( \mu s \)) so the \( H_2 \) loop can have a wider bandwidth (in quefrency) and this \( H_2 \) estimate of motion can be removed prior to narrow-band processing in the \( H_1 \) loop.

As an example of the performance attained, consider the following:

1. Let the received signal (at the space coupling node) have a SNR of -20 dB. After the receiver's front end, the effective SNR is -28 dB, for a 20 kHz bandwidth front end. The \( H_2 \) system is chosen (for example simplicity) to be critically damped, with \( \omega_n = 1/150 \) seconds, with (worst case) rate 55%. 

2. Let the processing gain (due to narrowbanding the receiver front end for the composite sample, to peak sampling, etc.) be 20 dB, and let there be no skywave to enhance the processing in \( H_2 \) (for a worst case situation). Let the \( H_2 \) loop also be critically damped with \( \omega_n = 1/1.5 \) seconds.

3. Then the overall dual-loop will track the groundwave sampling point (time of arrival) with a standard deviation of 0.1 \( \mu s \) and will do so through maneuvers that are as described above. An aircraft at 210.5 kt in a 30° banked turn will experience a peak bias of 0.2 \( \mu s \) (all of which is along-track error) for example.

Note that signal censoring techniques continue to be applicable to the two loops; as a caution, for each sample which is dropped (hole-punching), both the \( X_1 \) and \( X_2 \) samples should be dropped in order to be mathematically nice and avoid offsets.

7. Choice of time for sampling the composite signal:

The composite signal should be sampled at or near the peak of its envelope, in order to maximize the SNR of this sample. A workable (though sub-optimal) algorithm for selecting a sample time is as follows.

a. For the case where the receiver input is a pure groundwave, compute the time delay from the groundwave \( H_1 \) loop sampling point to the peak of the envelope of the (narrower RF bandwidth) \( H_2 \) loop sampling point; let this delay be \( d \).

b. Detect the peak of the envelope of the \( H_2 \) RF signal.

c. Phase-track the zero-crossing (of the appropriate polarity) next following this peak.

d. When the peak detector wants to move the \( H_2 \) sample in one direction by 20 \( \mu s \), jump the strobe by 10 \( \mu s \) in that direction, but do not insert the 10 \( \mu s \) into the \( H_1 \) loop.

e. When the jumps of item d take the \( H_2 \) strobe earlier than \( d \) minus some convenient time (e.g., 30 \( \mu s \)), jump the \( H_2 \) sample ahead to the new higher envelope peak, and do not insert this jump into the \( H_1 \) loop.

Of course, many other methods are equally useful.
Figure 4 - Dual-loop symbolic representation
LORAN-C MINI-CHAIN ON THE ST. MARYS RIVER

Darry P. Kane
Lieutenant, USCG
Systems Development Branch
Electronics Engineering Division
U.S. Coast Guard Headquarters
Washington, D. C. 20590

Abstract
A mini Loran-C chain will be installed on the Saint Marys River to demonstrate the potential of using precision Loran-C in a river and harbor environment. This paper describes the chain configuration, ground station equipment and projected accuracies to be realized. The coverage planned is for the river area extending from Detour Passage, Michigan to Whitefish Bay. To meet the desired accuracies over this area, a four station chain will be installed. Stations will be unmanned with remote control being provided by dedicated telephone lines directly to the manned monitor located at Sault Ste Marie, Michigan. Extending the navigation season on the Saint Marys River is the ultimate objective of this program.

INTRODUCTION
The St Marys River is the only link between Lake Superior and the rest of the Great Lakes. It is one of the major arteries of the iron ore carriers that transit from the iron fields in the Duluth area to other depots located throughout the Lakes. Last winter, the Lakes were kept open through the entire ice season, and the shippers found themselves faced with a severe navigation problem. The buoys had been removed from the channel so that they would not be damaged by the moving ice, or perhaps worse, be moved from their station by the ice. Without the buoys, safe navigation becomes extremely difficult especially in periods of poor visibility. Radar does not provide sufficient accuracy because the shoreline in that area is not definitive. The entire problem can be stated as such: How do you safely navigate a 1000 foot long, 105 foot wide, ship through a buoyless channel in periods of low visibility? The problem becomes more acute when the channel is only 275 feet wide.

The Coast Guard has undertaken to demonstrate the feasibility of using a mini Loran-C chain to solve this problem. The coast guard will use a Cesium beam oscillator as a frequency reference, while each of the secondary stations can either use a cesium or be phase locked to the master through the timing receiver. The latter method, referred to as synchronized operation, was chosen for this chain. This should reduce both the magnitude of the necessary Local Phase Adjustments (LPA) and the frequency with which they are applied.

Each transmitting site will consist of a 300 foot square plot of land. The antenna, a Rohn model 456, will be located in the center and will be top loaded as shown in figure (2). The antenna is 150 feet high, triangular in shape, and 18 inches on a side. The ground plane will consist of 120 radials spaced every three degrees. The transmitting equipment will be located in a 10 foot by 14 foot concrete block building. Input power requirements for the equipment can be either 110 or 220 vac. The station uses approximately 4 KW of power in addition to the frequency reference.
to whatever heating and/or air conditioning is needed. For property security, an 8 foot chain link fence will be constructed around the perimeter of each site.

The monitor station will have 4 tracking loop receiver and strip charts to maintain control of the chain. Ultimately there will be a calculator and interface that will indicate to the watchstanders the amount of LPA's to apply. The monitor is the only station that will be manned.

Besides watching the signals of the other stations, the monitor can remotely interrogate each of the stations for the status of various elements of the station and give commands to correct some of the problems. The status inquiries that can be generated by the monitor station are as follows:

1) General Status - This bit is an ANDing of all other status bits. If it is positive, all of the other status bits are also positive.
2) Power supply status - on or off;
3) Timing receiver status - locked on or not;
FIGURE 3 TRANSMITTING ANTENNA

4) Timing reference - cesium or timing receiver; 5) Cesium status - operating or not; 6) Transmitter trigger status - present or not; 7) Primary building power status - power available or not. If a station failure should occur, the watchstander can determine to some extent what the problem is before the maintenance technician goes to repair it.

The commands that can be given to the transmitting stations from the monitor include: 1) The insertion of LPA's in the amounts of 10 nanoseconds, 100 nanoseconds, 1 microsecond, 10 microseconds, 100 microseconds and 1 millisecond; 2) The starting or stopping of transmitter triggers; 3) The switching of timing reference from the cesium to the timing receiver and back again; 4) The switching of phase codes; 5) The turning on or off of the transmitter power supplies.

All of the above inquiries, answers and commands are transmitted through a "data link", permitting close control of the transmitting stations without having those stations manned.

SIGNAL CHARACTERISTICS

The stations will transmit a t^2exp-2t/65 pulse shape with the portion of the pulse between 15 and 50 microseconds being within .5% of the ideal shape. A Group Repetition Interval (GRI) of 49300 will be used. Normal phase codes will be implemented. The signal-to-noise ratio at the peak of the pulse will range between +3db and +12db. The user equipment should be able to successfully track at the peak of the pulse because there should be no skywave interference problems with the short baselines used. The Coast Guard is currently evaluating a prototype calculator based control algorithm for use on the East Coast chain and has experienced great success with tighter control of the time differences. This system will be put into operation in the mini-chain and it is expected that chain control will be within 20 nanoseconds at all times, with the mean error and standard deviation of the error being less than that figure.

The contracts for this effort have already been awarded and chain completion is scheduled for mid November. The chain calibration and demonstration will follow. If this chain successfully demonstrates that Loran-C can be used with this precision and accuracy, future applications can be explored, particularly with respect to Harbor and Harbor Entrance (HHE) navigation.
ABSTRACT

The United States Coast Guard Office of Research and Development is contracting for two navigation systems to investigate the capability of state-of-the-art Loran-C in providing precision vessel guidance on the St. Marys River. The systems, which will be demonstrated during the 1975-76 winter navigation season extension, have an accuracy goal of 25 to 50 feet to guide the typical user, a Great Lakes ore carrier of 1000-foot length and 105-foot beam, through channels as narrow as 275 feet.

COGLAD (Coast Guard Loran Assist Device) was developed several years ago to navigate a vessel to a destination (along a Rhumb line) by providing steering information to the helmsman; it also plots a record of the vessel's position on a standard navigational chart. This calculator-based system, which utilizes two Loran-C lines of position (LOPs), is being upgraded to navigate the St. Marys River using serial tracklines between pre-stored waypoints.

A minicomputer-based system relying heavily on off-the-shelf hardware and software is being procured to add capabilities beyond the COGLAD modification. The system will receive three LOPs and will utilize filter algorithms to estimate and calibrate errors associated with system dynamics. An optional graphics capability may provide a real-time display of the vessel's position superimposed on a pre-stored background showing channel edges and prominent geographic objects. The flexibility of the minicomputer will facilitate using the system as a research and development tool in future precision navigation investigations.

INTRODUCTION

Navigation through confined waters of the Great Lakes and St. Lawrence Seaway is normally accomplished with the aid of buoys, shore aids, and the ship's radar. Conditions of low visibility and winter ice render these conventional aids to navigation ineffective or unusable, particularly for large ships. In the winter conventional buoys are removed because ice movement can cause buoy movement, creating a hazard to navigation. Shore aids become obscured by snow, and ice ridges along shorelines cause radar systems to project distorted images. These unsafe navigation conditions combined with ice blockage normally require the suspension of activity on the Great Lakes and St. Lawrence Seaway from mid-December until early April. As a result, commerce and commerce must stockpile materials to last through the winter.

Commercial shipping interests have for many years sought an extension of the navigation season to allow maximum use of the Great Lakes waterway system. The Great Lakes Season Extension Program has worked towards this goal for the past several winters. Icebreaking efforts have kept waterways open but the basic problem of navigation in restricted waters has not been solved. The Coast Guard, as an adjunct to the Season Extension Program, is installing a Loran-C "mini-chain" and procuring user equipment to evaluate the feasibility of using a short-baseline Loran-C system to satisfy the precision navigation requirements of the St. Marys River from Whitefish Bay in Lake Superior to Detour Passage in Lake Huron (Figure 1).

The U. S. Coast Guard Office of Research and Development is procuring two Loran-C user equipment systems to provide vessel guidance through the St. Marys River. The typical user of the systems will be a Great Lakes ore carrier with a maximum 1000-foot length and 105-foot beam. The channels in the river vary from over 2000 feet to a narrow 275 feet. The major goal for the user equipment is to provide a vessel's pilot with an indication of distance from the centerline of the channel, accurate to within 25 to 50 feet. A demonstration of the mini-chain/user equipment system is planned for the winter season of 1975-76.

USER EQUIPMENT I

System Description

COGLAD, the Coast Guard Loran Assist Device, was developed several years ago by the Applied Physics Laboratory (APL) of Johns Hopkins University to enhance the shipboard use of Loran-C. The system uses an AN/SPN-45 Loran-C Receiver and a Hewlett-Packard 9100B Programmable Calculator. An interface unit matches the receiver output to the calculator, provides high-speed digital data processing and smoothing, and displays position and velocity information to the ship's navigator. A remote display (to provide navigation information to the commanding officer), a remote data unit (to enter reference and destination information), a printer, and a plotter round out the system's components. Figure 2 shows these units plus a receiver simulator used for testing.

COGLAD provides straight-line navigation information to a specified destination and plots a record of the ship's position on a standard navigation chart. COGLAD has been installed on several Coast Guard cutters since 1971, where its primary use has been maintaining a plot of vessel's tracklines and guiding vessels to buoy positions.

The original COGLAD system described above provided straight-line guidance to a single destination. APL is presently upgrading COGLAD to provide the capability for multiple destinations. The St. Marys River will be divided into a series of desired straight tracklines with "waypoints" at the intersections. Each waypoint will be entered into COGLAD as a
Figure 1. St. Marys River
desired destination. COGLAD will then provide guidance along the entire river by giving navigation information to each waypoint in sequence.

Approximately 25 waypoints will be required to define either the upbound or downbound course through the St. Marys River. Each waypoint will be defined in software in terms of its three Loran-C hyperbolic time differences (TDs) from the four stations of the mini-chain. The SPN-45 receiver will track the signals from the master station and two secondary stations to give only two TDs. Software will compare the waypoint information with the receiver's output to determine which two of the three possible secondary stations are being used at the moment. To obtain the best crossing angles from the Loran-C lines of position (LOPs), and hence the best possible fix accuracy, the system should utilize the TDs from the two closer secondaries. Therefore, midway through river transit the receiver must be locked onto a different secondary station, an undesirable feature. Future efforts with COGLAD may incorporate two receivers or a single three-LOP receiver.

The "25 waypoints" predicted for each transit through the river accounts only for the intersections of straight-line channel segments. Intermediate waypoints may be required to minimize algorithm inaccuracies due to distortion of the Loran-C grid and hyperbolic curvature of the LOPs near the transmitters. All the waypoints will be pre-stored before river transit. An extended memory option is being added to the HP-9100B calculator to store waypoint information and additional operational software required by the modified system. Figure 3 is a block diagram of the new COGLAD system.
Figure 4 shows a new display being constructed by APL for COGLAD. Neon bar graph displays give an analog indication of distance from the desired trackline, cross-track velocity, along-track speed, and distance to the next waypoint. A switch-selectable digital display will indicate the number of the next waypoint and the desired bearing, time, and distance to that waypoint. Much of this helm-display information will be repeated on the interface unit for the ship’s navigator. The X-Y plotter, previously used to record a ship’s trackline on a standard navigation chart, will be reconfigured to plot distance from the trackline, for each channel segment, on an expanded cross-track scale. Different charts will be prepared in advance, as in Figure 5, for each of the desired cross-track scale. Different charts will be prepared in advance, as in Figure 5, for each of the desired routes through the St. Marys River. The plots will be especially useful for post-mission analysis of the system’s operation.

System Demonstration

Accuracy requirements dictate that the mini-chain be used in the “repeatable mode” for this project. The Loran-C TDs used to define the waypoints will be measured rather than predicted. The COGLAD system will initially be installed aboard a Coast Guard vessel at Sault Saint Marie, Michigan. Using COGLAD in its “statistical” mode, the TDs will be measured
At each waypoint and stored in the calculator's memory. Following this initial calibration and verification, the system will be demonstrated along the length of the river. Accuracy will be determined by comparison with an independent horizontal positioning system. The Cubic Corporation's Autotape System is being considered for this use. Following successful demonstration aboard one or more Coast Guard vessels, COGLAD may be demonstrated aboard Great Lakes ore carriers.

USER EQUIPMENT II

A second set of user equipment is being procured to include features beyond the capability of the COGLAD system. The commercial system desired here will be a modification to an existing Loran-C-based navigation system. This approach should be more cost-effective than a "from scratch" development. Also, the limited project time frame requires a heavy dependence on off-the-shelf hardware and software.

System Description

This Loran-C precision guidance system will be based on a general purpose minicomputer; a conceptual block diagram appears in Figure 6. While the immediate objective is to provide a system for the demonstration of Loran-C in the St. Marys River, the system will also have the flexibility and functional capability to be used as a research and development tool in future development of precise navigation techniques.

Dual 2-LOP receivers, or a single 3-LOP receiver, will enable the system to determine vessel position using all the information available from the mini-chain. Digital filtering algorithms will be used to process the receiver information and to estimate and calibrate errors associated with system dynamics. An indication of the "quality" of the position fix will be derived from factors such as chain availability (all stations on air, not blinking), approximate crossing angles of the expected LOPs, noise conditions, and signal stability. The quality factor will be displayed to help the user judge the value of the system's information, and should instill user confidence in the system.

The system will function much like COGLAD. The user will be guided from waypoint to waypoint through the St. Marys River using the information from the Loran-C receiver and display equipment. An extra input to the system will be heading information from the ship's gyro compass. Since the true bearing of each channel segment is known, the heading information will allow calculation of the vessel's "crab angle" (attitude in the channel). A display of crab angle would be especially helpful to pilots of the larger bow-bridged vessels to indicate "what the stern is doing."

Table I lists the information to be displayed by the system. "Lead distance" is the separation between the waypoint and the turning point, as described in Figure 7. A turning point is defined as the point along the trackline where the vessel's rudder is first put over to initiate the turn. The lead, which will rarely be zero (indicating a turn at the waypoint), will vary from vessel to vessel and from turn to turn. Lead will not be calculated by the system, but will be input by the user. The distance and time remaining on a channel segment is calculated relative to the turning point rather than the waypoint.

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>UNITS</th>
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<tbody>
<tr>
<td>QUALITY FACTOR</td>
<td>PERCENT</td>
</tr>
<tr>
<td>CROSS-TRACK DISTANCE</td>
<td>FEET, LEFT OR RIGHT OF TRACKLINE</td>
</tr>
<tr>
<td>ATTITUDE</td>
<td>DEGREES LEFT OR RIGHT OF TRACK</td>
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<tr>
<td>ALONG-TRACK SPEED</td>
<td>DEGREES TRUE</td>
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<tr>
<td>CROSS-TRACK SPEED</td>
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<tr>
<td>LEAD DISTANCE</td>
<td>PERCENT</td>
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<tr>
<td>DISTANCE TO NEXT TURN</td>
<td>FEET PER SECOND, LEFT OR RIGHT</td>
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<tr>
<td>TIME TO NEXT TURN</td>
<td>FEET</td>
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<tr>
<td>PRESENT COURSE</td>
<td>STATUTE MILES</td>
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<tr>
<td>NEXT COURSE</td>
<td>HOURS: MINUTES: SECONDS</td>
</tr>
<tr>
<td>LOOK-AHEAD DATA</td>
<td>DEGREES TRUE</td>
</tr>
</tbody>
</table>

Table I. User Equipment II Information Display

Figure 6. User Equipment II Conceptual Block Diagram

Figure 7. Turning Point vs. Lead Distance
The system includes a predictive capability to provide a "look-ahead" on the information display, based on present position and calculated velocity. The interval of look-ahead is selected by the user.

To improve the user's understanding of the alphanumeric position information in Table I, a graphical analog display will show the vessel's attitude and cross-track distance. Perhaps a line representing the desired track and a simple shape representing the vessel would be used as illustrated in Figure 8. This display could contain electro-mechanical devices, or could be presented together with the Table I information on a CRT.

A paper or magnetic tape device will provide a periodic recording, for post-mission analysis, of the parameters in Table II. Data will be recorded upon operator command or automatically at an operator-selected interval.

**DATE/TIME**

**LORAN-C HYPERBOLIC TIME DIFFERENCES**

**LATITUDE/LONGITUDE**

**DISTANCE TO TURN**

**CROSS-TRACK DISTANCE**

**QUALITY FACTOR**

Table II. User Equipment II Data Recording

Extended Graphics

User Equipment II may include an extended graphics capability to provide a real-time analog CRT display of the vessel's position superimposed on a pre-stored background. Background features include the channel edges (showing variations in channel width), navigational aids (buoys, lights), prominent geographic objects (rocks, trees, structures), and the desired trackline with turning points. Look-ahead information is displayed as a scaled leader extending from the reference point on the vessel. Variable scale factors will allow the simultaneous display of up to ten miles of channel.

**System Demonstration**

Verification and demonstration of User Equipment II will closely follow that of User Equipment I (COGLAD). After checkout aboard Coast Guard vessels, the system will undergo a demonstration and data collection phase aboard one or more lake carriers.

**CONCLUSIONS**

The user equipment/mini-chain demonstration phase is scheduled to terminate on 1 June, 1976. The Coast Guard Research and Development Center will prepare a comprehensive final report for the project including a summary of pertinent information gathered during the demonstration phase, recommendations for system improvements, and suggested expanded applications for similar Loran-C-based systems.

**ACKNOWLEDGEMENTS**

Visual aids for the COGLAD equipment were supplied by Mr. R. B. Hester and Mr. C. R. Edwards of the Applied Physics Laboratory. The St. Marys River chart of Figure 1 was provided by Mr. D. Westheiser of the Detroit District, Army Corps of Engineers.

**REFERENCES**


LORAN CALIBRATION BY PREDICTION

L. B. Burke, R. H. Doherty, and J. R. Johler

Institute for Telecommunication Sciences*
Office of telecommunications
U.S. Department of Commerce
Boulder, Colorado

ABSTRACT

Loran propagation is uniquely predictable by using the integral form of Maxwell's Equations. The demonstrated high precision repeatable accuracy of loran time differences has provided a mechanism with sufficient resolution to detect the extremely small phase variations caused by propagation. By inputing specific terrain and electrical ground impedance into the theoretical computer analysis, these small variations as denoted by grid warp can be predicted. This provides a technique with greater accuracy than the more commonly accepted measurement process. Thus, a completely unrestricted three dimensional precision calibration becomes economically feasible.

1. Introduction

Low frequency radio signals propagate over the earth's surface at nearly the velocity of light in a vacuum. However, Maxwell's equations dictate that the ground wave (surface wave) will be influenced slightly by the surface parameters of geometry and electrical properties. In the Loran-C/D radio navigation system, high accuracy positioning is obtained by using pulse transmissions and selecting only the ground wave mode of propagation.

Since earth surface parameters remain nearly constant, Loran-C/D has demonstrated a highly repeatable accuracy. Now through the use of computer technology, and the rigorous mathematical solution of the propagation theory, it is possible to obtain the repeatable accuracy of loran by computerized prediction. This becomes very profound when one considers that a calibration must encompass all of the three dimensional space enclosed by the loran service area, including altitude. In areas where measurements are not possible due to political boundaries or inability to independently determine position, prediction provides the only calibration possible.

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*The views expressed in this paper are those of the authors and do not necessarily reflect those of the Department of Commerce or the Office of Telecommunications.
2. The Grid Warp Problem

Loran-C has established its usefulness as a maritime radio navigation system. Position determination within one-quarter mile accuracy on the open sea is generally considered to be acceptable. However, over land or in the vicinity of land masses, the signal propagation velocity deviates from the uniform speed of radio propagation that occurs over homogeneous, spherical, finitely conducting ground. In an uncorrected navigation system, errors in excess of one nautical mile often occur in regions of rugged terrain or extreme ground imperfections, even for relatively short propagation paths of 100 nautical miles. This phenomenon of loran grid distortion is of immediate concern and must be accounted for in a precision tactical system.

Figure 1 presents an artist's concept of the static loran grid depicting hyperbolic grid warpage over irregular terrain or inhomogeneous ground. The variations in the grid lines are grossly exaggerated as can be seen from figure 2.

A true grid line would be represented by a total phase as shown in figure 2, but the grid warp is associated with the secondary phase correction. In this comparison of the total phase delay to the secondary phase correction over the very irregular terrain of Death Valley, California, the scales are 100 to 1 different, so the secondary correction is only about 1/3 of 1% of the total phase delay. In the total phase curve, the secondary phase correction is added to the primary delay (the delay caused by the speed of light propagation), but it cannot even be detected in this graph due to the overwhelming effect of the primary delay. Although the secondary correction is such a small portion of the total delay time, it can produce positioning errors of several thousand feet if it is not properly included in the prediction or positioning calculations.

In addition to the surface values of the secondary phase corrections as shown in figure 2, there is a three dimensional aspect of this problem. Figure 3 shows the changes in the secondary phase corrections at ground level and at two different altitudes for a simplified terrain feature. The observed loran signals change because radio waves propagate in three dimensions. Since the solution to Maxwell's equations as incorporated into our propagation model is of a generalized three dimensional form, the change in secondary phase correction with altitude is completely predicted.

It has been quite well established by measurement that loran exhibits excellent repeatability, even under extremely rugged and anomalous conditions. The often published figure of 50 feet of repositioning accuracy has naturally extended loran usefulness considerably. Thus, once an area is extensively calibrated, the positioning accuracy will depend only upon repeatability. The 50-foot figure, although optimistic, is achievable and realistic in many areas, reference [1]. Actually, repeatable accuracy is dependent upon chain geometry (geometric dilution), receiving equipment and system stability. But in general, repeatable accuracy will remain better than 300 feet anywhere, within the defined service area. Consequently, to make full use of the repeatable accuracy, a complete calibration is required.

3. Solution to the Grid Warp Problem

The obvious question now becomes: How should calibration be accomplished? Of course the most straightforward approach is direct measurement throughout the entire service area. But, obtaining a calibration via measurement presents a number of objections. Cost, time, and political restrictions are the most significant. Even a partial measurement calibration entails enormous expense and is anything but timely. Also measurement in enemy territory may be extremely hazardous or completely impossible. First the service area must be systematically crisscrossed in sufficiently small increments to obtain the required degree of accuracy. The crisscross pattern must
also be performed at several altitudes for application in airborne systems. At each location enough measurements must be obtained so that statistical analysis can be utilized to remove the system effects, the receiver effects and the variable propagation effects.

On the ground, extreme care must also be taken to avoid power transmission lines or other man-made structures, as these can disrupt or obliterate a measurement. The surveyed position of each measurement location becomes crucial and must be absolutely verified. Clearly, a complete calibration via measurement is impractical. In the past, only the most critical areas could even be considered for such a calibration. And, when the task was undertaken, meaningful results required years to obtain. For, it was painfully learned that measurements had to be complete and detailed, because empirical interpolation or extrapolation produced totally unacceptable results. Figure 4 indicates that an alternative calibration method exists.

The science of radio wave propagation has been under development for the past seventy years. In 1908, reference [2], the first predictions transpired as an attempt to explain the "remarkable results of the Marconi wireless experiments." Since then, the contributions of numerous renown scientists desperately advanced the theory. In 1952, a rigorous mathematical solution was finally obtained for irregular, and non-homogeneous propagation paths. Because the mathematics is rigorous, proof of the solution lies in the validity of Maxwell's equations, the very foundation of electromagnetic theory. Even after attainment of a proven solution, prediction remained untractable until advanced computer technology produced a breakthrough in late 1974. Some notable milestones in this historical development are listed in Figure 5 (for examples, see references [3], [4], [5], and [6].

Figure 4. Calibration by measurement or prediction.

The alternative to calibration via measurement is calibration via prediction, where prediction entails the mathematical simulation of ground wave propagation. The science of radio wave propagation has been under development for the past seventy years. In 1908, reference [2], the first predictions transpired as an attempt to explain the "remarkable results of the Marconi wireless experiments." Since then, the contributions of numerous renown scientists desperately advanced the theory. In 1952, a rigorous mathematical solution was finally obtained for irregular, and non-homogeneous propagation paths. Because the mathematics is rigorous, proof of the solution lies in the validity of Maxwell's equations, the very foundation of electromagnetic theory. Even after attainment of a proven solution, prediction remained untractable until advanced computer technology produced a breakthrough in late 1974. Some notable milestones in this historical development are listed in Figure 5 (for examples, see references [3], [4], [5], and [6].

Figure 5. Three quarters of a century of theoretical studies culminate in the propagation prediction program.

Prediction is now attainable for loran in the form of a total, automatic package. Acquisition of such a package involves the integration of a number of existing computer programs and development of a master control program. Provided the input data are sufficiently available and accurate, use of this package allows unrestricted prediction or calibration capability in any predefined area of interest. If desired, a complete service area calibration could even be performed before the loran transmitters are turned on. Verification of the prediction method is primarily embodied in the mathematical proof. The electromagnetic theory, as derived from Maxwell's equations, is a rare instance where complicated physical phenomenon can be defined by a totally unique solution. The only limitation to utilizing this unique solution for many years has been the inability to manipulate the large amount of input data required, and the limited ability to economically perform the tremendous numbers of calculations necessary. Modern day computers have overcome both of these problems.

Measurement verification of the prediction technique has been accumulating since 1969. Beginning then, actual terrain and impedance manually digitized and input to the Propagation Simulation Program. Later, the Fort Hood, Texas Loran C/D chain was examined with a combination of theoretical prediction methods (references [4] and [7]) before chain turn-on. Subsequent measurements verified the value of pre-operational prediction. The final clincher for propagation theory involved the prediction of an altitude effect several years before the receiving equipment was capable of measuring the variation. Rigorous propagation simulation has consistently demonstrated the ability to predict beyond the present equipment measurement resolution. Specifically, no measurement has

PROPAGATION SIMULATION HISTORY

1900-1917 Diffraction Theory developed as a result of Marconi Radio Propagation Experiment
1918 Watson Transformation produced classical theory for smooth homogeneous sphere
1952 Theoretical proposal for an irregular and inhomogeneous sphere which could be reduced to classical theory
1956 Computers first applied for solution of classical theory
1967 Propagation Simulator Program written which could handle mathematical irregularities
1969-1973 Actual terrain and impedance manually digitized and input to the Propagation Simulation Program
1974 Automatic retrieval of predefined terrain and impedance which permits immediate and unlimited prediction capability
been found that disagrees with the prediction technique.

Additionally, the prediction technique readily identifies measurement errors and can be used to force the observer to recheck his position and measurement. This was clearly demonstrated in the Ft. Hood Loran C/D chain calibration. Several measurement errors were identified as a result of a forced recheck because of an apparent discrepancy between measurement and prediction. In every recheck case, the prediction proved to be correct, and a fault was uncovered somewhere in the direct measurement procedure. Generally, a location or survey error accounted for the problem. Measurement positioning errors of as little as 80 feet were uncovered.

4. Prediction Methodology

The prediction program inputs from two digital magnetic tapes, one defining terrain and the other defining surface lithology. Figure 6 shows the process involved in preparing a specified loran service area for input to the prediction program. In many cases the terrain data is already available in digital form, but it is necessary to compact the information to a density commensurate with resolution requirements. If the terrain digitization must be performed from scratch, the optimum resolution and data manipulation will be selected. The final compaction involves optimization of the tape format to give maximum retrieval speed. Lithologic and physiographic features (geological substructures, overburdens, etc.) are generally well documented in map form. These maps must be digitized and again compacted into a format readily acceptable to the prediction program.

PREDICTION PROGRAM FLOWCHART

The anticipated accuracy of the prediction program is 35 nanoseconds rms along each loran propagation path for distances up to 1000 kilometers. In the time difference mode of operation, the propagation change due to the Master station path is subtracted from the propagation change due to the secondary station path. Therefore, the resulting time difference error is the algebraic difference of the propagation changes along the Master and Slave paths. It is expected that time differences (TDs) can be predicted to a one standard deviation of error of 50 nanoseconds of the observed TDs. Thus, prediction would provide an accuracy that is beyond the present resolution or duplication capability of receiving equipment, i.e., the ability of equipment manufactured by different vendors to reproduce the same measurement.

5. Program Direction

The current activities associated with the U.S. Air Force sponsored program include the following: (1) Developing terrain compaction methods and retrieval programs, (2) Defining lithology digitization requirements, (3) Developing lithology compaction and retrieval programs, (4) Assigning electrical impedances to each lithology structure and surface parameter necessary, and (5) integrate terrain, lithology and propagation programs into a single package.

Since the theory is rigorous, the ultimate accuracy attainable using prediction techniques is completely dependent upon the accuracy and detail of the input. Because that input is directly related to physical reality, any initial disagreement with measured data can be corrected by reexamination of the ground structure along the discrepant propagation path. The prediction package will be specifically structured...
for quick and easy modification of either terrain corrections or impedance conversions. Thus, any corrections, improvements or service area enlargements will produce no impact on the overall prediction package operation.

Since the ultimate value of loran is directly related to the positioning accuracy, the prediction ability becomes a significant factor in lorans future. The first order of recommendation is to thoroughly verify the prediction results for Central Europe on a statistical basis. Any discrepancies can be removed by proper adjustment of the physical inputs as described earlier. Conversion of lithology to electrical impedance is a rather new science. Using loran measurement to verify the prediction program inputs not only adds confidence, but also advances the scientific knowledge of the earth's physiography.

Techniques for implementation of the prediction results in receiving equipments should be studied and optimized. Any implementation will require thorough error analysis and statistical verification.

The areas of prediction should be extended to include other portions of the world where loran coverage is available. We feel the continental U.S. is an excellent candidate. The eastern portion of the U.S. can be a test area in view of the extensive measurement programs previously conducted. Furthermore, many of the proposed loran uses can appreciably benefit from an improved calibration by prediction capability. We appreciate that loran without this additional sophistication is better than almost any other long range navigation system operational today. Therefore, loran with the added sophistication should overcome even the most stubborn opposition and bring on many new applications and users.

Finally, it would be advantageous to have a potential precision loran capability anywhere in the world. Then, if need were to arise at any location, a small loran chain could be installed. After preparation of the digital tape inputs, the prediction program is ready to use. Any area of the world would be available for calibration by merely selecting transmitter site locations and initiating the program. In this manner a newly selected loran chain could be fully calibrated when usable signals become available.

6. Acknowledgements

The techniques described in this paper are presently being applied to a specific area in Central Europe under the sponsorship of the U.S. Air Force Tactical Loran SPO, L.G. Hanscom Field, Bedford, Massachusetts.

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The AN/ARN-101 Loran Receiver

Arthur F. Gaunt and Donald L. Gray

Lear Siegler, Incorporated

Grand Rapids, Michigan

ABSTRACT

The AN/ARN-101 Loran receiver is a linear receiver which operates in a tactical environment under very severe signal conditions. It operates in one of four possible modes ranging from Integrated Loran/Inertial to Loran Only depending upon sensor availability. The receiver has been extensively tested at Eglin AFB first by LSI and then by the HSAF aboard an F-4D aircraft and exhibited excellent performance throughout the test phase of the program.

The system utilizes three orthogonal H-field antennas. The optimum antenna is selected for each station using heading and attitude information. The effects of CW interference on the Loran performance is minimized with automatic hardware notch filters operating in conjunction with a software interference detection technique. The Loran Receiver contains a digital preprocessor which serves as a signal sampler and data accumulator. This reduces the real time computational load of the computer. All commands for the Loran receiver originate via software processing functions contained in a central processor called the Navigational Computer. The central processor is a 16 bit, multi-register machine with a completely programmable memory.

The software functions implemented in the digital processor include: Search and Synchronization, Cycle Selection, Phase Tracing, Automatic Gain Control, Interference Suppression, Rate Aiding Interface, and Signal Alarms. A software implementation of these processes allows the receiver to be adaptive to varying signal and noise conditions.

Testing at Eglin AFB has shown that the receiver operates down to -15 dB signal-to-noise ratio (measured at peak of Loran pulse) and in the presence of up to four large CW, FSK or pulsed type interference frequencies. Six-g maneuvers were performed on an F-4D with no loss of lock.

INTRODUCTION

The AN/ARN-101(V) Digital Modular Avionics System is an integrated navigation and weapon delivery/reconnaissance system for the RF-4C and F-4E aircraft (Figure 1). The overall system features long-range and tactical navigation in three coordinate systems (Lat/Long, UTM and Loran TM's), all-weather blind bombing, uncanned weapon delivery profiles and reconnaissance steering data. A central computer processes both inertial platform and Loran data via a Kalman filter to provide precise position and velocity information. An interactive control-display is utilized for data input and output.

The description of the AN/ARN-101 Loran Receiver and its performance is discussed in this paper. The data pertaining to performance characteristics is a result of LSI testing and does not include HSAF tests.

This work was sponsored by the U. S. Air Force System Command, Electronic System Division under Contracts F10628-73-C-0188 and F10628-73-C-0292.
Antennas

An all-attitude antenna which was optimized for Loran reception has been fully achieved by utilizing a three-axis H-field system. In conjunction with Spears Associates, LSI has thoroughly analyzed and evaluated this configuration via laboratory tests, mock-up tests and flight tests.

The antenna system is designed to operate in fields of 20 µv/meter for the XY axis and 35 µv/meter for the Z axis. Linear operation over a range in excess of 100 dB and with less than 1 degree of differential phase between antennas has been verified.

Antenna Coupler

The Antenna Coupler (Figure 3) switches to the proper antenna based upon commands from the Navigation Computer. The selection takes place at the input to the coupler and all signal paths are thus similar. Three gain states of +33dB, +13dB, and -17dB are used in the coupler along with polarity switching which depends upon whether the front or back antenna lobe is used.

The search filter is a two pole Butterworth filter with a 6kHz bandwidth and the track filter is a two pole Gaussian filter having a 36kHz bandwidth. In the track mode, further filtering in the receiver reduces the overall track filter bandwidth to 25kHz.

In addition to the 3 antenna inputs a fourth input is provided for both envelope calibration and Built-in-Test (BIT). Under control of the NC, a simulated signal is sent to this input and the operation of the unit tested.

Signal Processor

The Signal Processor consists of four notch filters, gain control circuits and digital processing. Essentially, it has two operating modes. The first mode is utilized during both initial station search and when interference data are taken. A second mode is used during signal track and is not limited to a fixed number of stations. In both cases, the automatic notch filters and gain circuits of the RF section are initialized from the instruction set received via the DMA channel. The instructions to the Signal Processor consist of station phase codes, adaptive sampling control, the time between station intervals, the memory address for data storage, and the memory address for the next instruction set.

The unit then independently takes samples on the Loran pulse according to the timing functions stored in its own memory for the sample groups. The sample pattern for a single pulse (Figure 4) consists of 3 samples from which all track data are derived. A timing counter generates the sample pattern from constraints stored in memory. The Signal Processor will, in this track mode, thus take the pulse data at the specified times and integrate the data of the next pulse with it according to the proper phase code. After each station interval the summed data for each

Notch filters are implemented by an up/down mixing technique (Figure 5). The local oscillator signal used for mixing is derived by synchronously counting down the 8MHz clock and then multiplying this signal by 1000, in an analog phase lock loop. The digital counting is controlled by the NC software either by the automatic frequency estimation algorithm or set manually. The overall frequency control is from 70kHz to 130kHz in 50kHz increments. The local oscillator signal is then multiplied with the input signal and the resulting signal attenuated in a crystal notch filter. The remaining signals in the frequency spectrum are down converted in the second mixer using the same local oscillator signal. Output filters are used to remove unwanted mixing signals and to recover the desired Loran signals. A total attenuation to unwanted signals of up to 50 dB has been achieved.
Useable Loran signals have a dynamic range of at least 120 dB with up to 80 dB differentials between stations at some locations. In order to accommodate this range, wide band amplifiers in combination with digitally controlled attenuators are used. The Antenna Coupler gain ranges from -17 dB to +33 dB and the digital gain control (DGC) of the Loran Receiver controls gain from +2.5 dB to +91.25 dB. This results in a system gain range from -14.5 dB to +124.25 dB in increments of 1.25 dB. Over this entire range, the digital gain control board maintains its phase integrity within 0.50 degrees. The sampler and A/D converter sample the rf signals directly from the DGC and send it on to the preprocessor. The conversion time is approximately 8 µsec.

The preprocessor is the heart of the Signal Processor. In addition to governing all timing and sequencing it relays digital control settings from the NC to the notch filters, and the digital gain control, and sends accumulated sampled data back to the NC. It has been described elsewhere in the literature and will only be summarized here. (1) An important advantage of this system is that the small special purpose preprocessor is synchronous with the NC and has freed it from the routine Loran functions. The design of the preprocessor also provides for future system changes in the ETCM (Electronic-Counter-Counter-Measures) areas of pulse coding. For instance, if pulse position modulation was considered in the Loran system, the timing for these functions could be accomplished via memory change where the new timing data could easily be held in scratch memory and changed according to different synchronization codes. The design of this preprocessor has thus minimized hardware changes that would result from system concept changes.

The preprocessor has a small ROM memory on a single card which stores the program required to sequence through the sampling pattern requested by the NC. A RAM memory stores the program constants, derived in the NC, for each station interval and serves as an accumulator for the sampled data.

An instruction set is received from the NC each station interval, and defines the program constants for that period. A timer provides the real-time counting of the preprocessor and is controlled via station timing data from the NC. The timer is a 24-bit counter with a least significant bit of 0.125 µsec which provides the sampled data timed to a real-time resolution of 0.125 µsec with the remaining cycle resolution provided by software processing in the NC.

The time between samples is stored in the preprocessor memory and entered into the counter. A full count initiates the processing of sampled data. The next sample time is then entered into the counter. This is repeated until all data are taken. The time to the next station is entered and this time interval counted, while new instructions and the summed data are transferred. This counter is the only hardware timer and serves all stations in a serial manner with the total GPR time kept track of in the NC by software.

Navigation Computer

The Navigation Computer is a parallel general purpose computer using a binary two's complement, fractional number system in all its computations. Instruction words are 16 bits in length. Computations are performed as normal words (16 bits) or double-precision words (32 bits). The computer (Figure 6) is composed of a control unit, arithmetic unit, digital I/O, working register, memory unit and power supply.

![Navigation Computer Diagram](image)

The control unit coordinates all the functions of the computer. It uses instructions for the orderly transfer of information between all parts of the system. This unit generates all timing and gating signals necessary for making other sections interact and form a true general purpose digital computer. A micro-program is used to provide maximum versatility and speed. It also contains an instruction register and program counter.

The arithmetic unit processes the data under the command of the control unit. It performs the mathematical operations as well as the data manipulations such as transfers and shifting. It operates in conjunction with the banks of working registers and the memory and contains two 32-bit registers, a parallel adder/subtractor and the gating necessary to perform the basic arithmetic.

The basic computer has working registers grouped in banks of 8 words each. For software purposes, they are arranged as: 16 16-bit single precision registers or 8 32-bit double precision registers. The purpose of the registers is to provide a high speed temporary storage "on-line" to the program to reduce the need for storing intermediate results of calculations.

The digital I/O unit has both discrete and digital data input/outputs. Up to 64 input discretes and 64
output discrete are available. The digital data interface can handle up to 64 serial channels either in or out and a single parallel channel in or out. Both the serial and parallel channels use a 1 MHz clock.

The programmable real-time counter (RTC) is used to establish time intervals for solution of the various processor tasks. This 16-bit counter has a resolution of 32 µsec and a range of up to 2 seconds. An interrupt is generated when the counter equals zero.

Two modules are used to provide the main memory storage for the ARM-101 system. These modules are core memory and contain 32768 words of 16 bits. The memory can be expanded to twice this capacity by the addition of two additional but identical modules. The memory functions as a permanent store for the operational flight program and as a temporary store for changing information such as target locations and time variable mission related results. The permanent storage capability is assured by memory protection circuits.

SOFTWARE

The Loran Receiver software consists of functional modules which create clearly defined and minimal interfaces between basic receiver processes. The receiver software modules are shown in Figure 7. All communications is via the common read-write memory shared by all receiver processes. The software functions contain all the processing necessary to acquire and track Loran signals as well as suppress interfering signals through digital detection and the appropriate placement of automatic notch filters. The basic processes of control, antenna and gain control, search and synchronization, phase tracking, signal alarms, interference suppression and built-in test are described in the following sections.

Loran Processing Control

The Loran Processing Control function coordinates the processing of all receiver functions as well as controlling the sampling and gain of the linear signal processor. Communication with the signal processor is accomplished through a block of words in the Navigational Computer memory called a command block. The signal processor is slaved to these command blocks and proceeds to adjust its timing as directed by these commands. When it has completed its task it places sampled data in specified memory locations, reads a new command block from memory and generates an interrupt. Each command block contains the following basic information.

1. Memory location of next command block
2. Memory address for Data Storage
3. Type of sampling pattern (NDEF)
4. Time interval to next station
5. Notch filter setting (one of 5)
6. Digital gain control setting
7. Antenna coupler control word
8. Phase code pattern

Antenna and RF Gain Control

The antenna and RF gain control function selects the appropriate antenna axis and adjusts the RF gain to optimally receive the signals from each of the Loran stations being tracked. The antenna axis which gives the maximum signal-to-noise ratio is selected independently for each station based upon the azimuth angles to the transmitters and upon aircraft heading and attitude (both pitch and roll).

The RF gain is adjusted depending on the state of signal acquisition. During master synchronization, the gain is adjusted so that 68% of the noise samples are less than 1.0 of full scale of the A/D converter. This reduces the effect of atmospheric noise and allows an adequate detection margin for the range of signal-to-noise ratios of from -15 dB to +8 dB.

During master and slave groundwave searches, the gain is adjusted independently for each station such that the rms value of samples taken in the expected signal time window is equal to 1/8th full scale of the A/D converter. This allows the gain for a strong station to be reduced bringing it out of saturation while that for a weak station can be increased, thus enabling detection with large signal unbalances.

The gain when the receiver is tracking is adjusted so that the composite signal consisting of Loran signal, noise, and long-delay skywave (if present) does not saturate the A/D converter. The Loran signal amplitude and noise amplitude are estimated by filtering samples both on the Loran pulse and in front of it. The presence and amplitude of a long-delay skywave of up to 4 milliseconds is estimated by correlating arrays of samples from the Loran pulse groups with delayed phase codes.

...
The groundwave search process consists of correlating sample sums taken in time windows that are chosen based on the estimated present position of the receiver and are sufficient to cover long delay skywave conditions. One integration level of 96 GRP's is used which is adequate to extract signals of -15db for Loran C and -18 db for Loran D. The search for the master and slave groundwaves is performed simultaneously. During all search processing the receiver is rate aided with the best source available with the optimum antenna selection being chosen each GRP.

The Fine Search process detects the leading edge of the Loran pulse. It accomplishes this using a set of 16 quadrature samples spaced 12.5 usec apart taken on each pulse. These sixteen samples are summed by phase code and sampling code for each pulse (8 for Loran C and 16 for Loran D). These samples are coherently integrated and each sampled sum compared to a threshold which is based upon the ambient noise level. The sample sums are interrogated beginning at the front of the pulse and the first sample sum which passes a threshold is chosen as the beginning track point. Two consecutive sample sums are then resolved to locate a correct phase zero crossing.

Cycle Selection

The Cycle Selection process has the task of positioning the tracking strobos on the correct zero crossing of the groundwave. This is accomplished by a combination of envelope measurement and groundwave detection. Envelope measurement uses the shape of the leading edge of the pulse to determine the desired cycle and groundwave detection accumulates samples several cycles before the tracking point to determine if a groundwave signal exists in front of the present track point. Figure 4 indicates the sampling pattern taken for cycle selection and tracking. The samples G and Gc (see Figure 4) are 24 usec spaced quadrature samples used for groundwave detection. Samples F0, F1, F2, E0, E1, E2, are amplitude samples used for the envelope measurement. The C sample is the input to the phase tracking loops.

The envelope measurement is made by calculating a function of the slope of the leading edge of the Loran pulse and relating this to the position on the pulse where this slope was evaluated. A function of the slope called \( R(F_m, F_{m-1}) \) is defined as

\[
R(F_m, F_{m-1}) = 1 - \frac{E_m - E_{m-1}}{E_m} ; m = 1, 2, 3, \text{ and } 4
\]

To provide a desired confidence level measurement, \( R \) is only calculated when the sum of a number of \( E \) samples passes a threshold which is a function of signal-to-noise ratio.

The \( R \) values are calculated at two points 10 usec apart on the pulse for both a calibrate pulse and the received signal. The calibrate pulse is an internally generated Loran type pulse.

The \( R \) values for the received pulse at the track point and 10 usec earlier can be related to those of the calibrate pulse from known transmitter characteristics by the expression.

\[
R_{SO} = A_0 + A_1 R_{CO}
\]

and

\[
R_{SI} = B_0 + B_1 R_{C1}
\]

where

\( R_{CO}, R_{C1} \) = the measured calibrate \( R \) values

\( A_0, A_1, B_0, B_1 \) = stored station pulse shape parameters

\( R_{SO}, R_{SI} \) = predicted station \( R \) values

The location of the track point on the envelope can then be determined from the expression

\[
tp = C_1 + C_2 R_{SO}
\]

\[
tp-10 = C_1 + C_2 R_{SI}
\]

where

\( t_p \) = predicted location of the track point on the envelope

\( t_{p-10} \) = predicted location of the point 10 usec before the track point

Coefficients \( C_1, C_2 \) are determined by the expressions:

\[
C_1 = \frac{R_{SL}}{R_{SO}}
\]

where \( T_D \) is the desired track point on the envelope.

The estimated tracking position \( T_E \) is then compared to the desired track point \( T_D \) and corresponding cycle jumps made to adjust the tracking point to the correct cycle.

During acquisition, \( R \) values from all consecutive pairs of \( E \) samples are calculated to allow faster settle to the correct cycle. However, after the initial envelope acquisition phase, \( R \) values are measured only for sample pairs \( (E_0, E_1) \) and \( (E_1, E_2) \) thus giving essentially a two point curve fit of the leading edge of the Loran pulse. The difference between the measured pulse position \( T_E \) and the desired position \( T_D \) is filtered to yield an estimate of the envelope to cycle (ECD) discrepancy for each station. These ECD measurements are used for two purposes.

1) As a bias eliminator for current absolute envelope measurements on individual stations, \( E - ECD \) is tested to determine if a 10 usec adjustment is necessary. If \( |T_E - ECD| > 5 \) usec a jump is made.

2) As a differential envelope test between the master station and the slave stations. If the slave ECD differs by more than 5 usec from the master ECD the slave track point is adjusted to more closely agree with the master position.
Phase Tracking

The phase tracking is accomplished as shown in Figure 8. The sample processor delivers the phase sample as two sums of 4 samples for Loran C, and 4 sums of 4 samples for Loran N. These sample sums are immediately compared to a threshold and clipped if they exceed it to minimize the effects of non-gaussian atmospheric noise when it is present in the signal data. Following the clipping operation the C samples from all the Loran pulses in a group are combined for phase-lock loop (PLL) processing.

The phase samples C are normalized by dividing by A* to give
\[ \Phi_e = \frac{C}{A^*} \]
where \( \Phi_e \) is the phase error in radians which is input to the phase-lock loops.

The phase tracking is accomplished by cascaded PLL's where the first PLL is a wide band (coarse) PLL \( (C_{\text{TDA}} = 0.14 \mu\text{sec}) \) followed by a narrow band (Fine) PLL \( (C_{\text{TDA}} = 0.035 \mu\text{sec}) \).

Both PLL's are second order and of the form
\[ \tau = \frac{\text{GRP}}{W_c} (W_{1A} + W_{1D}) + K_1 \Phi_e \]
\[ W_{1A} = W_{1e} + K_2 \Phi_e - W_{1d} \]
where GRP = group repetition period
\( W_c \) = carrier frequency
\( K_1/K_2 \) = PLL gains
\( \Phi_e \) = phase error
\( W_{1e} \) = PLL doppler estimate
\( W_{1d} \) = velocity aiding (if available)
\( W_{1D} \) = bootstrap acceleration estimate (in Loran only mode)

The receiver uses the best rate aiding available at all times. In the Loran/Inertial Integrated and Loran INS modes, the aiding is derived from the INS system. In the true airspeed the heading mode, velocity aiding is derived from three sensors. During the Loran Only mode an estimate of turn acceleration is achieved by combining the estimated Loran velocities with the rate of change of aircraft heading. This yields an incremental velocity change estimate \( (W_{1D}) \) corresponding to the acceleration towards the station. Either the velocity aid \( (W_{1D}) \) or the acceleration estimate \( (W_{11}) \) will be zero depending on the system mode.

The gains of both PLL's are adaptive to changing signal-to-noise conditions through the use of a Kalman filter to give the desired steady-state variance in minimum settle time. In addition, continuous bandwidth expansion functions are incorporated which operate on accumulated phase error to give a larger bandwidth when needed.

The output of the coarse PLL is used to adjust the sample point of the receiver. The receiver sample point adjustments are multiples of 0.125 µsec and residues are retained and used to rotate samples to the desired track point so that the tracking resolution is actually on the order of 0.01 µsec. The fine PLL output is used to calculate the precision time differences to an accuracy of 0.05 µsec (lo).

System Alarms

Two types of signal alarms are computed and annunciated: lost signal and transmitter blink.

Lost signal is indicated when the signal-to-noise ratio at the track point continues to be below -25 dB. It is computed by accumulating samples and comparing the result to a threshold during receiver track. If a lost signal is indicated the receiver will turn on the settle light on the controller and return to Fine Search for the station which was lost. If a Fine Search fails to locate a signal a full search will be automatically instigated.

Slave blink is computed by monitoring the first 2 Loran C pulses, or first 4 from Loran D pulses, and comparing them to the other pulses. If a blink condition occurs, the no-Loran light on the controller is blinked on and off continuously until the transmitter blink stops.

Interference Suppression

Interference suppression removes CN, ON-OFF CN and FSK interference signals by estimating the frequency of the interfering signal and positioning a notch filter on the signal. The position of all notches and their status (manual or automatic) is continually available for display on the control display unit. If a pair of FSK interferences is detected a notch will be placed halfway between them to eliminate both signals with one notch filter.

The estimation technique is digital in nature with 127 samples taken at three different rates of 80 KHz, 68,376 KHz, and 64 KHz. Each rate is pro-
cessed individually in a 2nd order loop. The samples are processed in pairs by the expressions:

\[ \phi_{I+1} = \phi_I + \Delta \phi_I + K_I \Delta \phi_I \]
\[ \Delta \phi_{I+1} = \Delta \phi_I + L_I \Delta \phi_I \]

where \( \Delta \phi_I \) is the difference in phase between two consecutive samples and \( K_I, L_I \) are loop gains.

All consecutive pairs of samples are processed until all 127 samples are exhausted. A frequency estimate is then calculated as

\[ F_P = \frac{\Delta \phi_{126} f_s}{2\pi} \]

where

- \( F_P \) = frequency estimate
- \( f_s \) = sampling rate
- \( \Delta \phi_{126} \) = final output of 2nd order loop

This process is repeated for each of the three sampling rates. Agreement within 1500 Hz between two loop outputs is necessary for an interference to be suspected. These initial interference estimates are made using the 25 KHz track filter. After an interference is suspected, a very narrow passband filter (2 KHz) is placed at the suspected interference frequency. Samples are then taken and processed. If the presence of an interference is confirmed, a notch filter is placed on that interference. This allows the estimation of low level interferences. The RF gain is controlled for all sampling so that interferences do not saturate the A/D converter.

This process operates for several seconds prior to Loran search to remove any interferences present and continues to operate during track to verify that the interferences are still present or to detect and reject any new interferences.

Built-in Test

The receiver built-in test automatically tests the operation of the antenna coupler and signal processor when commanded from the controller. If a fault is present in either box, it is isolated and displayed on the controller. The receiver is exercised by use of an internal 100 KHz CW and the internally generated Loran type calibrate pulse. The test exercises all notch filters, the A/D converter, the digital gain control circuits and the antenna coupler filters.

PERFORMANCE

The performance of the receiver has been established through a large number of simulator tests as well as an LSI conducted flight test at Eglin AFB. Areas of special interest are:

1. Antenna System
2. Acquisition
3. Accuracy
4. Operation with Skywaves
5. Envelope/Cycle Discrepancy
6. Aircraft Dynamics
7. Interference Suppression

Antenna System

The LSI three-axis H-field antenna system has demonstrated excellent sensitivity. No break-locks have been attributable to the loss or distortion of antenna signals during flight tests. This system is immune to the signal loss or distortion previously encountered in flights involving tanker hook-ups and other electrical disturbances. This immunity is attributable to the inherent properties of H-field antennas and to careful design. In addition, the incorporation of low-noise preamplifiers within the structure of the antenna itself has contributed to systems immunity to on-board noise sources.

The XY antenna possesses the normal figure eight pattern for each axis. Therefore, the variation in signal level is no more than 3 dB between any two headings while in level flight. In addition the Z-axis antenna with its figure eight pattern results in a system which maintains the signal level within 5 dB for all attitudes.

Antenna data were recorded during flight test. Figure 9 is a plot of the signal-to-noise ratio versus heading angle of the Dana station taken during a 5g turn. The received noise is nonpolarized and therefore the plot represents the signal strength during the turn. The top curve indicates the antenna system using only an XY antenna. The deep nulls are inherent in the XY configuration when flying toward or away from the station because the X antenna is not effective due to the high bank angle. As indicated, most of the turn was completed on the Y antenna. However, when the XYZ combination was used, a nearly constant signal versus heading was realized and equal time was spent on both the Z and Y antennas.

The flight tests conducted at Eglin AFB further demonstrated the worth of the Z-axis antenna in extreme dynamic maneuvers such as 360° rolls and 90 degree knife edges. Testing was conducted with and without the Z-axis antenna to prove its value under high dynamic situations.

Figure 9. Antenna Response (5g turn)
In summary, the all-attitude aspect of the antenna design is necessary for quality Loran operation if no dynamic flight restrictions are to be placed upon a high performance aircraft such as the F-4. It allows great maneuverability of the aircraft just before critical mission functions without concern for producing high offset errors in the receiver.

**Acquisition**

The receiver acquisition time consists of the time required to initially estimate the interferences present, perform the search process, and lock onto the correct cycle of groundwave signal for all stations. This includes the time required to verify whether a groundwave is in front of a short delay skywave with skywave to groundwave ratios of up to +35 dB. The time required for acquisition depends upon the ambient signal-to-noise ratio and the Loran rate. In Loran 0 the presence of twice as many pulses per GRP further decreases the acquisition time. The additional pulses are utilized in both search and settling. Table I lists the total acquisition time (settle to 0.05 usec ± 10) for the receiver under various signal-to-noise conditions for Loran C and Loran D.

**TABLE I**

<table>
<thead>
<tr>
<th>Typical Loran Lock-On Times</th>
<th>LORAN C</th>
<th>LORAN D</th>
</tr>
</thead>
<tbody>
<tr>
<td>0Peak of Loran Pulse</td>
<td></td>
<td></td>
</tr>
<tr>
<td>+10 dB</td>
<td>3.5 min</td>
<td>2.0 min</td>
</tr>
<tr>
<td>0</td>
<td>5.0</td>
<td>3.0</td>
</tr>
<tr>
<td>-10</td>
<td>13</td>
<td>4.5</td>
</tr>
</tbody>
</table>

All receiver processes are rate aided with the best aiding available at any time on the aircraft. With good rate aiding acquisition is possible at velocities up to 2000 knots. In the Loran only mode acquisition is possible at velocities of up to 600 knots at signal-to-noise ratios greater than 0 dB. Several re-searches of the receiver during flight on an F-4 were conducted to verify this ability and no difficulty was encountered.

The acquisition process is not hindered by atmospheric noise. This was verified in testing at LSI using an atmospheric noise generator and at Eglin AFB where a great deal of natural atmospheric noise occurs at some times of the year. This performance is due to proper gain setting in the presence of atmospheric noise and judicious clipping of phase tracking samples when large spikes of noise are present.

Simulator testing has verified that the receiver acquires and locks onto signals with an imbalance between stations of 80 dB. It is able to accomplish this through individual station gain adjustments for both search and track.

**Accuracy**

The receiver has a time difference accuracy in the presence of noise of 0.05 usec ± 10 over a wide range of signal-to-noise ratios. It maintains this accuracy down to a signal-to-noise ratio of -12 dB at the track point. Below -12 dB the variance is allowed to increase to allow better dynamic performance. This constant standard deviation of the time differences is achieved because of the adaptive phase-lock loops which vary their bandwidth in exact proportion to the square of the signal-to-noise ratio. TD biases are less than 0.01 µsec at all times. The resolution of the timing measurements is less than 0.01 usec due to the rotation of the phase tracking samples as described in the software description above.

The dynamic error due to signals from different stations being received at different positions if the aircraft is in motion is removed by a synchronization process. The measurement of all time of arrivals is interpolated to common 50 microsec time boundaries for TD calculations.

**Operation in the Presence of Skywaves**

Receiver operation in the presence of large amplitude short and long delay skywaves has been given a great deal of attention. The ARN-101 receiver operates with short delay skywaves 35 dB above the groundwave with from 50-500 usec delays. Operation with delays down to 35 usec has also been shown. Measurement of the envelope shape at both the track point and 1 cycle earlier allow accurate cycle selection under these severe conditions.

Receiver operation is maintained with long delay skywaves of up to 4 microsec. Software processes estimate both the delay and amplitude of any long delay skywave present and adjust the RF gain to maintain receiver linearity.

**Envelope to Cycle Discrepancy**

The receiver can operate with individual station envelope to cycle discrepancies of up to 4 usec. Further assurance of accurate cycle selection is achieved by a differential envelope to cycle measurement between the master and slave stations. This is possible due to transmitter chain control of the differential envelope to cycle discrepancies to a closer tolerance than individual station envelope to cycle discrepancies.

**Aircraft Dynamics**

The receiver dynamic performance on the F-4 aircraft has been excellent. It experienced up to 6-g turns in the INS aided mode many times and never lost lock. Peak errors were minimal with only a few seconds settle time. Due to the synchronization of the rate aiding inputs, the lag was reduced to essentially zero. This combined with the three-axis antenna which minimizes the loss in signal-to-noise ratio removes much of the strain from the receiver tracking.

Software bandwidth expansion coupled with heading information allows much dynamic capability even in the absence of rate aiding. Tracking velocities of 2000 knots are no problem due to the second order phase-lock loops.

**Interference Suppression**

Interference suppression is achieved through the digital estimation and subsequent placement of notch filters on the interfering frequencies. The accuracy of the interference estimates is a function of the interference to noise ratio. The accuracy is better than 10 Hz for interference to noise ratios.
greater than +10 dB. This accurate estimation along with deep notches allows 50 dB rejection of interference signals.

The estimation process estimates a variety of interference types, namely synchronous and non-synchronous CW, ON-OFF CW (Even down to 25% duty cycle) and PSK. The receiver eliminates the strongest four signals of any of these types or combinations thereof. A pair of PSK frequencies is removed by one notch thus allowing a typical removal of 2 CW interferences, 2 FSK interferences and 1 ON-OFF CW interferences with the four notch filters.

A search for interference frequencies is conducted before a Loran search is started. A continuous interference interrogation and search is conducted during receiver tracking so that the notches are placed on current interference conditions.

Operation with interference to Loran ratios of more than 30 dB is possible. Low level interferences of -6 dB interference to noise can be detected by use of the 2 KHz tunable CW estimation filter.

**SUMMARY**

The ARN-101 Receiver has achieved a great deal of flexibility and adaptability to changing ambient conditions and system modes through the concept of a hardware signal processor controlled by the Navigational Computer. The basic receiver processes are all controlled by algorithms programmed in the Navigational Computer and hence are extremely flexible.

Future receiver modifications as might be needed for security reasons are easily added to the receiver due to the modular software structure and the total control of the signal processor by the Navigational Computer where all sampling control originates.

(1) A. Dimitriou; RF Signal Processing Via Control of Special Purpose Pre-Processors, presented at 27th Technical Meeting of AGARD, NATO. Athens, Greece, 1974.
LORAN-C/D AND ELECTRONIC COUNTERMEASURES

Larry Drayer
Tracor, Inc.

Abstract

The purpose of this paper is to consider the degradation on Loran-C/D operation caused by man-made interference. The utility of Loran-C/D is fundamentally limited by the ability of the receiver to acquire and track (phase lock) to the desired accuracy the time of arrival of the groundwave signal. Figure 1 identifies a variety of anti-jam techniques. All but the last item, Pseudo Random Coding, are already built-in standard Loran-C/D technique. Basic design theory for each item is developed and related quantitatively to their rejection to potential man-made interference. A variety of possible interfering signals including brute force broad band noise, continuous wave and sophisticated jammers producing Loran like pulses are considered. In conclusion the approximate jammer cost is related to the jammed area.

Synchronous detection is accomplished in the receiver by sampling the incoming Loran pulses with respect to a local reference, unscrambling the pulse code to obtain positional information and integrating. This is shown in block diagram form in Figure 2. The degree of interference which a jamming signal can create in the receiver is a function of how well it correlates with the local reference. This mechanism develops a "comb filter" with harmonics of one divided by the code interval. In the frequency domain this can be analyzed by two filters connected in series as shown in Figure 3. The first filter integrates over one code interval; the second, over a number (n) of code intervals. Figure 4 shows the resulting frequency response for Loran-C, SSO for a number of different code intervals integrated. The depth of rejection between the teeth of the comb is seen to increase as the integration time is increased. Signals lying between the teeth are suppressed. For an integration of 10 code intervals the rejection is approximately 20dB.

Interfering signals lying on or very near to a tooth of the comb filter are called synchronous. Synchronous interference is suppressed by selectively integrating certain pulses and ignoring others. For example the odd pulses in Loran-C repeat every Group Repetition Interval, GRI, as shown in Figure 5. The even pulses repeat every other GRI. This effectively separates the teeth of the filter into two groups. A synchronous interference is rejected by dropping either the odd or the even pulses. There is a corresponding loss of signal to noise ratio, SNR, of 1/ \sqrt{2}. As previously mentioned the integration time determines the depth and characteristics of the comb filter. In Loran-C/D receivers the integration is usually performed by a type II servo as shown in Figure 6. The characteristics of a type II servo are completely determined by the damping factor, \zeta, and the undamped natural frequency, \omega_n, as developed in the literature. However, heuristically, as the gain constants are increased the system will be more responsive to vehicular maneuvers but will also respond more to interference and random noise. This is shown mathematically in the figure. The standard deviation of the phase tracker is proportional to the square root of the loop noise bandwidth, \beta, and inversely proportional to SNR. The lag error due to a vehicle acceleration is proportional to the acceleration and inversely proportional to the square of the loop noise bandwidth. \beta is the reciprocal of the time constant of the system and is completely determined by the two gain constants.

Figures 7 and 8 quantify the standard deviation in each servo as well as the peak error caused by an acceleration step sustained for 10 seconds to a Loran-C type II servo. The independent parameter is the time constant. Since the period of a Loran-C/D signal is 10 microseconds, a phase error of microseconds will generally, because of noise, produce break lock in a short period of time. Figure 7 indicates that a time constant of about 2.5 seconds would be required to maintain a 2 microsecond phase error in a 5G acceleration sustained for 10 seconds, while time constants of 10 seconds and 100 seconds could be tolerated for 1G and 0.2G accelerations sustained 10 seconds. Figure 8 presents a plot of the standard deviation as a function of SNR for various time constants. A two microsecond standard deviation is not reached until the SNR drops to -30dB, -36dB, -36dB and -43dB corresponding to time constants in seconds of 2.5, 10, 25 and 100 respectively.

When the Loran servo is rate aided from an external sensor, the bandwidth of loop may be made more narrow. Figure 9 summarizes the immunity to CWI due to the comb filter for various possible applications. For example, a loop time constant of 1 seconds might be appropriate for a helicopter where no rate aid was available. The design would produce minimal static jitter of typically 30 to 120 nanoseconds in each phase servo, maintain lock in 2G turns and provide 40dB of suppression to CWI. A second example might assume the addition of a fair rate aid, such as a Doppler system, would reduce the acceleration experienced by the Loran servo by 90% to 0.2G's. The time constant could be lengthened to 25 seconds reducing the jitter to a typical range of 20 to 80 nanoseconds and increasing the suppression to CWI from 40 to 50dB. A very good rate aid, such as a wall integrated inertial system, as might be justified in a fighter aircraft, absorbs essentially all short term vehicular maneuver effects and reduces the dynamics as experienced by the loop to that which is caused by time internal oscillator variations and other minor effects. In this case a time constant of 100 seconds raises the advantage of the Loran over a CWI to 60dB and reduces the jitter to 10 to 40 nanoseconds. A receiver naturally experiences little vehicular acceleration and can also tolerate a long 25-100 second time constant.
The groundwave signal, as mentioned, contains the positional accuracy. To preserve this accuracy and prevent skywave contamination, the signal is processed in a relatively broad bandwidth (16-23 kHz) with a limited number of clocks (3 to 4) and only the leading edge is utilized. The whole of the pulse filtered in a narrow bandwidth (4 kHz) may be used to develop a useful internal rate aid signal. The result is naturally in the desired coordinate system - radial to the emitters. Figure 10 summarizes the field strengths for a variety of groundwave paths and skywave possibilities. Figure 11 presents a block diagram of one mechanism designed to take advantage of the energy in the whole pulse. A second independently tracking servo is established after a narrow bandwidth filter to track the peak of the pulse. Velocity from the peak tracking servo is coupled into the groundwave tracker and internal rate aid is accomplished. Analysis shows the resultant improvement corresponds to about 6dB for Loran-D and 9dB for Loran-C at operation less than 500 to 600 miles from the transmitter. However at ranges in excess of 500 miles the improvement increases to 20 to 50dB depending on the skywave conditions. This is summarized in Figure 12. Note this improvement is in signal strength and therefore gives the advantage over random and CW interference. Notch filtering of discrete interfering frequencies give additional suppression. Figure 13 presents a block diagram of one possible mechanism for a low cost computer controlled notch filter. The incoming signal is passed through two parallel paths: one unmodified; the other, through a narrow (1 to 2 kH) passband filter which shifts phase by 180 degrees and a gain adjusted amplifier. The two signals are recombined, and compressed by a log amp. The result is digitized by an A/D converter and transferred into the computer. The computer minimized the resulting input by adjusting the frequency control on the narrow passband filter. Then further minimization is achieved by adjusting the gain (which compensates for variations due to frequency and temperature) making the gain in the two signal paths equal. The computer controlled gain adjust eliminates the need for costly analog circuit compensation. The log amp may be mechanized by tapping off of stages of an AGC system. For receivers with some linear processing the log amp and A/D converter may be time shared between normal signal processing and a number of notch filters. With this mechanization a notch depth of 40dB is easily achieved. One point of caution is necessary. A notch filter causes some distortion in the front of the Loran pulse. Generally, if more than four notch filters are used in the Loran band cycle identification becomes unreliable. Two notches may be deployed on a single interfering frequency giving 80dB of suppression.

As mentioned previously the degree of interference which a jamming signal can cause in the receiver is a function of how well it correlates with the local reference. If the Loran pulses are transmitted on a pseudo random time base any jamming signal will look like random noise. A signal based on a random function implies that the random series extends to infinite time and that any part of the random sequence is independent of any other part. Thus, to correlate the incoming signal with the receiver reference, it is necessary that the receiver "have knowledge" of the sequence in absolute time. As derived above a standard receiver will operate in random noise down to SNR's of -36dB to -42dB depending on the time constants employed. An additional 6dB advantage is achieved with a dual tracking loop on a Loran-D signal (9 to 50dB for Loran-C). However when the pseudo random time base is used, the jammer must transmit all of the time to be "on" when the Loran transmitter emits. Since Loran operates on roughly a 5% duty cycle the jammer must emit approximately 20 times as much power as the Loran transmitter. This results in an additional 13dB advantage. This is summarized in Figure 14.

Figure 15 summarizes the various suppression ratios in dB derived from the Loran techniques previously discussed when applied against CW, sophisticated and broadband interference. Figure 16 summarizes some examples of some typical receiver mechanizations. For example for the jammer to jam the area defined by a line half way between the Loran transmitter and the jammer, the jammer would have to transmit somewhere between 40,000 and 1,000,000 times as much power as the Loran transmitter. Loran-D transmitters have approximately 30KW capacity. Assuming a cost for power electronics of approximately $1.50 per Watt, the cost of the jammer would run in excess of a billion dollars. Clearly, it is practical to jam only a small area in the vicinity of the jammer. One may graphically generate the contours of these small jammed areas by using a set of curves as shown in Figure 17 which is a plot of field intensity as a function of range to the transmitter for a number of paths with different conductivities. Figure 18 is a plot of the radius of the jammed area as a function of the distance between the Loran transmitter and the jammer for a number of assumed power ratio advantages. Figure 19 presents a few examples from the plot. Figure 20 presents a hypothetical geometry of a jammed area in relation to the three Loran transmitters.

*The actual shape of the jammed area tends to look more like a tear drop - but for small areas a circle may be assumed.
Acknowledgements

My co-workers Benny Jay, Ed Fraser, Jerry Setliff, William McKemie contributed useful ideas and much understanding to the generation of this paper.

Bibliography & References


Anti-Jam Capability Derived From

Synchronous Detection
Sampling
Phase Coding
Selective Strobing
Notch Filtering
Narrowbanding
Rate Aiding From Total Pulse
Rate Aiding From External Sensor
Pseudo Random Coding

Figure 1 — Loran-C/D Anti-Jam Techniques

Figure 2 — Block Diagram of a Loran-C/D Synchronous Detector

Figure 3 — Two Filters in Series

Figure 4

Figure 5 — Selective Strobing the Loran-C/D Phase Code

Figure 6 — A Loran-C/D Type II Servo Block Diagram
Figure 7
Type II Loop Time Constant (seconds)

Figure 8
Standard Deviation—nsec

Figure 9
<table>
<thead>
<tr>
<th>Time Constant</th>
<th>Jitter SNR</th>
<th>Loop SNR</th>
<th>Rate Aid</th>
<th>Application</th>
<th>CW Rejection</th>
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<td>Good</td>
<td>60</td>
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</table>

Figure 10
Night Time Skywave is Generally 10dB Greater than
Day Time Skywave

Figure 11
1 Level of Operation Attainable on
Groundwave without Dual Tracker
2 Level of Operation Attainable on
Groundwave with Dual Tracker
3 Level of Operation Attainable on
Skywave without Dual Tracker
4 Level of Operation Attainable on
Skywave with Dual Tracker

Figure 12
6dB for Loran D
9dB for Loran C @ <600 miles
20—50dB >600 miles

Figure 13
Log Amp
A/D

Degraded Operation to $-36$ to $-42$ dB

Sampling $10$ to $13$ dB

Dual Tracking

Loran D $6$ dB
Loran C $<600$ $9$ dB
Loran C $>600$ $20$--$50$ dB

Figure 14

<table>
<thead>
<tr>
<th>Tech</th>
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<th>Broadband</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comb Filter</td>
<td>36</td>
<td>36</td>
<td></td>
</tr>
<tr>
<td>Selective Strobing</td>
<td>40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Notch Filters</td>
<td>80</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td>Dual Track</td>
<td>9</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>Rate Aid</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>PRC</td>
<td></td>
<td>36</td>
<td></td>
</tr>
<tr>
<td>Sampling</td>
<td>13</td>
<td>13</td>
<td>13</td>
</tr>
</tbody>
</table>

Figure 15 -- Suppression ratios in dB derived from Loran signal processing techniques when applied against CW, sophisticated and broadband interference

Loran Advantage

Power Ratio

<table>
<thead>
<tr>
<th>Loran Advantage</th>
<th>Power Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>46 dB</td>
<td>40,000</td>
</tr>
<tr>
<td>53 dB</td>
<td>200,000</td>
</tr>
<tr>
<td>60 dB</td>
<td>1,000,000</td>
</tr>
</tbody>
</table>

Figure 16 -- Power advantage ratios for typical receiver/Loran mechanizations

Figure 17

Figure 18 -- Radius of jammed area versus distance between the Loran transmitter and the jammer for a number of power ratio advantages

<table>
<thead>
<tr>
<th>Distance from Loran D Transmitters</th>
<th>Jammer Power</th>
<th>&quot;Radius&quot; of Jammed Area Kilometers</th>
</tr>
</thead>
<tbody>
<tr>
<td>400 Km</td>
<td>Equal</td>
<td>3.75</td>
</tr>
<tr>
<td>400 Km</td>
<td>X10</td>
<td>10</td>
</tr>
<tr>
<td>200 Km</td>
<td>Equal</td>
<td>1.2</td>
</tr>
<tr>
<td>600 Km</td>
<td>X100</td>
<td>46</td>
</tr>
</tbody>
</table>

Figure 19 -- Some examples of jammed areas

Figure 20
ABSTRACT

A unified plan for electronic navigation in the Caribbean is non-existent. A multitude of navigation systems spread across the radio frequency spectrum cover the area in a patchwork fashion, none completely, and none effectively. The VOR/DME system with its line-of-sight propagation range is of limited use. The LF/MF non-directional beacon system has found the widest acceptance; however, it provides only limited navigation information and is extremely susceptible to the tropical thunderstorms. Loran-A covers the largest areas, but the scheduled shutdown has sent users scurrying to find new navigation techniques. Omega remains in its infancy and is plagued with the problems of high equipment costs, system interruptions, and the threat of sudden ionic disturbances.

The Coast Guard has used the Caribbean as a proving ground for new Loran-C equipment and navigation experimentation. The Caribbean provides an area of marginal strength, skywave contamination, and varying atmospheric noise conditions. Thus, it is an excellent experimentation area. This paper describes the Coast Guard flight tests and discusses further fields of investigation revealed by the unexplained Coast Guard successes.

THE CARIBBEAN

The sunshine, mild winds, and temperate climate of the Caribbean area appear to have a strong attraction to tourists. Cold winter winds and blustery, snowy weather seem to heighten that appeal to the people of the northern United States. The slow pace and easy manner of the Caribbean people are far more relaxing than the crowded, polluted cities of Europe with their high tempo of political and social activities. Thus, the Caribbean has become a vacationland for Americans and Europeans alike. It promises a paradise type atmosphere and conjures ideas of pleasure and rest.

Substantiating the influx of tourists, Table I presents a compilation of airline passenger statistics for the Caribbean area. Figure I is a graphic portrayal of traffic flow with the shaded areas proportional to the number of passengers deplaning at selected destinations. Compilation of similar general aviation statistics is an impossible task. A search of the 1974 aircraft accident reports (Ref. 1), however, revealed that ten per cent of all U.S. registry accidents, caused by a pilot being lost or disoriented, occur in the Caribbean.

A tragic example of this fact is the case transcript of N7196G, a Cessna 172, which departed St. Croix for the island of St. Lucia on March 15, 1975.

10:50:00 Cessna: Martinique, this is N7196G. I'm at 600 feet heading 150. My (fuel) endurance is 30 minutes and I'm climbing for (VOR) bearing.

10:55:00 Cessna: Martinique, N7196G receiving VOR (audio) on frequency 117.5. Out of 3000 feet and climbing; no bearing.

10:59:00 Cessna: Martinique, N7196G receiving VOR 250 radial from Martinique.

11:03:00 Cessna: Martinique, endurance 15 minutes. Heading 140 to Martinique, indicating 240 radial from Martinique.

11:06:00 Martinique Approach: N7196G, change heading to 060; no VHF DF bearing yet.

11:07:00 Cessna: What is the direction of St. Lucia? VOR indicates 230 radial from Martinique.

11:13:00 Cessna: I'm at 6000 feet. I have Martinique in sight about 30 n.m. away. I think I have enough fuel to make it.

11:18:00 Cessna: I'm 25 n.m. out, 5000 feet. I see an island heading 110.

11:22:00 Cessna: I'm 20 n.m. out heading 110 and my fuel is empty now.
TABLE I (Ref. 2)

<table>
<thead>
<tr>
<th>LOCATION</th>
<th>SEPT'73</th>
<th>DEC'73</th>
<th>MAR'74</th>
<th>JUN'74</th>
<th>MONTHLY AVG.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aruba</td>
<td>6,636</td>
<td>8,443</td>
<td>15,096</td>
<td>12,492</td>
<td>10,644</td>
</tr>
<tr>
<td>Barranquill</td>
<td>6,112</td>
<td>7,119</td>
<td>8,298</td>
<td>3,128</td>
<td>6,164</td>
</tr>
<tr>
<td>Caracas</td>
<td>71,402</td>
<td>50,715</td>
<td>47,071</td>
<td>49,699</td>
<td>54,721</td>
</tr>
<tr>
<td>Curacao</td>
<td>16,702</td>
<td>22,575</td>
<td>21,011</td>
<td>19,532</td>
<td>19,055</td>
</tr>
<tr>
<td>Fort de France</td>
<td>1,022</td>
<td>1,526</td>
<td>3,226</td>
<td>2,176</td>
<td>1,988</td>
</tr>
<tr>
<td>Havanna</td>
<td>2,942</td>
<td>1,885</td>
<td>2,435</td>
<td>1,966</td>
<td>2,307</td>
</tr>
<tr>
<td>Kingston</td>
<td>27,784</td>
<td>24,923</td>
<td>24,359</td>
<td>21,721</td>
<td>24,697</td>
</tr>
<tr>
<td>Maracaibo</td>
<td>6,736</td>
<td>5,958</td>
<td>4,661</td>
<td>5,260</td>
<td>5,654</td>
</tr>
<tr>
<td>Montego Bay</td>
<td>38,226</td>
<td>40,478</td>
<td>45,407</td>
<td>39,036</td>
<td>40,787</td>
</tr>
<tr>
<td>Port Au Prince</td>
<td>12,919</td>
<td>11,866</td>
<td>15,407</td>
<td>10,556</td>
<td>12,687</td>
</tr>
<tr>
<td>Port of Spain</td>
<td>20,164</td>
<td>17,533</td>
<td>19,419</td>
<td>10,741</td>
<td>16,964</td>
</tr>
<tr>
<td>Santo Domingo</td>
<td>18,921</td>
<td>17,635</td>
<td>21,870</td>
<td>18,154</td>
<td>19,145</td>
</tr>
<tr>
<td>St. John, Ant.</td>
<td>16,984</td>
<td>12,866</td>
<td>18,450</td>
<td>6,244*</td>
<td>16,100</td>
</tr>
<tr>
<td>San Juan</td>
<td>21,821</td>
<td>40,659</td>
<td>37,842</td>
<td>35,628</td>
<td>33,988</td>
</tr>
</tbody>
</table>

* NOTE: Incomplete traffic flow data available.

The sad exchange of messages continues. Tension and anxiety are quite evident in the pilot's voice. An island is visible but he remains unsure of which island or where the airport is located.

11:33:00 Cessna: I think I have a coast in sight about 5 miles away.

11:34:00 Cessna: I'm going down definitely; we are a hundred feet off the water.

Several calls were made by Martinique without answer. The supposition is that the pilot planned a low level flight from St. Croix to St. Lucia across the open stretch of water bounded by the crescent of Leeward Islands. Having lost the VOR signals from St. Croix, the pilot hoped to make landfall by receiving Martinique's VOR. Midcourse navigation was to be accomplished by DR. Unfortunately, the head wind component was greater than forecast, and the pilot found himself with dire problems. If midcourse position fixing had been available, he would have detected the high headwind factor and altered his course to one of the intermediate islands and a happy ending to the story.

Although a great number of "whys" in this case will remain forever unanswered, one cannot leave the circumstances of this case without a haunting belief that "navigation" was a key factor. An examination of the navigation facilities in the area leads to the conclusion that no unified plan for electronic navigation in the Caribbean exists. The fact is, a multitude of navigation systems spread across the radio frequency spectrum cover the area in a patchwork fashion, none completely, and none effectively.
Loran-A has found use in the area, primarily among the maritime community, but its scheduled shutdown has sent users scurrying to find new navigation techniques. Omega remains in its infancy and is plagued with the problems of high equipment costs, system interruptions, and the threat of sudden ionic disturbances. Loran-C coverage exists for the area, but it remains largely an unexplored resource. The dashed lines appearing at the bottom of Figures 1 and 2 represent the expected signal coverage of Loran-C with a signal-to-noise ratio of 1:10 with a confidence factor of 95 per cent.

COAST GUARD ACTIVITIES

The Coast Guard has used the Caribbean as a proving ground for new Loran-C equipment and navigation experimentation. A harsh environment is desired in order to exploit new systems to the limit of their capabilities. The Caribbean, with its regions of marginal signal strength, skywave contamination, and varying atmospheric noise, provides a "worst case" environment. The first series of Coast Guard flight tests took place during May 1974. Exploratory in nature, the tests served multiple purposes. A cursory examination of Loran-C signal suitability was made. Since a cooperative program had been established with the FAA to furnish Loran-C receivers to selected air carriers, the test flights provided an excellent opportunity to obtain operational experience with the receivers and to examine their reliability.

A major objective of the program was to determine the capability of the Coast Guard C-130 aircraft navigation system. Although the AN/AYN-1 Navigation Computer and ADL-21 Loran-C receiver system are being rapidly surpassed by today's technology, they performed well throughout the test. Limitations encountered with the system were considered further contributions to the "worst case" conditions of the test. Point-to-point navigation was an easy task for the Loran-C; only through use of the system as an approach-to-landing aid could its limiting capabilities be determined. Area navigation (RNAV) approaches were executed over Jamaica, Puerto Rico, the Virgin Islands, and the islands of Curacao and Aruba.

Loran-C signals were available over the entire area and were suitable for navigation. Visual fade of the ground wave was observed on the receiver scope, descending through 8500 feet over Curacao and Aruba. Nevertheless, skywave signal was present and was sufficiently accurate to perform multiple, auto-pilot coupled approaches. Despite the exhibited high amplitude broadband noise along the Puerto Rican coast, the ADL-21 was able to acquire and track signals while sitting on the ramps at San Juan International Airport and Roosevelt Roads Naval Air Station. The Jamaican vicinity presented the greatest challenge with persistent, severe skywave contamination of the groundwave signals. As a grand finale to the flight tests, the testbed C-130 with Loran-C auto-pilot guidance was flown from Guantanamo Bay, Cuba to an RNAV approach terminating one mile short of the runway at Andrews AFB, Washington, D.C.

One of the receivers used during the flight test was installed on an Eastern Air Lines L-1011 and flown on various routes to and from San Juan International Airport. Eastern amassed over 50 hours of observed tests and concluded:

"Loran-C with cycle matching is a satisfactory substitute for Loran-A in navigating the routes over which this evaluation was performed when usable signals are available. In general, its accuracy is excellent." (Ref. 3)

Flight tests were officially ended in January 1975; however, the receiver was left in the aircraft until late May for voluntary use by the aircrews. Not one system failure occurred during the period of October 1974 through May 1975.

In March 1975, preparations were made to provide a receiver to Continental Airlines for the second Loran-C evaluation. Continental's avionics personnel were invited to participate in a final system shakedown flight prior to equipment consignment. Again a C-130 testbed aircraft was used, and the flight was scheduled in conjunction with a routine logistics flight to the Caribbean. Urgent search and rescue requirements were encountered which resulted in the diversion of the testbed aircraft from its planned mission. Ironically, the aircraft was deployed to search for the Cessna 172, N71966, and Loran-C was employed as the primary navigation sensor for low-level search activities.

Since the datum area for search was in the vicinity of the windward islands, a mix of groundwave and skywave signals were used for tracking. A synthesized correction factor was generated by the computer and applied to the navigation solution. Two days of search were conducted in this manner, spanning the time periods from early morning to late afternoon. The traversed area spanned seven degrees of latitude and seven degrees longitude. A continual comparison was made with an onboard palleterized inertial system, and Loran-C accuracies were sufficiently high that a very slight, constant platform drift was detected. Upon landing at Seawell International Airport, Barbados, W.I., following eight hours of continuous Loran-C autotrack, the computer latitude/longitude read only 1.1 n.m. radial difference from the published general field coordinates. On a much sadder note, the debris of N71966 was located without survivors.

Encouraged by the Loran-C successes of two days' search, the testbed aircraft departed Barbados for Elizabeth City, N.C. via Miami, Florida. Attachment (A) is the message transmitted to the Commandant highlighting the accomplishments of the trip. The following geographic fixes extracted from trip data illustrate the comparative performance of the systems:

<table>
<thead>
<tr>
<th>Geographic Fix</th>
<th>Loran-C Fix</th>
<th>Inertial Fix</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fort de France, Martinique</td>
<td>N 14-35</td>
<td>N 14-36.8</td>
</tr>
<tr>
<td></td>
<td>W 61-00</td>
<td>W 61-01.4</td>
</tr>
<tr>
<td>Dorado, Puerto Rico</td>
<td>N 18-28</td>
<td>N 18-28.0</td>
</tr>
<tr>
<td></td>
<td>W 66-25</td>
<td>W 66-25.3</td>
</tr>
</tbody>
</table>

* NOTE: Inertial position updated at Dorado to remove accumulated platform drift.
signal acquisition and tracking, can the challenge be accepted. Greater knowledge of the Loran-C grid parameters must also be obtained if improvements are to be made to the system. The phenomena of increased signal strength associated with increased altitude must be exploited. Similarly, skywave augmentation and tracking must be explored. Yes, the challenge is there, and Loran-C should be part of the solution.

REFERENCES:
1. Anon, "Aircraft Accident Reports" Issues 1-4 of 1974 Accidents, NTSB-BA-74-4, NTSB-BA-74-6, NTSB-BA-74-7, and NTSB-BA-75-1, National Transportation Safety Board.

ATTACHMENT A

R 220004Z MAR 75
FM COGARD AIRSTA ELIZABETH CITY NC TO CGGDSEVEN PORTSMOUTH VA
CO LANTAREA COGARD NEW YORK NY
COMDT COGARD WASHINGTON DC
INFO CGGDSEVEN MIAMI FLA
COMGANTSEC COGARD SAN JUAN PR
BT UNCLAS
P10/POTENTIAL ENHANCEMENT COGARD IMAGE
A. COGARD AIRSTA ELIZABETH CITY 121745Z MAR 75
B. CGGDSEVEN 130424Z MAR 75
C. AMBASSARY PORT APRIRE 212040Z MAR 75
D. SAN JUAN SAR COORD 151730Z MAR 75
1. RECENT MULTI-MISSION OPERATIONAL/LOGISTICS/SAR FLT FOR EC130E CGNR 1414 PROVIDES OPPORTUNITY FOR INTERNAL/EXTERNAL P10 RELEASE FAVORABLE TO COAST GUARD INCLUDING POSSIBLE INTERNATIONAL AVIATION RECORD.
2. IN CONJUNCTION WITH SAR LOGISTICS (REF A) SPECIAL URGENT HUMANITARIAN FLT CONDUCTED (REF B AND C) TO PROVIDE CRITICAL SURGICAL INSTRUMENTS FOR LIFE SAVING OPERATION ON 3 YR OLD HAITIAN BOY.
3. UPON COMPLETION ABOVE AND ANOTHER SEPARATE SAR MISSION (REF D) EC130E CGNR 1414 COMMENCED RECORD FLT FROM BARBADOS BWI TO ECITY NC VIA MIAMI WITH LORAN-C NAV INFO COUPLED TO AUTO PILOT. FLT OF 2136 MILES COMPLETED IN 8.6 HOURS. FLT POSSIBLY IS INTERNATIONAL RECORD FOR COUPLED ELECTRONICS NAV TECHNIQUE.
4. OF SIGNIFICANCE:
A. DURING FIRST 4.5 HOURS FLT THE COMBINATION OF LORAN-C SKY WAVES AND GROUND WAVES USED AS SIGNAL INPUTS WITH A CORRECTION SYNTHESIZED IN THE AN/AYN-1 NAV COMPUTER
B. RCVR WAS ADL-21 STANDARD IN C-130 ACFT
C. PALLETIZED LTN-51 INS USED TO VERIFY AND VALIDATE COMPUTER CORRECTIONS
D. EFFECTIVE RANGE OF LORAN-C WAS ALMOST DOUBLED DURING FLT CLEARLY INDICATE OPERATIONAL EFFECTIVENESS OF LORAN-C/INS INTEGRATION FOR HIGH PRECISION NAVIGATION OVER GREAT DISTANCES.
5. FLT CREW FOR EC130E CGNR 1414:

<table>
<thead>
<tr>
<th>NAME</th>
<th>TELEPHONE</th>
</tr>
</thead>
<tbody>
<tr>
<td>LT G. A. ROGERS</td>
<td>237 54 5013</td>
</tr>
<tr>
<td>LT C. H. DAVIS</td>
<td>180 38 9221</td>
</tr>
<tr>
<td>LCDR R. H. WEHR</td>
<td>290 34 6543</td>
</tr>
<tr>
<td>LCDR T. G. STANDLEY</td>
<td>573 25 5314</td>
</tr>
<tr>
<td>ADT D. B. THOMPSON</td>
<td>466 50 0221</td>
</tr>
<tr>
<td>AOS D. R. DUNN</td>
<td>229 82 6265</td>
</tr>
<tr>
<td>AT2 P. F. GABRIEL</td>
<td>057 30 0455</td>
</tr>
<tr>
<td>AE2 S. K. MIDGETT II</td>
<td>237 96 9625</td>
</tr>
<tr>
<td>AT3 R. B. WINDSOR</td>
<td>219 62 8098</td>
</tr>
</tbody>
</table>
Abstract

The interest shown by potential land-based users of the Loran-C system has increased rapidly over the past year. Applications range from tracking moving vehicles, locating terrestrial features, and executing rendezvous. A Loran-C receiver/processor was operated in modes slanted at the different user requirements and the experiences and results of these operations are reported in this paper.

Introduction

Over the past several years attempts have been made to use Loran-C for tasks that are not considered in the normal navigational domain. For example, the Department of Transportation sponsored a Philadelphia experiment for vehicle location where one of the candidate systems was Loran-C. Another non-navigation application has been the weather balloon positioning system being operated successfully as a direct result of the Beuker's laboratory efforts. There has been some other Loran-C non-navigation operational activity (as opposed to paper studies), but much of this activity has been sponsored and executed by commercial interests. Consequently, descriptions of task applications, operational techniques, and performance data are not readily available to the Loran-C community.

With the increased coverage resulting from the designation of Loran-C as the navigation system for the U.S. Coastal Confluence region, increasing interest is being shown by non-navigation type users. Among these are governmental and commercial organizations described in yesterday's sessions - i.e., the papers presented by Captain Cass and Captain Stephany.

In anticipation of a large increase in potential users, Telcom has investigated the feasibility of applying low-cost Loran-C for locating land-based platforms during the past two years. Initial results for automobile positioning were presented at the Third Annual Wild Goose Convention in October, 1974. Since that time considerable effort was made to determine the different needs of potential users. During the course of this effort, numerous agencies, bureaus, managers, and field personnel (such as helicopter pilots and policemen) were contacted and made aware of Loran-C's capabilities. The interest curve in practically all cases took an immediate and steep upswing. Unfortunately, for many of the interested parties, Loran-C coverage did not exist in their operating areas. However, total U.S. coverage predicted for 1980 softened their disappointment.

It was discovered that every user's application was a little different from the others. The only common requirement is the availability of a reliable processor. Some users can tolerate limited operator inputs; there are others who require full automaticity. The peripheral devices which translate Loran-C coordinates into useful information varies directly as the number of user types.

Armed with requirements of these different users, Telcom developed operational techniques, made equip-
Loran-C by such unfortunate occurrences. As the Loran-C signal coverage area increases and the number of users increases rapidly, discipline in the transmitting networks must necessarily become more rigid, and the periodic network malfunctions which presently occur will have to diminish greatly.

Tracking Data

Control and dispatch centers have an interest in the real-time position of moving vehicles in the field. Accuracy requirements which have been indicated by various potential users range from 250 feet to one-half mile. Telcom's test program for this application consisted of obtaining Loran-C positioning data for various speeds and different land conditions (rural, suburban, and urban). Detailed Loran-C charts do not exist for specific areas, therefore, time difference readings were taken and repeatability was employed as a measure of performance. For some of the areas in which Telcom has operated, enough data has been obtained to generate "home-brew" charts. Other Loran-C operators (Coast Guard, NAVOCEANO, Merchant Marine Academy) have been encountered during the tests, and comparison of readings indicated all parties were at the same location. Data are presented for rural airborne, rural vehicle, suburban, and urban operations.

Rural Airborne Tests

On 14 May 1975, the receiver/processor was installed on a single-engined Beech Bonanza aircraft. A simple long-wire antenna was installed with the aft end fastened to the top of the tail assembly. From there a 12-foot run was made through the door directly into the receiver and no special coupler was used. In flight the antenna was oriented at an angle of about 10 degrees with the horizontal. For this test the equipment was powered from its own 6 volt battery as is normally employed for all portable field tests.

Take-off from the Manassas, Virginia, Airport was executed at 10:50 a.m. The weather was clear with some haze. Automatic acquisition of the Loran-C signals had taken place while taxiing to the runway in the normal time of about 5 minutes.

The flight path proceeded west to Warrenton, Virginia, at an altitude of 1000 feet and 90 m.p.h. The receiver tracked consistently with no indications of cycle slippages at any time. Then the pilot flew on a northeasterly course to Reading, Pennsylvania, which took the aircraft directly over Dulles Airport. Loran-C data was taken periodically, and the position was plotted. Altitude on the flight to Reading was 7500 feet. The unit continued to track nicely for the entire trip to Reading. Ground speed readings from the aircraft's distance measuring equipment indicated 166 m.p.h.

After landing at Reading, Pennsylvania, the receiver/processor was shut down. Complete restart operations were commenced after a one-hour shutdown and automatic acquisition operations were conducted during the climb-out.

When approaching the northeast bank of the Susquehanna River, the "A" slave station time difference once again toggled through 52200, exactly as it did on the morning flight. The Eastern U. S. Naval Oceanographic Chart shows that the "A" line (52200) parallels the northeast river bank in this area.

On the return flight, operational tests consisted of turning off the equipment and commanding the receiver to automatically execute complete signal acquisitions. The purpose was to verify ability of low cost equipment to perform fully automatic restart operations at these speeds. Ground speed during these operations varied from 175-200 m.p.h. as measured on the DME. For example, the receiver/processor acquired and properly selected the correct cycle for the weakest station (Dana, Indiana) in one minute 50 seconds. Sample times for a complete restart (acquire and cycle select all three stations) were typically 6 minutes 17 seconds and 6 minutes 3 seconds. This compares favorably with stationary operation on the laboratory bench at Telcom in Vienna, Virginia.

At the conclusion of the flight in Manassas, the time differences at the runway threshold were the same as noted at the start of the morning take-off. The rural airborne test appeared to prove that the low-cost vehicular Loran-C receiver/processor installation could be operated successfully in a low performance aircraft environment and speeds without requiring any modifications or special techniques.

Rural Vehicle Tests

In early May of 1975, Telcom's receiver completed a round trip in a station wagon between Washington, D. C., and Lexington, Kentucky, a total distance of 1150 miles. Operations were carried out in open areas as well as heavily wooded highways in mountainous country. Time difference readings were taken at numerous identifiable landmarks and are tabulated below. The upper numbers are for the westbound trip on 4 May 1975 in clear weather. The lower numbers were observed on the eastbound trip on 10 May 1975 with considerable electrical, rain, and hailstorm activity during the afternoon.

<table>
<thead>
<tr>
<th>LOCATION</th>
<th>TOA</th>
<th>TDB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manassas, Va., Exit</td>
<td>53312.9</td>
<td>69684.9</td>
</tr>
<tr>
<td>I-66</td>
<td>53312.5</td>
<td>69685.4</td>
</tr>
<tr>
<td>Thornton Gap, Skyline</td>
<td>53397.1</td>
<td>69529.5</td>
</tr>
<tr>
<td>Drive, Va.</td>
<td>53397.0</td>
<td>69528.5</td>
</tr>
<tr>
<td>Intersection I-81</td>
<td>54099.5</td>
<td>69586.0</td>
</tr>
<tr>
<td>and US50, Virginia</td>
<td>54100.4</td>
<td>69586.9</td>
</tr>
<tr>
<td>Intersection I-64</td>
<td>54217.6</td>
<td>69198.2</td>
</tr>
<tr>
<td>and US50, Caldwell, West Virginia</td>
<td>54217.8</td>
<td>69198.5</td>
</tr>
<tr>
<td>Intersection I-64</td>
<td>54067.3</td>
<td>68247.5</td>
</tr>
<tr>
<td>and US53, St. Albans, West Virginia</td>
<td>54077.1</td>
<td>68257.1 (wrong M indication)</td>
</tr>
<tr>
<td>Motel Parking Spot, Lexington, Kentucky</td>
<td>54382.7</td>
<td>67205.0</td>
</tr>
<tr>
<td>Lexington, Kentucky</td>
<td>54382.6</td>
<td>67204.2</td>
</tr>
</tbody>
</table>

The apparent differences between readings at the "same" point can be contributed chiefly to the following two factors:

1. On the westbound trip, a one-man crew drove the vehicle and dictated readings "on the fly" into the tape recorder.
2. On the eastbound trip, a two-man crew was used, one driver, and the other recording data.

It is believed that the eastbound set of numbers (two-man crew) is therefore more accurate. For
example, the numbers recorded at the motel parking lot in Lexington, where the operator did not have to drive, show excellent agreement.

For the St. Albans readings, note the 10 microsecond discrepancy between the sets of readings during the eastbound passage. The receiver was indicating "wrong master" at the time but the automatic features in the machine provided the corrections shortly thereafter. This occurrence stressed the requirement of a vehicle tracking unit not only to be able to indicate an erroneous position but also have the capability to take automatic self-corrective action.

Near Buena Vista, Virginia, an extremely intense thunderstorm with rain and hail was encountered. The machine tracked and operated well until an extremely close (50-100 feet away) lightning strike upset all of the timing and signal tracking was completely lost. Within seconds, an automatic restart was executed. After 4 1/2 minutes, positioning data was again being delivered even though the thunderstorm area had not yet been cleared.

Suburban Vehicle Tests

For suburban or semi-rural areas the Capital Beltway encircling Washington, D.C., was used as a test ground. The comparative data presented below was obtained at a spacing of approximately one year and demonstrates to users the stability of the Loran-C grid over a long time period. Furthermore, the time differences for 1974 were measured on a different processor than those for 1975. Consequently, internal bias of the machines (if any exists) adds to the apparent difference in the positions.

### LOCATION AND DATE

#### Exit 1

**Capital Beltway**

<table>
<thead>
<tr>
<th>Date</th>
<th>TDA</th>
<th>TDB</th>
</tr>
</thead>
<tbody>
<tr>
<td>15 July 74</td>
<td>52981.2</td>
<td>69816.7</td>
</tr>
<tr>
<td>16 July 74</td>
<td>52980.0</td>
<td>69816.3</td>
</tr>
<tr>
<td>5 Sept 75</td>
<td>52980.14 Avg*</td>
<td>69816.04 Avg*</td>
</tr>
<tr>
<td>9 Sept 75</td>
<td>52980.62 Avg*</td>
<td>69816.42 Avg*</td>
</tr>
</tbody>
</table>

#### Exit 14

**Capital Beltway**

<table>
<thead>
<tr>
<th>Date</th>
<th>TDA</th>
<th>TDB</th>
</tr>
</thead>
<tbody>
<tr>
<td>15 July 74</td>
<td>52929.8</td>
<td>69711.7</td>
</tr>
<tr>
<td>16 July 74</td>
<td>52929.9</td>
<td>69711.7</td>
</tr>
<tr>
<td>9 Sept 75</td>
<td>52929.64 Avg*</td>
<td>69711.52 Avg*</td>
</tr>
</tbody>
</table>

#### Exit 29

**Capital Beltway**

<table>
<thead>
<tr>
<th>Date</th>
<th>TDA</th>
<th>TDB</th>
</tr>
</thead>
<tbody>
<tr>
<td>15 July 74</td>
<td>52825.1</td>
<td>69772.3</td>
</tr>
<tr>
<td>16 July 74</td>
<td>52825.0</td>
<td>69772.1</td>
</tr>
<tr>
<td>9 Sept 75</td>
<td>52824.66 Avg*</td>
<td>69771.74 Avg*</td>
</tr>
</tbody>
</table>

#### Woodrow Wilson Bridge

<table>
<thead>
<tr>
<th>Date</th>
<th>TDA</th>
<th>TDB</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 May 74</td>
<td>52976.5</td>
<td>69821.7</td>
</tr>
<tr>
<td>15 July 74</td>
<td>52976.1</td>
<td>69821.6</td>
</tr>
<tr>
<td>16 July 74</td>
<td>52976.2</td>
<td>69821.1</td>
</tr>
<tr>
<td>5 Sept 75</td>
<td>52975.90 Avg*</td>
<td>69821.02 Avg*</td>
</tr>
<tr>
<td>9 Sept 75</td>
<td>52975.98 Avg*</td>
<td>69820.92 Avg*</td>
</tr>
</tbody>
</table>

*Ten consecutive time differences are averaged by the receiver/processor prior to display.

An inspection of the data will indicate that the averaging technique yields positioning data that differs from the instantaneous readings. This difference was converted to distance and was found to be on the order of 250 feet for the A reading and 240 feet for B. For the Washington, D.C., area, this yields a CPE of 358 feet, well within the requirements of the average tracking user.

The Woodrow Wilson Bridge data showed closer agreement than the others. Construction was underway on the bridge and the averaged readings were taken at a speed of approximately 20 m.p.h. As will be seen in the downtown urban traffic data which follows, the agreement between averaged and instantaneous time differences greatly reduces as vehicle speed decreases.

### Urban Vehicle Tests

Urban and downtown vehicle tracking operations have been conducted in Norfolk, Virginia; Richmond, Virginia; Washington, D.C.; Lansing, Michigan; and Philadelphia, Pennsylvania. Compared to suburban and rural operation, downtown areas present a more difficult tracking problem because of the vast and rapid changes in signal and noise levels. These changes are caused by the presence of overhead wires, underpasses, and local pockets of interference. Strangely enough, certain bridge structures (suspension and beam type) did not cause difficulty. Even the closed beam type structure at the southern end of the Baltimore Tunnel caused no problems.

The only extensive experience Telcom has had in skyscraper areas is in the downtown section of Philadelphia. Three days of operations were conducted in that area with the following results:

1. No problems in areas where the buildings are 22 stories or less.

2. For the area where buildings rise up to 44 stories, tracking of the signals was as follows:
   a. Nantucket Slave - 100% of the time.
   b. Cape Fear Master - 90% of the time.
   c. Dana Slave - 10% of the time.

3. Local overhead power and trolley lines caused no problem.

Lansing, Michigan, which lies approximately 700 miles from the master, and 750 and 250 miles from the slaves of the East Coast network, yielded 100% tracking performance over a ninety-minute test period. Norfolk, Richmond, and Washington, all of which are located in good service areas, caused no problems in acquiring and tracking the signals. Constitution Avenue in Washington, D.C., was traversed numerous times and comparative data for different times, processors, and methods of generating time differences are presented below.

### Constitution Avenue, Washington, D.C.

<table>
<thead>
<tr>
<th>Location and Date</th>
<th>TDA</th>
<th>TDB</th>
</tr>
</thead>
</table>
| 6th St., N.W., Westbound
| 16 July 74        | 52918.3      | 69782.5      |
| 18 Sept 75        | 18.26 Avg    | 82.42        |
| 18 Sept 75        | 18.20 Avg    | 82.48        |
Constitution Avenue, Washington, D. C., continued

<table>
<thead>
<tr>
<th>LOCATION AND DATE</th>
<th>TDA</th>
<th>TDB</th>
</tr>
</thead>
<tbody>
<tr>
<td>6th St., N.W., Eastbound</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16 July 1974</td>
<td>52918.5</td>
<td>69782.1</td>
</tr>
<tr>
<td>18 Sept 1975</td>
<td>18.43 Avg</td>
<td>82.42</td>
</tr>
<tr>
<td>18 Sept 1975</td>
<td>18.45 Avg</td>
<td>82.34</td>
</tr>
<tr>
<td>15th St., N.W., Westbound</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16 July 1974</td>
<td>52922.5</td>
<td>69779.4</td>
</tr>
<tr>
<td>18 Sept 1975</td>
<td>22.56 Avg</td>
<td>79.09</td>
</tr>
<tr>
<td>18 Sept 1975</td>
<td>22.52 Avg</td>
<td>79.00</td>
</tr>
<tr>
<td>15th St., N.W., Eastbound</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16 July 1974</td>
<td>52922.8</td>
<td>69779.1</td>
</tr>
<tr>
<td>18 Sept 1975</td>
<td>22.73 Avg</td>
<td>79.06</td>
</tr>
<tr>
<td>18 Sept 1975</td>
<td>22.69 Avg</td>
<td>78.92</td>
</tr>
<tr>
<td>16th St., N.W., Westbound</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16 July 1974</td>
<td>52923.3</td>
<td>69778.7</td>
</tr>
<tr>
<td>18 Sept 1975</td>
<td>23.30 Avg</td>
<td>78.45</td>
</tr>
<tr>
<td>18 Sept 1975</td>
<td>23.31 Avg</td>
<td>78.41</td>
</tr>
<tr>
<td>16th St., N.W., Eastbound</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16 July 1974</td>
<td>52923.7</td>
<td>69778.3</td>
</tr>
<tr>
<td>18 Sept 1975</td>
<td>23.82 Avg</td>
<td>78.15</td>
</tr>
<tr>
<td>18 Sept 1975</td>
<td>23.83 Avg</td>
<td>78.34</td>
</tr>
</tbody>
</table>

Based on the Constitution Avenue results, it appears that the 10-sample averaging technique is the preferred mode of operation for tracking vehicles in an urban environment.

Location Data

A series of tests was conducted to determine the accuracy to which a terrestrial feature could be located utilizing Loran-C. Conversations with potential users indicated that the time required to obtain position data was not critical for this application.

Test 1

One of the experiments was conducted along the passenger departure service ramp at Dulles Airport. On this ramp, which has a heavy concrete overhang, eight airline gates, spaced exactly 80 feet apart, were used as position identifiers. The processor was used in the 10-sample averaging mode and slow passages (approximately 5 m.p.h.) were made. The vehicle was not stopped and readings were taken opposite each entrance.

Data was taken on three different days and a total of 0.09 microseconds/gate on the Nantucket leg and 0.08 microseconds from the Dana reading. The maximum deviation from the "correct" readings for the gates was 0.07 microseconds. In other words, a position uncertainty of one gate or 80 feet existed.

Based on the Constitution Avenue data in the section entitled "Urban Vehicle Tests" and Dulles Terminal data herein, it appears that for many applications the 10-sample averaging technique yields positions with an 80-feet certainty for stop and go type driving applications.

Test 2

Because one of the potential users of Loran has an interest in the accurate location of personal residences, readings were taken while parked at each of seven driveways for adjacent houses in Springfield, Virginia. The processor was allowed to operate in the 100-sample averaging mode while the operator waited for the data. The houses and driveways are not equally spaced but were all on the same block in a typical suburban community. Two 100-sample averages were obtained at each driveway - one for each slave time difference. It was clearly evident that an operator could readily distinguish between houses if he was able to utilize a processor display in hundredths of a microsecond. The total changes between driveways at each end of the test area were 0.55 microseconds for one slave and 1.11 microseconds for the other.

Test 3

Instead of measuring the distances between driveways in the previous test, an experiment with better control was conducted. A straight line path was marked off at 100-foot increments across a large shopping center parking lot. The total length of the path was 700 feet. At each 100-foot mark, five 100-sample averages were obtained for each time difference. These five readings were then averaged to yield the "best TDA and TDB" for the 100-foot incremental positions.

The incremental changes for each 100-foot segment are presented in the following table:

<table>
<thead>
<tr>
<th>Mark</th>
<th>ΔTDA (usecs)</th>
<th>ΔTDB (usecs)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(TDA = 53028.55)</td>
<td>(TDB = 69791.13)</td>
</tr>
<tr>
<td>0</td>
<td>0.06</td>
<td>0.04</td>
</tr>
<tr>
<td>100</td>
<td>0.07</td>
<td>0.37</td>
</tr>
<tr>
<td>200</td>
<td>0.08</td>
<td>0.22</td>
</tr>
<tr>
<td>300</td>
<td>0.06</td>
<td>0.19</td>
</tr>
<tr>
<td>400</td>
<td>0.07</td>
<td>0.19</td>
</tr>
<tr>
<td>500</td>
<td>0.07</td>
<td>0.18</td>
</tr>
<tr>
<td>600</td>
<td>0.04</td>
<td>0.16</td>
</tr>
<tr>
<td>700</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

From the above table it is apparent that the TDB reading at the 100-foot mark is in error. The 0.04 change between "0" and "1" most likely is 0.17. Therefore, an error of almost 100 feet would have resulted if the observed reading had been taken as valid.

A review of the field data showed that the maximum deviation from the average at a mark was 0.07 microseconds except for one instance. This occurred in the TDB reading at the 100 foot marker (the reading that is obviously in error) where a 0.19
One additional test was conducted on the 700-foot line. The 100-foot segment between the 400 and 500 foot marks was divided into 20-foot segments and readings were obtained at each of these marks. Again five 100-sample averages were obtained. The five spaces for TDA should have incremented 0.014 microseconds per 20-foot segment based on the readings at each end. For TOB the increments should have been 0.038 microseconds per 20 feet. The changes that were observed are shown in the following table. (Figures in parentheses indicate the change is in the wrong direction.)

<table>
<thead>
<tr>
<th>Mark</th>
<th>ATDA (usecs)</th>
<th>ATDB (usecs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>0.02</td>
<td>0.05</td>
</tr>
<tr>
<td>420</td>
<td>(0.01)</td>
<td>0.06</td>
</tr>
<tr>
<td>440</td>
<td>0.01</td>
<td>0.04</td>
</tr>
<tr>
<td>460</td>
<td>0.03</td>
<td>0.01</td>
</tr>
<tr>
<td>480</td>
<td>0.02</td>
<td>0.03</td>
</tr>
<tr>
<td>500</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

It appears that this technique cannot yield 20-foot resolution.

Test 5

After concluding the 700-foot exercise, a parking spot exercise was carried out. Painted parking slot stripes are spaced exactly 9 feet apart. Readings were taken (in the five 100-sample mode) at every fifth slot (45-foot spacing). The orientation of this path was approximately 45 degrees to the original 700-foot line. The time differences at the start were 53028.15 and 69789.59. The observed results are presented in the following table.

<table>
<thead>
<tr>
<th>Parking Slot</th>
<th>TDA</th>
<th>TDB</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>53028.15</td>
<td>69789.59</td>
</tr>
<tr>
<td>5</td>
<td>28.14</td>
<td>9.68</td>
</tr>
<tr>
<td>10</td>
<td>28.09</td>
<td>9.74</td>
</tr>
<tr>
<td>15</td>
<td>28.05</td>
<td>9.73</td>
</tr>
<tr>
<td>20</td>
<td>28.07</td>
<td>9.79</td>
</tr>
<tr>
<td>25</td>
<td>28.00</td>
<td>9.86</td>
</tr>
</tbody>
</table>

From this exercise it appears that a 45- to 50-foot positioning capability may be achievable, but the time to record time difference data must be increased.

Test 6

In order to determine what order of improvement results with increased data, a longer term sampling experiment - again using real world signals - was carried out at Telcom's laboratory in Vienna, Virginia.

One hundred 10-sample averages were recorded at a fixed location for each time difference. This was followed by one hundred 100-sample averages for each reading. These data batches were then subjected to the standard statistical procedures with the following results:

<table>
<thead>
<tr>
<th>10-Sample Data</th>
<th>100-Sample Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>TDA</td>
<td>TDB</td>
</tr>
<tr>
<td>Mean</td>
<td>Mean</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>Std. Dev.</td>
</tr>
<tr>
<td>52968.82</td>
<td>52968.78</td>
</tr>
<tr>
<td>0.109</td>
<td>0.033</td>
</tr>
<tr>
<td>69723.39</td>
<td>69723.39</td>
</tr>
<tr>
<td>0.168</td>
<td>0.043</td>
</tr>
</tbody>
</table>

If the above results are related to the Loran-C grid geometry and distance units, the improvement in position certainty can be estimated.

For the 10-sample mode, 68% of the positions are within 135.5 feet of the mean, and practically all (the 3 sigma value) are within 406.5 feet. For the 100-sample mode, the figures are 35.99 and 107.9 feet respectively.

This last test does not confirm the results that are initially indicated in the street data reported earlier in the paper. However, it should be remembered that the navigation procedures down a street or road are in a restricted area of maneuverability, and it is that feature which led to the 30-foot conclusion. Consequently, it is concluded that a 135-foot capability exists for street navigation.

If the vehicle had been guided down Constitution Avenue by Loran-C 10-sample readings, some excursions over the sidewalks, flowerbeds, and grassy areas would have occurred. If the driver wants to remain within the curb boundaries of the street, the 100-sample mode must be executed.

Search and Recovery Exercises

In order to test the capability of recovering a previously visited location whose position was recorded in Loran-C coordinates, three limited exercises were conducted. Two used the Beech aircraft as a platform, and one utilized an automobile.

Exercise 1

In the moving platform test discussed in the section entitled "Rural Airborne Tests," the time difference readings for the Manassas exit on Interstate 66 as previously measured by a vehicle were:

<table>
<thead>
<tr>
<th>TDA</th>
<th>TDB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Westbound</td>
<td>53112.9</td>
</tr>
<tr>
<td>Eastbound</td>
<td>53112.5</td>
</tr>
</tbody>
</table>

The first test was to check the ability of the airborne processor to duplicate ground-based vehicle readings of this intersection while in an airborne environment. On 14 May 1975, at an altitude of 1000
feet and a ground speed of 90 m.p.h., the pilot crossed the intersection. At "visual rendezvous" the time differences were 53113.6 and 69684.9 which results in possible errors of 165 feet (Nantucket line) and 336 feet (Dana line) or a CPE of 389 feet.

Exercise 2

On that same day, a "recovery" operation was carried out. The "recovery" exercise consisted of picking out a clearly identifiable object on the ground. Then the aircraft was flown directly over the object several times to record the time differences for that point as accurately as possible. The recovery portion then required flying some distance away and being able to accurately "recover" that object location utilizing Loran-C as the only navigational aid.

For this exercise the "Casanova" VOR was designated as the object to be recovered and was overflown with Telcom's Loran-C processor indicating TDA = 53293 and TGB = 69663. The numbers were recorded to the nearest microsecond with the CPE for 1 microsecond being 1250 feet. The processor yields time difference values to the nearest 0.1 microsecond (CPE = 125 feet) as a normal readout, but in this case the operator did not attempt to use the smaller resolution for the exercise.

The aircraft was flown away from the VOR for a distance of 12-14 statute miles. At that point, steering information in the form of headings was verbally relayed to the pilot by the operator who was watching the time difference behavior on the Loran. Guidance provided by the operator resulted in a "miss to the right" of about 1000 feet. However, the operator did predict the miss during the final moments of the recovery operation because he accidentally gave a course heading correction to the right instead of the left.

Contributing to the error was the operator's ability to respond only to one microsecond increments, plus the operator-to-pilot human interface between the Loran-C processor and the steering controls of the aircraft. It is felt that an automated system which could have provided continuous corrections would have avoided the tendency to overcorrect which was observed during this test.

Both of these exercises depended heavily on the "human element" in the response loop. This element constituted the weakest portion of the system and most likely contributed the largest error. But even with this weakness, rendezvous and recovery capabilities were adequately demonstrated.

Exercise 3 - Milepost Recovery

The Dulles Airport access road outside Washington, D.C., is marked with prominent mileposts. During the morning of 5 September 1975, a clear sunny day, stops were made at the 1, 5, and 10 mileposts on the outward (toward Dulles) and inbound sections of the highway. One 100-sample reading for each time difference was recorded. During the afternoon of the same day, the mileposts were recovered - that is, the operator visually blocked out all outside references and was only able to see the Loran display. He then instructed the driver when to slow down, stop, back up, and/or move forward based on his Loran-C observations. The operator's command decisions were based on one 100-sample average for each time difference. When the "at milepost" decision was given, the miss distance was measured. Four days later during heavy rainstorms the recovery exercise was repeated.

The following results were obtained with a minus sign indicating "short of mark" and a plus sign showing overshoot.

<table>
<thead>
<tr>
<th>MILE 1</th>
<th>MILE 5</th>
<th>MILE 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>-10 feet</td>
<td>-3 feet</td>
<td>-60 feet</td>
</tr>
<tr>
<td>+3 feet</td>
<td>-15 feet</td>
<td>-64 feet</td>
</tr>
<tr>
<td>-30 feet</td>
<td>-35 feet</td>
<td>-10 feet</td>
</tr>
<tr>
<td>+5 feet</td>
<td>-20 feet</td>
<td>+200 feet</td>
</tr>
</tbody>
</table>

The population of data samples is not considered large enough for statistical analysis. Another factor which must be considered is the restricted area of maneuverability which undoubtedly contributed to the relatively good results.

If maneuverability had not been restricted, the operator believes his procedure would have been to track along the Loran-C line of position (fixed time difference) that has the smaller gradient and use the higher gradient line as a cut-off or "stop" indicator. Perhaps guidance along the line with the higher gradient and cut-off by the tower may be a better mode of operation. This thought presents an interesting exercise and should be carried out and carefully evaluated.

Conclusion

The exercises reported in this paper indicate that low-cost Loran-C has the potential to meet many requirements posed thus far by potential users of land navigational data. It is felt that perhaps the most important result of the exercises is not the performance data itself that has been reported, but the evolution of operational algorithms for different user applications. With the frequent and sometimes misuse of the new word "microprocessor" - touted to solve any problem that "comes down the pike" - the precise definition of working, operational, or application algorithms becomes extremely important. For land-based applications, adequate positioning performance and precise working algorithms are required inputs for land-based platforms. The exercises described, data obtained, and algorithms evolved constitute a large step toward fulfilling this requirement.

Author's Note

The restrictions placed on page count and illustration requirements for the reproducible manuscript made it impossible to include the visual material used in the presentation. Copies of the visual material may be obtained by writing Telcom, Inc., 8027 Leesburg Pike, Vienna, Virginia 22180.
LORAN C SEISMIC SURVEY IN BRISTOL BAY, ALASKA

John R. Stoltz
Teledyne Systems Company
Northridge, California 91324

ABSTRACT

The TDN-6000 is a navigation system that processes the LORAN C signal to produce the optimal estimate of a ship's position and velocity. Currently, the TDN-6000 has been performing seismic surveying operations in the Bristol Bay area of Alaska. Two LORAN C receivers were employed simultaneously in order to select more measurements and reduce the measurement noise through smoothing. The modes of operation are either hyperbolic or rho-rho with transit satellite data used for calibration to improve the long term accuracy. This paper will document some of the results obtained during the seismic surveying operation.

The TDN-6000 LORAN C system can be modified to provide high accuracy navigation to various cargo carrying vessels. The optimal processing of multiple and redundant measurements will improve the navigation accuracy substantially beyond that attained by simple two hyperbolic LOP coordinate conversion. The report describes the integration of LORAN C receivers, computer, and display system in order to produce an effective, high accuracy, marine navigation system.

INTRODUCTION

This paper describes the operation of the TDN 6000, a high precision LORAN C navigation system. The TDN 6000 served as the main navigation system for a seismic surveying operation. The TDN 6000 was augmented by a separate Transit satellite system which provided periodic position data. The satellite system served as a validity check on the TDN 6000 LORAN C system.

The seismic survey operation took place in Bristol Bay, Alaska. The Bristol Bay area is excellently covered by the North Pacific LORAN C chain. The received LORAN C signals were very strong and the background noise at 100 KHz was very minimal. Two of the transmission paths were entirely over water. One path travelled over the Aleutian chain, but was only minimally perturbed. The fourth transmission path from the northern most station travelled a considerable portion of the distance over land which induced secondary phase factor errors.

A seismic survey operation consists of what is known as shot lines. The lines are a predetermined grid that is laid out over an area of interest to the oil exploration community. A typical grid is illustrated in Figure 1.

![Example Oil Survey Grid]

Each of the lines are identified by a number designation. The seismic survey is performed by transmitting an acoustic signal and then recording the times of arrivals of the reflected signals. It is very important that the acoustic signals called shot points occur at precise predetermined points or distance intervals along the various shot lines. The purpose of the TDN 6000 is to provide accurate navigation data that will indicate when the next shot point should be activated.
AREA OF OPERATION

The area of operation was in the Bristol Bay of Alaska as indicated by Figure 2 which was covered by the North Pacific LORAN C chain. The master station is located on St. Paul Island and has a transmitted power of 400KW. The two slave stations that were employed were Attu and Sitkinak both transmitting at 400KW of power. The survey area was located just south of the master and between the two slave transmitters Attu (X) and Sitkinak (Z). The transmission path was entirely over water for the master and Attu. The transmission path from Sitkinak was only minimally interrupted by the Aleutian Island chain.

GEOPHYSICAL SURVEY OPERATION

The geophysical exploration community places high demands on the accuracy of marine navigation systems. The surveyed area is in the St. George Basin. This area will be opened for lease bids from the U.S. Government. The seismic survey or will collect data that will be used to evaluate the extent of future oil field developments. The seismic data is obtained by acoustic soundings. The reflected acoustic soundings are received by a trailing hydrophone array. The data obtained by the array is used to predict the geological structure of the ocean bottom. An accurate navigation system is necessary to pinpoint important geological structures. All the above information will be used to determine how much a particular oil company will bid.

TDN-6000 SYSTEM DESCRIPTION

The TDN-6000 consists of equipment that has a proven history with the geophysical exploration industry. The TDN-6000 equipment diagram is contained in Figure 3. The heart of the system is Teledyne TDL-601G LORAN C receiver. Most of the geophysical exploration boats with LORAN C equipment employ the TDL-601G. The TDL-601G is noted for its high accuracy and reliability and ease of operation. A Hewlett-Packard 16 bit minicomputer system has been employed to perform the data processing and navigation functions. Hewlett-Packard computer systems have long been a standard in the marine navigation community.
Figure 3. TDN-6000 Equipment Diagram

The TDN-6000 system incorporates a redundant receiver design. The design allows for increased reliability and additional cross-chain processing capability. The cesium clock is employed where rho-rho navigation is desired. The cesium clock provides a stable external frequency to the TDL-601G receivers that will not drift appreciably over a few days. The CRT/keyboard is used to provide real-time control of the TDN-6000 system by the navigator. All system initialization and mode changes are performed at the CRT/keyboard console.

The paper tape reader is used for loading the system software programs and diagnostics. Two printers are employed to record all operator requests, system status, and seismic shot point data. The oscilloscope is primarily used in the rho-rho mode of operation where the master station is not available. Additionally, the oscilloscope is useful in evaluating which signals should be processed.

TDN-6000 SOFTWARE DESCRIPTION

The Teledyne TDN-6000 is a high precision self-contained LORAN navigation system. The TDN-6000 provides a complete navigation capability including

- Lat/Long
- Course/Speed
- Range/Bearing
- Steering Data
- Shot Point Data Recording
- System Status
- External Position Correction

Description of the Navigation Functions

Lat/Long - The latitude and longitude of the navigation system is determined by optimal processing of the LORAN C measurements. The LORAN C measurements are gathered every pulse group repetition interval and smoothed over a 5 second period. The result is that the random errors on the signals are greatly reduced which in turn produce a more stable position.
Course/Speed - The course and speed of the vessels is derived by the Kalman filter which takes advantage of the correlation of the velocity errors and the position error. Thus, the improved position error reduction will allow for a more accurate estimation of the vessels velocity components.

Range/Bearing - The range and bearing from the vessels present position to a preselected destination is computed by the Andoyer-Lambert geodesic range routine and a great circle bearing routine. The range routine is accurate to within a few feet for ranges of over 1000 miles. The bearing computations are accurate to within a fraction of a degree.

Steering Data - The steering data consists of the off track error of the vessel from a predetermined great circle line determined by the end points D1 and D2. When the off track error is reduced to zero, the vessel is on the desired great circle path.

Shot Point Data Reading - The shot point data reading consists of computing and printing the computed Lat/Long of the vessel and the ranges to the various LORAN C transmitters in microseconds.

System Status (Error Alert) - The system status is determined and the summary of results is printed every 5 minutes.

External Position Correction - The TDN-6000 position can be corrected if external sensors have determined that there is an offset. Thus, if a Sat/Nav system were used in conjunction with TDN-6000, position offsets could be incorporated to correct for the effects of propagation errors.

Navigation Modes

The navigation modes of the TDN-6000 take advantage of the fact that there are two TDL-601G Receivers. The Modes of operation of the TDN-6000 for either single or cross chain LORAN processing are

- Rho-Rho
- Rho-Rho-Rho
- Hyperbolic (up to 4 lines of position-LOP)

Hyperbolic Navigation

With two Teledyne TDL-601G receivers a maximum of 4 hyperbolic LOP's can be processed. Two hyperbolic LOP's are obtained from each receiver. Thus, 4 LOP's can be processed from a single LORAN C chain or 2 LOP's can be processed from two separate LORAN C chains to provide cross chain operation.

Rho Navigation

When a cesium clock timing reference is provided, a ranging mode of navigation can be operated. With two TDL-601G receivers a maximum of 6 ranges can be processed. There are 3 ranges from each TDL-601G. A cross chain mode of operation can be implemented where 1 range is taken from one LORAN C chain and a second range using the other receiver is taken from another LORAN C chain.

The TDN-6000 program design consists of two classes of software modules. The first is the interrupt modules which service the real-time hardware requests. Example interrupt modules are:

- Real-time clock processor
- LORAN interrupt processing
- Input/Output device processing

The interrupt modules are written in assembly language and are usually only 100 to 200 words long. The second class of modules are those under control of a background executive. The routines in the background executive perform most of the complex numerical computations. Most of these routines are written in Fortran. The Fortran compiler minimizes the software development and checkout time. Memory sizing tradeoffs were made that showed that the length of the Fortran routines were only slightly longer. The computer uses semiconductor memory which is quite inexpensive. Example routines called by the background executive are:

- LORAN data processor
- Kalman filter (4 states)
- Cross track computations
- Shot point data computations
- Great circle range and bearing
- Display input/output data processing
SYSTEM PERFORMANCE

As discussed earlier, the TDN-6000 operated on a seismic survey vessel in the Bristol Bay area of Alaska. The seismic survey was performed during the summer season from May until September of 1975. The TDN-6000 was used in conjunction with a transit satellite system which was primarily used to provide calibration data. Prior to going to the Bristol Bay area, a LORAN C accuracy analysis was performed for both the hyperbolic and Rho-Rho modes of operation. The expected accuracy of the TDN-6000 was computed and is illustrated in Figures 4 and 5. The results are based on filtering of the LORAN C data and Transit calibration of the secondary phase factor errors.

Kodiak Island Performance

The TDN-6000 system used two different types of whip antennas for each receiver. One was connected to a 3 meter whip and the other was connected to an 11 meter whip. The nearest station, Sitkinak, was only 50 miles away; a voltage level of near 3 volts was recorded on the 11 meter whip, 1 volt on the 3 meter whip. The farthest station was Attu on the western most end of the Aleutian Islands. The Attu signal could be seen above the noise on the 11 meter whip but not on the 3 meter whip. The TDL-601G receiver could acquire all stations on the 11 meter whip but not Attu on the 3 meter whip. The system showed an offset from chart positions in the harbor of Kodiak of 50 feet in latitude and 300 feet in longitude using stations M, Y, and Z. As we moved out of the harbor on test runs, the longitude error increased to 2 or 3 minutes and the latitude error increased to about 1 minute. The large errors were probably caused by geometry and being near large mountainous islands.

Dutch Harbor Performance

The primary stations employed in the Dutch Harbor area were stations M, X, and Z. At the dock the TDN-6000 and Transit satellite system were tested statically to determine the offset between the two. It was determined that there was virtually no offset in longitude and 300 feet in latitude. The probable reason for the latitude offset is that the dock was located directly at the base of a 2000 foot mountain that is situated on the transmission path from the master station to the receiver.

The LORAN C signal levels were very good at Dutch Harbor. The master station measured near 3 volts on the 11 meter whip. The signal levels on the 3 meter whip were about 10 db lower. Both receivers could track the M, X, and Z stations. The smoothed time difference values were displayed on the CRT. The jitter varied between 20 and 30 nanoseconds for each time difference value. The jitter of the system position was analyzed. The TDN-6000 employs a Kalman filter whose gains can be controlled from the CRT/keyboard. Thus, the effective time contract of the system employed would correspondingly determine the amount of jitter reduction. The positions jitter could be varied from 50 to 10 feet.

Bristol Bay Performance

The primary stations employed during the seismic survey were M, X, Z. The signal strength was very good and the TDN-6000 operated both day and night. The satellite system and the TDN-6000 LORAN C system generally agreed to within 200 feet. On the 15th of August, 1975, there was one line where the satellite system and the TDN-6000 LORAN C system agreed to within 50 feet for six consecutive satellite passes. The position accuracy of the satellite system is a direct function of the accuracy of the velocity input derived from the TDN-6000. Thus, the close agreement of the two systems indicates that the TDN-6000 was able to provide very accurate velocity data.
Figure 4.

LORAN NORTH PACIFIC CHAIN
STATIONS M,X RHO–RHO
WITH FILTERING

Figure 5.

LORAN NORTH PACIFIC CHAIN
STATIONS M,X,Z HYPERBOLIC
WITH FILTERING
This paper discusses the collision of the British flag tanker Gliptik Sun, with a fixed oil well platform in the Gulf of Mexico. The Environmental Impact Statement for the Gulf of Mexico Loran-C Chain specifically addresses the possibility of such an incident when discussing the need for improved aids in the Gulf. Six lives were lost in the fire which followed the collision and the monetary loss was more than the cost of the entire Gulf chain. Although Loran-C alone could not have prevented the incident, its use as indicated in the paper, should materially reduce future occurrences.

In the Gulf, fairways have been left for navigation of vessels through offshore structures but the reduced maneuvering of the larger carriers makes more accurate position determination necessary for minimizing grounding and collisions with structures and other vessels. An example of the values involved is that the economic loss of a single 300,000-deadweight-ton tanker would be more costly than the cost of installation and operation of the proposed Loran-C expansion for the Gulf for ten years. More difficult to assess would be the environmental losses.

Final EIS for the Gulf Loran-C Chain
July 1975

Introduction:

The offshore oil and gas exploration industry continues to expand off the Louisiana and Texas coasts. A special Local Notice to Mariners, published by the Eighth Coast Guard District in New Orleans on 1 June 1975, lists 2839 offshore oil well structures. In addition to these, there were at last count some 98 mobile units operating in the Gulf which maintain stationary positions for two weeks to two months at a time while drilling exploratory wells.

The investment which these rigs represent is fantastic. The fixed platforms range in cost up to $20M each and the mobile units range from $20M to $60M each. The mobile units are, of course, manned at all times, but many of the fixed platforms operate unattended, being primarily pumping stations which pull oil from ten or twenty drilled wells and push it to shore through pipelines resting in troughs along the bottom.

Fairways:

Marine traffic, enroute to or from many Gulf ports must thread its way through what is rapidly becoming a maze of structures. For safety’s sake, well-defined fairways have been laid out and printed on navigational charts, as shown in Figure 1. These unmarked, two-mile wide fairways provide reasonably direct routes to such major ports as New Orleans, Port Arthur, and the Houston/Galveston area. They are situated, however primarily in international waters and there appears to be no effective way of enforcing their use. It is probable though, that they will be adopted by major shipping interests because they insure an obstruction-free path through the area. Should the ocean floor beneath a fairway look promising for exploratory drilling, it can be sampled by slant drilling from rigs located outside of the fairway.

The obvious question, and one which seems all too often to be discarded as trivial, is how the vessels determine their locations with respect to the fairways. The obvious answer, at least for the case shown in Figure 1, is with Loran-A. With transmitters at Galveston (center left), Grand Isle (off figure to center right), and Port Isabel (off figure to bottom left) this area is well covered and an adequate receiver should allow a vessel to transit the two-mile wide fairways. There’s only one minor problem—there are no U. S. regulations that require vessels of any class to use, or even have on board, Loran-A equipment.
The same, of course, is true for Loran-C, Omega, Decca, Transit, and believe it or not, radar. The radar problem has at least been approached by a proposed change in the ports and waterways regulations. The change was published in the Federal Register on 26 June 1974, and attached as Appendix A. Implementation of the proposed rule is being delayed due to numerous objections by commercial shipping interests.

The Globtik Sun:

At 0135 on 15 August 1975 the Coast Guard received an urgent message that the SS Globtik Sun, a fully loaded 734-foot tanker, had collided with a structure in position 28-25 N 92-55 W and was on fire. Immediately, cutters from Galveston, Texas and Gulfport, Mississippi were ordered to proceed to the scene and aircraft were launched from New Orleans, Houston, and Corpus Christi. A broadcast was made to all merchant vessels in the area to proceed to the scene and assist.

On board the Globtik Sun the fire apparently spread very rapidly, causing the crew to abandon ship by jumping into the sea. (The aluminum life boats were later found in place but melted by the intense heat.) By the time our first aircraft arrived on scene, commercial vessels had picked up thirty-five survivors. One man was later found in the water by a search helicopter leaving six unaccounted for. The probable remains of three men were later located in a crew recreation room and the other three were never found.

Our first aircraft at the scene reported, at 0338 local time, that the local weather was excellent. Visibility was unlimited, the wind was SE at 7 knots and the seas were from the south at 2-4 feet. The structure, which had been hit, was a fairly new fixed platform owned by the Chevron Oil Company and located in West Cameron Block 533. The ship was on fire fore to aft, was spilling oil (cargO) from a gash in the port bow, and the resultant oil slick was also on fire. Damage to the unmanned platform appeared minimal but extensive tests will probably be necessary to determine the integrity of the supporting structure.

How could such an accident occur? The evidence shows that the only electronic navigation aids on board were a Decca receiver, an ADF, a radar, and a fathometer. The Decca equipment, of course, was totally useless in the Gulf and, since the ocean bottom contours were not remarkable in the area, the fathometer was not of particular value for position fixing. There is reason to believe that the ADF was uncalibrated and known to have large errors. This leaves the radar, which is believed to have been operating at the time of the collision. One other piece of electronic equipment also appears to have been in operation at the time of the collision---the auto-pilot.

The vessel was on a northwesterly heading when the collision occurred and judging by the location, it appears that the intent was to use the established fairway to Galveston. It is considered very probable that the vessel’s last position fix was obtained by celestial observation at 2000 on 14 August. From the position obtained, a desired course to Galveston was most likely determined and set into the auto-pilot and progress then estimated by DR.

Assuming that all of the above are absolutely correct, it is still difficult to imagine how the vessel could collide with a rig equipped with navigational lights and a continuously operating fog horn. No one observed, either by radar or by eye, that personnel on a nearby rig observed the lights to be operating prior to the collision. However, this has not been corroborated and, for the sake of argument we can assume that they were not operating. As noted earlier, there is reason to believe that the radar was operating at the time and even that the platform was detected possibly as much as thirty minutes before the collision. From this it must be concluded that the radar presentation indicated a safe passage or that an error was made in the range measurement so that the tower was upon them much earlier than expected. No one knows for sure what happened because the incident occurred in international waters and legal problems relating to jurisdiction have severely hampered an investigation.

It is not uncommon for some large merchant vessels to have an “at sea” deck watch of one mate and one able-bodied seaman, with steering accomplished by auto-pilot. At most times this is a sufficient watch to detect problems and take responsive action. However, there are times when one or even both watch standers might have their attention diverted for appreciable periods of time. To guard against such occurrences, some forms of automated alarms would seem to be advisable to warn of impending danger. In the case of the Globtik Sun it is probable that the mate was in the chart room at the time of the collision estimating his time of arrival at Galveston so that he could make arrangements for a pilot.

Some Preventive Medicine:

The Globtik Sun incident would seem to make a good case for collision avoidance radar. Such a radar, which would automatically acquire targets and sound an alarm when a CPA less than that considered safe was determined, would have provided sufficient notice for the vessel to take
evasive action. Appendix A includes the proposed requirement for a collision avoidance radar on all vessels, foreign and domestic, using U. S. ports and measuring in excess of 10,000 gross tons.*

To avoid getting into such a situation in the first place, however, some means of position fixing must be required. A study of Appendix A will reveal that no such required equipment is even proposed. Since Loran-C was established last year as the primary radio navigation aid for the coastal confluence region of the U. S., a logical step would be its required use by vessels of certain classes. As stated in Appendix A,

The purpose of any regulation to be proposed is to prevent maritime casualties and the resultant discharge of oil or hazardous substances into the navigable waters of the United States by regulating the operating requirements of major vessels on those waters...

The use of modern electronic aids-to-navigation would seem appropriate for inclusion in such regulations.

Although the basic TD receivers would undoubtedly be useful, the crying need is for guidance information. The presence of fairways should allow for very simple devices (from the operators point of view) which would greatly encourage fairway utilization.

As mentioned earlier the fairways are two miles wide. Use of Loran-C would allow a fairway to be divided into two one-half mile lanes with a one-mile separation for inbound and outbound traffic--not the most desirable traffic separation scheme, but a workable one. Points along the centers of the separated lanes could be stored in permanent memory so that when a specific fairway was selected by the operator, the system would automatically provide guidance information to the closest point on the fairway. The technology is available now and some equipments have been built which could do this--this paper points out an important application.

The cost of such a system need not be prohibitive with today's technology. An excellent system, including the Loran-C receiver, should be able to be marketed for less than $15,000. Such a cost can hardly be considered significant when compared with the cost of a vessel or its cargo. To emphasize this point, consider again the Global Sun incident. This vessel is 734-foot long with a carrying capacity of approximately 55,000 metric tons. Its replacement cost is about $30M. At the time of the collision, she was carrying 346,000 barrels of crude oil, valued at approximately $4.5M (at $13/barrel). The platform which she struck was valued at nearly $16M. This one incident had a potential direct cost of more than $50M with millions more undoubtedly lost in indirect costs.

Imagine yourself on the bridge of a ship headed for Galveston through the maze of offshore structures. You would, of course, be standing a very attentive watch. You are taking Loran-A fixes every twenty minutes, checking the radar every five or ten minutes, and scanning the horizon with your Mark-I eyeball at every opportunity. A weather front, with associated thunderstorms, increases the atmospheric noise level to such a degree that the Loran-A receiver becomes useless. Three hours later, with a DR of questionable value your radar shows six targets within twenty miles; there's only one way that they can be made to correlate with the structures shown on your chart, and that would mean an eight-mile error in your DR. What would you do? Suppose you move your DR to make sense out of the radar picture. Thirty minutes later you find yourself in the same situation on another chart. As you turn out the next chart you find another one of the contacts was a new rig not on your charts and another was a mobile rig on a fixed station--your chart keepers should pay better attention to the Notices to Mariners. Failure to move your DR based on the radar information could have the same consequence. Ridiculous? Over stated? I don't think so.

Imagine now another vessel on the same night in the same area. As she approaches the offshore oil rigs, the mate on watch selects "Fairway 17-A" on his Loran-C guidance unit which provides the auto-pilot with the necessary data to arrive at the seaward entrance of the fairway and proceed up it automatically. Near Block 533 the unit calls the mate's attention to the fact that he is approaching a fairway junction and must let the unit know whether he wants "Fairway 15-A" to Galveston or "Fairway 20-A" to Sabine (Fairway numbers for purposes of example only). Upon being told of the choice, the unit provides steering data for the new fairway. The thunderstorms which had caused grief to the other vessel are of no immediate concern to the Loran-C-equipped vessel. Safeguards would, of course, be required to ensure that the Loran-C data remains valid--such things as transmitter blink detection, cycle jump detection, and four-station tracking would be most desirable. The TD information would also be available to allow the mate to fix his position on a chart. Ridiculous? Not at all--the problem is that such systems are totally unknown to most potential users.

*(U. S. vessels constructed with MARAD (Maritime Administration) subsidies are presently required to have collision avoidance radar systems.)
Things might be changing though. Recently the States of Maine and Alaska have seriously considered requiring tank vessels, using their ports, to be equipped with Loran-C. Washington, Oregon, and California are apparently going to consider this problem also because of the future supertanker and LNG vessel traffic from Valdez, Alaska down to the West Coast. There is, however, some question concerning the constitutional rights of the states to place such requirements on vessels engaged in interstate commerce. At any rate, the LNG vessels now under construction for El Paso Natural Gas (at $160M each) for use in the Valdez to West Coast trade, are planned to be outfitted with Loran-C as well as Omega and Transit.

Meanwhile, back in Galveston, the Globtik Sun remains at anchor eight miles offshore, an abandoned hulk. Anyone interested in some scrap steel?
FIGURE 1: Charted Fairways Through Oil Field Areas Off Of The Louisiana and Texas Coasts
APPENDIX A

FEDERAL REGISTER

Part IV

Vol 39 - No 126

Friday
June 28, 1974

PROPOSED RULES

COMMENTS ON ADVANCE NOTICE

Interested persons are requested to assist the Coast Guard by submitting written comments, data, views, or arguments to the Marine Safety Council (G-CMC/82), room 8234, U.S. Coast Guard, Washington, D.C. 20590. A participant in this rule making procedure should submit comments, views, data, or arguments to the Coast Guard as soon as possible but no later than August 19, 1974. Copies of material received will be available for examination in room 8234. Arrangements for State and local governments, representatives of the marine industry, port and harbor authorities, environment groups, and other interested parties to discuss with representatives of the Coast Guard the proposal in this advance notice may be made with the Executive Secretary at 202-426-1477.

Oral comments may be submitted on this advance notice at the public hearings the Coast Guard will hold on Docket CGD 74-32, the notice of which appears on page of this issue of the FEDERAL REGISTER. The public hearings will be held on July 23 and 24, 1974, beginning at 9:00 a.m., in the Shaw Room, Seattle Center, 303 Harrison St., Seattle, Washington, and on July 30 and 31, 1974, beginning at 9:00 a.m., in Room 3228, 500 Seventh St. SW., Washington, D.C. It is requested that anyone desiring to make oral comments at either hearing notify the Executive Secretary, at the above-stated address by July 19, 1974, and specify the approximate length of time needed for his presentation. Submission of a written summary or copy of the oral presentation is encouraged.

DISCUSSION OF PROPOSED REGULATIONS

Senate Report No. 92-724 (March 28, 1972) states that the purpose of the Ports and Waterways Safety Act of 1972 (Pub. L. 92-340, 86 Stat. 424) is to promote the safety and protect the environmental quality of ports, waterfront areas, and the navigable waters of the United States. Broad authority is granted by title I of the Act to establish, operate, and maintain vessel traffic services and systems for ports, harbors, and other waterways, and to control “vessel traffic in areas determined to be especially hazardous, or under conditions of reduced visibility, adverse weather, vessel congestion, or other hazardous circumstances” in order to “prevent damage to, or the destruction or loss of any vessel, bridge, or other structure or in or on any navigable water or any water of the United States subject to Congression structure or shore area immediately adjacent to those waters; and to protect the navigable waters and the resources therein from environmental harm resulting from vessel or structure damage, destruction, or loss . . . .”

In addition, title II of the Ports and Waterways Safety Act of 1972 authorizes comprehensive regulations for the design, construction, alteration, repair, maintenance, and operation of tankers and certain other vessels. The reason stated for this provision of the Act is as follows: “(H)The carriage by vessels of certain cargoes in bulk creates substantial hazards to life, property, the navigable waters of the United States, and the resources contained therein . . . (and) that existing standards for the design, construction, alteration, repair, maintenance, and operation of such vessels must be improved for the adequate protection of the marine environment.”

The Federal Water Pollution Control Act (86 Stat. 862, 33 U.S.C. 1321(b)(1)) states the policy of the United States as follows: “(T)here should be no discharges of oil or hazardous substances into or upon the navigable waters of the United States, adjoining shorelines or into or upon the waters in the contiguous zone.” Regulations issued under the authority of section 311(j) of this Act are required to be consistent with maritime safety and navigation laws.

Section 101(a) of the National Environmental Policy Act of 1969 (83 Stat. 582, 42 U.S.C. 4321) states that it is the continuing policy of the Federal Government, in cooperation with State and local governments, and other concerned public and private organizations, to use all practicable means and measures, including financial and technical assistance, in a manner calculated to foster and promote the general welfare, to create and maintain conditions under which man and nature can exist in productive harmony, and fulfill the social, economic, and other requirements of present and future generations of Americans. The Act authorizes and directs that to the fullest extent possible the policies, regulations, and public laws of the United States must be interpreted and administered in accordance with the policies set forth in the Act.

In view of the policy stated in these statutes and in view of the increasing vessel traffic carrying hazardous cargoes, the Coast Guard has determined that there must be an improvement in the existing practices aboard all major vessels on the navigable waters. The increasing number of large vessels carrying hazardous cargoes in bulk on the navigable waters and the United States has created a significant and growing hazard to life, property, and the marine environment. Eighty percent of vessel casualties occur within coastal and harbor regions. The Torrey Canyon grounding, the Tamano grounding, the Oregon Standard and the Arizona Standard collision, and the tug Carolyn and Weeks Barge collision have resulted in a tide and the loss of one of the Chautauqua Bay bridge and Tunnel, exemplary casualties that have occurred in waters adjacent to shore areas. Each of these casualties poses a significant threat to life, property, and the environment. Information regarding these incidents and similar incidents reveals that human error is often the primary cause of casualties. The conclusion of a study based on Coast Guard investigations is that
Proposed Rules

Substance of Regulations To Be Proposed

1. All U.S. and foreign vessels in the navigable waters except vessels in innocent passage not bound for or departing U.S. ports would be required to comply with:

   a. The specific requirements of any vessel traffic system through which the vessel passes.

   b. The orders of the Captain of the Port when he makes an individual case determination that a particular area is especially hazardous or that hazardous circumstances exist within his jurisdictional boundaries. The Captain of the Port considers the following factors among others before issuing any order:

      (1) Configuration of the waterway involved including the depth and width of the channel to be transited.
      (2) Wind direction and velocity.
      (3) Tidal current and stage of tide.
      (4) Visibility.
      (5) Time of day.
      (6) Type and amount of cargo being carried.
      (7) Hull design of the vessel involved including the presence or lack of a double hull, double bottom, and cargo segregation.
      (8) Propulsion system of the vessel including factors such as horsepower, number of shafts, size of propellers, bow thrusters, stern thrusters, and other systems which affect controllability and maneuverability of the vessel.
      (9) Tugs in attendance.
      (10) Inoperative or deficient equipment aboard the vessel that may affect its ability to safely transit the navigable waters.
      (11) Type and density of other vessel traffic operating in the same waterway.
      (12) The presence of a pilot aboard the vessel.
      (13) The vessel's master, person in charge, or pilot.
      (14) Vessel speed and intended time of transit.
      (15) Intended route and destination.

2. All U.S. and foreign vessels that are self-propelled seagoing vessels of 150 gross tons or more, or seagoing towing vessels with tow in any configuration whose aggregate tonnage exceeds 150 gross tons, except those in innocent passage not bound for or departing U.S. ports, would be required to have personnel on board comply with the following requirements when underway within the navigable waters:

   a. Vessels of more than 150 gross tons. (1) One radar.

      (2) A properly adjusted magnetic compass.

   b. The master, person in charge, or pilot of a vessel would be required to be familiar with the details of each notice to mariners relevant to the vessel's intended track since the date of the correct chart being used to transit the area.

   c. All U.S. and foreign vessels that are self-propelled seagoing vessels of 1600 gross tons or more, or seagoing towing vessels with tow in any configuration whose aggregate tonnage exceeds 1600 gross tons, except those in innocent passage not bound for or departing U.S. ports, would be required to have personnel on board comply with the following requirements when underway within the navigable waters:

   (1) Steering (all modes and stations).
   (2) Emergency generator.
   (3) Remote machinery controls.
   (4) Main propulsion for power ahead and astern.
   (5) Internal vessel communications.
   (6) Vessel alarms and signaling devices.

   The purpose of any regulations to be proposed is to prevent maritime casualties due to negligence or failure to produce safer conditions for congested or hazardous maritime traffic since any vessel over 150 gross tons can collide or create an imminent collision or grounding situation involving a vessel carrying oil in bulk. Therefore, it is the ultimate goal of the regulations under consideration to establish safer standards for the operation of vessels capable of causing a major casualty within the navigable waters.

Regulations To Be Proposed

The purpose of any regulations to be proposed is to prevent maritime casualties due to negligence or failure to produce safer conditions for congested or hazardous substances into the navigable waters of the United States by regulating the operating requirements of major vessels on those waters. The equipment and operating regulations to be proposed would apply to foreign vessels when bound for or departing from United States ports and to United States seagoing vessels that operate within the navigable waters of the United States.

Seagoing vessels generally include those vessels on coastal and ocean trade routes. Vessels on the St. Lawrence Seaway, the Great Lakes, and vessels operating only within rivers, lakes, bays, and sounds would be excepted from the requirements of paragraphs 2, 3, and 4 of this advance notice. However, the proposed requirements of paragraph 1 of this notice would apply to all vessels including those operating on the Great Lakes, and rivers, lakes, bays, and sounds.

Further regulations for the Great Lakes are dependent upon final agreement between Canada and the United States. Further requirements for vessels operating exclusively on rivers, lakes, bays, and sounds will depend upon additional evaluation of the practical and economic impact of operating requirements on these vessels by the Coast Guard.

This advance notice is not intended to indicate that the Coast Guard has formed final conclusions on any aspect of the proposal. Public comment on the functions to be required, the tonnages specified, and the applicability of the requirements to a particular class of vessels is requested and will be used in determining the regulations to be proposed. The Coast Guard proposes specific functions and tonnages in order to provide a starting point for public comment. The following description sets forth the substance of the regulations to be proposed.

In the March 1, 1974 issue of the Federal Register (39 FR 7948), the Coast Guard published an advance notice of proposed rulemaking regarding regulations to authorize each District Commander and Captain of the Port to control vessel traffic in order to mitigate the effects of hazardous areas or during hazardous circumstances, and to direct the movement of a vessel when its movement may result in preventable damage to or by that vessel. This document paragraph is intended to supplement the advance notice published in 39 FR 7948.

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Within the confines of harbors and hazardous waterways (to be identified by the Captain of the Port in the Federal Register) sufficient competent personnel on board self-propelled vessels would:

1. Stand by the primary steering machinery space to handle a steering casualty.

2. Man the anchor windlass or similar equipment in order to be ready to drop anchor. One bow anchor on these vessels would be ready for letting go.

3. Man the main steering control station to manually control the vessel direction.

b. Set the main ship's propulsion system to maneuvering mode. The vessel's main propulsion spaces would be manned with personnel competent to manually answer engine maneuvering orders if any automatic engine maneuvering system fails to perform properly.

c. Plot the vessel's movement on the corrected chart for the area being transited. Towing vessels with tow in any configuration whose aggregate tonnage is less than 10,000 gross tons would not be required to comply with this requirement. The person maintaining the plot would be required to lay out a trackline of intended vessel movement on the chart. Position fixes would be plotted at sufficiently frequent intervals so that the position of the vessel with respect to the trackline is indicated. If a casualty occurs, the chart would be required to be retained. It is contemplated that a licensed deck officer or licensed operator other than the person actually controlling vessel movement would maintain the plot. The person actually controlling vessel movement would obtain from the person maintaining the plot information on the vessel's movement that is timely, accurate, and understandable.

d. Maintain a bow lookout with adequate communication to the bridge. The master of the vessel would not be required to station a lookout on the bow when conditions prevented the lookout from performing his assigned function.

Dated: June 25, 1974.

W. M. BENKERT,
Rear Admiral, U.S. Coast Guard,
Chief, Office of Merchant Marine Safety.
LORAN-C PHASE CODE AND RATE MANIPULATION
FOR REDUCED CROSS CHAIN INTERFERENCE

by Commander William F. Roland
United States Coast Guard

The Loran-C System is constrained by ITU regulation to ensure that 99% of all energy radiated from any station falls in the 90 to 110 kHz band. All stations radiate pulsed signals with a 100 kHz carrier frequency, and because a very wide band signal is transmitted, all signals have frequency spectra which overlap. Within a chain of stations, mutual interference is avoided by ensuring that each station's group of 8 pulses occur at a unique time such that there is no time overlap of signals, as shown in Figure 1. Between standard Loran-C chains, each operating with a different group repetition interval (GRI), mutual interference is controlled by selecting GRI's which minimize the effects of cross rate signals. Recent proposals for high accuracy limited coverage by Loran-C type stations either for harbor coverage or for privately owned radio location service, has brought out a need for discussion of the methods of assessing mutual interference between adjacent chains. This paper attempts to address that need, and provide the tools for assessing mutual interference.

Referring to Figure 1, a group of 8 pulses is transmitted from each station is a chain. Additionally, a ninth pulse is transmitted by the master station for visual identification of the master signal. The spacing of the pulses is 1000 usec, except the master ninth, at 2000 usec.

Each pulse has a non-symmetric envelope shape, rising to a peak in about 65 usec, and falling in less than 500 usec. Within the envelope, a positive going first half cycle of the carrier is defined as "zero" phase code, and a negative going first half cycle as 180° phase code. These are the only phases used in present codes. For simplicity, a (+) is used to designate zero phase code of a particular pulse, and a (-) to indicate 180° phase code of a particular pulse.

All carrier phase tracking Loran-C receivers operate on these signals by a process of cross correlation (1). Cross correlation is mathematically defined as:

\[ C(\gamma) = \frac{1}{T} \int_{0}^{T} s(t)r(t-\gamma) \, dt \]

In this formula, \( C(\gamma) \) is the average value of the instantaneous product of the signal \( s(t) \), and the receiver's sampling waveform \( r(t-\gamma) \) over the time period \( T \). \( \gamma \) is the time error between the receiver's time reference and the signal time reference. In the receiver, 'T' is a long period of time and \( \gamma \) may vary during that period. However, since \( s(t) \) and \( r(t-\gamma) \) are periodic in 2GRI, it is only necessary to look at the integral for that period. Also, \( \gamma \) will not vary significantly during that time.
Figure 1. Loran-C signal format
The mechanization of \( r(t) \) and the correlation processing may vary significantly from receiver to receiver, however the effect is the same. \( s(t) \) and \( r(t-\gamma) \) contain a \( \sin wt \) and a \( \cos w(t-\gamma) \) term respectively. Therefore, the product inside the integral can be rewritten:

\[
s(t)r(t-\gamma) = A(t,t-\gamma) \sin wt \cdot \cos w(t-\gamma)
\]

\[
= A(t,t-\gamma) (\sin w(2t-\gamma) + \sin \gamma)
\]

The receiver circuits filter and discard the \( 2wt \) term and keep the \( \sin \gamma \) term. The \( C(\gamma) \) expression can then be written:

\[
C(\gamma) = \frac{\sin \gamma}{T} \int_{0}^{T} A(t,t-\gamma) \, dt
\]

\( C(\gamma) \) is the error signal for a phase locked loop which drives \( \sin \gamma \) (hence \( \gamma \)) and the receiver's clock reference error) to zero.

The following diagrams show pictorially the process. Figure 2 shows how the product of \( s(t) \) and \( r(t-\gamma) \) varies with different \( \gamma \) and how the sampling is used to decode the pulse phase code. In 2a, the \( \gamma \) is zero, the \( \sin \gamma \), and therefore \( C(\gamma) \). In 2b, \( \gamma \) is 1.0 usec early and so the \( C(\gamma) \) is positive. In 2c, \( \gamma \) is 2.5 usec late and so \( C(\gamma) \) is negative. In 2d, the signal is phase coded (-) and so the carrier has the opposite polarity compared to 2c; but since the \( r(t-\gamma) \) is also phase coded, the product has the same sign as in 2c.

Extending this thought, Figure 3 shows how the eight pulses of a group are sampled and decoded, and that the samples are summed (integrated) to get \( C(\gamma) \). Note that one of the purposes of summing is to permit averaging to reduce the effects of noise.

Another very important concept is the handling of very large \( \gamma \), such as occurs during search or in the presence of long delayed skywaves. Whenever all the signal phase code factors and the \( r(t-\gamma) \) sampling pulses have the same polarity, the \( C(\gamma) \) value for \( T=2GRI \) equals 16 times any one sample. However, if some of the \( r(t-\gamma) \) phase code factors are of opposite polarity, \( C(\gamma) \) will be less. This occurs when the sampling pulses are aligned on the wrong pulses. Figure 4 illustrates the point. The Figure is identical to Figure 3, except that \( r(t-\gamma) \) is earlier in time than \( s(t) \) by exactly 1000 usec.

Note that \( C(\gamma) \) equals the sum of the products of the phase code signs of \( s(t) \) and \( r(t-\gamma) \) times the amplitude of a single sample. The sum of products of phase code signs is a measure of the correlation function of the signal and the receiver's sampling at a given value of \( \gamma \). If the sum is zero, no matter what the magnitude of the individual samples, the net effect on the receiver will be zero. Since it is not desired to have the receiver track \( s(t) \) except with \( \gamma \) very close to
Figure 2. Instantaneous Product of $s(t)$ and $r(t-\gamma)$ for various $\gamma$. Only one cycle of $s(t)$ is shown, and $r(t-\gamma)$ is shown as a narrow sampling gate.
Figure 3. Correlation Integral during one interval of the Master Signal, $\gamma = -2.5$ usec.

$C(\gamma) = 8[A \cdot \sin(\frac{\gamma_0}{2} \cdot 2\pi)]$
Figure 4. Correlation Integral during one interval of the Master Signal, $\tau = -2.5 - 1000 \mu\text{sec}$.

$A \sin \left( \frac{\tau}{10} \cdot 2\pi \right) = A$

$C(\tau) = -3A$
zero, the sum of signs is used to make this not possible, by carefully
designing the phase code. Table 1 below is a part of the set of possible
mis-alignments by N x 1000 usec of the master signal and the receiver
master phase code, and the resultant sum of signs. Note that the
individual amplitudes of the samples are not shown. Over a 2GRI time,
C() will sum to zero, because the sum of signs is zero, for " values
of -1000 usec, -2000 usec, -3000 usec, and -4000 usec.

<table>
<thead>
<tr>
<th>RECEIVER CODE</th>
<th>CODE IN RECEIVER INTERVAL A</th>
<th>CODE IN RECEIVER INTERVAL B</th>
<th>SUM OF PRODUCTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>S(t) @ γ = -1000</td>
<td>+ - - + -</td>
<td>+ - + + +</td>
<td>0</td>
</tr>
<tr>
<td>PRODUCT OF SIGNS</td>
<td>+ - + - -</td>
<td>0 - + + +</td>
<td>0</td>
</tr>
<tr>
<td>S(t) @ γ = -2000</td>
<td>0 + - + -</td>
<td>0 + - + +</td>
<td>0</td>
</tr>
<tr>
<td>PRODUCT OF SIGNS</td>
<td>0 - - + +</td>
<td>0 - + + +</td>
<td>0</td>
</tr>
<tr>
<td>S(t) @ γ = -3000</td>
<td>0 0 + - -</td>
<td>0 0 + - +</td>
<td>0</td>
</tr>
<tr>
<td>PRODUCT OF SIGNS</td>
<td>0 - + + -</td>
<td>0 - + + +</td>
<td>0</td>
</tr>
<tr>
<td>S(t) @ γ = -4000</td>
<td>0 0 0 + -</td>
<td>0 0 0 + -</td>
<td>0</td>
</tr>
<tr>
<td>PRODUCT OF SIGNS</td>
<td>0 0 0 - -</td>
<td>0 0 0 + -</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 1: Sum of the product of Signs for various γ, using the Master
phase code in the receiver against the master signal.

It is obvious that a simple method of determining the sum of the
products of signs would be helpful, when many different interfering
situations are to be studied. It can be shown (or 'it is left as an
exercise for the student') that if a table is made up as in Table 2,
that the products of signs can be determined by entering in each column,
the products indicated. The darkly outlined area contain the products
of signs. At the top of each area is the receiver code (earliest
sample to the left), to the left is the signal code with the earliest
pulse on the lower end. In this table, the receiver has master phase
code, interval A, in the left hand outlined areas, and master phase
code, interval B, to the right. In the upper areas, s(t) has master
phase code in the same interval as the reciever, ie N x 1000 = γ,
which varies from -7000 usec to +7000 usec. In the lower areas, the
s(t) intervals and r(t-γ) intervals are reversed, ie(15-N) x 1000
± GRI = γ . To fill in the product of signs areas, each sign in the
s(t) column is visualized to move to the lower right, one column at a
time. The sign is then entered as the product of its sign and the
sign of r(t-γ) at the top of that column. Each column then is the
s(t) code from bottom to top, multiplied by the sign of r(t-γ) in that
column. The sum of products is the algebraic sum of all the pluses
and minuses in each row (but not including the s(t) column.
Certain information can be deduced from the presentation of Table 2:

a. When $N = 0$, +/- 9, +/- 13, $C(\gamma)$ may not be zero, depending only on $\sin \gamma$. If $N$ equals some other value, $C(\gamma)$ is zero regardless of $\sin \gamma$, or the magnitude of $s(t)$.

b. Therefore, in a receiver just turned on and beginning the search process, with no known initial value for $\gamma$, $\gamma$ is varied until $|C(\gamma)| > 0$. The receiver must check for a false alignment on $N = 9$ or 13. The receiver must not indicate proper synchronization until these checks are made.

c. A long delayed skywave of the master is equivalent to a signal for which $N = +1, 2, 3, \text{etc. to 7}$. If this occurs, $C(\gamma)$ for that skywave, when the receiver is tracking ground wave, is zero. Therefore long delayed skywaves will not cause an error in the receiver. Skywave delays for $N = +/-8$ Through +/-15 are not possible, so these will not cause errors either.

A slight format change of Table 1 will permit removal of the middle $s(t)$ column, removing confusion when forming the sum of products. For reasons which will become clear later, it is convenient to form the sum of products in the center column. Table 3 is in the form I will use for the remainder of this paper. Step sum is explained later.

Table 3 looks at the effect of a secondary signal received during the receiver's master interval, such as might occur during master search. The following information can be derived from Table 3:

a. $C(\gamma)$ is not zero for all $\gamma$ and hence during master search, the receiver's search process must check to ensure against incorrectly detecting secondary signals and assuming that they are master signals.

b. Long delayed secondary skywaves from a previous interval, equivalent to $N = +9, 11, 13$, could cause errors in the reception of the master signal. Therefore in the design of a chain, sufficient time must be allowed between the last secondary and the master signal to make this event unlikely.

Cross Rate Interference

Cross rate interference is the condition which exists when a receiver is receiving and operating on the signals from one Loran-C chain while signals from another chain are also being received. The 'other' chain is usually geographically adjacent to the one being received, and in fact the chains may share a 'dual-rated' station.

The Loran-C system rate structure (i.e. the set of possible GRI's from which a chain rate may be selected) consists of GRI's which are multiples of 100 usec. If a receiver is operating on GRI'A', there are GRI'A' usec • 100 possible time locations in GRI'A' in which the pulse group from a station in chain B could occur. (These time locations vary with geographic location and are the basis of cross-chain time differences.) If GRI'A' • 100 and GRI'B' • 100 are prime numbers or have no common prime factors, then the pulse groups from chain B will occur in all possible locations in GRI'A', but not necessarily sequentially. If there are common numbers between the A and B rate factors, then less than all locations will be used.
Table 2: Computation of $C(t)$ for Master Signal received and Receiver set to Master Code.
Table 3. Computation of $C(M)$ for Secondary Signal Received and Cross Correlated with Master Sampling.
During any single A interval, the eight pulses from the station on rate B will occur. If this coincides with the sampling of signals on rate A, the samples will be contaminated by the B signals. Since the pulses and sampling strobes on both rates are spaced at exactly 1000 usec, from one to eight samples could be contaminated.

We would like to evaluate the effect of this contamination using the sum of products table. If there is interference the magnitude of the sum of sums will not be zero, and the magnitude of this sum will be a relative indication of the magnitude of the effects. However, if the sum of sums is zero, we can say with confidence that interference will not occur.

To demonstrate this conclusion, refer to table 3, and suppose that the signal GRI, (GRI'B') is 1000 usec longer than 'A' (the rate set into the receiver), and that the receiver is tracking an A rate secondary as a B rate secondary signal begins to cross over. In the first interval that the signals overlap, condition 1 exists. In the next interval, the interfering signal is 1000 usec later and condition 2 exists. Then 3 and so on. During each of these intervals, the magnitude of the sample is the same, because B advanced exactly 1000 usec. The 'step sum' is the sum of the individual interval sums as the interfering signal steps through.

Note that the crossover could also have started on the right hand side of the upper section of the table, or on either side of the lower set of sums of products. There are a total of four possible crossing conditions, but only one has a step sum other than zero. During the cross over represented by this step sum, an offset would be put into the receiver's time reference for the signal being tracked. Therefore, cross rate interference exists in this example.

If all step sums, or simply the sum of all "sumA" and "sumB" entries, is zero, cross rate interference will not occur if both rate A and rate B have no common prime factors. Also the special case of rates different by exactly 1000 usec will not result in cross rate interference, if the step sums are zero.

Designing Rate and Phase Code Combinations for Minimum Interference:

In order that the step sums or the sum of sums is identically zero, the code for one of the two adjacent chains must have a balanced phase code. That is in order for there to be an equal number of pluses and minuses in each section of the products table one of the phase codes must be balanced (equal number of + and -). If in addition all step sums are zero and a rate difference of exactly 1000 usec is selected, then each crossing takes precisely 15 intervals and the net error contribution during that crossing is zero. A 15 interval crossing will take less than 1.5 sec. Since this is less than the typical receiver time constant, it is quite possible to not only make the net offset zero, but to also not significantly increase the standard deviation of receivers subjected to this cross rate signal.
There are seventy possible balanced phase codes for each interval of a two interval code, and therefore 4900 possible two interval codes. Half are complementary and half of those have reversed intervals, leaving 1225 codes. In order to select codes, a scheme is needed to minimize that list. Generally speaking it is convenient for the hardware to have the second interval code related to the first by some logic constant. For example in the present Loran-C codes, the B interval of both the master and secondary codes is the same as the A interval but with the even numbered pulses inverted (phase code sign changed). This same scheme will work for balanced codes only if an equal number of even numbered pulses are + and -. This cuts the available set of codes to 48! It is now only necessary to form them and test. Reading References 2, 3, and 4 will help.

Once a code is found, and I'll throw one out for fun:

```
+ + - - - - - + + - - - - +
```

we need to test the code to see if it is useful and then select a GRI to minimize cross rate interference. (Note that the scheme between the first and second intervals of the above code was to invert even numbered pairs of pulses.) It may also be necessary to come up with an alternative code for secondary stations.

First it is necessary to test the cross correlation of the code with itself, Table 4, and find that:

a. The search scheme in a receiver must guard against correlations at $N = \pm 4$, $\pm 10$, $\pm 12$, and $\pm 14$.

b. There is protection from long delayed skywaves only through $N = +3$.

From this we conclude that a receiver for this code would have a search algorithm modified from that in a standard Loran-C receiver, and that the chain would probably best be used only when short base lines preclude the possibility of long delayed skywaves becoming significant.

Tables 5 and 6 show the sum of products for the cross correlation of the special code and the master and secondary codes used in the Loran-C system. Inspecting the step sums for a GRI difference of $\pm 1000$ usec, it can be seen that there will not be cross rate interference. To emphasize this, the plots of Figure 4 represent the step sums of the four possible crossing situations of Table 5, and show the instantaneous relative value of $C(\tau)$ during each crossing. Similar plots could be made for Table 6. These plots show that the $C(\tau)$ for the interfering signal never becomes as great as the $C(\tau)$ for the desired signal sampled over only one interval.

Further inspection of the step sums of Tables 5 and 6 shows that a GRI difference of $\pm 2000$ usec will also produce step sums equal to zero. What's more a check of the step sums for Table 4 indicates that 2 chains, both using the special code, but with a GRI difference of $\pm 1000$ usec or $\pm 2000$ usec would not cause interference to each other. This says that not only is this an acceptable code from the standpoint of interference to a Loran-C chain, but that the code could be used on two chains adjacent to a Loran-C chain and to each other. One chain would operate at the Loran-C GRI - 100 usec and the other at the Loran-C GRI - 2000 usec.
Table 4. Special Code, cross correlation with Receiver on the same code.
Table 5. Special code, cross correlation with receiver on Loran-C master code.

<table>
<thead>
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<th>N</th>
<th>SUB INTERVAL A</th>
<th>SUB INTERVAL B</th>
<th>SUM</th>
<th>SUM</th>
<th>SUM</th>
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Step: Sum b
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<th>$S_{\text{Sig}}$</th>
<th>RECEIVER INTERVAL $A$</th>
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<th>SUM $B$</th>
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</table>

Table 6. Special code, cross correlation with receiver on Lorqn-C secondary code.

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It is appropriate to point out here that the receiver processing is presumed to maintain its designed linearity during the signal crossings. If, for example, the crossing rate signal is so strong that the antenna preamplifier saturates, then this analysis may not apply. The analysis does however apply to a hard limited receiver, so long as no nonlinearities occur in linear portions of the receiver.

![Graphs](image)

Figure 4. Plot of step sum vs N for the four possible crossing situations of Table 5.

The next step is the design of a second code for the secondary stations. This must be checked for:
- a. search correlations
- b. skywave correlations
- c. correlations with the first special code
- d. correlations and step sums against the Loran-C master code
- e. correlations and step sums against the Loran-C secondary code.

A possible code is: $+ - + - + - + - + - + - + +$

This code has properties similar to the first special code, and has been checked under all the same conditions.

Recommendation:

That codes and GRI's such as these, tested as described herein, be required for use in small Loran-C chains erected within or adjacent to standard Loran-C chains.
Bibliography:


