THE WILD GOOSE ASSOCIATION

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TECHNICAL SYMPOSIUM
October 23 - October 25, 1990

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THE WILD GOOSE ASSOCIATION

The Wild Goose Association (WGA) is a professional organization of individuals and organizations having an interest in Loran (LOng RAnge Navigation). It is named after the majestic birds that navigate thousands of miles with unerring accuracy. The WGA was founded in 1972 and its membership now includes hundreds of professional engineers, program managers, scientists and operational personnel from all segments of government, industry, academic and research institutions and the user community throughout the world, all working for the advancement of Loran.

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1990 TECHNICAL SYMPOSIUM FOREWARD

In order to more widely publicize this announcement, we, the Co-Chairmen for the Nineteenth Annual Technical Symposium which was held in Long Beach, California, opted to publish this item in the Goose Gazette in place of sending individual letters. We want to congratulate all the Session Chairmen for their outstanding participation and accomplishments. The persons cited are Commander Tom Guenther from Coast Guard Headquarters, Dave Scull from NAVCOM in Virginia, Mike Moroney from Volpe National Transportation Systems Center in Massachusetts, John Illgen from IST in California, and Walt Dean from ARNAV in Oregon. These people were greatly responsible for what we felt was an affair without glitches. The persons who actually performed in chairmen roles were not always the same individuals that we had expected only moments before session times. What we mean is that a couple of our chairmen undertook their roles without the benefit of any prior preparation, in particular, Dave Scull and John Illgen. They took the places of Zeke Jackson and John Castonia, respectively, who were unable to attend. We sincerely thank you all for your efforts because we couldn't have gotten along without you.

We also want to express our appreciation to our presenters all of whom did an outstanding job of preparing manuscripts and visual aids, and succeeded in giving very interesting and professional presentations. Several nations were represented from three continents, and we also recognize those people who travelled great distances to get to Long Beach. Your manuscripts were expertly prepared and, for the most part, received on time.

Thanks are also extended to Dick Arnold, the Loran Program Manager for the FAA, to Laura Charron from the U.S. Naval Observatory, and to General Anatolli Funtikov from the Soviet Union, for taking the podium and giving the audience the benefit of their knowledge on Loran and navigation related issues. These people also contributed significantly to the symposium by adding additional interest in their very professional discussions which could not be recognized as extemporaneous preparations.

We want to acknowledge Mrs. Peggy Kool of II Morrow for her great assistance in preparing this publication as well as several of the published materials and projections used by us at Long Beach. Thank you very much, Peggy

We hope that all WGA members will recognize these people for performing a service to the organization overall.

As you read this, we are pleased to announce that the official proceedings should be out of the printers and on their way to you or you already have them. Thus comes the Nineteenth Annual Technical Symposium to a formal close and to opening the pathways for the Twentieth in early October of 1991 at Williamsburg, Virginia, under the direction of Zeke Jackson and Dave Scull. We would like to take this opportunity to encourage all WGA members to strongly consider both participation and attendance.

Larry Cortland Bob Miller

PREPARATORY RESEARCH FOR THE LORAN NORTH ATLANTIC ADVISORY CIRCULAR

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ABSTRACT

The Federal Aviation Administration (FAA) has requested an Advisory Circular be written to guide the aviation public in selecting both equipment and areas of coverage for Loran navigation outside of the National Airspace System (NAS). This first Appendix to the Advisory Circular will focus on the North Atlantic area; subsequent appendices will address other areas of the world.

1. INTRODUCTION

An increasing number of aircraft are flown across the North Atlantic using Loran signals as their primary means of navigation. Portable Lorans are also being used as standby navigation systems for transatlantic ferry flights ranging from light single-engine aircraft to a Swearingen Merlin turboprop. A corresponding increase has been observed in navigation errors of aircraft equipped with Loran. Since few published guides discuss areas outside the NAS, the FAA has requested that a new Advisory Circular be created to help aviators select equipment and locate areas of Loran coverage, thus enhancing safety and instilling aviators' confidence.

2. BACKGROUND

Loran has been approved for use under VFR (visual flight rules) and IFR (instrument flight rules) within the conterminous United States, Alaska, and surrounding United States waters under provisions of the Advisory Circular (20-121A). To use Loran in the North Atlantic a new Advisory Circular is needed. Receiver manufacturers also must install appropriate software for the chains in the area of operation (North Atlantic) so that the Supplemental Type Certificate will not impose limits which preclude the use of the navigation system.

3. RESEARCH

Loran accuracy depends on the user's location within the signal coverage area of the Loran chain. A pilot flying east across the North Atlantic normally uses the following chains: Northeast U.S., Canadian East Coast, Labrador Sea, Icelandic, and Norwegian Sea. Two elements are needed for the Advisory Circular: the typical route that a pilot takes across the North Atlantic, and the expected Loran coverage along that path. A standard North Atlantic flight path for small aircraft is the one taken by Liberty II, a Wipaire converted Cessna 206 equipped with floats. Tom Casey, a veteran pilot from Everett, WA chose this path for one portion of his attempt at a new world record for a flight around the globe landing only on water.

Casey's path (as shown in the July/August 1990 issue of **Wings West**) goes from Moncton, New Brunswick to Gander, Newfoundland to Goose Bay, Labrador, then across the Davis Strait to Sondrestrom, Greenland [Figure 1]. (Pilots seeking a shorter water path over the strait continue to Frobisher, Northwest Territories, and then cross to Greenland.) From the west coast of Greenland, the path crosses to Kulusuk, then across the Denmark Strait to Keflavik, Iceland. The flight continues to Waldergrove, Ireland and thence to the European Continent. All path choices were influenced by the need for float-plane refueling facilities. (Auxiliary Blue Spruce routes heading eastwardly across the North Atlantic go from Deer Lake, Gander, or St. John's in Newfoundland by the tip of Greenland to Keflavik, Iceland. From there, aircraft can go to Ireland, England, or overfly the Faeroe Islands to Norway.)

The National Field Office for Loran Data Support (NFOLDS) provides the FAA with Loran coverage diagrams using the

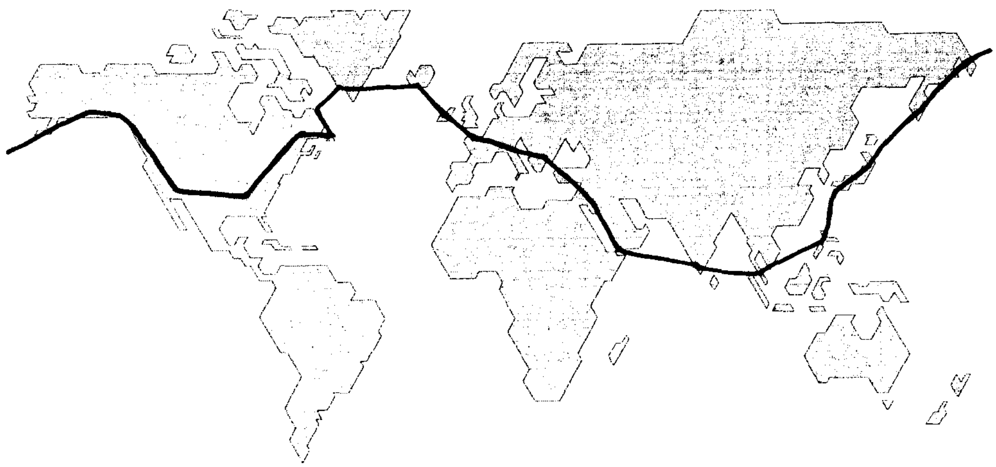

FIGURE 1. LIBERTY II FLIGHT PATH

theoretical Loran Coverage Model. This model has been validated over the United States but not in the North Atlantic. This model is established on two fundamental assumptions:

1. Geometric relationships between transmitter and aircraft receiver, and

2. An input signal-to-noise difference, which is the limit, in decibels (dB), by which atmospheric noise may exceed signal strength at the receiver location for the signal to be useful.

The model predicts field strength based on inputs of transmitter location, radiated power, and a database of ground electrical conductivity values derived from a conductivity map. Signal strength and atmospheric noise values require measurement to validate the theoretical predictions. NFOLDS located a geographic database for the North Atlantic land masses and entered it into the model, along with the latest published values for ground conductivity and atmospheric noise in this area.

A coverage diagram of Norwegian Sea Chain (Group Repetition Interval identification 7970) was run with the new data, and the results compared with published coverage diagrams from Transport Canada and the United States Coast Guard (USCG). NFOLDS reviewed publications of the Wild Goose Association, Institute of Navigation, and the IEEE Position Location and Navigation Symposium for actual data to validate model plots. The analysis, highlighting differences in the extent of coverage east of a line between Bø, Norway and Sylt, West Germany, emphasized the need for validation by empirical measurement [Figure 2].

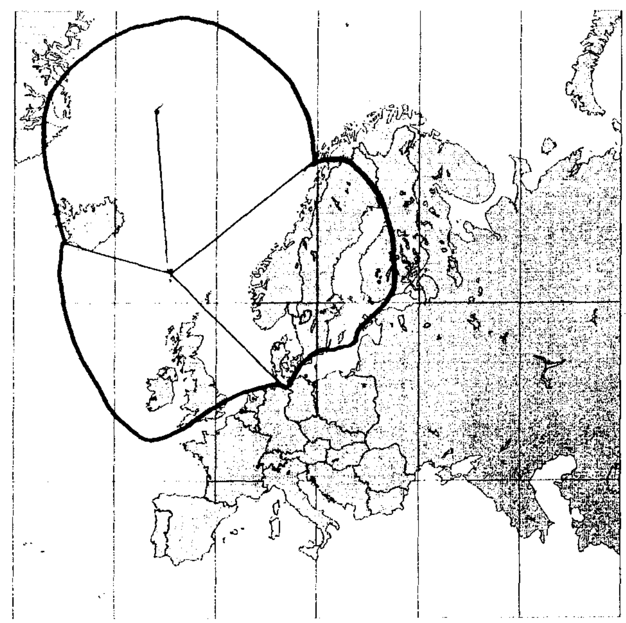

FIGURE 2. PRELIMINARY COVERAGE

The coverage diagrams for other chains in the North Atlantic show close agreement with published literature. The model reveals the existence of coverage between 50 and 60 degrees north from Canada to Iceland and between 50 and 70 degrees north from Iceland to the coast of Norway. It also discloses a lack of signal coverage northwest of the baseline between Fox Harbour, Labrador and Angissoq, Greenland, a result consistent with the literature, especially that of the Transport Canada model.

Note: Transport Canada investigated a promising add-on scenario for the Fox Harbour chain with a new secondary at Kuujjuaq, Quebec. It appears that the Kuujjuaq transmitter would be responsible for significant Loran coverage expansion along the coast of Labrador and over the Davis Strait to the coasts of Greenland and Baffin Island. Plans are underway to collect additional data using a Transport Canada Flight Inspection aircraft in those areas off the Canadian coastline along, and possibly north of the special routes to Europe.

4. DATA COLLECTION

Andrews Air Force Base, MD is the home of the USAF Flight Test Project Speckled Trout. An aircraft of opportunity, Speckled Trout serves as a research and development test bed for evaluating progress in communications and navigation equipment. The Chief of the Flight Test Project offered to collect Loran data in the North Atlantic to confirm the coverage predictions. The NFOLDS staff went over computer-generated coverage diagrams for the North Atlantic with the flight crew.

The area from Finland to The Faeroe Islands (triad MWX of the 7970 chain) had to be validated with empirical data. (Of minor concern was area between the tip of Greenland and Labrador, where NFOLDS coverage agreed with the published data.) A sequence of triads to use on the flight was given to the flight crew. The triad to use approaching the east coast of Greenland is MWX of the Icelandic Chain (9980). On the west coast, the Chain is the Labrador Sea Chain (7930), triad MWX. The Loran station at Angissoq, Greenland supports both chains and the geometry is poor north of the transmitter. From Labrador towards Greenland the Chain to use is the Canadian East Coast Chain (5930), the triad MYZ. The flight should go from strong signal areas to weak, and from weak to strong. Aircraft position (+/- one nautical mile) and time (+/- one minute) should be recorded continuously and entered as footnotes to the record.

The FAA directed NFOLDS to put a data collection package on the aircraft and prepare the data collection and analysis plan.

NFOLDS selected the ANI 7000 Loran receiver, which measures the required parameters (signal strength and atmospheric noise) and outputs data records every second. In the vicinity of transmitters, the unit may sample the transmitted power and give an erroneous reading easily detected in the data stream. The ANI 7000 requires a skilled operator to set it up and insure it is in the track mode. The equipment operates unattended while in the primary triad and when in track.

The FAA Technical Center supplied an ANI 7000 and checked their equipment for ability to operate proper software in the North Atlantic. The data is recorded through the RS-232 outlet into a personal computer. Hard disk storage has floppy disk backup. Ground check of the system with local flights had the dual role of verifying system integrity and training the operators. Installation problems were resolved by the NFOLDS field team. NFOLDS provided all the expected values for the measurements, informed the USCG of the program, and generated a plan for reduction of the flight data.

After two test flights to insure the data collection package was working correctly, Speckled Trout flew across the North Atlantic recording Loran signals [Figure 3]. The path was up the US East Coast across Nova Scotia, Cape Breton, and Newfoundland then direct to London, England and to Bonn, Germany. When Loran signals faded near Ireland, data collection ceased. Data was collected on flight segments from Bonn to the Faeroes and eastward to Helsinki, Finland. A reverse segment was flown from Helsinki to the Faeroe Islands then back to Bonn. The ANI 7000, while tracking the correct triad, measured field strength from Ejde (M), Bø (X), and Sylt (W). The return trip was from Ramstein, Germany to Andrews AFB by way of Keflavik, Iceland and Angissoq, Greenland. On each flight

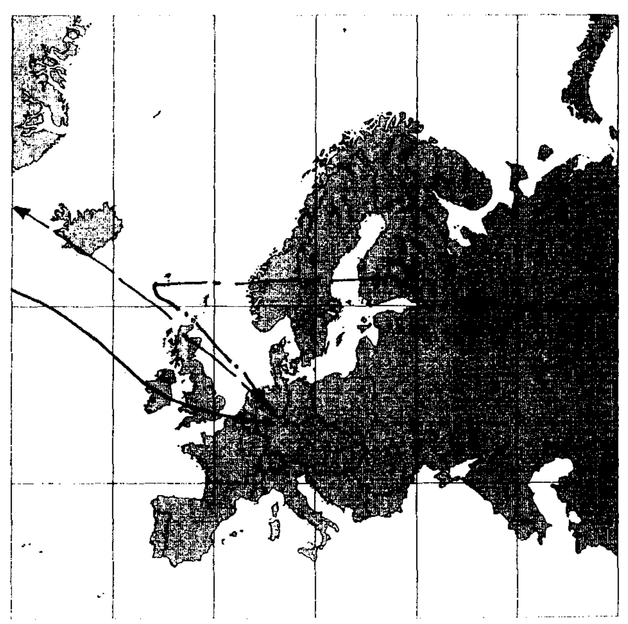

FIGURE 3. DATA COLLECTION FLIGHT PATHS

segment the test engineer annotated the data record with position locations and time from the aircraft's navigation system.

5. DATA ANALYSES

When the Speckled Trout data was processed, the time tag was offset by three minutes between the navigation system and the data collection system. This was calculated by comparing the position location of both Loran and the inertial navigation system, and then synchronized. The position location for each record from the receiver was interpolated from the footnoted flight journal. A graphical comparison was made of empirical and theoretical values for atmospheric noise and radiated field strength.

In the model the geographical area is segmented into cells. Each cell is assigned a conductivity value. Because the propagation path is over cells of mixed conductivity, the Millington method is used to calculate the signal attenuation between transmitter and receiver. Because most of the paths were sea water, few adjustments were made to the conductivity cells. The atmospheric noise grid has larger cells. Worst-case average noise values (of a receiver bandwidth of 30 khz) for the six daily four-hour periods in the summer season were used. The cells of the model were then modified so the theoretical values concurred with the empirical data (precision of +/- 2 dB). The model was modified to permit a read-out of the noise and field strength values for specific locations stored in the database. These were directly compared with analogous positions in the data collection record. The noise values in each cell were reconciled with measured data. Adjacent cells were subsequently adjusted to eliminate discontinuities across cell boundaries. After adjustments were made and checked, new diagrams were created. Coverage diagrams from the validated model then produced maps that matched the empirical data and agreed with other published charts [Figure 4].

The validated model was used to develop signal-to-noise contours for each transmitter. The model also can produce field strength plots for all the transmitters. The -10 dB threshold around each transmitter was identified [Figure 5]. (This threshold determines how far an aircraft must fly by dead reckoning to intersect the signal of the next transmitter if an intermediate one failed.) Each chain was run, with and

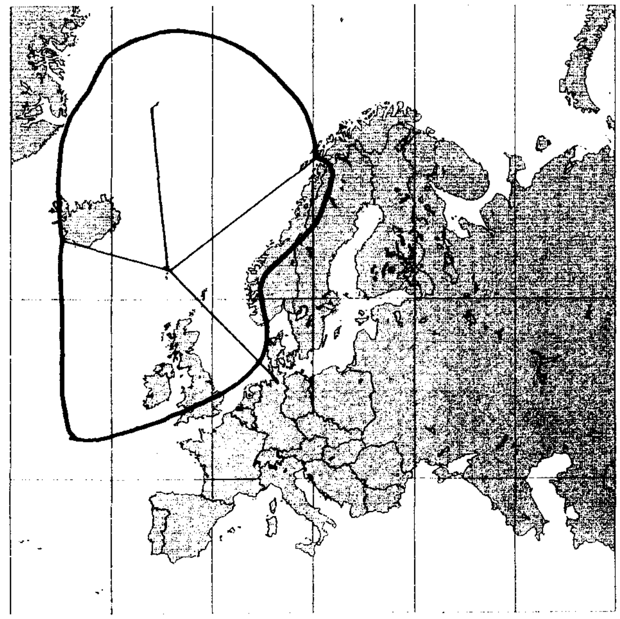

FIGURE 4. VALIDATED COVERAGE

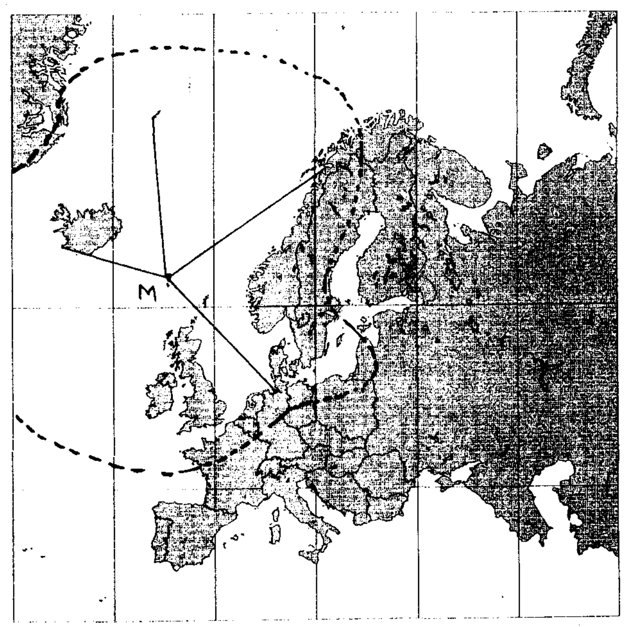

FIGURE 5. 10dB PERIMETER FOR EDJE (M)

without transmitter failures. If the master fails, the receiver operates in the master independent mode. Cross chain receiver capability helps bridge the gaps in coverage. Of course, a catastrophic antenna failure could eliminate a double-rated station providing redundant coverage in the Icelandic and Labrador Sea.

The analysis shows that an aircraft can navigate in the Loran coverage of the North Atlantic if its receiver can

1. operate in a master independent mode,

2. can fix positions via multiple lines-of-position, and

3. create alternate triads via "cross-chaining".

6. CONCLUSIONS

An Advisory Circular is needed to provide guidance to the aviation public in the selection of equipment and the area of coverage for Loran navigation outside of the National Airspace System. An increasing number of aircraft are flown across the North Atlantic using Loran signals as the primary means for navigation. As flights increase, so do Loran navigation errors. Two elements are needed for the advisory circular, the typical route that a pilot would take across the North Atlantic and the expected Loran coverage along the path.

In the fall of 1989, a Loran equipment package was installed in a U.S. Air Force research aircraft to evaluate Loran signals across the North Atlantic. The data was processed and a Loran coverage model adjusted to agree with the empirical data. With new coverage diagrams in hand, a draft of the Advisory Circular will be coordinated and issued, perhaps by late fall, 1990. Small aircraft that cross the Davis Strait north of a line between Fox Harbour, Newfoundland (52 degrees, 22 minutes, 35.2 seconds north; 55 degrees, 42 minutes, 28.4 seconds west) and Angissoq, Greenland (59 degrees, 59 minutes, 17.3 seconds north; 45 degrees, 10 minutes, 27.5 seconds west) are in a poor Loran coverage area. Though coverage north of Angissoq suffers from poor geometry, all routes south of Greenland and north of 50 degrees do have Loran coverage.

7. RECOMMENDATIONS

The NFOLDS is preparing to do the following:

1. Consult equipment manufacturers for receiver inputs.

2. Prepare the draft Advisory Circular.

3. Circulate the draft for comments.

4. Prepare the final Advisory Circular.

8. REFERENCES

Advisory Circular 20-121A, Airworthiness Approval of LORAN-C Navigation Systems for Use in the U.S. National Airspace System (NAS) and Alaska (Washington, August 24, 1988.)

Bleau, Charles, & MacKenzie, Frank, "Model for Forecasting Loran-C Coverage," Proceedings of the Wild Goose Association (Boston, November, 1984).

"Evaluation of Extending Loran-C Coverage in Canada: Discussion of Expansion Options," Transport Canada (Ottawa, July, 1990).

North Atlantic Systems Planning Group, 26th Meeting, Agenda Item 5.2 (Paris, 21 May - 1 June, 1990).

ELECTRONIC EQUIPMENT REPLACEMENT PROJECT (EERP)

by
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1. Abstract

The Coast Guard's Loran-C system has been in operation throughout the world for nearly 35 years. Many changes to the equipment making up this vast system have occurred throughout this period. As with any system, support of the field equipment is a day to day challenge. As technology moves forward, the Coast Guard's support structure is constantly being faced with equipment and components which are no longer available from the commercial market place. In addition, much of the Loran-C equipment suite is custom built for Coast Guard use and this presents an additional support challenge. Finally, as the use of Loran-C continues to expand, new requirements are being placed upon it. These new requirements must often be addressed by the development and implementation of new equipment.

To coordinate these support driven issues, as well as the implementation of new system requirements, the Coast Guard's Electronic Engineering Center has been assigned a multi-year project which is titled the "Electronics Equipment Replacement Project". The primary purpose of this project is to identify immediate support problems, develop near term solutions to these problems, and chart the course for system improvements, while addressing new requirements. This paper reports on progress to date and sets the stage for some long term goals.

2. Introduction

Redesign of various portions of the Loran-C system is necessary to meet the demands of maintaining and operating the system into the next century. Before this redesign activity can begin, it is necessary to ask some basic questions and formulate planning activity so redesign work can proceed with purpose. This paper was prepared relying on some basic System Analysis concepts. Before proceeding, it is necessary to define some of the basic terms and how they are used.

a. **System**. A system consists of a collection of subsystems, each of which contribute to the accomplishment of some tangible system objective. As used here, the term system refers to the entire Loran-C equipment network operated and maintained by the Coast Guard. It does not include the user community, i.e., navigation and timing users. The objective of the Loran-C system is to provide an uncountable number of Loran-C users with signals which can be used for navigational and timing purposes.

b. **Subsystem**. A subsystem consists of a collection of processes, each of which contribute to the accomplishment of tangible subsystem objectives. Subsystems are lower level components of the entire system. This paper defines three subsystems in the Loran-C system. Each subsystem has an associated objective. They are defined later in this paper.

c. **Process**. Subsystem level activity is accomplished by various processes. Processes are performed by partial, single, or multiple pieces of equipment working together. This paper breaks each subsystem into basic processes. Each process has definable inputs and outputs.

d. **Functions**. Individual pieces of equipment serve a purpose in the overall system by accomplishing specific functions. Although noted here for completeness, the details of function level activity are considered to be outside the scope of this paper.

This paper begins with a simple block diagram (defining the subsystems) of the present day Loran-C system followed by specific requirements which must be adhered to during the redesign phase. This paper then summarizes current critical initiatives and concludes with recommendations as to what portions of the system need to be considered for redesign work.

3. System Definition

A simple diagram of the existing, overall Loran-C system is shown in Figure 1.

The three large blocks represent subsystems. The smaller blocks represent similar subsystems which form the overall system. The objective of the entire system is to provide the users, shown as ovals in Figure 1, with Loran-C signals. Each of the subsystems contain various processes which contribute to meeting the respective subsystem's objective, i.e., to control, to transmit, and to monitor. The subsystems are linked by the flow of information, or more simply, data.

4. Bounding the EERP

Requirements placed on the EERP project were previously dictated by the EERP Steering Group. This group is comprised of senior U.S. Coast Guard members who have been, or are presently, assigned to key Loran-C billets associated with operations, maintenance, logistics, and engineering. One of the group's primary functions was to place requirements on EERP activity addressing redesign initiatives. They are:

a. The redesigned equipment must maintain the system's historical availability of not less than 99.95% per station.

b. The System Area Control practice (the Monitor subsystem in Figure 1) will not be changed through redesign work. Alternative control methods may be implemented later, but until such a change is mandated, redesign efforts will continue to follow the existing philosophy.

c. Other than addressing support concerns for two of the existing transmitter types, the AN/FPN-44A/45-series tube-type and the AN/FPN-64(V) solid-state transmitter, redesign work will not concern itself with transmitters. The AN/FPN-3 and the AN/FPN-42 transmitters are not addressed, as they are expected to be phased out.

5. Criteria For Redesign

Targeting portions of the Loran-C system for redesign is based on the following criteria:

a. The supportability of present day equipment. Immediately address those portions of the overall system which can no longer be repaired, supported, or cost effectively maintained today.

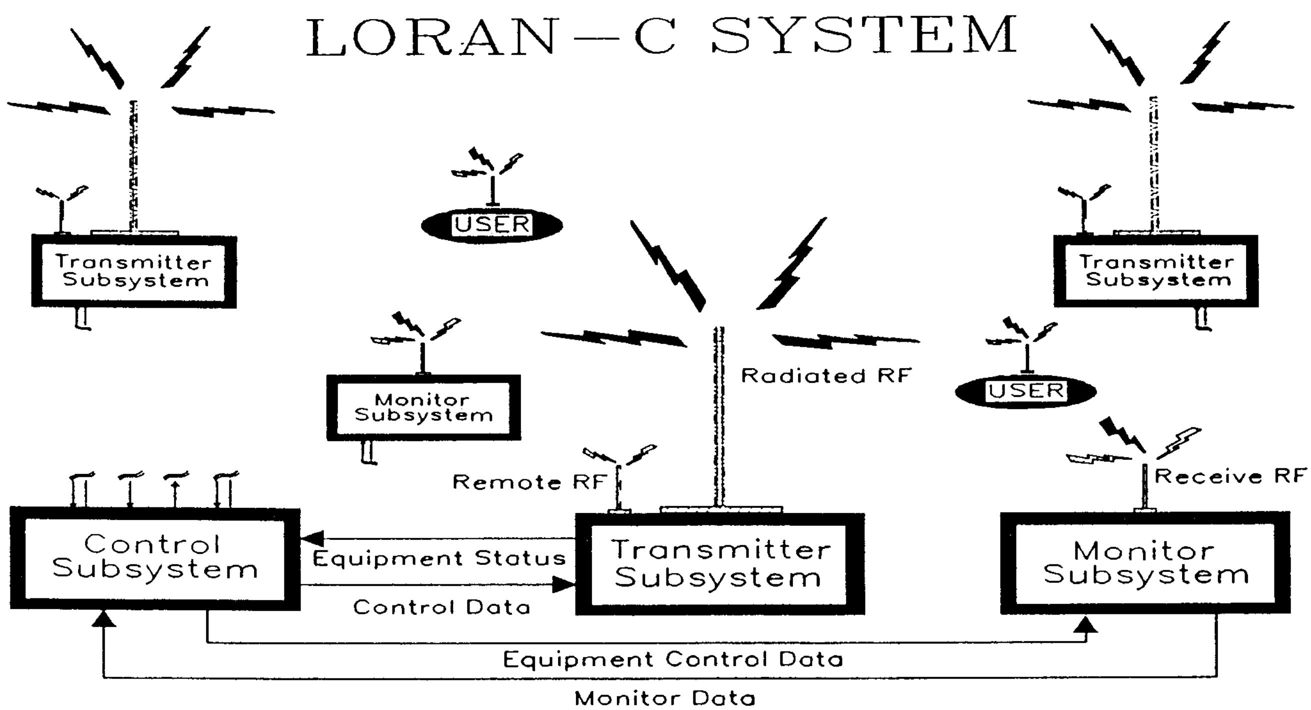


Figure 1

b. The support and maintenance of existing equipment projected ahead five years, i.e., screen the system by asking the question: "Do potential support problems appear imminent?" Projecting beyond five years is judged to contain too many uncertainties.

c. The desire to enhance and expand automation.

d. The need to respond to new system requirements.

e. The desire to remain in close step with technology.

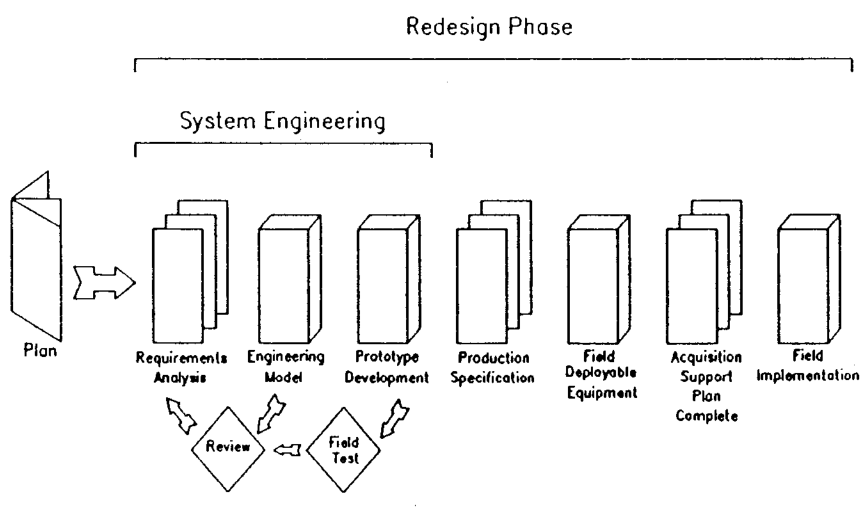


Figure 2

If a particular process does not exhibit some sort of deficiency in at least one area, then that particular process has not been identified for redesign work. These five criteria will be referred to again later in this paper.

6. **Redesign Definition**

The term redesign, as used here, comprises a series of seven steps. The seven steps are shown in Figure 2. Before specific redesign projects can begin, each project must be based on a Plan. These Plans, as depicted on the left-hand side of Figure 2, are not part of the overall redesign phase but rather the impetus for each respective redesign effort. Each Plan, if properly developed and followed by a successful redesign project, will ultimately contribute to the desired system structure. The formulation of these Plans is a primary objective of the EERP.

As stated here, a typical redesign project is assumed to span a five-year period. The first three steps shown in Figure 2, requirements analysis, engineering model and prototype development, fall under the heading of System Engineering.

The steps following those which define System Engineering will be accomplished on a Plan-by-Plan basis through coordinated efforts between the engineers, the equipment managers, the support managers, commercial contractors, and the operators. This paper does not address details of these steps, but they are extremely important if redesign efforts are to be successful.

Unfortunately, there are some support critical issues facing the Loran-C system today which can not be afforded the luxury of a detailed systems engineering approach. Timely solutions are paramount. In these cases, it is imperative to address those issues with very flexible, multi-option solutions so as not to constrain the redesign plans to be discussed in the next section. Furthermore, in that these issues are critical, they must be addressed immediately and low risk rapid solutions implemented. The following paragraphs will summarize the low risk EERP efforts currently underway at EECEN. In each case, it will become clear that the System Engineering phase has been accelerated and rapid implementation achieved through the use of very flexible, rather obvious solutions as opposed to creative, well planned long range strategies. Nonetheless, all are good solutions and lend themselves well to future enhancements and integration into the Loran-C system of the future; the urgency of the situations simply prevented these solutions from being a part of that evolution.

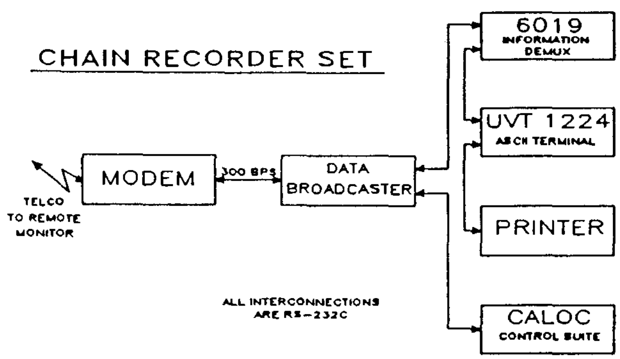


Figure 3

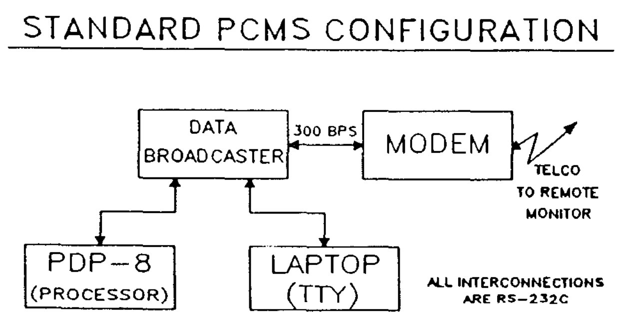


Figure 4

a. **DELTEC 1210 UPS Replacement.** The DELTEC 1210 UPS presently protects the line AC power path for the Primary Chain Monitor Set (PCMS). It has not been supported by the manufacturer for many years and has become a high failure maintenance item. The ELGAR UPS-102 has been an integral part of the Remote Operating System (ROS) for many years and has proven itself to be a reliable unit. Furthermore, support is still available from the manufacturer. The ELGAR UPS-102 was evaluated as a form-fit-function replacement for the PCMS and found to be acceptable. Such a replacement in no way constrains future PCMS redesign since any such replacement will most certainly require UPS protection and the 1KVA rating will certainly be sufficient for the intended application. This change is currently being implemented by EECEN.

b. **ELGAR UPS-501 Replacement.** The UPS-501 has been used to provide backup AC power in the event of commercial or station power loss for the timing reference at LORSTAs as well as the Calculator Assisted Loran Controller (CALOC) and the Remote Site Operating Set (RSOS) at control sites. In all cases, the UPS-501 has become a maintenance nightmare. No support (manufacturer nor Coast Guard) has been successful. Two efforts are underway to resolve this.

At the control sites, two UPS-501s are in use to backup the CALOC and the RSOS (one each). One UPS-102 is perfectly capable of doing the job of the two UPS-501's. In this regard, the UPS-102 was selected for the same reasons listed for the DELTEC 1210. This modification is in its implementation phase.

With regard to the UPS-501 in use to protect the LORSTA timing reference, a more involved approach is needed to solve yet another system anomaly, i.e., lack of standardization. Through the years, LORSTA backup power configurations have evolved to the state that no two sites are similar. This has created a serious configuration management problem. The UPS approach to AC power backup was questioned and ultimately DC power backup was found to be more appropriate. The simple addition of another DC power unit (reliable support already in place) will do the job. The desire to standardize has been met through the development of a DC power interface. All DC power is provided to the interface and distributed to the required equipment through meters and breakers. A clean, attractive, supportable and standard means by which timing references are protected was developed. This upgrade is also in the implementation phase.

c. **Teletype Replacements.** Perhaps this effort is having the greatest impact on the field. It is a far reaching endeavor that has brought a highly antiquated system truly within reach of the state of the art. While this hardly sounds low risk and multi-optioned, it was in fact accomplished with relative ease resulting in a very versatile and attractive arrangement. The undertaking upgrades three systems; the Chain Recorder Set, the Primary Chain Monitor Set (PCMS) and the control and administrative teletype systems.

1) **Chain Recorder Set.** Figure 3 depicts the new configuration. The Texas Instruments 733 teleprinter (support virtually nonexistent) was replaced by a simple ASCII terminal off the existing Coast Guard Standard Workstation (CGSW) contract which provides for UNISYS support. In addition, the old 60 mA interface was upgraded to an RS-232C standard and the data rate increased to 300 BPS (formerly 110 BPS).

This new configuration deletes archaic, difficult to support equipment and the RS-232C replacement scheme will lend nicely to any future PCMS upgrades. Most importantly, a critical system problem was resolved through an effective upgrade that will not constrain future, more encompassing evolution via the EERP.

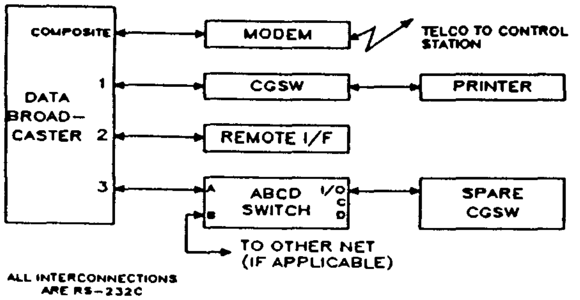
2) **Primary Chain Monitor Set (PCMS).** Figure 4 depicts this new arrangement. Again, the Texas Instruments 733 teleprinter was replaced by a PC compatible laptop computer from the CGSW contract. The 60 mA interface was upgraded to the RS-232C standard.

When replacements for the Austron 5000A receiver are evaluated, the PC compatible laptop will provide much flexibility. It may remain as a simple teletype or may be programed to act as the main processor replacing the outdated DEC PDP-8.

3) **Control and Administrative Teletype.** Figure 5 depicts the standard Loran-C station and Figure 6 the standard control site configurations. The word standard is emphasized since until now, standardization was far from the case.

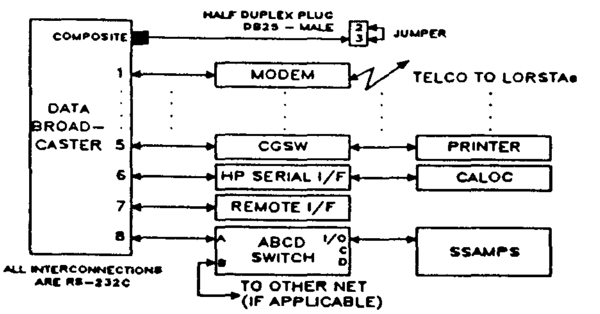
The CGSW was selected to replace the aged Model 40, Model 42 and Texas Instruments Model 732 teletypes. Again, the 60 mA interface was replaced by the RS-232C standard. This flexible arrangement has been implemented on the sophisticated X.25 packet switching system operated in Alaska and also on the less complex, albeit historic, 60 mA hubber system still in use on the

Canadian West Coast. Future evolution of this system may allow for the consolidation of CALOC and ROS on the single processor eliminating two systems altogether. Current efforts include the automated compilation of COCO reports; altogether a very flexible solution to an immediate problem providing even greater opportunities for future evolution.



STANDARD LORAN STATION LAYOUT

Figure 5



STANDARD CONTROL STATION LAYOUT

Figure 6

7. **Presentation of Plans To Initiate Redesign Projects**

In the recommendations which follow, each Plan (referring back to Figure 2) includes the following:

a. A brief explanation of what the redesign project will address.

b. The subsystem where the redesign work applies, i.e., Transmitter, Monitor or Control subsystems.

c. The specific processes to be addressed by the redesign.

d. The equipment which may be impacted using the present day system as a reference.

e. The reason(s) why the particular process was identified for redesign. The criteria for selection are as discussed in section (5) of this paper.

Following the presentation of these five items, a suggested method of addressing each Plan is presented using input and output diagrams. If the Plans are determined to be worth further consideration and specific projects are assigned, then the steps indicated in Figure 2 will be used to pursue the respective Plan through the redesign stages.

PLAN 1
EPA/PGEN/LORDAC REDESIGN

The equipment presently used to generate drive waveforms at tube-type transmitting stations requires a significant amount of "hands-on tweaking" to maintain proper transmitted pulse characteristics. This is accomplished by visually observing oscilloscope presentations of the transmitted pulse ground return signal and manually adjusting a multitude of switches to obtain the desired signal shape. The automation of this process will require improved monitoring methods as well as new control functions. Additions to present day manual methods may be the automation of alarm detection followed by a decision as to what equipment choice is appropriate (operate or standby paths). With proper design, the monitoring functions could be recorded and desired operational data stored for historical purposes. Another feature which could be designed into the unit is analogous to the present day Loran Data Acquisition (LORDAC) equipment. This equipment, twelve of which were constructed in the early 80's, provides a more through analysis of the transmitted pulse. Its use is limited by non user friendly features characteristic of obsolete technology, and the limited number of available equipment. With today's state-of-the-art hardware, the capabilities of the present day LORDAC can be easily incorporated, significantly improved, and permanently installed at each station. Additionally, with proper design, the unit could also be developed in a modular fashion so that the monitor and recording processes could be used at SSX stations.

o SUBSYSTEM IMPACTED:
The Transmitter Subsystem

o PROCESSES AND EXISTING EQUIPMENT IMPACTED:
Signal Generation: Pulse Generator (PGEN)
Signal Monitoring: Electrical Pulse Analyzer (EPA)

o REASONS FOR REDESIGN:
Support of present day equipment: portions of the Electrical Pulse Analyzer are no longer available as form-fit-function.
Improve automation: pulse building at a tube-type transmitter is a manual process using the present Pulse Generators (PGENs).
Respond to new system requirements: there is a new system requirement called "Aviation Blink." This Plan, if pursued with this objective, has the potential of being a distant future solution to meet the requirements of Aviation Blink. It does not address the immediate need to respond to this requirement. The subject of Aviation Blink is discussed in more detail in PLAN 3.

The input and output diagram in Figure 7 is a suggested approach to implement this plan. There is a project underway at EECEN which began in FY90 addressing this plan.

PLAN 2
INTERCHAIN TIMING

Interchain Timing is a requirement defined in Public Law 100-223, Section 310. The present day Loran-C system has no automatic method of synchronizing the Loran-C Master transmitters to an independent reference. Although the Law does not require that this be done automatically, the Law does require a tightening of allowable limits which makes the present day method of manual control significantly more labor intensive. What must be developed is a means of monitoring the Time of Transmission (TOT) of master stations and a means of automatically controlling that TOT to within 100 nanoseconds of a reference which is also common to other Loran-C Master stations. The method of maintaining synchronization from Master transmitter to Master transmitter relative to the independent reference is a communications problem which can be addressed as policy issues are resolved. The primary focus of this Plan is to develop the interface to the existing Timer Control Equipment (TCE) so the human dependency in the process can be significantly decreased or eliminated altogether.

o SUBSYSTEM IMPACTED:
Transmitter Subsystem

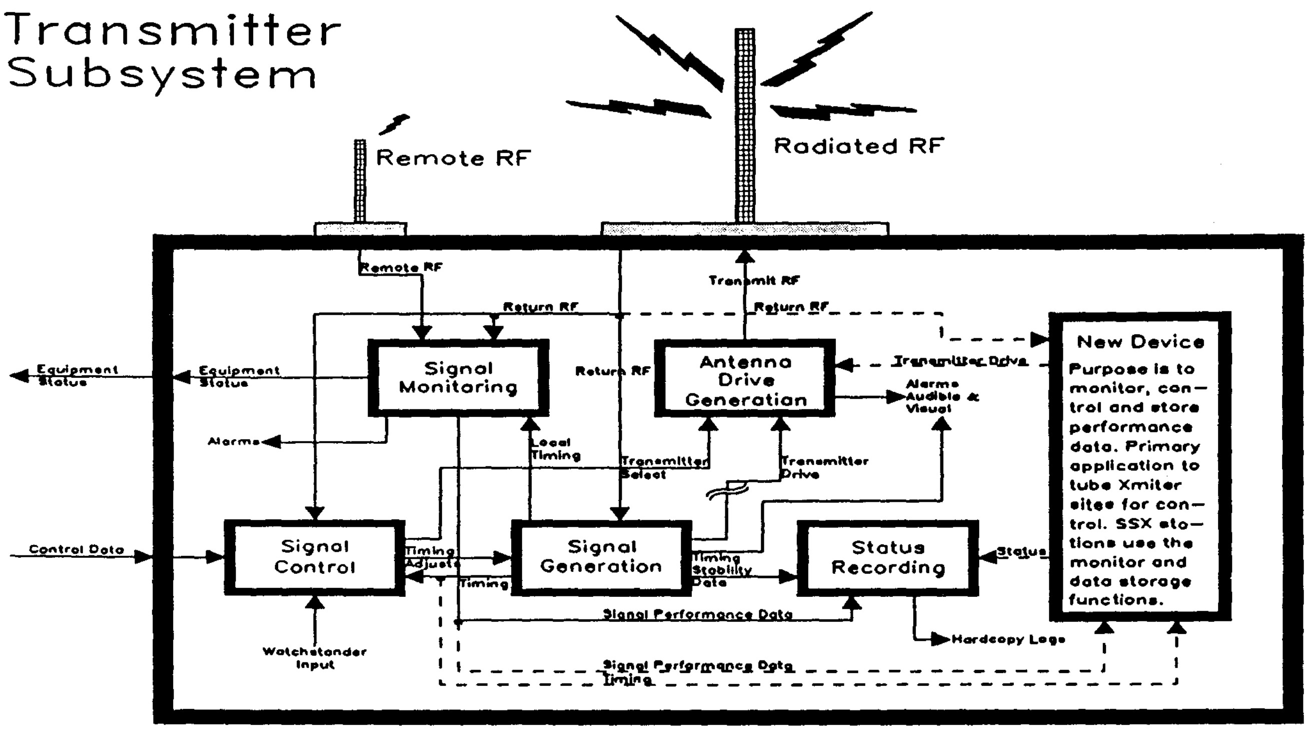


Figure 7

o PROCESSES AND EXISTING EQUIPMENT IMPACTED:
Signal Generation : Timer
: Microstepper

o REASONS FOR REDESIGN:
Improve automation: an automatic method of control is desired.
Respond to new system requirements: the requirements of Public Law 100-223, Section 310 must be addressed.

The input/output diagram in Figure 8 is a suggested approach to implement this plan. There is a project underway at EECEN which began in FY89. This project has already accomplished a good portion of the "Requirements Analysis" and developed an engineering model which performs the monitoring portion of this Plan. What needs to be further developed is the controlling process.

PLAN 3
AVIATION BLINK

Loran-C is rapidly becoming an integral navigational tool of the aviation community. A new requirement being discussed is the automatic detection of a signal problem followed by appropriate action to warn the users. The time to detect and react to a problem is presently undefined. This Plan addresses the new requirement focusing solely on the transmitter equipment. The Plan begins by specifying three basic requirements which must be followed in the redesign phase:

a. The method ultimately chosen to "react and warn" the user after the detection of a problem must not violate the requirements indicated in section 4 of this paper; namely, "Redesigned processes within the subsystems must maintain the historical system's availability of not less than 99.95% per station."

b. The method ultimately chosen to "react and warn" the user must not include human intervention

c. The parameters monitored to detect a "problem" at the transmitter equipment can not be assigned tolerances which are more stringent then those presently required of the Loran-C System.

o SUBSYSTEM IMPACTED:
Transmitter Subsystem

o PROCESSES AND EXISTING EQUIPMENT IMPACTED:
Signal Generation : Timer
(automatic warning modification)
Signal Control : New Device
Signal Monitor : New Device

o REASONS FOR REDESIGN:
Improve automation: an automatic method of control is desired.
Respond to new system requirements: Aviation Blink is a new system requirement which requires automatic detection followed by automatic initiation of blink or off-air.

The input and output diagram in Figure 9 is a suggested approach to implement this plan As indicated in Plan 1, a future "fix" may be realized using that specific Plan. Plan 3 addresses the subject directly and independently. There is no project underway at EECEN to address this Plan.

PLAN 4
PRIMARY CHAIN MONITOR SYSTEM REPLACEMENT

The Monitor subsystem equipment is approaching the day when it will be a major support problem. Redesign work should address the entire subsystem. The equipment making up this subsystem is commonly referred to as the Primary Chain Monitor Set (PCMS). If this Plan is pursued soon, this will be a low-risk project for the following reasons:

a. Development to the prototype stage can occur easily in the lab environment using actual Loran-C signals or simulated signals.

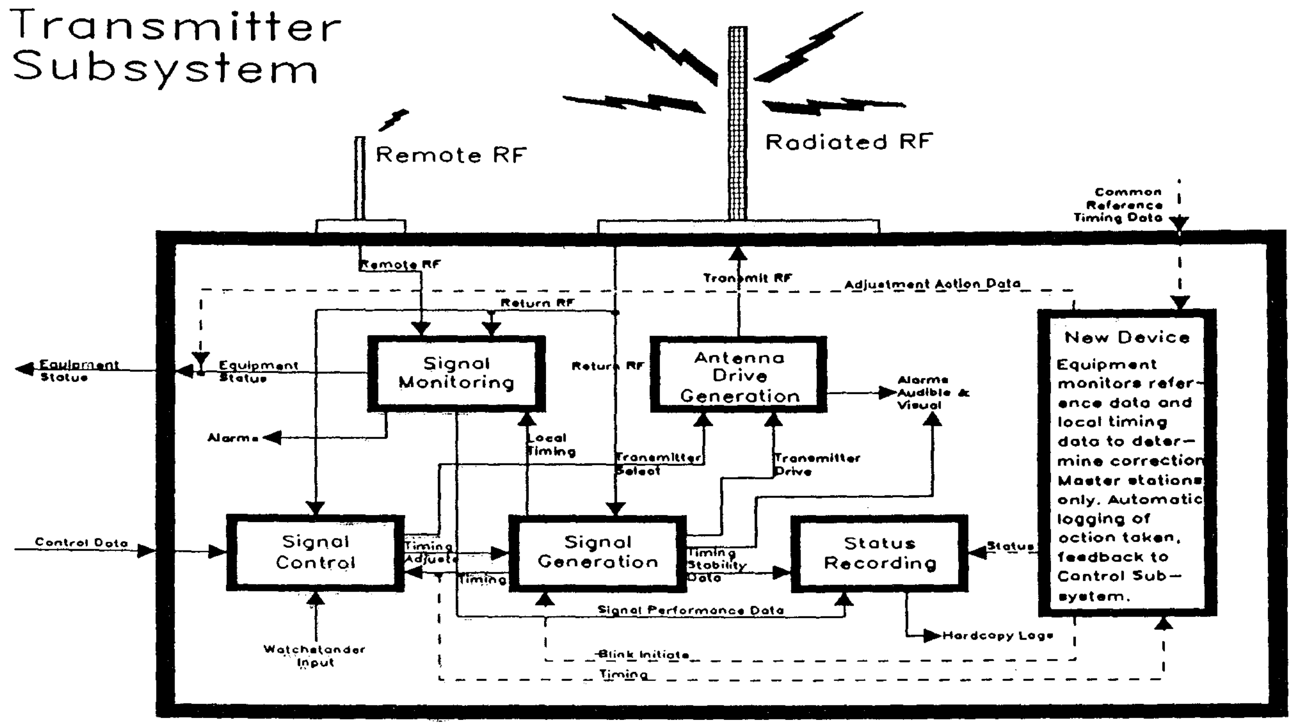


Figure 8

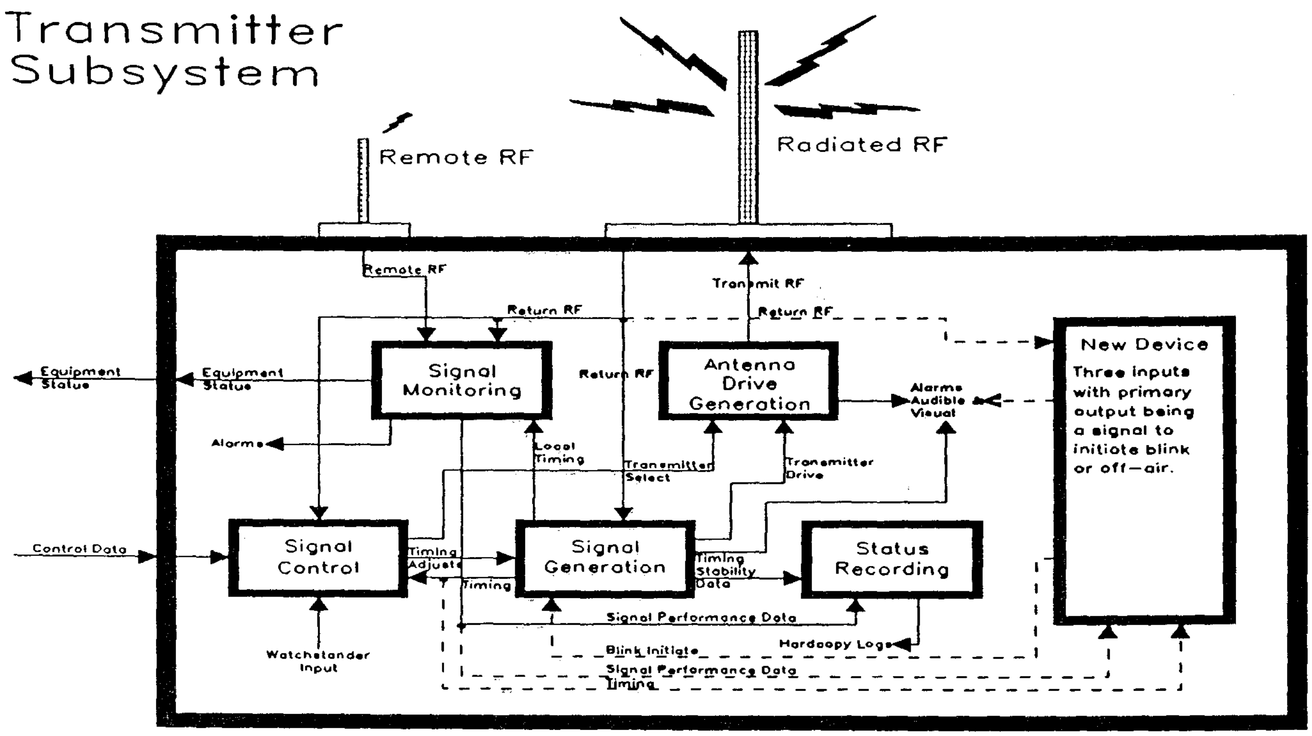


Figure 9

b. Once the prototype is developed it can be installed in parallel with an operational PCMS system. In this configuration, it can be tested in a standby status to iron out problems. Ultimately, as confidence in the prototype design is gained, it can be tested in an operational mode with the present day equipment serving as a "truth" reference. This is a luxury which does not apply to redesign efforts at either of the other two subsystems.

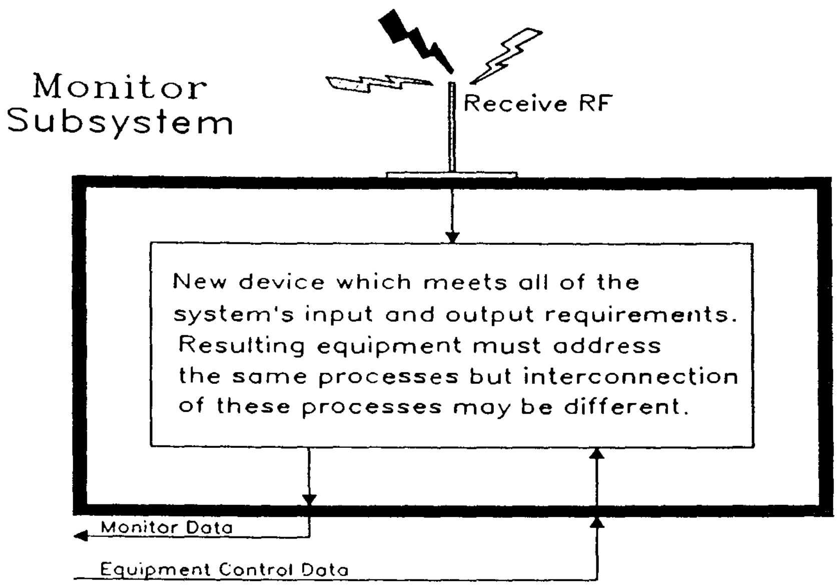


Figure 10

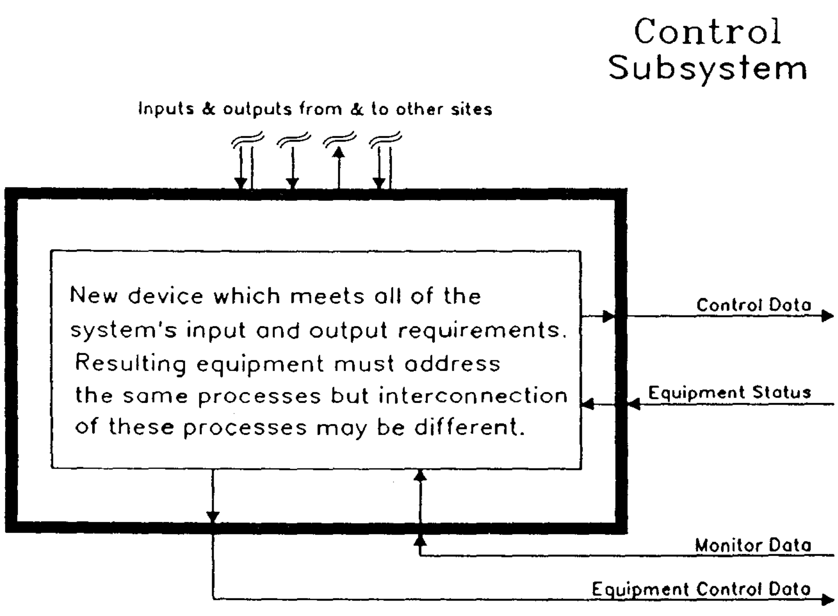


Figure 11

Minor changes to the existing system parameters, data format, receiver status and report messages to the Control subsystem will most likely be necessary. This will have some impact on the Control subsystem. The specifics will be determined once a project is assigned and the Requirement Analysis (referring back to Figure 2) is developed.

o SUBSYSTEM IMPACTED:
Monitor Subsystem

o PROCESSES AND EXISTING EQUIPMENT IMPACTED:
Signal Tracking: All equipment
Signal Interface and Control: All Equipment

o REASONS FOR REDESIGN:
Support and maintenance of the equipment projected ahead five years: essentially every major piece of equipment in the Monitor subsystem is, or shortly will be, a maintenance problem. Now is the time to plan for a replacement.
Remain in step with technology: technology has progressed significantly since the late 1960's. To avoid escalating repair and maintenance costs the upgrading effort must begin now.

The input and output diagram in Figure 10 is a suggested approach to implement this plan. The inputs and outputs essentially remain the same (possibly a different format) with the equipment making up the subsystem changed. There is a project, which began in FY91, underway at EECEN to address this Plan.

PLAN 5
CONTROL EQUIPMENT CONSOLIDATION

From the perspective of information presentation, one major flaw in today's Control subsystem is the dependency on human watchstanders to evaluate incoming data from multiple sources. Today's control watchstanders must understand visual and audio outputs from multiple pieces of equipment with no means of interpreting what a single device is telling them, if they can not correlate this data with information from another piece of equipment. For example, if a Monitor subsystem indicates a problem on Transmitter subsystem "X", and if that is the watchstanders' only piece of information (the monitor subsystem error), they cannot make an intelligent decision as to whether Transmitter subsystem "X" has a problem, or if the Monitor subsystem has a problem. Combining the Monitor subsystem data with information from the Transmitter subsystem "X" is vital if the watchstanders are to make a decision. Eliminating the need to combine information is not the solution, but rather consolidation of all available information into one piece of equipment is proposed. This consolidation will significantly simplify the watchstanders' job. Once accomplished, further development can be pursued to automate the decision process and ultimately present the watchstanders with suggested actions or possibly let the device take those actions and advise the watchstanders what happened. To a limited degree, this project could be developed to the prototype stage and run in a parallel mode with the present day equipment, but this will need to be addressed only after the Plan is approved and a project is assigned.

o SUBSYSTEM IMPACTED:
Control Subsystem

o PROCESSES AND EXISTING EQUIPMENT IMPACTED:
Signal Monitoring: New Device
Signal Control: New Device
Signal Alarms: New Device
Status Recording: New Device

o REASONS FOR REDESIGN:
<u>Support and maintenance of the equipment projected ahead five years</u>: the majority of the existing equipment in the Control subsystem is now supported through pipeline spares, in-house repair, and buying of excess equipment outside of the Loran-C community. In some isolated cases, manufacturer repair can still be obtained.
<u>Improve automation</u>: operation of the Control subsystem is labor intensive. Many watchstander actions can be handled by equipment modernization. Such simple actions as transforming Transmitter subsystem daily operation reports from teletype hard copy messages back to data entered through another keyboard can be eliminated.
<u>Remain in step with technology</u>: the technology to manipulate multi-input sensor data into a central computer processor has advanced significantly since the equipment making up the present day Control subsystem was designed.

This is basically a complete redesign and consolidation effort. The inputs and outputs shown in Figure 11 are essentially the same as those depicted in the present day Control subsystem, only the equipment making up the subsystem will change.

There is presently no project underway at EECEN to address this Plan.

8. <u>Summary</u>

The Loran-C system which is maintained and operated by the United States Coast Guard has proven itself as a very reliable tool for navigation and timing purposes. The use of Loran-C, as well as the availability of Loran-C in new areas, continues to grow. Within the next few months, two additional chains will become operational within the Mid-continent region of the United States. On the international scene, a joint U.S. and Soviet Loran-C chain is forthcoming, to provide coverage in the Bering Sea. The Coast Guard must maintain a constant focus on the support of the present day system, as well as a clear path toward system modernization and adherence to new requirements. This paper has provided a brief look at the planning and coordination efforts being addressed by the Coast Guard's Electronics Engineering Center in Wildwood, New Jersey.

This paper also identifies some of the immediate support problems confronting the Loran-C program. The problems vary from simple replacement and standardization of backup power methods, to addressing the format and equipment used in the exchange of information within, as well as between, the various subsystems of the overall system. As these problems are being addressed, one major factor must be considered: immediate solutions must not limit nor adversely impact long term plans and must integrate into those plans without major redesign.

With regard to long term redesign goals, five Plans have been presented which are intended as foundations for follow-up engineering efforts to upgrade the overall Loran-C system. The driving forces behind redesign recommendations are tied directly to support issues (both immediate and projected), expanded automation, new system requirements, and advancing technology.

The opinions and positions expressed herein are solely those of the authors and do not constitute the policies of the United States Coast Guard, or any other government agency. The information provided is for information purposes only and may not be quoted or used for any other purposes.

9. <u>**Bibliography**</u>

LCDR Doug Taggart graduated from the U.S. Coast Guard Academy in 1976 with a B.S. degree in Electrical Engineering. After graduation, he was assigned to the U.S. Coast Guard Cutter Hamilton as Communications Officer. Next came a tour at the Department of Transportation's Transportation Systems Center in Cambridge, Massachusetts. LCDR Taggart was then accepted in the Coast Guard's Electronic Engineering postgraduate study program. Upon graduation from Purdue University in 1980 with an MSEE, LCDR Taggart was assigned to the Electronics Branch of the U.S. Coast Guard Research and Development Center in Groton, Connecticut. During this tour he was project manager of three R&D Loran-C projects directly related to the use of Loran-C; Harbor/Harbor Entrance Surveying, Loran-C Stability Study and the Loran-C Guidance Equipment project. The next tour, from 1985 to 1987, took him overseas as the Coordinator of Chain Operations for the Mediterranean Sea Chain. In 1987, he was transferred to his present assignment at the Coast Guard's Electronic Engineering Center in Wildwood, New Jersey. He is the Transmitter Section Chief, serving as Project Manager on a number of projects, one of which is the Electronic Equipment Replacement Project (EERP).

LT Ben Stewart graduated from the U.S. Coast Guard Academy in 1982 with a B.S. degree in Electrical Engineering. After graduation, he was assigned to the U.S. Coast Guard Cutter Bibb as the Electrical and Damage Control Assistant. LT Stewart was then accepted in the Coast Guard's Electronic Engineering postgraduate study program. Upon graduation with an MSEE from the Naval Postgraduate School (Monterey, CA) in 1986, LT Stewart was assigned to the Electronics Engineering Center in Wildwood, New Jersey where he presently serves as the Receivers and Control Section Chief in the Loran-C Branch. During his four year tour in Wildwood, LT Stewart has served as Project Manager on a number of projects requiring extended periods of both domestic and international travel. He specializes in Loran-C remote operating and communication systems and the majority of his recent efforts have directly related to the EERP. Last month he also completed an off-duty postgraduate program with Monmouth College attaining an MBA degree.

THE NORTH WEST EUROPEAN LORAN-C SYSTEM - AN UPDATE

ANDREAS STENSETH

Norwegian Defence Communications and Data Services Administration (NODECA)
(Chairman LORAN-C Policy Group)

I. INTRODUCTION

Those of you who were present at the Wild Goose Convention last year were introduced to the plan for a North West European LORAN-C System and the main events leading to the development of this plan. For the next ten minutes or so I intend to update you on the latest developments towards the fulfillment of the plan based on last years more detailed introduction. However, for the benefit of those of you who were not present at the last Convention, I will make a short recap.

The system as visualized a year ago looks like this and is essentially the same today. The countries presently involved are: Canada, Denmark, France, Germany, Iceland, Ireland, Norway and the United Kingdom. A LORAN-C Policy Group with official representatives from each of these countries is the focal point in planning and directing this effort.

The staffing of an International Agreement hopefully to be signed by each of the participating countries, is in the concluding stage - by the way last year it was called a Memorandum of Understanding. The Policy Group meeting in September last year put off the date for a final decision by 4 to 6 months -basically because some nations needed more time to consult the potential users and verify the technical capabilities of the system. These 4 to 6 months have now become 12. A final yes or no to the system is now expected within the next half year.

In the proposed International Agreement, Norway has accepted the role as so called Coordinating Agency - that is to take care of the minimum joint technical, operational and administrative efforts necessary to have the system work as a system. The Royal Norwegian Ministry of Fisheries have asked my organization; the Norwegian Defence Communications and Data Services Administration - NODECA - to take care of the executive functions in this regard.

The organizational structure of the system as presented last year looks like this and is still the concept from which we work. In my closing remarks last year, I said I would be very disappointed if I am not in the position to report progress from an ongoing project at this Convention. Well, the project has still some way to go before the agreement is signed. The reason is basically unexpected and unforseen problems in one member country. However, while I am not that disappointed after all, it is because a number of things have happened which makes me believe that we will reach our goal at the end, and the rest of my brief will be a short introduction to some of the events supporting my optimism.

II. MILESTONES

The most important milestone this year was the political decision taken in the United Kingdom to go for LORAN-C - true enough on certain specified conditions, and it is interesting to note that one of these conditions was that the system should preserve its international flavour - . This is a concern which we in Norway share with the UK and it is from that point of view encouraging to note all the global LORAN-C activities, I am referring to the contract with India, serious interest in Venezuela and other countries and last but not least IALAS engagement in the Mediterranean and the Far East towards the establishment of LORAN-C planning groups across national borders. The pronounced interest by the Soviet Union for combined use of CHAYCA/LORAN-C in the North East European area is of particular importance to my country.

As some of you will know, Denmark was one of the nations that asked for more time to consider its continued participation in the development of a NW European LORAN-C system. Part of the background is believed to be that Denmark took over the DECCA-stations on Danish soil when the commercial operation of this system ceased in 1987. The necessary investments obviously did not give the best possible basis for new investments in LORAN-C a few years later. The radionavigation requirements at Greenland and the Faroe Islands are however, not met by DECCA and complicates the issue. Realizing this, the other members of LORAN-C Policy Group offered Denmark a considerable reduction in the up to then, agreed Danish contribution and we are still awaiting a final Danish decision. It is however, clear that whatever this decision will be, Denmark is prepared to continue the operation of the stations at Angissoq and Ejde if required for the NW European system and contribute towards the maintenance of these stations. The rest of the Group is still committed to LORAN-C - this commitment was again confirmed at the Policy Group meeting in Oslo 19-20 July. However, the offer of reduced Danish share or indeed a possible Danish withdrawal from the project, will have to be compensated for by reductions elsewhere in the system since the national shares agreed with full Danish participation represented the maximum possible from each one of the remaining members of the Group. To this end alternative configurations were considered and technical and logistics arrangements at each site were analyzed. The result was that a so called "Option 2" was adopted.

Under Option 2 the present configuration is kept as it is, but with reduced power outputs at certain sites, re-arrangements within the logistics field and a few other economy initiatives. By these measures we are very close to bridging the gap created by a possible reduced Danish participation. However, there are a number of other reasons why a Danish withdrawal from the project would be seen as a set back for the system, the reduced international flavour is one, another is that close to 30 years of experience in the operation of LORAN-C stations would be lost to the system and finally the idea of a common system for the region with potential for further developments in the Baltics and other areas would to some extent be compromised.

The delays basically caused by the Danish situation, would have to be made up for in order to avoid delays in the completion date of the system since this date is closely related to the USCG withdrawal of its stations in the area - stations which are part of the new system. To this end the Policy Group at its meeting 19-20 July this year approved the establishment of a provisional Co-ordinating Agency to make it possible to start the planning process including preparation of specifications, negotiations with the vendor and all the other bits and pieces necessary to have an operational system available on the 1st of January 1995 at the latest. The provisional Coordinating Agency was established as of 1 September this year in my headquarters with one Project Manager, and a head of the Co-ordinating Agency Office both directly subordinate to me. We will try to fill other posts to finally reach the total of 7 as authorized in present plans. In the meantime consultants will be hired to help us solve specific problems. One such problem is the time control concept which if you recall from previous briefs, is to be based on Time of Transmission Control and a study on the practical implementation of TOT in a larger system is already well under way.

III. NORWEGIAN POLICY

So much for the update. Before I conclude however, there is one more thing I would like to bring to your attention because recent events might have given you a wrong impression of the official Norwegian policy regarding radionavigation systems and their use. Present Norwegian policy as expressed by the Royal Norwegian Ministry of Fisheries responsible for coordination of all civilian radionavigation systems in Norway is in short as follows:

- Norway look at NAVSTAR-GPS as a valuable radionavigation aid, but will not rely on it as the sole navaid at least not until its continued operation and characteristics are guaranteed in international agreements and present technical problems are solved (integrity, availability, etc.).

- From a cost/effective point of view the present DECCA system in Norway is expected to reach the end of its useful life in 1995. Plan for its possible replacement by LORAN-C are in progress.

I would like to add that Norway does not see this as a defiance of NAVSTAR GPS, on the contrary GPS with its unique capabilities is expected to play an important role also in the civilian sector and Norway is for one thing expecting combined GPS/LORAN-C user equipment to meet requirements which today can not be met by either one of the two systems. Furthermore to get maximum benefit from GPS, Norway is actively participating in the Civil GPS Service arrangements under the direction of the US Department of Transportation, and has established a GPS information service to support civilian users.

In my opinion the key issue is whether or not satellite system should be adopted as a sole radionavaid and Norway's answer to this is that we should not, at least not until such systems are guaranteed by international arrangements which most nations are prepared to accept and technical problems in way of integrity and availability are solved. This policy in combination with the need for extensive investments in an elderly and incomplete DECCA system, led us to the conclusion that a terrestrial radionavigation system continued to be required and that this system should be LORAN-C. LORAN-C was chosen not only for its operational qualities, but also because it is a mature system under continued development and with a wide range of state-of-the-art user equipment to serve most categories of users at sea, in the air and on land.

FROM RUSSIA WITH LORAN

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Abstract

Until recently, the Soviet Union has shown limited interest in developing commercial international air routes through Soviet airspace. With the advent of peristroika and its outreach philosophy, however, the Soviets have begun to meet with the United States to open up the airways between Alaska and four U.S.S.R. geographic areas: Soviet Far East, Soviet Southeast Asia, Baikal Lake, and Soviet Middle East. Economic considerations suggest that it may not be possible to provide traditional ground-based communications and radio-navigation coverage. This paper explores whether the two countries' long-range radionavigation systems--Loran and Chayka--can be effectively integrated for common use. It aims to determine the feasibility of using Loran signals for navigation by examining the following:

1. The extent of Loran coverage in Soviet Far East
2. The extent of Loran coverage in Soviet Southeast Asia
3. Plans to expand the Soviet system, including coupling the chains of the Eastern U.S.S.R. Chayka with those of the U.S. North Pacific Loran.

The paper also touches on recent developments aiming to promote commercial air routes from Alaska to the Soviet Union.

1. Introduction

If James Bond were around these days, he'd be amazed at the cooperative efforts that we Americans and the Soviets have been making in the area of radionavigation. Both nations are keen on combining navigation systems, U.S. Loran and Soviet Chayka, into one efficient network. A landmark of this common interest was the Soviets' presentation of a booklet at the 1989 Wild Goose Association Convention (held in Hyannis, MA) entitled "Establishment of Soviet/U.S. Chain of Chayka/Loran Radionavigation System Related Documents." It marks not just peristroika's triumph over cold-war politics, but a giant step forward in the safe circling of our shrinking globe. Since the Soviet navigation system, Chayka, works on the same principles as the U.S. Loran, the early meetings between our two nations discussed specifications of signal characteristics that would avoid interference. Recent discussions have centered on common concerns of signal interference by overlapping signals and from other neighboring systems.

It wasn't until late 1987 that the Soviets suggested (in a working meeting at Washington FAA HQ) that the systems be joined via a dual rating station that would effectively open up the Bering Sea area for Soviet/U.S. chain of coverage. The U.S. Coast Guard acknowledged the joint proposal using the Loran North Pacific Chain 9990.

During the spring of 1988, representatives from the U.S. Coast Guard traveled to Leningrad to meet with delegates of the Soviet Union. Both groups had proposals for a chain configuration, which were modified into a mutually acceptable compromise. The proposed Bering Sea chain is:

1. Petropavlovsk (Master)
2. Kurilsk (Secondary)
3. Attu (Secondary)
4. Aleksandrovsk (Secondary) (to serve as test station until the presently low-powered Kurilsk is upgraded to compensate for range loss).

The advantages of this configuration will become obvious when you look at the plots in Section 6.

DISCLAIMER: The information contained in this paper is for academic and professional use only; the author intends no technical data included herein for any practical aviation applications.

2. U.S./U.S.S.R. Agreements

U.S. and Soviet meetings covering all aspects of civil aviation are becoming more frequent and productive. Recent discussions focusing only on U.S. and Soviet aviation routes include:

2/16/90, Washington: A Memorandum of Cooperation (MOC) was drafted and signed by both nations.

6/2/90, Washington: Civil Air Transport Agreement signed.

6/25-9/90, Moscow: Discussions on opening new air routes.

At the June meetings in Moscow, areas of focus agreed on were:

1. Implementation of the MOC (signed 2/90) via a letter of understanding.

2. Mutual familiarization visits to both countries' air traffic control services, with emphasis on radar, navigation, and communications (Annex 4 to the MOC).

3. Discussion of technical and operational issues related to U.S./U.S.S.R. flights. Widely discussed issues included communications, navigation requirements, air traffic control, alternate airports for emergency landings, ground services such as fuel and maintenance, weather information, the U.S.S.R. coordinate system, and plans to prepare a Flight Standards Annex to the MOC.

4. Use of Soviet airspace to reach the Asia Pacific Region. Recognized problems in opening air traffic routes were the provision for communication and navigational aids and English language training for aviation personnel. Proposed air routes were:

   a. Barrow to Mys Schmidta
   b. Gambell, St. Lawrence Island to Beringovsky
   c. King Island to Lavrentiya, Zaliv.

Both groups, pleased with the outcome of the discussions, pledged future meetings to discuss mutual air routes, the development of a Flight Standards Annex to the MOC, and related issues. This paper concentrates on the Navigation Requirements, those of Loran/Chayka in particular.

3. Air Safety a Top Priority

In the Bering Sea, winter fog can last for days. Winds often gust to 60 knots. Ocean swells may rise to 50 feet. Aviators across these waters are well aware of the potentially treacherous weather conditions, and the havoc it can play with the aircraft and signal reception. To improve navigation conditions in the dangerous North Pacific, technical anomalies must be reduced. One of these is Instrument Navigation System (INS) drift error. When a plane flies away from the coast and over the ocean, pilots gradually lose contact with land-based controllers and must rely solely on in-board navigation equipment, such as INS and OMEGA. Reduction of drift error thus becomes an increasingly important issue as North Pacific air traffic increases.

Two U.S. companies, Honeywell and Northwest Airlines, are working with the Soviets to explore the mutual use of satellite global navigation systems, U.S. GPS, and Soviet GLONASS. Plans include installing equipment aboard a Northwest Boeing 747 freighter to test its ability to receive and process signals from both systems. At present, neither system has much spatial continuity. Yet plans call for launching two dozen satellites and a "black box" to join location data from both networks to fill in the gaps. It's just possible that a single navigation device would then suffice to join position data from both U.S. and Soviet networks. The big advantage will be the virtual elimination of drift error: pilots would be able to update air locations nearly every second. Use of such a system might well have prevented the fate of Korean Air Line Flight 007 in 1983. That aircraft was the victim of drift, or wandering off course; the pilots had no means of confirming the aircraft's position, and the INS may have been set up with incorrect coordinates which could not be checked in flight.

This cooperative effort does wonders to rid the air traffic world of indecisiveness. Uncertainties in navigation such as drift error are the reason for wide spacing between aircraft over oceans. Controllers presently must keep clear airspace of 60 miles off an aircraft's wings, and 85 miles off its nose and tail. These high separation values are an increasing problem in a world of increasing air traffic with a narrowing window of desirable flight times. We need more precise navigation equipment to be able to decrease aircraft separation, and allow more simultaneous flights without jeopardizing the public safety.

4. Loran/Chayka Receivers

With the prospect of increased commercial air routes across the North Pacific, certain American vendors have shown interest in manufacturing receivers capable of accommodating both Loran and Chayka systems. To date, at least two U.S.-made receivers have proved perfectly capable of receiving Chayka signals.

Trimble Navigation of Sunnyvale, California, is one of them. Trimble's TNL-3000 GPS/Loran receiver system can acquire the 7950 and 8000 Soviet Chayka chains with a worldwide database available with an exchangeable database card. Airport data (for VORs, NDBs, and other important intersections) are easily accessed. The TNL-3000 is capable of automatically selecting Group Repetition Intervals (GRIs) and transmitters. It can also track multiple transmitters from multiple chains, an operation called "cross-chaining." Better yet, since the TNL-3000 can track the Soviet chain, it has in fact "cross Loran/Chayka" operation. This receiver is capable of "all-in-view" satellite tracking and three-dimensional positioning; it can receive signals and monitor the status of GPS, but not GLONASS. This type of versatile hybrid could well be the receiver of the 90s.

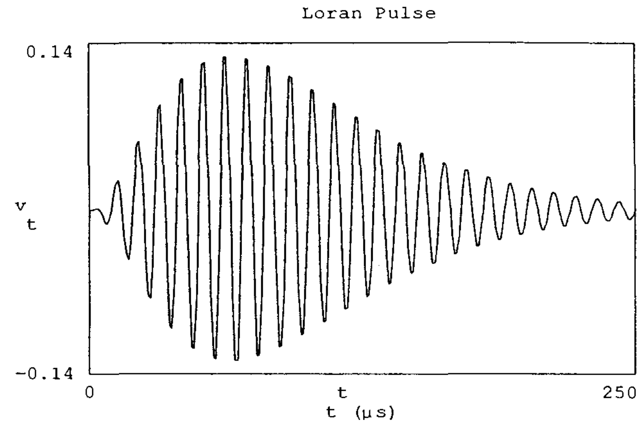
ARNAV Systems, Inc. of Portland, Oregon has a R-50i multichain receiver which has been bench-tested to receive the Eastern and Western Chayka chains. Its waypoint database has coverage spans from Alaska/Canada to the equator. This receiver is designed to receive up to 12 stations simultaneously. Though it receives neither GPS nor GLONASS signals and is not FAA-approved, this receiver, like the Trimble, might someday serve as an approved Loran/Chayka multisystem receiver.

5. Technical Differences Between Loran and Chayka

Loran and Chayka have both been widely used for air and sea navigation because of their long-range ground signals. Linking the Loran and Chayka chains would afford nearly blanket coverage in the area of the biggest gap--south of Attu Island in the Aleutians to the Kamchatka Peninsula. This near-total coverage would be advantageous to both aviation and maritime traffic. Since the present systems are in reasonable proximity, costs to finance a new link chain could be kept to a minimum.

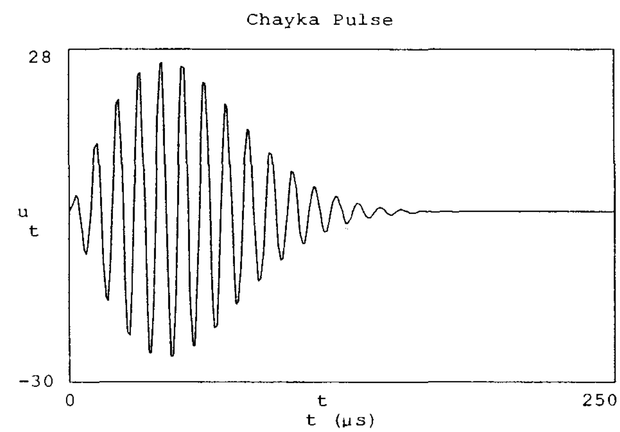
But can it be done? The systems do have many features in common. Both carrier frequencies run at 100 kHz. Both transmit Group Repetition Intervals (GRIs) in the range of 40,000-100,000 microseconds (usec). Both even have a similar "pulse rate": 8 per GRI at secondary and 9-10 at master stations. Chayka's "2GRI" phase code and period are much like Loran's.

But the systems differ in one important factor: the characteristics of the envelopes of their emitted pulses. This is critical because receivers begin their timing sequence based on the anticipated slope of the leading edge of the envelope. Loran transmits pulses at a slower climbing rate (in the leading edge) than Chayka does; a Loran pulse reaches its maximum amplitude at approximately 65 usec, Chayka at 43 [see Figures 1 and 2]. The fact that the Chayka pulse shape can be approximated by adjusting certain parameters to correspond to the Loran pulse makes a strong case for combining coastal stations into one common chain.



$$v_t := 1\cdot\left[\frac{t}{65}\right]^2\cdot e^{-2\cdot\frac{t}{65}}$$

Figure 1. Loran Pulse



$$u_t := 1\cdot\left[\frac{\sin(\beta\cdot t)}{\beta}\right]^m e^{-(\alpha\cdot t)}$$

$$\alpha := \frac{1}{65} \qquad \beta := 0.01$$

Figure 2. Chayka Pulse

An important consideration when linking chains is the avoidance of any kind of cross-chain interference. The repetition rate (in usec) must be chosen with respect to those of neighboring chains.

Note, too, that some dissimilarities exist in regard to the timing pulses. The ninth pulse in a Chayka master pulse train is placed differently than in a Loran chain. Some Chayka chains also frequently insert separate timing pulses. Thus some criteria are necessary for adjusting phase modulation tolerances and sampling points to account for the slightly advanced or retarded pulse formats.

As for actual differences in operational procedures, Loran is equipped with a "blink" warning to alert all Loran users, aviators and mariners, of out-of-tolerance conditions. Chayka has no such warning.

V. Bykov of the Soviet Ministry of Marine Fleet ran tests using Furuno (Japan-made) Loran marine receivers--models LC-90 and LP-1000, designed specifically for Loran chains--to see whether they could pick up the Chayka signals. The first step was to get geographic locations of the Soviet 8000 and 7950 chains added into Furuno's software. This new geographic data could be used to observe and evaluate the receivers' ability to properly track the Chayka signals and make analogies with the Loran signals.

From March to April, 1988, on-site tests used the Eastern U.S.S.R. chain to observe the receivers' likelihood of choosing the appropriate cycle. If a receiver could in fact select the right cycle, it was then tested to observe how long it needed to acquire signals under a variety of ranges. Results were impressive. Within 900 nautical miles (nm) of the principal coverage zone, the probability of correct cycle selection was about 97%. Moving further out into the 1000-1170 nm range, probability of acquisition diminished little, to 95% (with average transmitter acquisition times of about 3.5 minutes). The receiver acquisition success rate (i.e., getting a position fix) was 83%. Bykov concluded that the Furuno receivers would operate with the Chayka signals just as they did with the Loran signals.

Soviet testing has laid important groundwork for a potential Loran/Chayka unification. With the development of proper receiver designs and adaptable operational procedures, this goal can be achieved.

6. North Pacific Coverage Plots

The six North Pacific plots are run with the same conductivity and atmospheric noise values. The average atmospheric noise data used over the North Pacific is 53 dB, averaged over six four-hour intervals. Conductivity values are based on the following parameters: 5,000 milli-mhos per meter over salt water, 10.0 over good soil, 3.0 over fair soil, 1.0 over poor soil, 0.3 over mountainous areas, and 0.1 over extremely poor soil.

The model program for forecasting Loran coverage runs on an IBM PC-AT using FORTRAN and Basic; outputs are generated on a Hewlett-Packard 7550A plotter. All plots used the same en route threshold values for SNR and GDOP, that is, -10 Db and 7,700 ft/usec respectively. The key for chains is as follows:

CHAIN NUMBER	NAME	GRI Number
1	East U.S.S.R. Chain	7950
2	North Pacific Chain	9990
3	Bering Sea Chain	(proposed)

7. Conclusions and Recommendations

When the potential for increased Loran/ Chayka coverage in the North Pacific is achieved, air route navigation between the United States and the Soviet Union will become easier. Yet at present, only one U.S. carrier (Pan Am) provides any kind of scheduled air service for passengers or cargo. DOT, at the June meeting in Washington, has agreed to allow one new air carrier in the North Pacific: Alaska Airlines, whose prime routes of interest are from Anchorage to Magadan and to Khabarovsk.

Adoption of the following recommendations would open up a variety of potential air routes using a Loran/Chayka coupling:

1. Installing a transmitter at Cape Navarin, linked as a secondary to St. Paul Island (the North Pacific Chain's Master station), would produce two new triads in the North Pacific Chain, thus yielding more redundant coverage. (Look at Plot 4.) It should be noted that this site has yet to be visited to determine whether it is a suitable transmitter location. Suggestions are welcome.

2. Making Cape Navarin a dual-rated secondary to both the North Pacific Chain and the proposed Bering Sea Chain creates two more triads, thus "paving the runway" for more air routes. (Look at Plot 6 for this imaginary configuration.) Since Magadan and Khabarovsk both lie in the Soviet's East Coast Chain, the proposed Bering Sea Chain and a potential link to Cape Navarin would offer pilots many air routes within the Loran/Chayka network. Pending final DOT approval, these air routes could take effect April 1, 1991.

The present coverage in the Soviet Far East and Soviet Southeast Asia appears to be good, especially along the coastal areas. But the coverage gap in the North Pacific resembles the mid-continent gap in the CONUS, where pilots have the added redundancy benefits of VORTACS, beacons, and other land-oriented navaids. If more air routes are to be established across the Bering Sea and towards the Southeast Asian territories, (and if, indeed, Loran is to be used as a navaid!) coupling Loran and Chayka will surely be a necessity. A wider channel of coverage will need to be opened from the Loran North Pacific Chain to the Chayka Eastern U.S.S.R. Chain. With newly established monitors ensuring that transmitting stations function within cooperatively established tolerances, pilots will be able to fly through fog and other adverse weather conditions with greater confidence.

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About the authors:

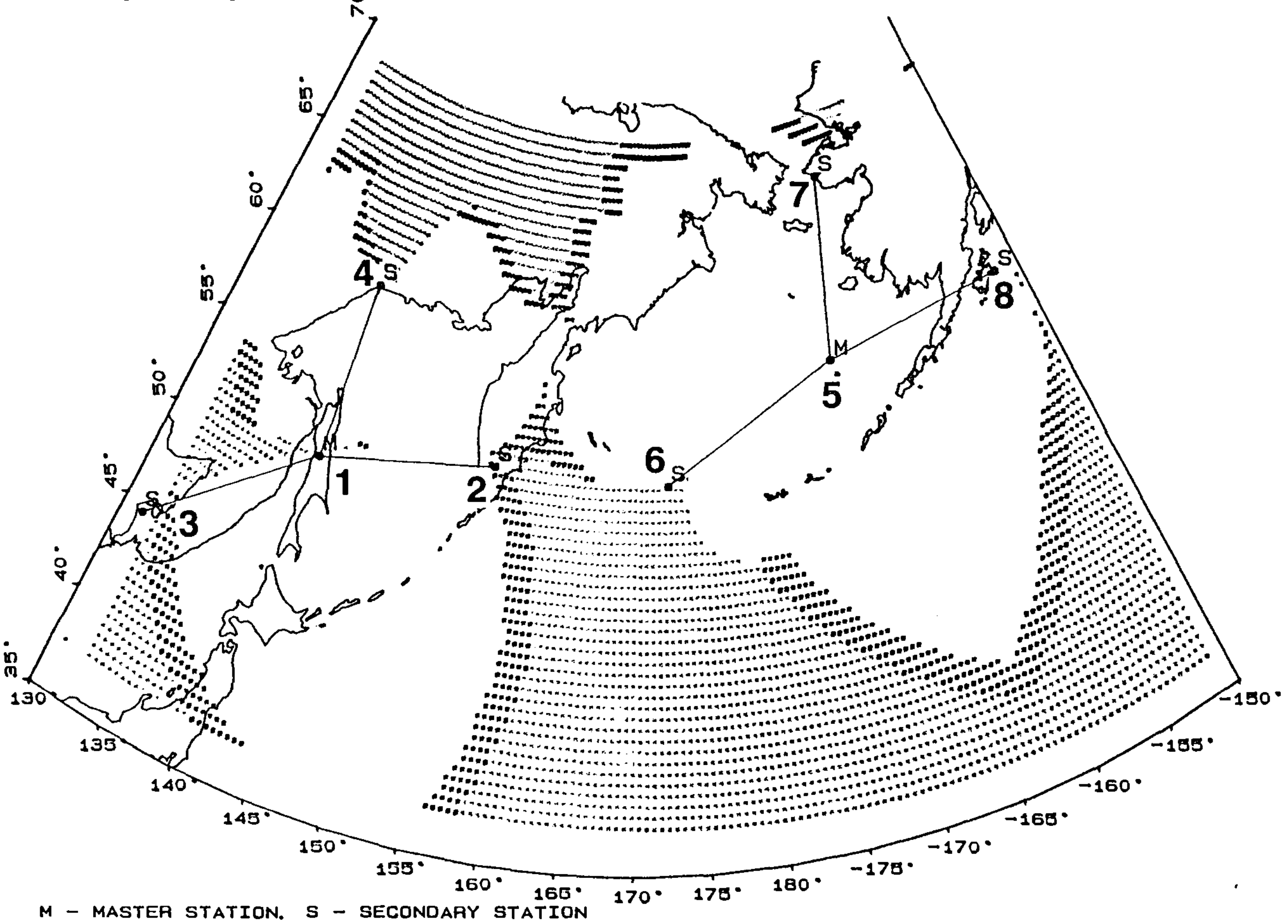
Stephen F. Nuzzi--an electronics engineer since 1986 with the National Field Office for Loran Data Support at the Research and Special Projects Administration/Volpe National Transportation Systems Center (VNTSC)--developed the FAA's Loran Coverage Model and its expansion to cover Loran operations within and outside the U.S. Nuzzi assisted Joseph Sturm of TSC's Office of Systems Assessment with the navigation and communications sections of the U.S. Delegation Briefing Book on the technical issues regarding expanded aviation service between the U.S.S.R. and U.S. He has a BS in Electrical Engineering from Northeastern University.

Joseph C. Sturm is the Senior Project Manager for VNTSC, dealing with international aviation development.

Plot #1 shows the existing transmitters in the North Pacific with some important clarifications. Station Okhotsk (north of master station Aleksandrovsk) is presently set to 6 KW and is used as a test station. This station operates on request; plans are to upgrade the power to the scenario depicted in Plot #2. All other transmitters are rated at 700 KW.

#	LOCATION	LAT	LONG	POWER	CHAIN	DUAL	MASTER
1	Aleksandrovsk, RU	51.08	142.70	700	1	00	TRUE
2	Petropavlovsk, RU	53.13	157.70	700	1	00	FALSE
3	Ussuriisk, RU	44.53	131.64	700	1	00	FALSE
4	Okhotsk, RU	59.42	143.09	6	1	00	FALSE
5	Saint Paul, AK	57.15	-170.25	325	2	00	TRUE
6	Attu Island, AK	52.83	173.18	625	2	00	FALSE
7	Port Clarence, AK	65.24	-166.89	1000	2	00	FALSE
8	Narrow Cape, AK	57.44	-152.37	300	2	00	FALSE

Existing Coverage in the North Pacific En Route Parameters Station OKHOTSK = 6KW 9/21/90

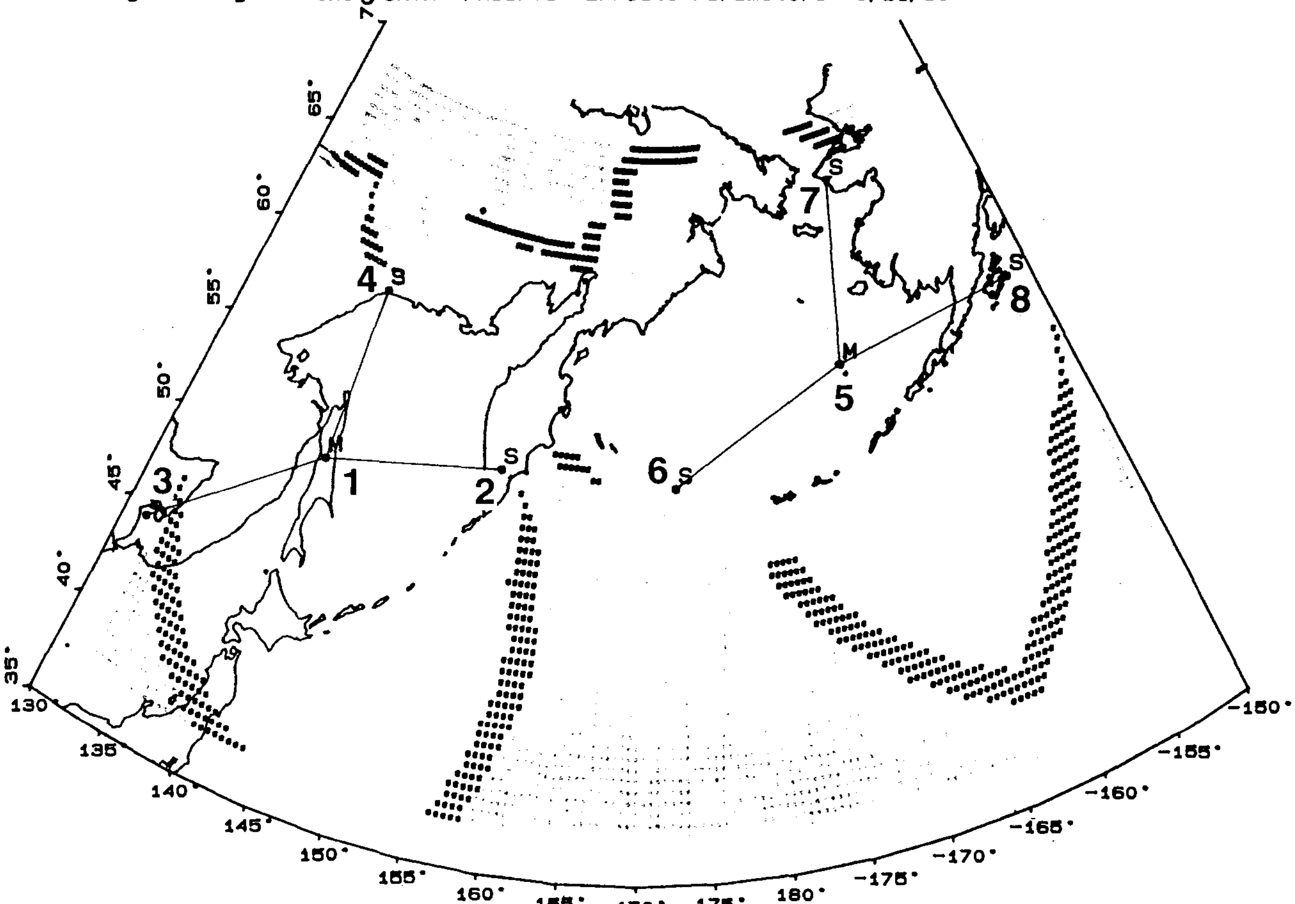


M – MASTER STATION. S – SECONDARY STATION
S – BAD SNR. G – BAD GDOP. E – SNR OR GDOP BAD. * – SNR + GDOP BAD

Plot #2 shows the Eastern U.S.S.R. Chain (7950) with its four transmitters and Okhotsk upgraded to 700 KW. Coverage is increased over the Kamchatka Peninsula.

#	LOCATION	LAT	LONG	POWER	CHAIN	DUAL	MASTER
1	Aleksandrovsk, RU	51.08	142.70	700	1	00	TRUE
2	Petropavlovsk, RU	53.13	157.70	700	1	00	FALSE
3	Ussuriisk, RU	44.53	131.64	700	1	00	FALSE
4	Okhotsk, RU	59.42	143.09	700	1	00	FALSE
5	Saint Paul, AK	57.15	-170.25	325	2	00	TRUE
6	Attu Island, AK	52.83	173.18	625	2	00	FALSE
7	Port Clarence, AK	65.24	-166.89	1000	2	00	FALSE
8	Narrow Cape, AK	57.44	-152.37	300	2	00	FALSE

Existing Coverage in the NORTH PACIFIC Enroute Parameters 8/21/90

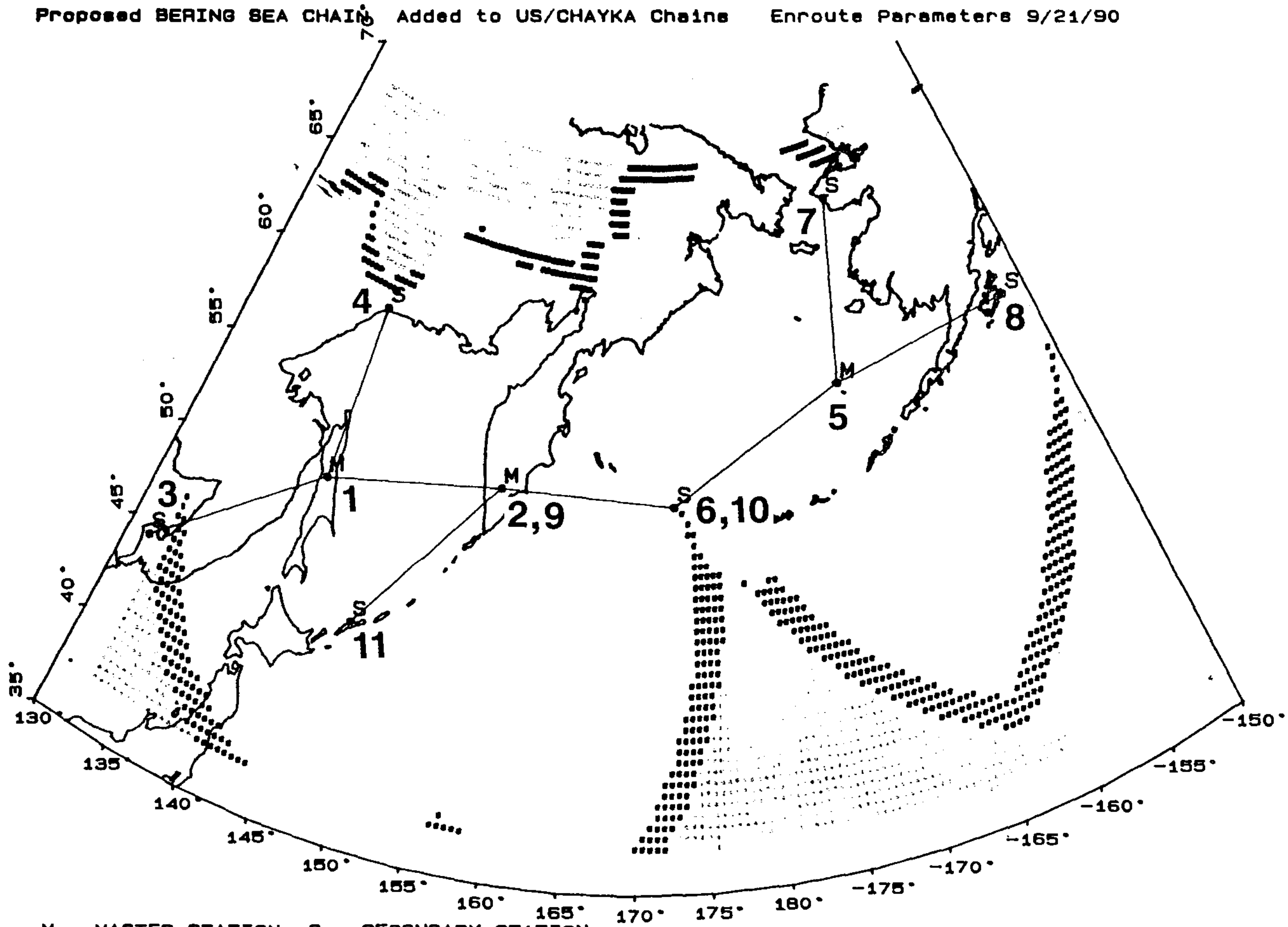


M - MASTER STATION. S - SECONDARY STATION
S - BAD SNR. G - BAD GDOP. E - SNR OR GDOP BAD. * - SNR + GDOP BAD

Plot #3 shows the proposed Bering Sea Chain, which links the Loran and Chayka Systems. It opens a large area of ocean coverage--from the 155 degree east meridian to the 170 degree meridian (West of the International Date Line)--by upgrading the low power Kurilsk Station (6 KW, similar to Station Okhotsk) to 300 KW. Kurilsk and North Pacific Chain's Attu are secondaries to the newly dual-rated master station Petropavlovsk.

#	LOCATION	LAT	LONG	POWER	CHAIN	DUAL	MASTER
1	Aleksandrovsk, RU	51.08	142.70	700	1	00	TRUE
2	Petropavlovsk, RU	53.13	157.70	700	1	09	FALSE
3	Ussuriisk, RU	44.53	131.64	700	1	00	FALSE
4	Okhotsk, RU	59.42	143.09	700	1	00	FALSE
5	Saint Paul, AK	57.15	-170.25	325	2	00	TRUE
6	Attu Island, AK	52.83	173.18	625	2	10	FALSE
7	Port Clarence, AK	65.24	-166.89	1000	2	00	FALSE
8	Narrow Cape, AK	57.44	-152.37	400	2	00	FALSE
9	Petropavlovsk, RU	53.13	157.70	700	3	02	TRUE
10	Attu Island, AK	52.83	173.18	625	3	06	FALSE
11	Kurilsk, RU	45.21	147.86	300	3	00	FALSE

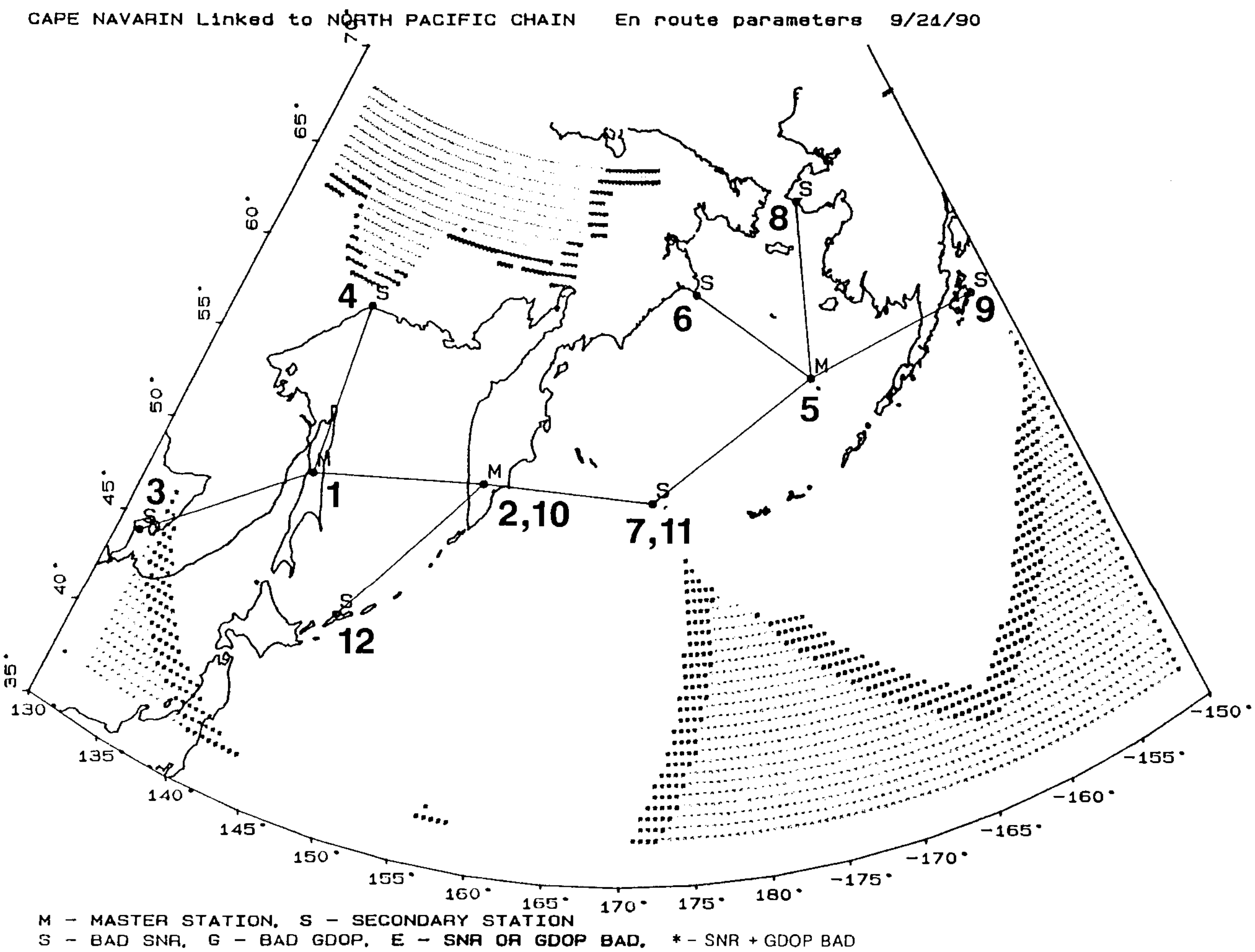
Proposed BERING SEA CHAIN Added to US/CHAYKA Chains Enroute Parameters 9/21/90



M - MASTER STATION, S - SECONDARY STATION
S - BAD SNR, G - BAD GDOP, E - SNR OR GDOP BAD, * - SNR + GDOP BAD

Plot #4 shows the addition of a transmitter at Cape Navarin linked into the North Pacific Chain, which effects an increase of coverage in the Northern Bering Strait area. The addition of the triad makes traveling north through the Bering Strait, Soviet Union, and Alaska towards the Arctic circle more accessible.

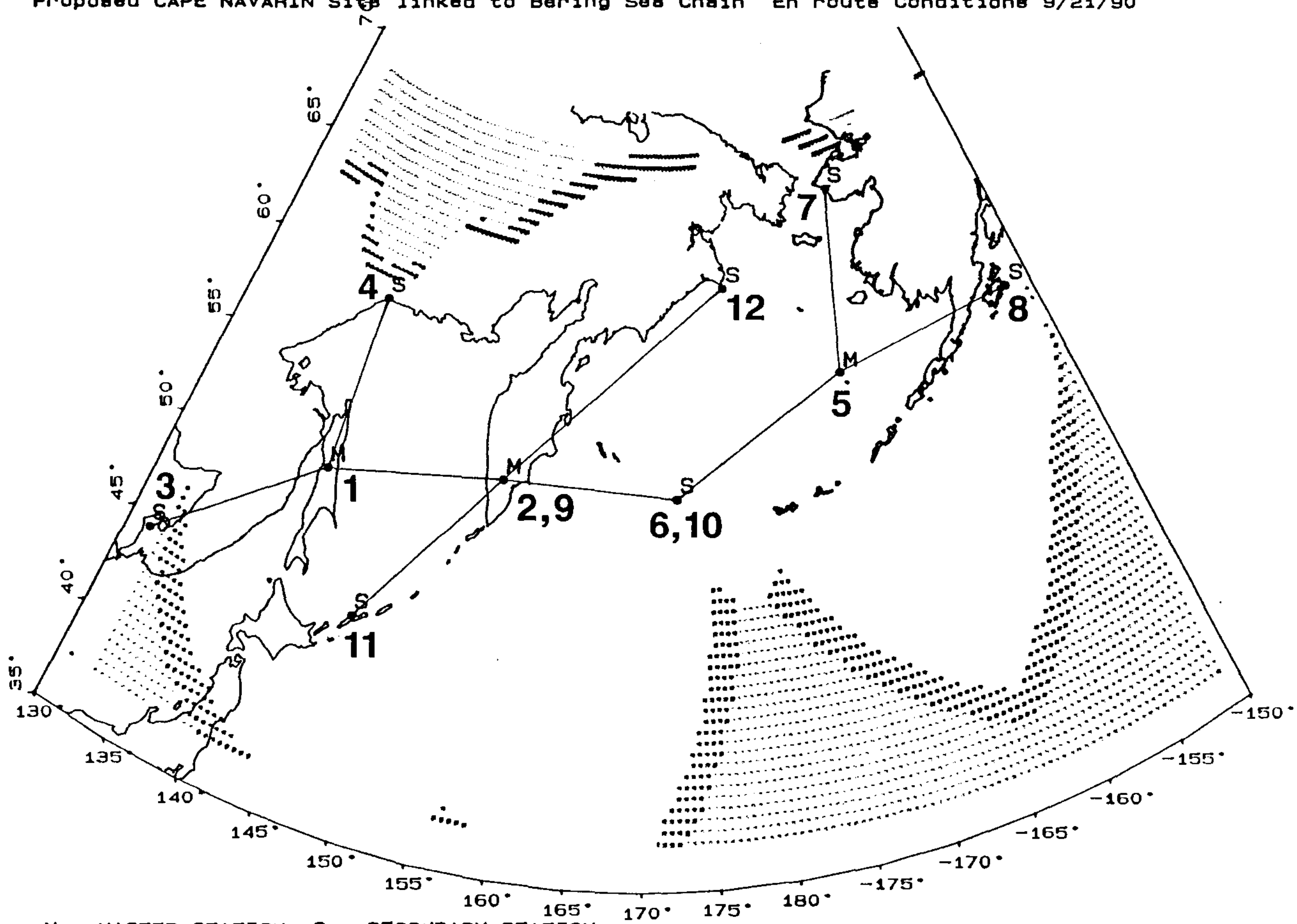
#	LOCATION	LAT	LONG	POWER	CHAIN	DUAL	MASTER
1	Aleksandrovsk, RU	51.08	142.70	700	1	00	TRUE
2	Petropavlovsk, RU	53.13	157.70	700	1	10	FALSE
3	Ussuriisk, RU	44.53	131.64	700	1	00	FALSE
4	Okhotsk, RU	59.42	143.09	700	1	00	FALSE
5	Saint Paul, AK	57.15	-170.25	325	2	00	TRUE
6	Cape Navarin, RU	62.14	179.2	700	2	00	FALSE
7	Attu Island, AK	52.83	173.18	625	2	11	FALSE
8	Port Clarence, AK	65.24	-166.89	1000	2	00	FALSE
9	Narrow Cape, AK	57.44	-152.37	400	2	00	FALSE
10	Petropavlovsk, RU	53.13	157.70	700	3	02	TRUE
11	Attu Island, AK	52.83	173.18	625	3	07	FALSE
12	Kurilsk, RU	45.21	147.86	400	3	00	FALSE



Plot #5 shows another possible connection for the Cape Navarin transmitter, linking it into the proposed Bering Sea Chain. The baseline is about 872 nautical miles. A good saltwater path is present. Although this new station adds some more coverage, its real advantage is to add a good geometrical triad traveling from Alaska to the Eastern area of Soviet Union across the Kamchatka Peninsula.

#	LOCATION	LAT	LONG	POWER	CHAIN	DUAL	MASTER
1	Aleksandrovsk, RU	51.08	142.70	700	1	00	TRUE
2	Petropavlovsk, RU	53.13	157.70	700	1	09	FALSE
3	Ussuriisk, RU	44.53	131.64	700	1	00	FALSE
4	Okhotsk, RU	59.42	143.09	700	1	00	FALSE
5	Saint Paul, AK	57.15	-170.25	325	2	00	TRUE
6	Attu Island, AK	52.83	173.18	625	2	10	FALSE
7	Port Clarence, AK	65.24	-166.89	1000	2	00	FALSE
8	Narrow Cape, AK	57.44	-152.37	400	2	00	FALSE
9	Petropavlovsk, RU	53.13	157.70	1000	3	02	TRUE
10	Attu Island, AK	52.83	173.18	625	3	06	FALSE
11	Kurilsk, RU	45.21	147.86	400	3	00	FALSE
12	Cape Navarin, RU	62.14	179.2	700	3	00	FALSE

Proposed CAPE NAVARIN Site linked to Bering Sea Chain En route Conditions 9/21/90

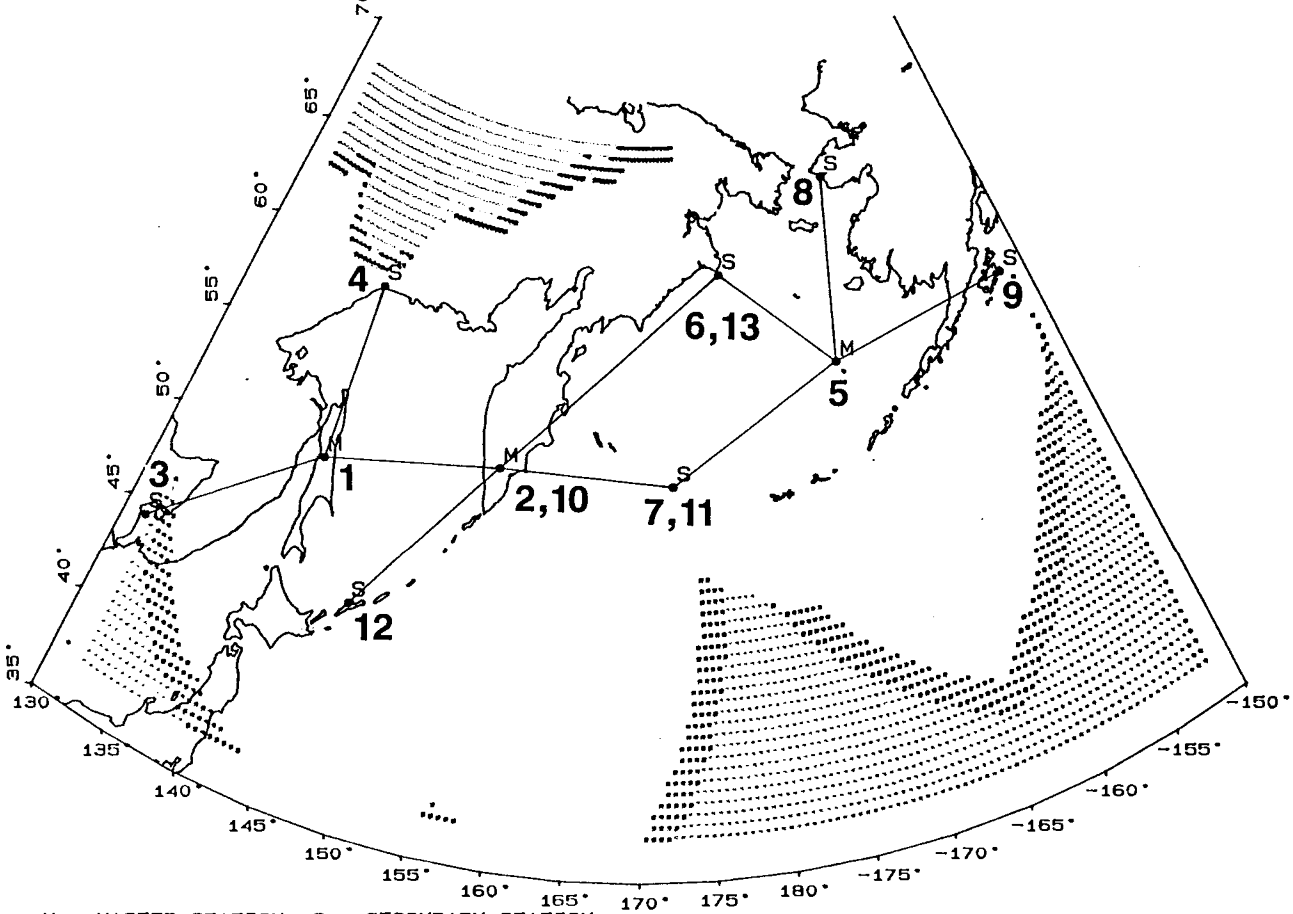


M - MASTER STATION, S - SECONDARY STATION
S - BAD SNR, G - BAD GDOP, E - SNR OR GDOP BAD, * - SNR + GDOP BAD

Plot #6 indicates the ultimate in coverage and triad tracking. With the proposed Cape Navarin transmitter linked to both the North Pacific and Bering Sea Chains, many combinations of triads exist. This newly expanded network makes traversing the North Pacific, whether by air or sea, a much safer venture.

#	LOCATION	LAT	LONG	POWER	CHAIN	DUAL	MASTER
1	Aleksandrovsk, RU	51.08	142.70	700	1	00	TRUE
2	Petropavlovsk, RU	53.13	157.70	700	1	10	FALSE
3	Ussuriisk, RU	44.53	131.64	700	1	00	FALSE
4	Okhotsk, RU	59.42	143.09	700	1	00	FALSE
5	Saint Paul, AK	57.15	-170.25	325	2	00	TRUE
6	Cape Navarin, RU	62.14	179.2	700	2	13	FALSE
7	Attu Island, AK	52.83	173.18	625	2	11	FALSE
8	Port Clarence, AK	65.24	-166.89	1000	2	00	FALSE
9	Narrow Cape, AK	57.44	-152.37	400	2	00	FALSE
10	Petropavlovsk, RU	53.13	157.70	700	3	02	TRUE
11	Attu Island, AK	52.83	173.18	625	3	07	FALSE
12	Kurilsk, RU	45.21	147.86	400	3	00	FALSE
13	Cape Navarin, RU	62.14	179.2	700	3	06	FALSE

CAPE NAVARIN Dual Rated to North Pacific and Bering Sea Chains En route Parameters 9/21/90



M – MASTER STATION, S – SECONDARY STATION
S – BAD SNR, G – BAD GDOP, E – SNR OR GDOP BAD, * – SNR + GDOP BAD

Loran-C Performance Assurance for Instrument Approaches

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Abstract

A signal or system used for navigation or guidance of aircraft, especially during an instrument approach, must be as nearly perfect as possible. Availability 100% of the time is obviously a goal, as is perfect system integrity. Availability may be sacrificed to gain integrity, but never vice versa.

The intent of this paper is to condense hundreds of technical and procedural elements into an understandable "integrity chain," and to emphasize the pilot's key role in the success of Loran-C in the National Airspace System.

Loran-C Performance Assurance: Technical items

The present-day National Airspace System (NAS) offers sophisticated navigation and guidance services, with guaranteed levels of accuracy and integrity, plus maximized availability. It is not surprising that Loran-C "fits in" rather easily. At nearly every turn, there are precedents in other contemporary navaids which serve to guide the activity.

Loran-C: New and different?

The answer is both yes and no. Yes, because when Loran-C is compared to traditional aviation aids it is:

- a long-range, wide-area system
- a low-frequency system
- earth referenced, rather than station referenced
- relatively complex for the user to operate.

The similarities exist because the flight operations supported by Loran-C are the same as those permitted by traditional navaids. Loran is just available at more locations.

For the Loran-C system to support approaches to land under instrument weather conditions, it must be shown that the system will not produce incorrect guidance without generating a timely warning. The integrity chain includes each of the major system components.

Transmitters: Automating the loop

A critical factor in the integrity equation is the immediate removal from service of any navigation transmitter which is not providing the required near-perfect signal.
FAA-owned systems have always employed an executive monitor to serve this function--without human intervention.

The US Coast Guard is the legal provider of the Loran-C signal [1]. For its originally-intended marine purpose (and for enroute aviation use) the established manually-activated alarm mechanisms are entirely satisfactory. Data collected during the Early Implementation Program [2] indicates a very low probability of guidance outside aviation tolerances without an alarm. To be certain, however, that this low-probability event never occurs, an automated blink function will be added to all US Loran-C transmitters.

To provide the fast-response system integrity monitoring function while automated blink is being developed, real-time monitors will be installed by the FAA at airports where the forthcoming public-use approach procedures will be commissioned.

Signals: Qualifying an airport

Before any instrument approach procedure is published, tests are necessary at the intended location, to verify that signals meet the criteria established as part of the system error budget and receiver test conditions. The Loran-C requirements for at least -6 dB SNR and gradients no greater than 3,000 feet/usec are examples.

FAA has developed a multi-step process for screening potential sites, including both user and FAA data collection steps. The approach path is flown (in good weather) by users, the airport is screened by FAA computer models and the signals are analyzed by the Loran Site Evaluation System. The site TD biases and

SNRs are determined, envelope quality is inferred and the presence of local interference may be detected during this process.

This signal survey cannot guarantee the presence of high-quality signals at all subsequent times, but successfully passing all the tests provides confidence that an approach procedure will be available to users a high percentage of the time.

Receivers: Known outputs for known inputs

During instrument approaches, the Loran-C receiver must perform signal integrity checks not accomplished elsewhere. The transmitter monitors insure in-tolerance raw position data, but the airport screening process predicts adequate signal quality only on the average.

The receiver must analyze the signal in real time and flag on low SNR, ECD variations or on any other condition which may result in incorrect guidance. It must, of course, respond quickly enough to transmitted blink or signal loss to prevent entry into unprotected airspace.

The receiver is tested in accordance with RTCA MOPS [3] and the FAA TSO C60b [4]. The effect of the test conditions is to place bounds on the signal characteristics which will produce known receiver outputs. This, in turn, places bounds on other system parameters.

Data Collection: Quantifying the variations

Loran-C signals are not perfect by the time they arrive at the receiver. They have been delayed by propagation over water and earth, signal strength has decreased and their pulse shape has changed. The C60b receiver is expected to measure and test the latter two factors; TD variations are undetectable.

In preparing for instrument approach use of Loran-C, characterization of TD variations and their causes was a major effort. It has been determined [2] that in the coverage region defined for instrument approaches, prediction of a correction value for the seasonal variations in TDs may be accomplished using a network of monitors each with a 90-nm radius of influence. Once this correction is applied to the received signal, the remaining variations are within the error budget.

Correction values are published by the National Field Office for Loran Data Support (NFOLDS). They will be available with Loran-C approach plates, and as an element in receiver data bases. For approaches, Loran-C is thus a "differential" system, albeit with a long update cycle.

It is important to note that the NFOLDS "monitor" network does not perform executive monitoring functions. It is a data-collection system which provides TD corrections.

Procedure Development: Applying the rules

All of the integrity chain elements could be discussed in the context of procedure development, since the Terminal Area Procedures (TERPS) [5] developed for Loran-C contain rules and criteria derived from each.

Examples are given here to illustrate unique Loran-C characteristics which must be taken into account, to insure that the receiver operates in conditions which TSO tests evaluated.

Loran-C TERPS surfaces are different in shape from other, station-referenced systems, partly since loran-driven CDI scale sensitivity does not change with distance from a waypoint. TERPS criteria are quite sensitive to flight technical error (FTE), and FTE is quite sensitive to CDI scale factor. There is room here for future developments.

Wide-area coverage is cost-beneficial, but procedures are affected in that a single transmitter off-air could shut down approaches over a large area. Initially, at least, use of loran for approaches to alternate airports will be restricted.

A circle around each transmitter has been established, within which approach procedures will not be commissioned. This circle excludes receiver operation during approach procedures where signal strengths exceed the TSO test limit of +110 dB(uV/m). While some receivers may work well with such high signal levels, TSO testing does not demonstrate this.

Initially, the circle has a 30 nm radius for all transmitters. We have recommended that protection circle size be based on transmitter power, for maximum system availability around lower-power transmitters.

Exposure to power-line carrier energy (PLC) should be brief during approaches; the speed of the aircraft, typically non-parallel geometry between the approach path and the power line, the short range of the PLC signal interference, and the intermittent nature of most PLC operations are all helpful. Still, the risk of PLC interference is real, and must be accounted for. Initial criteria have been established to keep approach paths separated from power lines.

FAA is continuing its PLC studies, to refine the approach-design criteria, and is working for FCC restriction of the 90-120 KHz band to navigation only, in contrast to the present non-interference permission granted to PLC users.

Flight Checking: Being certain [6]

After the airport screening and data collection process and the design of the approach procedure, an FAA flight check aircraft evaluates the approach and the surrounding airspace, using the same published correction values and waypoints as the public. This check and subsequent periodic flight checks validate all the work leading to the approach design, and demonstrate that the approach is flyable.

As for any other navaid, data collected during a Loran-C flight check is tested against error limits which are determined by the system error budget. Any out-of-tolerance condition causes the approach to be removed from service until the cause is located and eliminated.

Loran-C Performance Realization: In the aircraft

Technical issues aside, the safety of any system depends upon use by a knowledgeable, attentive and prudent pilot, who must have the necessary mental and physical tools readily available. The key factor is education. Here are a few examples:

Basic Proficiency: In instrument approach by any other name...

... is still an intricate and exacting maneuver. Loran-C approaches are easier to fly than NDBs (partly because loran uses the CDI), not all that different from VOR or localizer approaches, and not at all different from currently-published RNAV procedures.

A Loran-C approach is still an instrument approach; only instrument-rated pilots may fly them.

Situational Awareness: Two more coordinate systems...

Pilots should be aware of, but not confused by, the new coordinate systems introduced by Loran-C to the aviation community. Latitude and longitude can be helpful in staying "found" rather than "lost," and they are essential for entering waypoints. Minute-by-minute navigation (or second-by-second approaching) is still accomplished in the familiar rho-theta, or VOR-like, coordinates.

The fundamental loran measurement is made in the hyperbolic time-difference (TD) domain. Evidence of this new coordinate system comes to the pilot when TD corrections must be entered or verified for an approach. With experience, these TD values may take on positional meaning, but practically, it may be better to verify the numbers and not think too hard about what they mean. They do NOT represent east/north, or along-track/cross-track values, for example.

Rules: Loran-C receivers are not created equal

The Airman's Information Manual and other publications are being updated to reflect the critical importance of using the right kind of Loran-C receiver for instrument approaches. In fact, there is only one approved kind of receiver -- one that has been certified for approach use according to FAA Technical Standard Order (TSO) C60b.

It is always the pilot's responsibility to determine that the aircraft is suitably equipped for intended flight operations. Some receivers have VFR-only approvals; others are approved for IFR enroute and terminal (but not approach) operations.

There are very good, safety-related reasons for restricting approaches to TSO'd receivers. A large part of the system performance assurance is built into these units. Non-TSO'd receivers are not required to demonstrate fast response to transmitter blink codes or momentary outages, for example.

In short, it is just not safe to fly an approach with a receiver not specifically approved for the purpose.

Warning: Loran-C receivers do not even look the same

The Loran-C receiver is nothing like familiar single-purpose VOR or ILS avionics. The various brands of traditional avionics can be operated "cold," with no unit-specific training.

The Loran-C receiver is more like a flight-management system. There are multiple functions, options, pages, data bases and "bells and whistles." Planning an IFR flight dependent on an unfamiliar Loran-C set is asking for an adrenalin rush.

Maintenance: Low-frequency systems, reincarnated [7,8]

Airframe-generated noise has always caused problems for users of low-frequency avionics. Note that the term "p-static" has been used to describe the overall problem, but p-static is only one element.

- P-static charging is generated only when the aircraft is moving through particles. The impact with these particles causes static charging of the airframe, in the same way that scuffing the carpet and touching a doorknob sometimes reveals static charge. Cloud droplets can cause this, as can rain, ice or snow.

- Charge can also be imparted to the airframe as it travels through areas of strong charge separation, as in the close vicinity of thunderstorms or building cumulus clouds.

Interference is caused as the charge leaves the airframe via ions in the slipstream, or migrates from place to place on the airframe. There are three principal noise sources:

- Corona discharges consists of pulses of energy (packets of ions) which leave the airframe most readily from small-radius points. Their energy level is generally determined by the airframe geometry, and the pulse repetition rate is determined by the amount of charge on the airframe. This interference is heard as a hiss (in the ADF receiver, for example).

  If enough energy is generated in the loran passband, this interference reduces the receiver's ability to "hear" the loran signal.

  To minimize corona, place static dischargers specifically designed for low-frequency protection at points recommended by the airframe manufacturer. Keep the dischargers maintained! They can be "burned out" by very strong charging or may be broken mechanically.

- Charge separation on the airframe may cause electrical "streamers" to appear on windscreens, radomes or other nonmetallic airframe components. Some manufacturers put a conductive coating on such components, or embed metal to minimize streamering by providing a conductive path for charge-generated currents. Coatings must also be maintained periodically.

  Streamering is generally of shorter duration than corona discharges, but may be more energetic.

- As charge accumulates on an airframe, very high voltages may be produced. If, due to corrosion, lack of proper grounding straps or imperfect bonding between airframe components (including antennas), there are non-conducting areas on the aircraft, the voltage build-up will likely be non-uniform. Arcing may then occur across the gaps.

  Again, the arc is of short duration, but contains very high energy (and can produce much radio noise). Enough of these arcs can cause significant interference.

  To avoid these difficulties, the manufacturer, installer and user must become aware of the symptoms and the fixes. Keep the aircraft clean, eliminate corrosion and loose bonds, maintain dischargers and be sure the antenna installation is in good condition.

  Less technical, but just as troublesome, are maintenance-related noise sources; loose nav-light wires, loose, corroded or dirty antenna mountings or connections, water invasion of connectors, bad power-supply filters and more. Use of Loran-C must be accompanied by improved overall airframe maintenance awareness.

  These noise problems can be very elusive, and one is tempted to conclude that "black art" is required for solution. There are test equipment and procedures (and consultants...!) which are available to FBOs and manufacturers to maintain the fleet.

So What? - Commentary

We're ready, that's what! The technical, procedural and policy issues have been resolved, by a remarkable partnership among users, FAA, Coast Guard and state organizations. Everyone contributed, and "gave" a little in the vigorous process, with no safety compromise.

Of course it has taken time. We are witness to a new aviation service, based on a "borrowed" signal, in a frequency band once all but forgotten to aviation, with new error sources to be handled. Loran-C instrument approaches for public use will be available very soon, and they will be very safe.

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A study of the distortion and propagation time-delay of Loran-C pulse wave based on a model of the propagation path.

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Abstract

This paper presents a ASF prediction method for the current Loran-C digital receiver, which uses the received pulse wave shape and calibrates its distortion measures. These measures are on the basis of the results of calculation using the frequency characteristics (1~200kHz) of three homogeneous and one mixed propagation paths.
It is assumed that the amplitude and phase characteristics of the propagation path affect both the pulse wave distortion and propagation time-delay simultaneously. The authors estimate the relation between the above two effects by means of the numerical calculation, and give a good estimated ASF value to correct the time of arrival. The calibrated distortion measures are ECD and CHACLE (Change of HAlf Cycle LEngth). Consequently, we have a good estimated time of arrival and the error of ASF is reduced to less than about 20%.

1. Introduction

Loran-C system has been the most useful position fixing system for ship, but presently this system is expanded to use for land- or air-vehicle navigation. In future, it will be utilized for monitoring integrity of other navigational systems.
On any navigational systems, they have three significant properties (reliability, integrity and accuracy) to evaluate its utility. Although the former two properties in Loran-C system have been maintained in good condition and improved gradually by each operating agency, the last property has not been improved except for the ASF correction in USA. Consequently, it will be the most important thing that the accuracy should be improved for worldwide Loran-C coverage areas.

It is well-known that Loran-C has an excellent repeatable accuracy, which is better than 80m (2dRMS), due to the control of transmitting pulse timing, the received signal to noise ratio and GDOP etc. An absolute or predictable accuracy of Loran-C might be as poor as 500m to 1000m [1] because of the incorrect estimated time of arrival(TOA). Obviously, it would be impossible to reduce the repeatable accuracy without the systematic change of Loran-C. So, in order to improve the latter accuracy, this paper considers one method to obtain a good estimated value of TOA. At present, every Loran-C user can obtain good TOA using ASF correction values in CCZ[2] (only North America) if he wants, but still he could not obtain the precise ASF correction value with a variation of propagation path characteristics It is necessary and sufficient thatthese estimated values of TOA or ASF should be precise and adaptive for that variation.

The power spectrum (more than 99%) of the transmitted pulse wave in Loran-C is concentrated within thebandwidth of 90 ~110kHz. The propagation speed at the standard pulse point is different from propagation phase speed of a single frequency, which dependson the propagation path characteristics in signal bandwidth (within 20kHz). Ordinarily, a gradient of the amplitude and nonlinearity of the phase characteristic with propagation path caused not only a propagation time-delay (ASF) but also a wave distortion simultaneously.

Kouguchi et al.[4)5)] already had explained that the propagation time-delay (ASF) could be estimated using ECD[3)] as a measure of the wave distortion experimentally.

In this paper, first we propose CHACLE (Change of HAlf Cycle LEngth) as a measure of the pulse wave distortion, and second prove the relation between the propagation time-delay and two measures (CHACLE and ECD) of that distortion by means of calculation using the LF bandwidth propagation path model obtained by Jholer [6)7)] and mixed path calculation method obtained by Millington[8)] . Finally we explain the error correction effect of propagation time-delay using these measures.

2. Received pulse wave shape

The pulse wave shape of Loran-C is defined as a standard pulse antenna current Re $[i(t)]$ [9)], and is considered as an analytic signal,

$$i(t) = \{-jAt^2\exp(-Bt + jw_0 t)\} \quad t \geq 0$$
$$= 0 \quad t < 0 \qquad (1)$$

where,
A :constant related to the magnitude of the peak antenna current.
B : 2 / 65
t :time [μsec.]
w_0:angular frequency (0.2π [rad./ μsec.])

The transmitted electric field Re $[p(t)]$ is the time derivative of i(t), and is given by the following equation.

$$p(t) = (d/dt)\, i(t)$$
$$= (2/t + B + jw_0)\, i(t) \qquad (2)$$

The power spectrum of the transmitted pulse wave shape is given by eq. (3).

$$P(jw) = wA / [\pi \{-B+j(w_0-w)\}^3] \quad \text{—— (3)}$$

The mathematical model for the ground wave propagation whose source is an elemental vertical electric Hertz dipole, is obtained by Norton, Bremmer etc. In the diffraction region, a vertical electric field E(jw, d) is given as follows.

$$E(jw, d) = E_0 [\{\exp(jk_0 d)\}/d]\, F(d, \sigma, \varepsilon)$$
$$= |E| \exp[j\{k_0 d + \arg(F)\}] \quad \text{—— (4)}$$

where,

- d: propagation distance.
- k_0: wave number of the atmosphere at the source of the earth. (= w η/c, c: light velocity, η: the index of refraction of the atmosphere)
- F : secondary phase factor.
- σ : the conductivity of the medium.
- ε : the permittivity of the air.

| E | shows the amplitude component and arg(F) shows the phase lag in the secondary phase factor. The computation method of above two significant values and those computed results of the Low-Frequency ground wave were given by Jholer, et al[6)7)]. In this paper, three significant propagation path models (snow-covered volcanic mountain, cultivated ground or fresh water, and sea water) are used. Those models are interpolated every 1 kHz in frequency and use the quadratic approximation at distance. Fig.1 shows one example (cultivated ground or fresh water) propagation path characteristics. (The amplitude characteristic is normalized by 102.39kHz)

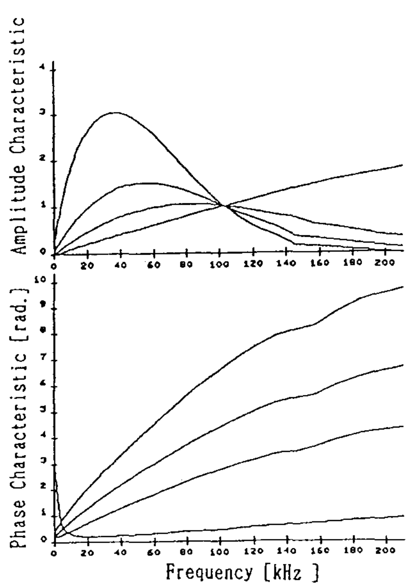

Fig.1 One example of the propagation path (σ=0.002 : cultivated ground or fresh water path)

The received pulse wave r(t, d) propagating homogeneous path at a distance of d from the source is givenin the form of the Inverse Fourier Transform of the product of the transmitted pulse frequency spectrum P(jw) and the transfer function of propagation path E(jw, d). So, we have

$$r(t, d) = \mathrm{Re}\left[\int_{-\infty}^{+\infty} P(jw)E(jw, d)\exp(jwt)\,dw\right] \quad \text{—— (5)}$$

Each distance of the mixed three paths model is d1, d2 and d3 respectively, and each path amplitude and phase characteristics are | E1 | · arg (E1), | E2 | · arg(E2) and | E3 | · arg(E3). Appling the Millington method[8)], the components toward the receiver from the transmitter are | Ef | · arg(Ef), and the components toward the transmitter from the receiver are | Eb | · arg(Eb), then the total path characteristics | Et | · arg(Et) are given by

$$E(jw, d) = |Et| \exp\{-j \arg(Et)\} \quad \text{—— (6)}$$

$$|Et| = \sqrt{(|Ef| \times |Eb|)} \quad \text{—— (7-1)}$$

$$|Ef| = |E1(d1)| \times \{|E2(d1+d2)| / |E2(d1)|\} \times \{|E2(d1+d2+d3)| / |E3(d1+d2)|\} \quad \text{(7-2)}$$

$$|Eb| = |E3(d3)| \times \{|E2(d2+d3)| / |E2(d3)|\} \times \{|E2(d3+d2+d1)| / |E3(d3+d2)|\} \quad \text{(7-3)}$$

$$\arg(Et) = \{\arg(Ef) + \arg(Eb)\}/2 \quad \text{—— (8-1)}$$

$$\arg(Ef) = \arg\{E1(d1)\} - [\arg\{E2(d1)\} - \arg\{E2(d1+d2)\}] - [\arg\{E3(d1+d2)\} - \arg\{E3(d1+d2+d3)\}] \quad \text{—— (8-2)}$$

$$\arg(Eb) = \arg\{E3(d3)\} - [\arg\{E2(d3)\} - \arg\{E2(d3+d2)\}] - [\arg\{E1(d3+d2)\} - \arg\{E1(d3+d2+d1)\}] \quad \text{—— (8-3)}$$

Accordingly, by substitution eq.(3) and E(jw, d) (obtained from (6-1) to (7-3)) into eq.(5), the received pulse wave r(d, t) is obtained by numerical integration.

3. Propagation path characteristics and propagation time-delay.

If an amplitude characteristic would be flat and a phase characteristic would be linear, then both the ASF time delay and wave distortion are not induced. So, in this chapter we use some simply propagation path models which have a gradient of the amplitude characteristic and nonlinearity of the phase characteristic, and discuss the relation between parameters of these models and the ASF time-delay.

3.1 Amplitude characteristic

Consider amplitude models as linear and quadratic equations in angular frequency (w). First, a linear amplitude model is defined as

$$E(jw) = -A_1 w \quad \text{—— (9)}$$

where, A_1 is a coefficient of this model.

The spectrum of the received wave pulse R(jw) is

$$R(jw) = -A_1 w\, P(jw)$$

Appling $w\,P(jw) = (1/j)\, jw\, P(jw)$, the received pulse wave $r_{A1}(t)$ is given by

$$\begin{aligned} r_{A1}(t) &= A_1 \mathrm{Re}\,[(-1/j)(d/dt)p(t)] \\ &= A_1 \mathrm{Re}\,[(-1/j)(d^2/dt^2)i(t)] \\ &= A_1(-4/t^2-4B/t+B^2-w_0^2)At^2\exp(-Bt)\cos(w_0 t) \\ &\quad -A_1(4w_0/t-2Bw_0)\exp(-Bt)\sin(w_0 t) \end{aligned} \qquad (10)$$

Next, taking into account the results of 2.2, a quadratic amplitude model is defined as

$$\begin{aligned} E(jw) &= -A_2\{(w-w_0)^2-w_0^2\} \\ &= -A_2(w^2-2w_0 w) \end{aligned} \qquad (11)$$

which is quadratic function in the center of w_0, where A_2 is a coefficient of this model. Similar to linear model, using $w^2P(jw) = (-1)(jw)^2P(jw)$, the received pulse wave $r_{A2}(t)$ is given by the following equation,

$$\begin{aligned} r_{A2}(t) &= A_2\{\mathrm{Re}\,[(d^2/dt^2)p(t)] - 2w_0(r_{A1}(t)/A_1)\} \\ &= A_2\{\mathrm{Re}\,[(d^3/dt^3)i(t)] - 2w_0(r_{A1}(t)/A_1)\} \\ &= A_2 b\,[\{(6B^2-6w_0^2)/t-B^3+3Bw_0^2\}\, At^2\exp(-Bt)\sin(w_0 t) \\ &\quad + \{-12Bw_0/t-3B^2w_0-w_0^3\}\, At^2\exp(-Bt)\cos(w_0 t) \\ &\quad - 2w_0(r_{A1}(t)/A_1)] \end{aligned} \qquad (12)$$

Further, this quadratic model is approximated as a sinusoidal ripple, which gives the following equation.

$$E(jw) = 1 - A_3\{\cos(m\pi w/w_0)\} \qquad (13)$$

where A_3 is an amplitude parameter, and m is a ripple periodic parameter. By substitution eq.(13) into eq.(5) and rearranging them, the received wave pulse is[11]

$$r_{A3}(t) = p(t) - A_3/2\,\{p(t-m\pi/w_0)+p(t+m\pi/w_0)\} \qquad (14)$$

For these results, the changes of these coefficients (A_1 and A_2) are independent of the pulse time-delay. The change of the coefficient (A_3) produces two echo pulses which occurs 5m μsec. before and after the standard received pulse point and it is considered that these echoes cause the change of the pulse time-delay. Fig.2-1 shows therelation between amplitude characteristic and propagation time-delay, and indicates that the amplitude ripple makes a very little change of the propagation time-delay.

3.2 Phase characteristic

Nonlinearity of phase characteristic is provided a quadratic phase characteristic in w, considering the results of 2.2, and given by following equation.

$$E(jw) = \exp[-jP_1\{(w-nw_0)^2 - n^2w_0^2\}] \qquad (15)$$

where P_1 is a phase parameter, and n is a ripple periodic parameter. As it is difficult to obtain the received pulse wave from the above equation analytically, it would be able to be obtained by numerical integration. The received pulse is obtained using Simpson's numerical integration by dividing from 1 kHz to 200kHz by 1 kHz.

Eq. (15) is approximated to the sinusoidal ripple.

$$E(jw) \fallingdotseq \exp\{-jP_1\sin(n\pi w/w_0)\} \qquad (16)$$

When it is assumed that this phase characteristic is very small, that is $P_1\sin(n\pi w/w_0) \ll 1$, then the received wave pulse $r_{P2}(t)$ is also approximated by the following equation.

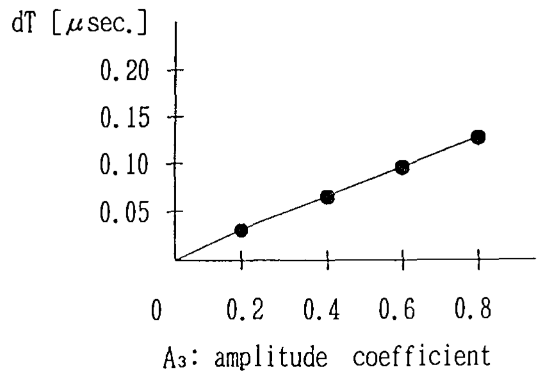

Fig.2-1 Relation between amplitude characteristic and propagation time-delay (m=0.5)

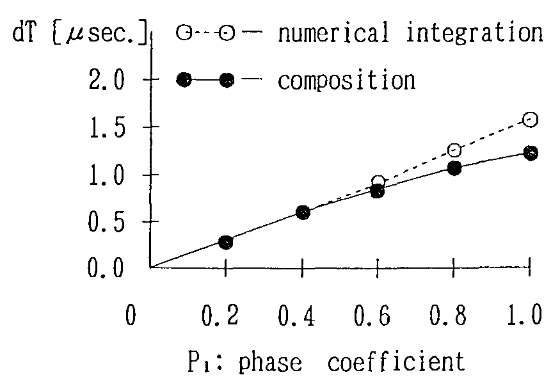

Fig.2-2 Relation between phase characteristic and propagation time-delay (n=0.5)

$$r_{p2}(t) \fallingdotseq p(t) + P_1/2 \ \{p(t-n\ \pi/2w_0) - p(t + n\pi/2w_0)\} \quad (17)$$

The change of these coefficient (P_1 and n) produces two echo pulses which occurs 5n μsec. before and after p(t), and changes its standard point of the time of arrival. Fig.2-2 shows the relation between the above phase characteristic and propagation time-delay, and indicates that the phase characteristic makes larger changes of the propagation time-delay than amplitude one. But when this phase characteristic is very small, it is shown that the result of the numerical integration is reasonable by the comparison of the two results (composition and numerical integration).

4. The measures of the pulse wave distortion

The propagation path characteristics which is due to the pulse wave distortion could be obtained by a comparison between the known transmitted pulse wave spectrum and the estimated received pulse wave spectrum which is obtained from the long period of the received wave data. On propagation of the LF band, there are some sky-waves reflected by the ionosphere. The Loran-C ground-wave could not be utilized to estimate that spectrum, because the pulse wave data 40μsec. after the leading edge of this pulse is mixture ground- and sky-waves.

Accordingly, in this paper two wave distortion measures are utilized to estimate the pulse time-delay. The first measure is CHACLE which would be proposed by authors, and the second is ECD which has been used as before. In this section, the definition and profile of the two wave distortion measures are described, and the possibility of CHACLE and ECD for utilizing to estimate the pulse time-delay are discussed.

4.1 CHACLE

Since the standard point of time of arrival(TOA) in Loran-C pulse wave is selected in the vicinity of the singular point for its envelope, it is considered that the envelope of this wave shape before the standard point raises the pulse rapidly and is constructed by the higher frequency component than the center angular frequency w_0, and the envelope after that point raises it slowly and is constructed by the lower frequency component than w_0. Accordinglyit is estimated that the effect of the propagation path characteristics gives an opposite distortion for the lower and higher frequency component. We propose the change of half cycle length on either side of the standard point as a measure of the wave distortion raised by these different effects, and call this measure CHACLE (Change of HAlf Cycle LEngth). CHACLE is defined as the next equation and Fig.3 shows the profile of this.

$$\mathrm{CHACLE} = (t_{sp} - t_{sp-1}) \quad (18)$$

where t_{sp-1} [n.sec.] is the half cycle length before the standard point, and t_{sp} [n.sec.] is the half cycle length after that point.

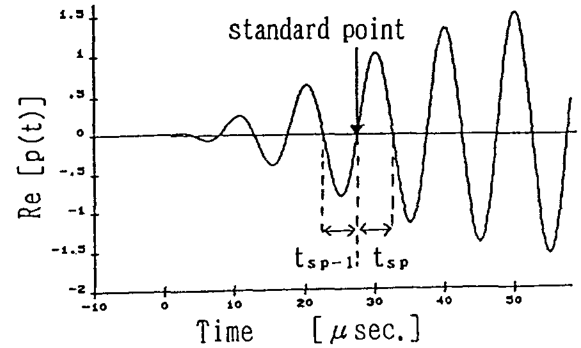

Fig.3 Profile of CHACLE

4.2 ECD

ECD is a wave distortion measure used to the examination for receiver performance or the establishment of the effective distance from the transmitter, and is defined as the following equation.[3]

$$h(t-\tau) = A(t-\tau)^2 \exp\{-B(t-\tau)\} \sin(w_0 t) \quad (19)$$

where τ is ECD value [μsec.] . It is clear that ECD is a pulse wave distortion measure which indicates a phase advance measure to the envelope on the antenna current wave shape.

In this paper, the same method as one used for the controlling ECD value of the transmitted antenna current at the transmitter is used to estimate ECD. In this method, the first 6 or 7 half cycle peak amplitudes of pulse wave would be measured and would be processed by the method of least squares.[12]

4.3 Effect of numerical integration

Using the calculated received wave pulse in section 3, it is considered that the numerical integration results affect the two distortion measures. To find the effect of numerical integration on those measures, we shall compare with two results of the calculated received pulse found in amplitude characteristic model before. One result is obtained by the numerical integration given in eq. (13). Another is obtained by the composition of the three pulse waves given in eq.(14). Fig.4-1 shows these two results with CHACLE, and Fig.4-2 with ECD. The results of ECD coincide with each other, but those of CHACLE do not. Since the error of CHACLE is regarded as a constant bias error and could be corrected, it is reasonable to use the calculated wave shape for investigating the relation between the two distortion measures and the propagation time-delay.

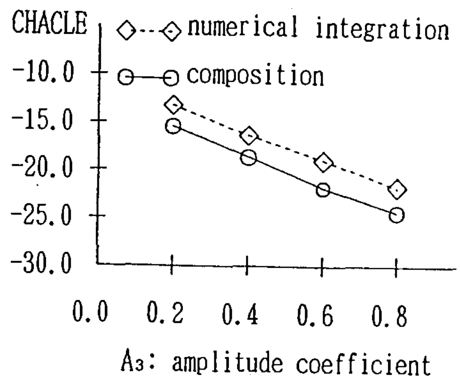

Fig.4-1 Relation between amplitude characteristic and CHACLE.

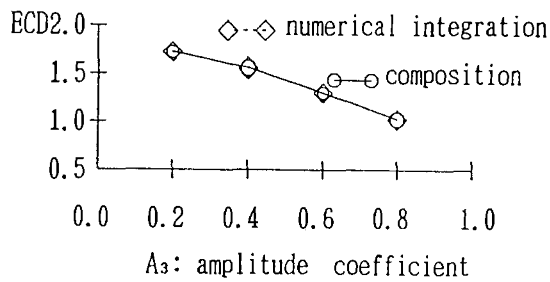

Fig.4-2 Relation between amplitude characteristic and ECD

5. Correction result for propagation time-delay

5.1 Correction method for propagation time-delay. To obtain the relation between those measures and the time-delay, we use three typical and homogeneous propagation paths explained in 2.2. Each path is sampled at intervals of 25 nautical miles (n.m.) and the total distance is 500 n.m. So, the total number of the samples are 60. (The substantial total number of samples are 58, because the ECD values of two samples are out of range -2.5 to +2.5 μsec. and are neglected.) The values of time-delay obtained by the linear or nonlinear regression are as follows:

(linear regression)

$$dT_{CHACLE1} = 4.195 \times (\mathrm{CdACLE}) \quad -21.56 \qquad \text{—— (20-1)}$$

$$dT_{ECD1} = -0.3074 \times (\mathrm{ECD}) \quad +1.565 \qquad \text{—— (20-2)}$$

(nonlinear regression)

$$dT_{CHACLE2} = 5.307 + 0.1819 \times (\mathrm{CHACLE}) - 3.982 \times 10^{-2} \times (\mathrm{CHACLE})^2 \qquad \text{—— (21-1)}$$

$$dT_{ECD2} = 4.177 - 1.605 \times (\mathrm{ECD}) - 8.233 \times 10^{-2} \times (\mathrm{ECD})^2 \qquad \text{—— (21-2)}$$

(correlation coefficient)

$\gamma_{CHACLE} = 0.97$

$\gamma_{ECD} = -0.69$

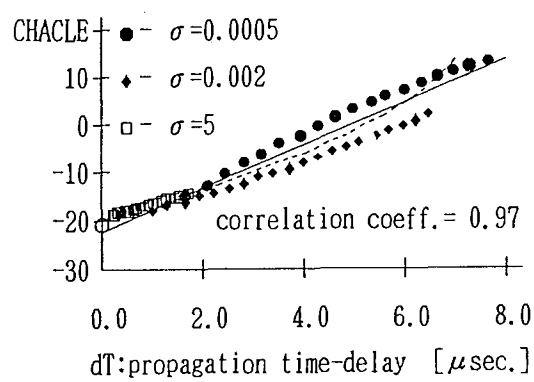

Fig.5-1 Correlation of CHACLE and propagation time delay. (— linear, ···· nonlinear)

Table 1 Residual error for each homogeneous propagation path after correction

		Sample Number	Average Error [μsec.]			RMS Average Error [μsec.]		
			raw	linear	nonlinear	raw	linear	nonlinear
Snow covered volcanic mountain (σ=0.0005)	ECD	18	4.76	0.05(1.0)	0.02(0.4)	5.10	0.24(4.7)	0.15(2.9)
	CHACLE	18	4.76	-0.45(9.5)	-0.41(8.6)	5.10	0.50(9.8)	0.63(12.4)
Cultivated ground & fresh water (σ=0.002)	ECD	20	3.83	1.59(41.5)	1.61(42.0)	4.17	2.16(51.8)	2.16(51.8)
	CHACLE	20	3.83	0.71(18.5)	0.50(13.1)	4.17	0.78(18.7)	0.52(12.5)
Seawater (σ=5)	ECD	20	0.94	-1.58(168.1)	-1.60(170.2)	1.06	1.61(151.9)	1.62(152.8)
	CHACLE	20	0.94	-0.28(29.8)	-0.13(13.8)	1.06	0.33(31.1)	0.13(12.3)
Total	ECD	58	3.12	0.02(0.6)	0.01(0.3)	3.80	1.59(41.8)	1.59(41.8)
	CHACLE	58	3.12	0.01(0.3)	0.00(0.0)	3.80	0.57(15.0)	0.47(12.4)

* ( ) shows the error reduction percentages.

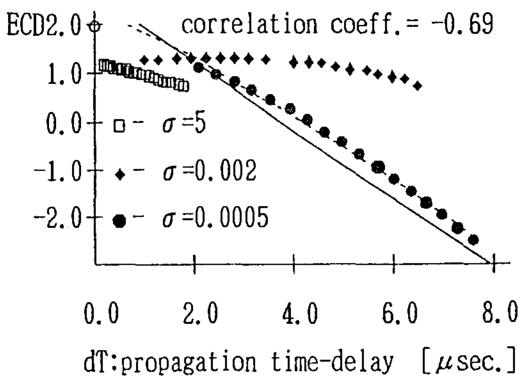

Fig.5-2 Correlation of ECD and propagation time delay.(— linear,---- nonlinear)

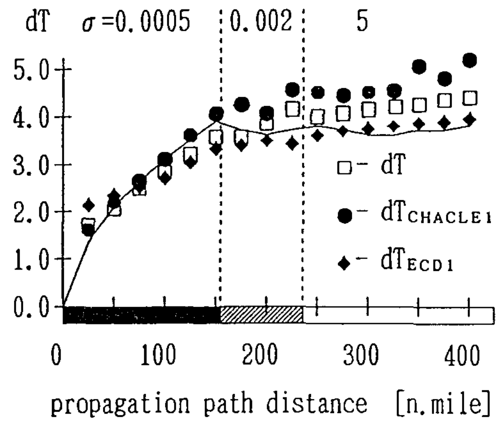

Fig.6 Residual error and propagation time delay

Curves and plots of these measures (CHACLE and ECD) obtaied by the linear and nonlinear regression methods as a function of the propagation time-delay are shown in Fig.5-1 and Fig.5-2. Since each point is close to the above two regression curves and the correlation coefficients are good enough, so eq.(20-1),(20-2) or eq.(21-1),(21-2) could be used for the correction equations toreduce the error of the estimated time delay. It is noticedthat CHACLE has better correlation coefficient and better correction equations than ECD.

Finally the total correction effects for three typical and homogeneous paths are shown in Table 1.

5.2 Applcation to the mixed propagation path

We use the mixed three homogeneous paths (σ=0.0005, 0.002,5) model which is resemble to the model used to verify the calculated ASF in U.S.A .[13]. Although these two models are not quite identical (as to a conductivity of the second path), it can be considered that the general correction effect using these measures for one mixed propagation path is understood.

Fig.6 and Table 2 show the comparison between the properly used model of SF (Secondary phase Factor), and the calculated time delay of the proposed method and it is easy to say that the two results have the same trend except for the results on the second propagation path.

6.Conclusion

The propagation path characteristics in Loran-C caused the propagation time-delay and wave distortion on its pulse wave simultaneously. It became clear that these two phenomena were related to each other. We proposed a new measure of pulse distortion (CHACLE), and the correction method for the pulse time-delay. It was proven that these correction equation had been applied to the mixed propagation path. By comparison CHACLE with ECD, it was shown that CHACLE was better correction measure than ECD. Moreover, CHACLE is measured by the zero-crossing period of the received pulse, on the other hand ECD measured by its amplitude level of it. Therefore, CHACLE may be a better measure than ECD from the viewpoint of noise immunity.

Therefore it would be necessary to continue studing the effect of the distortion measurements and the measuring system of them.

ACKNOWLEDGEMENTS

We wish to express our thankfulness to Prof. Yumio Yonezawa and Prof. Yasuo Arai (Marine Technical college) for many helpful suggestions during the course of this work.

Table 2 Residual error for mixed propagation path after correction

		Sample Number	Average Error [μsec.]			RMS Average Error [μsec.]		
			raw	linear	nonlinear	raw	linear	nonlinear
Mixed path model (σ=0.0005,0.002,5)	ECD	18	3.57	0.22(6.2)	0.14(3.9)	3.75	0.43(11.5)	0.31(8.3)
	CHACLE	18	3.57	-0.36(10.1)	-0.65(18.2)	3.75	0.45(12.0)	0.74(19.7)

* ( ) shows the error reduction percentages.

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Space Environment Effects on Navigation Systems

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Abstract

Large solar flares and the geomagnetic storms that may follow have a detrimental effect on the proper function of navigation equipment. LORAN–C, OMEGA, TRANSIT, and GPS are all subject to difficulties, although the physical mechanisms affecting the terrestrial systems are distinctly different from those that hamper space-based systems. Furthermore, satellite networks will respond differently depending on the orbital parameters of the spacecraft. X-ray effects from flares and ionospheric instabilities associated with geomagnetic storms and polar cap absorptions are the main irritants for LORAN–C and OMEGA. TRANSIT satellites must deal with orbital aberrations associated with increased satellite drag from Joule heating of the upper atmosphere by geomagnetic storm currents. Fluctuations in the ionospheric total electron content (TEC), most commonly related to geomagnetic storms, are bothersome for GPS. Quiet geomagnetic conditions are also potentially problematic for equatorial region users of GPS. Engineering around these problems is not entirely possible, so a prudent choice of more than one system is advisable to permit navigation under any circumstance.

1. Space Environment Effects

1.1 Solar Flares

The Sun produces various types of activity that may hamper the function of navigation systems. Solar flares, the sudden release of great amounts of energy spanning the electromagnetic spectrum, are most commonly associated with the concept of solar activity. Flares are at times very abundant in x-rays, and these produce abnormal ionization near Earth. This enhanced ionization alters the structure of the waveguide formed by the surface of Earth and the ionosphere where terrestrial navigation signals propagate. The onset of flare-induced x-rays may be very abrupt, so little warning can be given when an anomolous situation is imminent.

Flare activity is, however, somewhat cyclical. There is a tendency for flare occurrences to mimic the well-known 11-year sunspot cycle. (See Figure 1.) Flares are fueled by energy stored in strong magnetic fields on the Sun. These fields are at times as strong as 3,000 Gauss. Sunspots are a visible manifestation of these strong fields, and it's reasonable to assume that the more sunspots visible on a given day, the greater the likelihood of flares. Unfortunately, the relationship is not quite so simple because some type of instability must occur to trigger the release of the energy. Solar observers have seen sunspot groups that had strong fields but were very stable and, thus, produced no flares; in contrast, less impressive groups that were very contorted and non-potential in structure generated numerous large flares. A non-potential magnetic structure means there is free energy available to the flare process.

1.2 Sunspot Cycle 22

For more than two hundred years observers have been assiduously counting sunspots. In fact, a less complete record actually exists over a much longer time period, as there are many references to sunspots in the writings of the ancient Chinese, among others. This "modern era" record, though, contains what is believed to be the most accurate data, and in it scientists identified the 11-year periodicity. (See Figure 2.)

The current cycle, dubbed 22, began in September 1986. Early data put it on a pace that would have made it the highest yet seen. (See Figure 3.) Along with elevated sunspot numbers, flare activity during the ascending phase of the cycle was sometimes extraordinary. The March 1989 flares from a large and complex sunspot group saturated x-ray sensors on-board the Geostationary Operational Environmental Satellites (GOES) and precipitated a geomagnetic storm that was one of the most severe on record [1]. Additional dramatic flares in October 1989 generated solar protons in quantities rivaling the famous events of August 1972 [2].

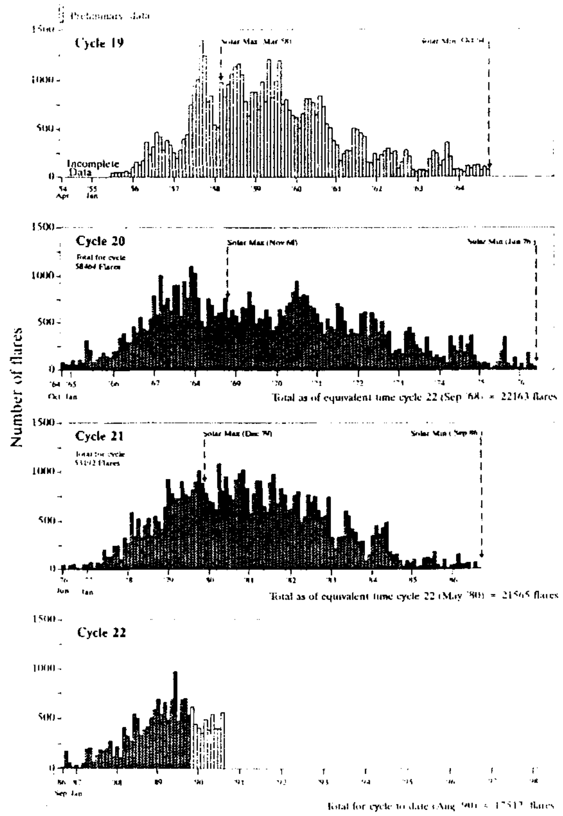

Figure 1. Solar flares by sunspot cycle. Note the times of sunspot maximum for cycles 19, 20, and 21.

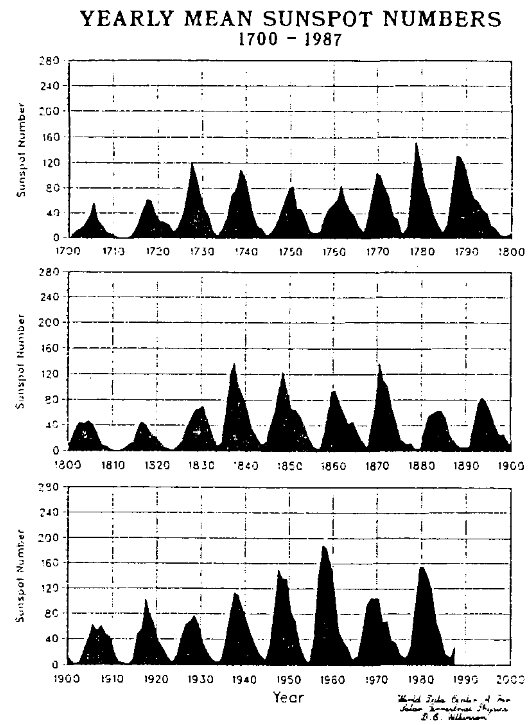

Figure 2. Yearly mean sunspot numbers, 1700–1988.

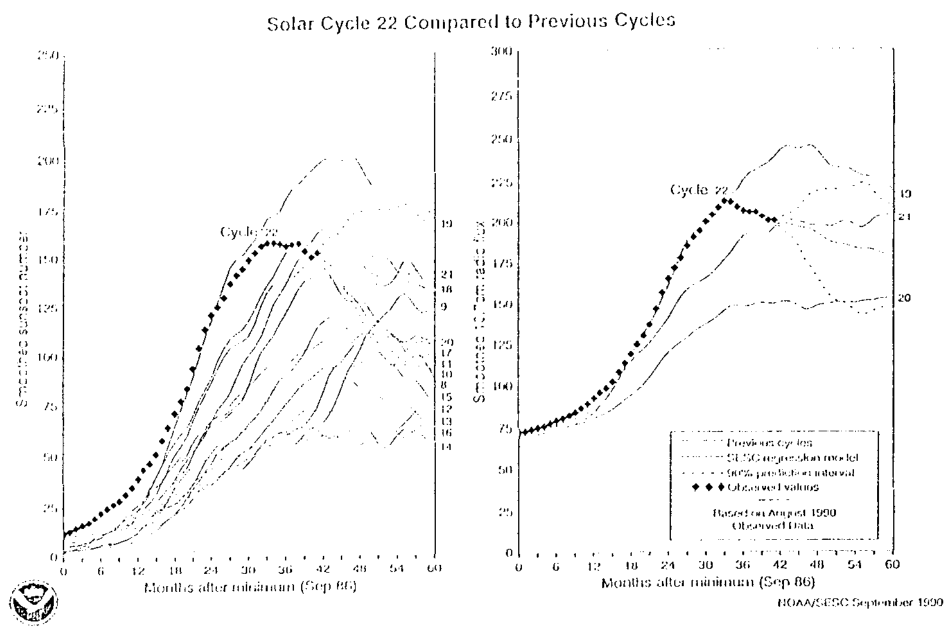

Figure 3. The relative performance of cycle 22 as measured by sunspots (left) and radio flux (right).

Recently, Cycle 22 has slowed its pace, and the fast start has become a fade down the stretch. Current data suggest that the maximum occurred in July 1989 with a value of 158.1, the third highest ever. There is a very real chance that the sunspot numbers may begin to increase anew and reach a mark greater than the July value; a prudent observer would still allow for this possibility. Preliminary data from August 1990 may herald an upward turn. If the July 1989 number does indeed prevail, it would be the fastest start-to-maximum time ever, 34 months. For perspective, the average start-to-maximum for all cycles is 51.5 months.

1.3 Geomagnetic Storms

Geomagnetic storms are yet another aspect of activity which occurs in the space environment. These phenomena may follow energetic solar flares. Unfortunately, a major player in the scenario of whether or not a storm will occur is the direction of the interplanetary magnetic field (IMF) near Earth. When the interplanetary magnetic field vector is anti-parallel to that of Earth's magnetic field, a necessary element is present. This condition allows the physical process, so-called "reconnection," to occur, facilitating the transfer of the energy carried by the solar wind into Earth's magnetosphere [3]. It is this new influx of energy that disturbs the equilibrium of the magnetic and electric fields near Earth.

Unlike flares, geomagnetic storms do not track well with the fits and starts of the sunspot cycle. (See Figure 4.) Storms may occur at any point in the cycle, and a look at the data reveals a time lag from sunspot maximum to the point at which geomagnetic activity is, in a general sense, most pronounced. The reason for this insensitivity to sunspot numbers is multifaceted. One factor, the parallel, anti-parallel, orientation of the IMF seems to be totally independent of the sunspot cycle, and this is a key element in the development of a geomagnetic storm. Another factor is that increased solar wind energy may also come from other solar phenomena, specifically coronal holes and coronal mass ejections. Coronal holes are most likely to spawn a geomagnetic disturbance during the descending phase of the sunspot cycle when they form nearest the ecliptic plane, and coronal mass ejections appear to have their origin in physical events on the Sun that differ from the flare process.

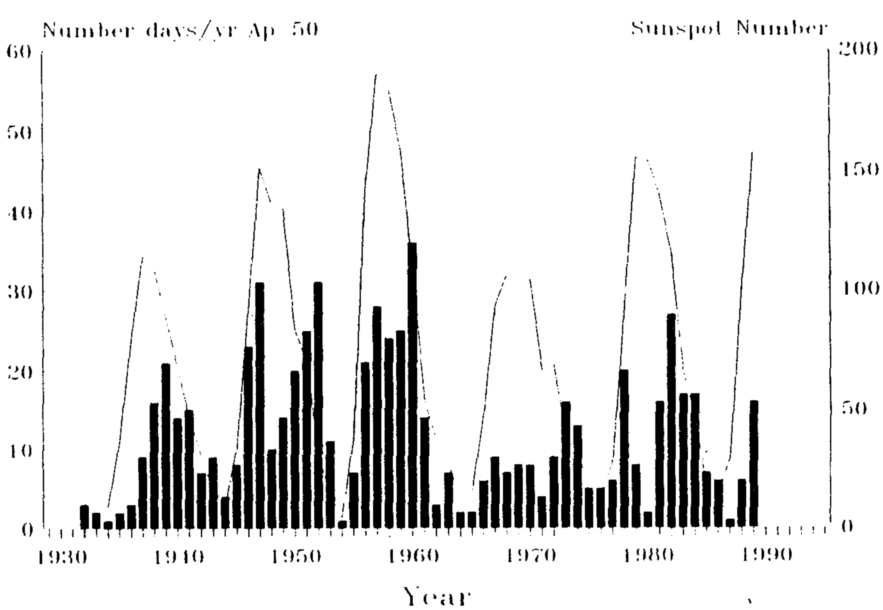

Figure 4. Sunspot cycle distribution of geomagnetic storms. $A_p > 50$ is defined as a major geomagnetic storm.

2. Navigation Systems and Environmental Effects

2.1 Terrestrial Systems

2.1.1. LORAN–C

LORAN–C, with a carrier frequency of 100 kHz, is reputed to be the most widely used long-range navigation system in the world. The current user population is estimated to be 750,000 navigators. LORAN–C groundwaves serve approximately 23 million square miles, and skywaves extend the footprint to about 60 million square miles [4]. Using a low-frequency (LF), pulse-type system, positions are obtained by measuring timing differences from the known locations of LORAN–C transmitters. The navigational fix occurs where two or more arcs of position intersect. Depending on how many stations are used, there may be some ambiguity as to the position, because two hyperbolas will intersect at two places (if they intersect at all). However, the intersections in this case will be very far apart, so the user can easily eliminate one. Clearly, the geometry of the LORAN–C grid greatly affects position accuracy. The preferred navigational situation is for the tangents to the hyperbolas to be normal to each other at their point of intersection.

LORAN–C operations on the dayside of Earth can be adversely affected by solar flare x-rays. The primary and preferred mode of LORAN–C navigation, the groundwave, is generally immune to the increased x-ray flux from flares because (as its name suggests), it hugs the surface of the Earth as it propagates. Groundwaves can reach approximately 1,600 km from the transmitter with high stability and be useful to navigators.

A problem arises when there is ambiguity at a receiver in distinguishing the groundwave pulse from the skywave pulse. This skywave is reflected by the ionosphere, and if the mirror layer is lowered by an increase in the ionization due to solar flare x-rays, the time of arrival by the skywave will be close to the arrival of the groundwave. Most LORAN–C receivers are designed to key on the third-cycle crossover, and to lock onto this portion of the pulse. (See Figure 5.) Because the carrier frequency is 100 kHz, each cycle takes 10 microseconds and the sought-for third-cycle crossover would arrive in 30 microseconds. If the delay to the arrival of the skywave is more than 30 microseconds, there is no problem distinguishing between the two waves. A flare-affected ionosphere lowers the height of the reflection point and may allow the skywave to arrive in less than 30 microseconds, and this is when problems occur.

At very long ranges, up to many thousands of kilometers, navigation using skywaves is possible, but the degree of accuracy may be greatly reduced. The repeatable accuracy using LORAN–C groundwaves is 10 meters [4]. Skywave fixes may be as much as two or three orders of magnitude less precise, as an unstable reflection height over the path of the skywave will make any calculation using the time of its arrival very dubious; the user cannot know exactly how far the signal traveled, or what changes in its phase and amplitude occurred enroute.

Other conditions that affect LORAN–C are geomagnetic storms and polar cap absorptions. Both of these are most acute in the polar regions, at least as to how they affect LORAN–C. The disruption to the stability of the ionosphere in this locale may linger for days, with the net effect being confusion as to the separation of a groundwave from a skywave by a receiver. Solar flare x-ray effects, in contrast, usually abate in minutes to hours.

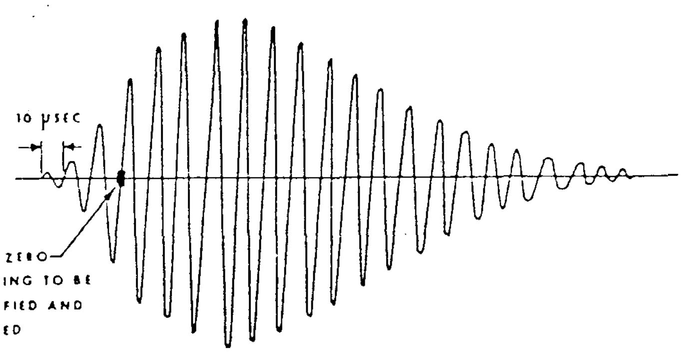

Figure 5. 100-kHz LORAN–C pulse. A receiver locks onto the third cycle crossover [6].

2.1.2. OMEGA

Omega is a very-low-frequency (VLF), continuous-wave system, with carrier frequency in the 10–15 kHz band. The eight transmitting sites around the world provide uninterrupted coverage to navigators at any point on the globe. Omega signals propagate within the spherical waveguide formed by the ionosphere and Earth's surface to reach very long distances. Omega, too, is a hyperbolic-type navigational system, with the user's location determined by the intersection of the available lines of position. The design accuracy of the system is specified to be 3.7–7.4 kilometers [5].

A problem analogous to the LORAN–C groundwave–skywave duo also exists with Omega signals. Conditions may vary along the length of the waveguide between Earth and the reflective layer of the ionosphere, resulting in multiple modes of the Omega signal being received by navigation equipment. The desired signal, called the primary mode, is the one that is most stable and useful for positioning: it has the cleanest reflection pattern. The secondary mode, the situation that occurs when changes in electron density cause the reflection to be nonuniform (i.e., the thickness of the waveguide changes as the reflections occur), poses difficulties for Omega receivers. Fortunately, attenuation of the secondary mode is generally higher than for the primary mode [6].

During quiet solar conditions (few flares), Omega primary modes are very predictable during daylight hours. Nighttime is a bit more disturbed, as secondary-mode amplitudes may increase, but the signal is still very good. Many years of data have been accumulated worldwide to compile correction tables for navigators who use Omega. The corrections mitigate diurnal ionospheric changes allowing better positional accuracy.

Flare activity is a different story. A sudden infusion of x-rays into the ionosphere changes the effective reflection height very rapidly. With the waveguide in a state of flux, little stability can be expected in the signals, and navigation by Omega may be impossible. The disturbed condition may persist for days as the ionosphere quiets. It should be noted that polar cap absorptions and geomagnetic storms also have a severe effect on the Omega system as they have a profound impact on the stability of the ionosphere.

It is clear that the ionosphere is the key domain in the space environment when assessing the proper function of LORAN–C and Omega. A stable reflective height is most desirable, but disturbed solar and/or geomagnetic conditions may cause that to be impossible at times. The effects may vary based on the geographic locations of the transmitters. Situations do occur, though, where the disruptions are ubiquitous, and all latitude domains are affected.

2.2 Satellite-Borne Systems

2.2.1 Transit

The Transit satellite system has been available for use by the general public since 1967. The network consists of six satellites, four being the older, Oscar type and two the newer, Nova class. The spacecraft, in circular polar orbits at an altitude of approximately 1100 km, have an orbital period of 107 minutes. They are spaced equidistant around the equator. Each satellite broadcasts two carrier frequencies, 150 MHz and 400 MHz, and positions are obtained by tracking the doppler shift of an individual satellite's signals as it passes overhead. The dual frequency transmissions allow for the correction of ionospheric dispersion of the received signal [7].

Doppler navigation has its roots in the tracking of early Sputniks by scientists at Johns Hopkins and at Portsdown, England. They found that a satellite's orbital parameters could be determined by analyzing the doppler shift of its transmissions from a known point on the ground. The technique employed by Transit is very similar, except that it uses the known position of the satellite in orbit. By doing a doppler analysis on the two carrier frequencies, a receiver on Earth could compute a position. Under optimum conditions (i.e., the satellite pass is directly overhead and the ionospheric structure is stable), an accuracy on the order of 15 meters may be obtained.

The main nemesis of the Transit system is the geomagnetic storm. During the storm, strong currents flow through the ionosphere and affect that environment through Joule heating. This influx of heat causes the atmosphere to expand and rise. Transit vehicles, in an orbit of 1100 km, fly in a regime where this increase in local atmospheric density has a great effect on satellite drag. When the drag is changing substantially, it is difficult to know the orbital parameters accurately. Since the receiver's position is computed relative to that of the satellite, any orbital uncertainty translates into degraded positions on the ground.

Also of concern to the Transit operation is the potential for hardware or software anomalies due to solar and geomagnetic activity. As low-altitude, polar-orbiting spacecraft, Transit satellites cross the polar cap and the auroral zones. Here two effects may be of significance: 1) geomagnetic control of the entry of solar and galactic cosmic rays, and 2) auroral precipitations. These factors enhance the likelihood of a circuit malfunction from a single-event upset, and they are most likely to occur during a geomagnetic storm [8].

2.2.2 GPS

The Global Positioning System (GPS) is the most expensive navigation system to date. Many of the contracts awarded by the Department of Defense were acclaimed to be the largest of that type ever let. The arrival of GPS has been celebrated by users who hope for a very reliable and accessible system with accuracies to less than a centimeter. Partially deployed, the system will number 21 satellites, plus spares, aligned in three orbital planes at an altitude of 20,000 km. This grid, when fully operational, wil give continuous 24-hour coverage at almost any point on the globe. Like the Transit satellites, two carrier frequencies, nominally L1 (1575.42 MHz) and L2 (1227.60 MHz,) are used to help correct for ionospheric irregularities. Superposed on the carriers are so-called "pseudo-random noise codes" that may be deconvolved by the receiver for very accurate positional information. There are two codes, the "C/A-code," which is a sequence of plus ones and minus ones emitted at a frequency of 1.023 MHz, and a second code, dubbed the "P-code," which is also a sequence of plus and minus ones sent at a frequency of 10.23 MHz. It is the P-code that is used for the most precise navigation, and that code repeats itself only after 267 days [7]. The reason for this lengthy period is that it allows the P-code to be cut into many different segments which are assigned to different satellites. This allows for ready identification by a receiver of which spacecraft's transmissions it may be receiving.

There is also a secret pseudo-random noise code that may be employed at times, called the "Y-code." It is similar in structure to the P-code but will replace the P-code at times when the Department of Defense, the proprietor of the system, wants only selected users to have the ability to obtain the most accurate positioning. In addition to this option, the threat of "selective availability" looms large for civilian users of GPS. Selective availablity means that the commercial navigation community may not be able to use the GPS signals to the limit of their capabilities. The Department of Defense may degrade the integrity of the superposed codes (i.e., the C/A and P codes) once all of the satellites are in orbit, with the net result being much less accurate fixes obtainable by the non-military users. Time will tell as to the magnitude of the impact on users due to this feature, but clearly it is not an aid to general navigation.

GPS signals transit the ionosphere. A stable ionosphere promotes reception of the transmissions on the ground and allows for phase stability of the signal. If the ionosphere is in a state of flux, specifically, its total electron content (TEC) is varying along the path of the signal, the density of this medium will change on small scales. These density irregularities can cause phase anomalies and abnormal path delays, and hamper the ability of a receiver in fixing a position.

The key question for a user is: "When might these TEC variations occur?" Unfortunately, the answer is not a simple one. First of all, it depends on the location on Earth. Middle and high latitudes are most susceptible to TEC variations during times of geomagnetic storm activity. In the equatorial zone, however, the reverse is true. Near the equator, quiet geomagnetic conditions may be more problematic for GPS than storms, as it is during quiet times that density irregularities are most commonly seen. The governing process is not completely understood, but it probably involves local plasma instabilities.

Analysis of years of ionospheric data has shown that seasonal effects also are significant. It is likely that GPS users, especially in the equatorial zone, will find more difficulty during the equinoctial months than at other times. Also the time of day can influence the abilities of GPS equipment, with the night hours preferred. Working around the maximum of the sunspot cycle will probably be more difficult than near the minimum.

Other problems that may befall GPS satellites are due to their orbit. The 20,000-km radius coincides with the outer Van Allen belt, an area of trapped radiation that has a large population of low-energy (< 1 MeV), solar-generated protons. More importantly, this orbit transits the heart of the so-called "outer zone," a location at which geomagnetic activity serves as a driver for the acceleration of trapped electrons. Increases in electron fluxes of five orders of magnitude above background have been seen to occur in less than 24 hours, and may take as long as 10 days to decay. High dosages of energetic electrons may cause surface charging, thick dielectric charging, sensor malfunctions, and radiation degradation [9]. GPS vehicles, as would be expected, have had difficulties at times. It has been observed that: "During the past few years there appears to be a clear qualitative correlation between high solar activity and repeatable upsets occurring on board GPS space vehicles. In general we have noted that 3 to 5 days following sustained high solar activity certain upsets are possible. Most of these upsets have had serious consequences to space vehicle health, mission accomplishment, or both" [10]. It is important to note that, although *solar activity* was mentioned in the previous quote, the actual condition was *geomagnetic activity*. This serves to illustrate a problem many users have when trying to diagnose mechanisms and situations that occur in the space environment.

3. Pertinent Solar and Geomagnetic Parameters

What do navigators need to know when trying to understand environmental effects on their systems? The quick answer is often "solar activity," but what does that mean?

Solar activity commonly refers to solar flare activity, the fast release of a large amount of energy from small areas on the Sun. This would be of interest to a user of LORAN-C or Omega on the dayside of Earth, but of little consequence to others. A synonymous term for solar activity would be sunspot activity, but that does not mean that the sunspot cycle and the solar activity cycle are the same thing. The sunspot cycle is just the counting of sunspots as a function of time, and smoothing those numbers; it has *nothing* to do with flare activity. Flares may occur at any time, and it's possible to have a high solar activity cycle that is a low sunspot cycle.

Another parameter that is often confused with solar activity is solar flux. Solar flux is a daily measurement of the quiet solar output (i.e., no flares are occurring) at local noon at Ottawa, Canada, at the frequency of 2800 MHz. (10.7 cm. wavelength.) Long-term averages of that value are used in various ionospheric models, but the daily value is of little use in diagnosing the state of the ionosphere because its time constants are much longer than 24 hours. Some scientists use solar flux as a substitute for EUV flux, the quantity associated with atmospheric heating. EUV flux measurements cannot be made from the ground, and 2800 MHz measurements can. In reality, no conclusions can be drawn about the stability of the ionosphere solely from the solar flux value.

During the interval of November 6–9, 1989, the Federal Geodetic Control Committee (FGCC), the official U.S. Government organization for testing GPS receivers, tested eight dual-frequency receivers in Washington D.C. constructed by one manufacturer. This company has since published the results of those tests and in that paper makes a number of references to the ionospheric conditions during that period. The author states that the tests were conducted while the ionosphere was disturbed, presumably to embellish the reputation of his product. The only datum included in the paper is a plot of daily values for the solar flux, and the claim: "Severe ionosphere activities existed during the...FGCC test as shown below in the Daily Solar Plot provided by...NOAA. The level of ionosphere activities was the highest (with a substantial margin) in the history of FGCC tests."[11] (See Figure 6.) Further on in the paper, the author makes repeated references to the high level of ionospheric disturbances that occurred during the tests.

This is an example of a very poor understanding of the use and significance of solar flux values. As mentioned earlier, *no conclusions on ionospheric stability can be drawn from the daily solar flux alone*. A look at appropriate data, the geomagnetic indices and TEC values, is more revealing: The geomagnetic field was unsettled to mildly active during this time, a situation not usually associated with ionospheric perturbations at middle latitudes. The TEC was high as would be expected for the Northern Hemisphere during that month, but stable throughout the week. Also scintillation, the effect associated with irregularities in ionospheric structure, was average. Based on these pertinent data, a very different characterization of the ionosphere during the test period would be made. It's no wonder that the test results were favorable!

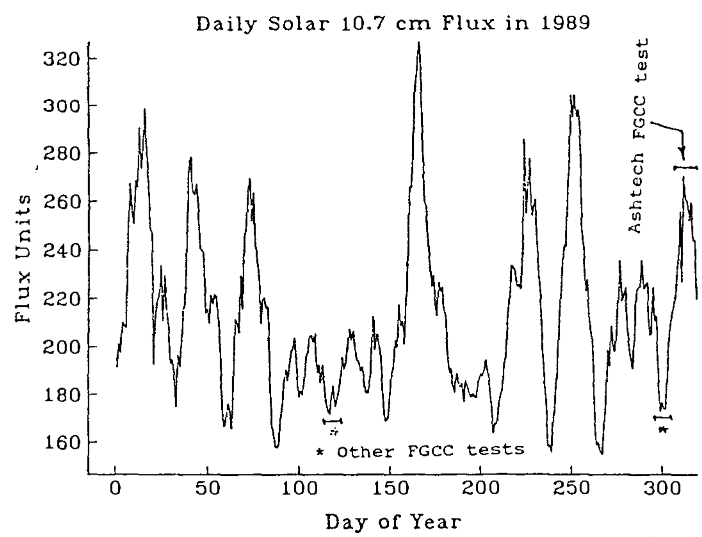

Figure 6. Solar flux data used to incorrectly diagnose ionospheric stability.

Geomagnetic activity is also confused with solar activity, as was seen in an earlier example in this paper. Geomagnetic activity may occur after a solar flare, but does not always. LORAN–C, Omega, Transit, and GPS users may all be affected by elevated geomagnetic activity, but low activity in the equatorial region may be a problem for GPS users located there. The ionosphere is variable both spatially and temporally, and, therefore, a look at a number of parameters is usually required to be able to describe its behavior.

4. Conclusions

Solar flare and geomagnetic activity have a great effect on the ionosphere. However, ionospheric irregularities may also occur at times when both the Sun and Earth's magnetic field appear quiet. Because of the dependence of modern navigation systems on the ionosphere, scientists and the navigation community share common ground in their desire to better understand that medium. Until that time when the ionosphere can be accurately modelled, or engineers can build electronic systems impervious to the vagaries of the operating environment, a prudent navigator would choose perhaps one satellite-borne and one ground-based system, to ensure some positional accuracy under any circumstances. This plan may be especially pertinent to the equatorial zone, where a quiet Sun and magnetic field are beneficial for LORAN–C, but may be detrimental for GPS operations.

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Biography

Joseph M. Kunches is the Lead Forecaster at NOAA's Space Environment Services Center, a world center for forecasting and monitoring solar and geophysical activity. He is also a lecturer at the Boulder Campus of the University of Colorado. His involvement in solar-terrestrial physics dates to the SKYLAB era of the early 1970s, when he began work as a solar forecaster at NASA's Johnson Space Center. More recently he has been interested in the effects of solar and geomagnetic activity on navigation systems. He is a member of the Wild Goose Association and the Institute of Navigation. His academic work includes a Bachelor of Science degree in Aerospace Engineering from the University of Notre Dame (1970) and a Master of Basic Science degree from the University of Colorado, Boulder (1985).

RAISIM - Receiver Autonomous Integrity and Signal Monitoring

Durk van Willigen

Delft University of Technology
&
Reelektronika bv

Abstract

Integration and hybridization of Navstar/GPS, Glonass and Loran-C areeminent tools to obtain adequate integrity and availability of radio positioning in the high-risk transport business. Until now, "Receiver Autonomous Integrity Monitoring " techniques are almost entirely based on consistence of a redundant set of pseudo-ranges and measuring the signal-strengths and signal-to-noise ratios. However, additional information is available by also analyzing the quality of the received signals. With GPS e.g., additional information can be found by searching for reflections, while with Loran-C, the signals should thoroughly be checked for alterations by skywaves, unexpected ASF's and interferences. Suggestions are given for how to detect various Loran-C signal deformations and how to use this knowledge in a strategy for "Receiver Autonomous Integrity and SIgnal Monitoring - RAISIM". Finally, the analysis of the received signals makes a better use of the Loran-C information often possible.

1 - INTRODUCTION

In marine and aeronautic navigation it has always been a good habit to cross examine found position data from more than a single source. Double, or even triple checking of the position of the craft is of extreme importance when lives, cargo or nature are at risk. Automating such procedures for cross checking is a complicated task. Entering all the acquired pseudo ranges e.g. into a Kalman filter is not the clue to every problem. For example, a filter cannot simply detect a wrongly selected Loran-C cycle in a non-redundant set of position equations. In such cases, the receiver itself should give the warning for possible cycle problems. And in case a redundant set of range equations is available, then there is still the problem of how to isolate and correct or just disable the erroneous pseudo range.

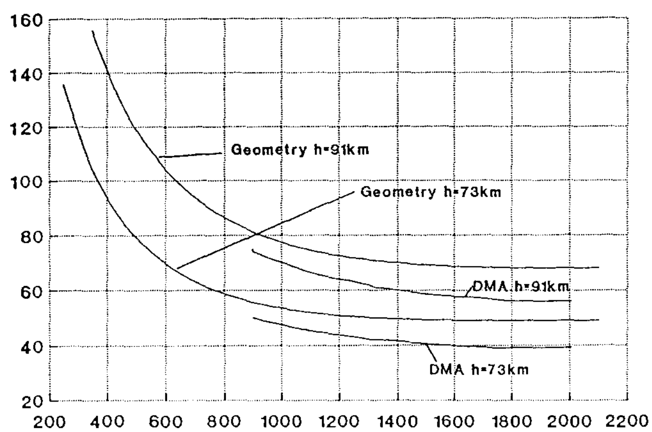

Fig. 1 Variation of skywave delay (μs) with distance for different effective ionospheric heights [1]. The geometry data are calculated, while the DMA data are derived from USCG tables.

Many interesting possibilities of RAIM (Receiver Autonomous Integrity Monitoring), integration and hybridization are published in the WGA Proceedings and in the ION Journals of Navigation. However, solutions for testing the signal quality in the receiver itself is far less mentioned. In the following paragraphs is shown that good methods for signal-quality control are possible. Applying such signal-quality-control techniques in conjunction with pseudo-range checking will then lead to RAISIM, the acronym for Receiver

Autonomous Integrity and SIgnal Monitoring. It may bring the integrity checking closer to the antenna of the receiver.

Continuous analysis of the quality of the received signals may also lead to significant improvements in tracking performance. By predicting or measuring the received signal parameters, one may select the best part of the signal for tracking.

2 - SOURCES OF SIGNAL DEGRADATION

Loran-C signals face two main threats on its way to the receiver. The first one stems from a variety of interferences while the second threat is caused by insufficient knowledge of the signal propagation characteristics along the transmission path. These two distinct types of error sources may easily lead to erroneous carrier and envelope tracking.

2.1 - INTERFERENCE

Interference of the Loran-C groundwave signal comes either from it's own ionospheric reflection or from a variety of Continuous Wave Interference (CWI) signals joining more or less the same LF frequency band.

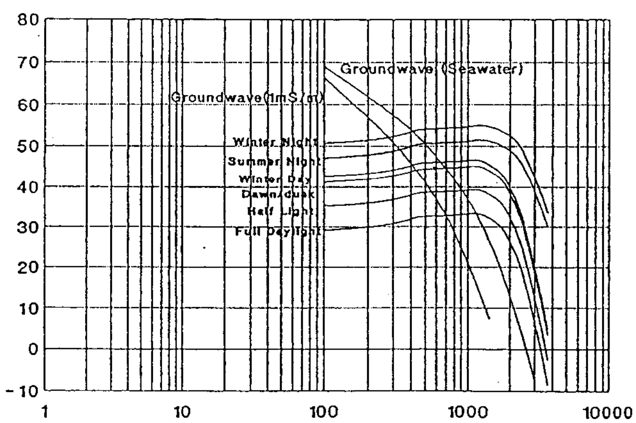

Fig. 2 Groundwave and skywave signal level as function of distance with time as parameter. Ground conductivity is 1 mS/m, fieldstrenth in dBµV/m, radiated power = 1 kW [1].

Skywave interference is widely studied and, therefore, its influences on the groundwave may be roughly predicted. Farnworth and Last [1] show in fig. 1 the delay of the skywave with distance for different effective ionospheric heights. The same authors give in fig. 2 the fieldstrenghts, as function of distance to the transmitter, of the groundwave and also of the 99 percentile skywaves, ranging from winter night to full daylight. So, for any distance of the receiver to the transmitter, and for any particular time of the day and the year, it is then possible to predict the composite signal formed by the summation of the ground- and the almost worst-case skywave at the receiver input [2]. The waveform of this composite signal is then further altered by the transfer function of the bandpass filter [3] before it finally arrives in the signal-processing circuits.

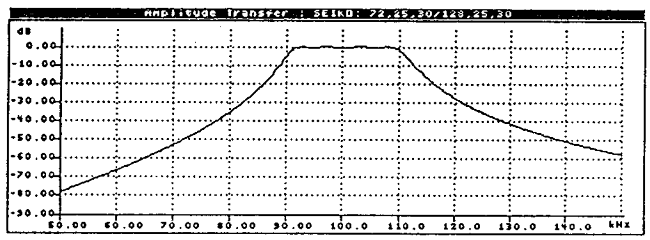

Fig. 3 Amplitude transfer function of 20 kHz wide simulated Seiko bandpass filter.

The RTCM Special Committee No. 70 has published a Report with specifications [4] which marine Loran-C receivers must comply. This report also gives skywave conditions which can be seen as a worst-case situation. Fortunately, in most parts of the coverage area the situation is more relaxed as can also be deducted from [1 & 2].

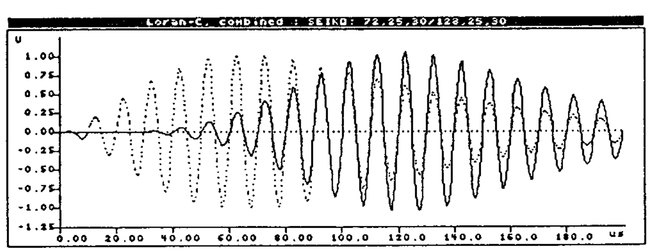

Fig. 4 Input (dotted line) and output (solid line) Loran-C signals of simulated Seiko bandpass filter.

To give an impression of what may happen in a Loran-C receiver, software simulations [5] will be used which are, throughout this paper, based on a linear-type signal processor preceeded by an industrial type (Seiko) bandpass filter with a bandwidth of 20 kHz. See also fig. 3 and 4.

For normally applied tracking-loop bandwidths, skywave interference may be considered as being synchronous. Key parameters are the Groundwave-to-Skywave Ratio, GSR, and the time difference between the groundwave and the delayed skywave. The effects of skywaves on phase tracking is easily understood [6]. Fig. 5 depicts the phase tracking error as function of skywave delay and SGR. Notice the remarkable difference in error for in-phase (40 μs) and in-quadrature (37.5/-57.5 μs) phase relations.

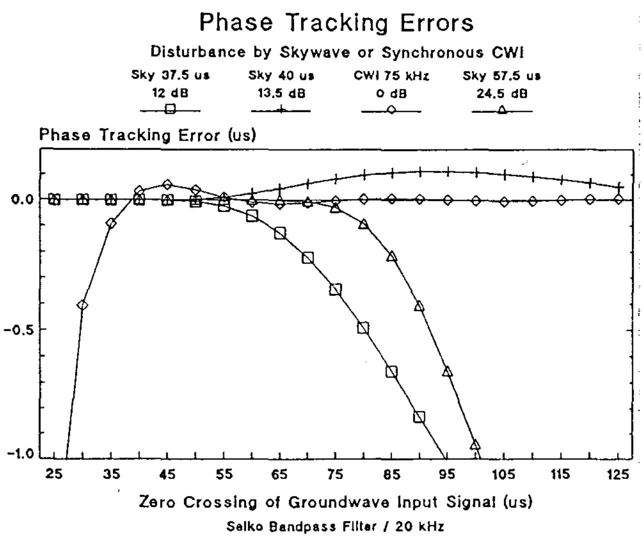

Fig. 5 Phase tracking error due to skywave or synchronous CWI.

The influences on envelope tracking are often even more dramatic as can be seen in Fig. 6. The slope of the envelope contains the only information about which cycle is actually being tracked. Any error in this envelope-tracking procedure means a range error of at least 3 km!
Figures 5 and 6 make clear that tracking the composite signal rather early (before e.g. 55 μs) minimizes the risk of phase-tracking and cycle-tracking errors. However, analyzing fig. 7 yield that tracking the signal 20 μs later, at 75 μs, improves the SNR about 8 dB. So, compromising is inevitable.

Synchronous Continuous Wave Interference, CWI, affects the Loran-C signal in a comparable way as skywaves do. Synchronous interference is a realistic threat in Europe. For example, the high-power Swiss radio station at 75 kHz and the Decca transmitter at 85 kHz are synchronous to all Loran-C signals [7]. Comparable effects can be expected from DC-offsets in the electronic circuits of the Loran-C receiver [6].

Asynchronous interference is generously available in the old continent. A blend of Decca, FSK and timing signals is permanently ready to escort the Loran-C signals. As far as these signals are asynchronous continuous waves, they can be treated as noise. So, it's effects can be reduced either by notch filters or by narrowing the tracking loop bandwidths. The latter at the cost of dynamic tracking performance.

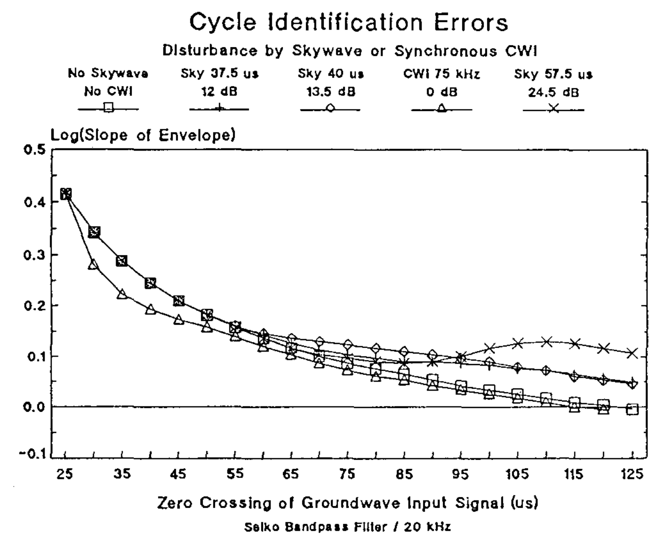

Fig. 6 Cycle identification error due to skywave or synchronous CWI.

2.2 - PROPAGATION

Limited conductivity and permeativity of the earth surface along the transmission path adds additional frequency-dependent delays to the free-space propagation time. This extra delay is called the Secondary Factor (SF) if the signal travels entirely over a seawater path. Land mass again adds some additional delay over the seawater delay and this is known as the Additional Secondary-phase

Factor (ASF). The SF is accurately known for standard seawater, while the ASF can be rather reasonably modelled [8]. These ground effects not only introduce delay in de propagation time, but may also, due to dispersion, slightly distort the form of the envelope of the Loran-C burst. As this distortion is often just considered as an additional delay of the envelope, relative to the groundwave, it is called the Envelope-to-Cycle Discrepancy or ECD. This difference between the phase delay and the group delay might cause serious difficulties in the cycle-selection processes of the receiver. The large Loran-C wavelength of 3 km makes this error of extreme importance.

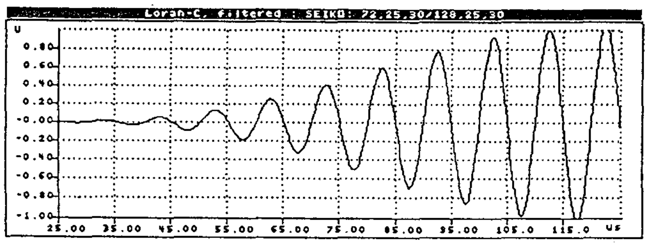

Fig. 7 Detailed part of Loran-C output signal of a 20 kHz wide bandpass filter.

3 - ERROR DETECTION

From the foregoing paragraphs can be seen that the three most important items to measure by a Loran-C receiver are skywave interference, continuous wave interference and envelope-to-carrier discrepancies.

Skywave interference can be measured in a number of different ways. Such methods are often based on taking signal samples at the estimated peaks of the carrier of the burst. Burst-synchronous avaraging gives after some time a rather accurate image of the composite waveform. From here on the various ways of processing divert.
The most straight forward method of skywave analysis is based on decomposition of the composite signal at the output of the bandpass filter. As the transmitted waveform and the transfer function of the bandpass filter are accurately known, it is possible to derive the delay and the relative amplitude of the skywave [9]. From these results the skywave-free part of the burst can be established.
Another, and rather simple to implement, solution is based on comparing the measured waveform with the expected waveform, again taking into account the transfer function of the bandpass filter.
The above measurement techniques are only useful if synchronous interference is not present. This requirement must be verified seperately.

Probably, the most effort requires the measurement of the levels and the frequencies of all relevant continuous-wave-interference signals. This can e.g. be accomplished by FFT-techniques on a batch of collected samples. The frequency of the interference is not easily determined as the required resolution is rather high. The carrier tracking bandwidth is often as low as .02 Hz while the bandwidth of the envelope tracking loop might even be not more then .0005 Hz. These values then also set the bounderies between the non-synchronous and near-synchronous interference regions. Consequently, the frequency determination process must be of comparable quality. Less accurate spectrum analysis processes may lead to a rejection of CWI signals which are wrongly identified as synchronous interferers. This then results in using notch filtering rather harmless signals. The detection of synchronous interference is very important as such signals may easily prevent a correct cycle-selection procedure (see also fig. 6).
Beckmann [10 & 12] describes how to measure signal parameters by means of time-discrete sampling and signal processing.

Finally, the ECD must be measured. It is derived from the same carrier peak signals as are used in the skywave-detection processor. The ECD calculation is either based on correlation with a time-shifted replica of the groundwave envelope or just on derivation of the slope at a selected part of the envelope. ECD's sometimes indicate propagation anomalies in urban or mountainous areas.

4 - ERROR PREDICTION

As will become evident in the next paragraph, error prediction is a very powerful tool in improving Loran-C performance. Here, ASF's, ECD's, skywaves and CWI are the important items to consider.

As already mentioned in paragraph 2, the expected level of the groundwave signal can be predicted. This prediction is based on the radiated power of the transmitter, on the distance to the transmitter and finally on an accurate knowledge of the ground-conductivity parameters along the transmission path [1]. Comparing the calculated signal level with the measured level might indicate shadowing or unexpected reflections. If the ground-conductivity data base is also frequency dependent, then ECD predictions may become eventually even more accurate than they are today [11].

For a given time of the day and the year, and for a specified distance from the transmitter, we can also predict the 99 percentile level and delay of skywaves. From this the groundwave-to-skywave ratio is calculated and the 'safe' part of the burst is then determined.

The level of all dangerous interference signals can also be computed from a data base containing the locations, the frequencies and the power levels of all CWI stations in the region. The calculated ratio of the levels of the CWI and of the Loran-C signal, and the frequency relation of this CWI with the GRI are perfect indicators for the amount of possible carrier-phase and envelope distortions [7 & 8]. The charm of such an approach is that no frequency and signal level measurements are required in the receiver.

5 - FLEXIBLE DATA PROCESSING AND COUNTER MEASURES

This part of the paper does not give a detailed instruction set of how to design a Loran-C receiver, but merely outlines some thoughts in which ways carrier- and envelope-tracking performances may be improved.

Present receivers are mostly quite rigid designs. It means that receivers always function in the same way although the signal and disturbance conditions might change considerably during the day and throughout the coverage area.

In the foregoing paragraphs we have seen that the most important parameters of the groundwave Loran-C signal, its's skywave reflection, and possible CWI signals can be measured and/or predicted. This is the basis to improve the capabilities of the Loran-C receiver.

To make the tracking fast and low-noise, it is strived for to track the signal as far towards the peak of the burst as is possible. The limit is where the influences of skywaves becomes unacceptable high. This limit is generally first met in the envelope tracker. For demonstration we have simulated a +37.5 μs/+12 dB skywave in the LOSP program. The simulated receiver establishes the envelope tracking from the derivate of the slope of the envelope at the carrier-phase tracking position. Fig. 6 depicts the envelope tracking error as function of the selected part of the envelope.
It must be noticed that the LOSP simulations as demonstrated in the figures 3..7 are based on a filter implemented with physical inductances, capacitances and resistors. Digital filters offer additional degrees of freedom which makes the design of bandpas filters with linear phase and flat amplitude response feasible. Such digital filters show very interesting properties in respect to increased effective SNR at the output of the filter over conventional filters under comparable skywave conditions [12].

The next threat is synchronous interference. We consider for our simulation a realistic European value for the frequency (75 kHz) and the level (GSR = 0 dB) of the interferer. Fig. 6 shows again the envelope tracking error. The error is large in the very beginning of the burst where the GSR is very poor. But quit unexpected, the error does not drop rapidly when the envelope is measured closer to the peak. The reason is that with the GSR increase towards the peak of the burst, the rate of change of the derivate of the slope decreases which makes it more sensitive for envelope errors [13].

Determining the standard deviation of the amplitude measurements of the carrier peaks around the phase-tracking position yields the apparant SNR of the carrier. The measured 'noise' level also contains all slipped-through non-synchronous interferences. Now, a compromise must be found between low-noise phase tracking and almost stationary errors due to skywave interference.

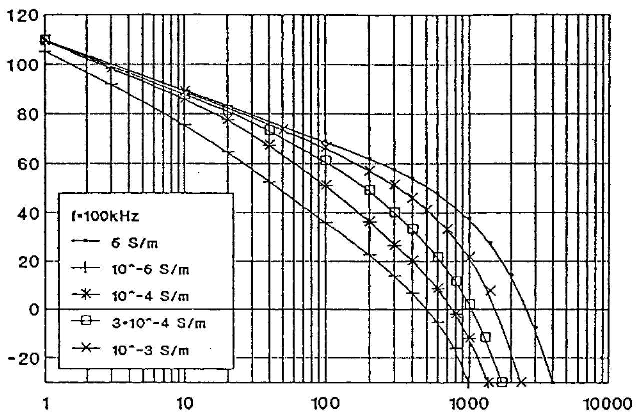

Fig. 8 Groundwave propagation for different values of conductivity [1]. Field-strength in dBμV/m, radiated power is 1 kW.

Measuring or predicting the CWI spectrum is the key to notch-filter control in the receiver. The CWI stations should be tabulated in a 'danger'-ascending mode. As the number of available notch filters is generally limited, only the most dangerous CWI signals must be rejected. The highest dangers form the synchronous stations as they may easily destroy the proper functioning of the cycle-selection procedure. So, smart notch-filter controllers do not just analyze the signal levels [7].

It is our experience that the cycle-selection procedure is the weakest part in Loran-C navigation. Therefore, it is important to use as much information as possible to verify this process.
ECD's should be measured and if possible predicted. Comparison of the two value may indicate a conflict caused by propagation deviations or synchronous CWI. Secondly, the selection procedure can be further checked by calculating the ratios of the signal levels of all tracked stations. These ratios are then compared with the measured ratios. Incorrect cycle selection is in this way often detectable. See fig. 8.

6 - CONCLUSION

The key element to a better performance of phase tracking and of carrier tracking is based on accurately analyzing the interference spectrum and the skywave content. These analyses can either be based on real-time measurements, on prediction or on both. Once the interference and skywaves parameters are collected, the best part of the Loran-C burst for processing can be selected. The best part is always a compromise between noise and biases. The noise in the tracking loops comes from the received atmospheric noise and the many non-synchronous interferences. The biases are generated by skywaves, synchronous interferences and by DC-offsets in the electronics.

7 - ACKNOWLEDGMENTS

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Biography

Dr. Durk van Willigen (1934) heads as professor at the Delft University of Technology a group of students and staff working on various navigation systems. The main topics are system performance studies, software/-hardware simulation and receiver design for Loran-C, Navstar/GPS and the Microwave Landing System.

He is active in studies for setting up the new North-west European Loran-C chain. The main concern of these studies is the so generously available European continuous wave interference. The Delft University of Technology and the University of Wales (UK) join their activities in this field.

Dr. Durk van Willigen is also the president of Reelektronika bv, a consultant for radar and radio navigation. He is a member of the Advisory Committee of the Netherlands Institute of Navigation, the Wild Goose Association, the Institute of Navigation (USA) and the Royal Institute of Navigation (UK).

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A Loran Based Aircraft Collision Avoidance System

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Abstract

This report describes the development of a new aircraft collision avoidance system (SCAN - Surveillance for Collision Avoidance Navigation[1]) which makes use of current Loran/GPS navigation technology. SCAN is a pilot oriented system requiring no additional ground support services. In the flight environment, SCAN can track as many as 100 aircraft simultaneously, giving a graphic presentation of each target aircraft's position, direction of flight, altitude, airspeed and flight vector and has the capability of predicting imminent collisions. SCAN lessens the potential for mid-air collisions by providing to the pilot a means of monitoring his local airspace. Additionally the pilot can be supplied with a moving map display, navigation vectors and terrain avoidance information. Passive monitoring of SCAN by ground stations could provide an alternate means for ground control to determine aircraft position, exclusive of the radar environment. By monitoring and recording SCAN position information, aircraft track and last known position can be obtained for location of downed aircraft. In the marine environment, SCAN can provide navigational assistance and improved safety in transiting, mooring and docking maneuvers. SCAN is based on readily available computer technology and is designed to be compatible with commercial Loran receivers.

Introduction

There are nearly 216,000 civil aircraft currently registered in the United States.[2] Of these aircraft, a relatively small number, approximately 5,600 (2.6%) are used by commercial air carrier operations; the remaining 210,000 are privately or business owned and belong to a class designated as "general aviation." A summary of the "AOPA 1990 Aviation Fact Card" (presented in table I) shows that although general and commercial operations fly about the same number of miles per year, general aviation flies twice as many hours and logs nearly 5 times the departures as commercial operations.

Table I

AVIATION STATISTICS 1988 [1]

ITEM	TOTAL	GEN AV	AIRLINE
Total Aircraft	215,926	210,266	5,660
% Aircraft		97.4 %	2.6 %
Piston, sngl	187,919	164,760	
Piston, mult		22,698	362
Turboprop	6,634	5,259	1,375
Turbojet	8,102	4,187	3,915
Rotocraft	6,414	6,406	8
Hours Flown	49.2M	33.6	15.6M
% Hours Flown		68.3 %	31.7 %
Miles Flown	8906.9M	4139.1M	4767.8M
% Miles Flown		46.5 %	53.5 %
Departures	58.4M	48.1M	10.3M
% Departures		82.4 %	17.6 %
Passengers	574.9M	120.3M	454.6M
% Passengers		20.9 %	79.1 %
Mid-Air Collisions[2]	19		
Mid-Air Fatalities	38		
Near Misses		550	
Encoding xpdr	107,410	101,750	5,660
Loran C		75,018	unknown

1) Source AOPA and NTSB
2) Mid-Air Collision data for 1989

Because high densities of traffic are clustered around large metropolitan areas, the opportunity for airspace conflict arises. During 1988, Los Angeles International Airport (LAX) handled 631,898 (mostly commercial) operations, or approximately 96 takeoffs and landings per hour. Van Nuys, a general aviation airport located 16 miles north of LAX, handled about 70 operations per hour while Santa Anna, 31 miles southeast from LAX, handled 80. These are statistics for just 3 of the busiest airports in the Los Angeles basin which has 23 charted airports.

One of the most interesting statistical comparisons is the number of transponder equipped aircraft (162,068) to those installed with Loran C units (74,418). In spite of the fact that transponders are required equipment when operating in and around major airports, its benefit is once removed from the pilot. On the other hand, the popularity of Loran C has grown dramatically in a few short years, evidence that Loran C information provides valuable aid to the pilot.

Visibility from an aircraft flight deck is an important safety concern to the pilot. Figure 1 is a graphic depiction of the pilot's area of visibility from inside a typical general aviation aircraft.

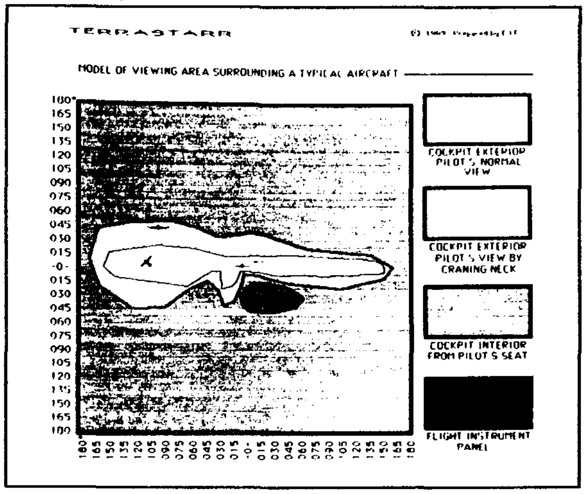

Figure 1

In straight flight, the pilot's view is generally limited to no more than 15% of total space surrounding the craft. In some commercial air carriers, the view is even less. Add to this the limited visibility in congested areas due to manmade causes (such as air pollution) and one can understand the increased potential for mid-air collisions.

Data collated by AOPA[3] for the year 1989 indicates that there were 18 mid-air accidents. 11 of those accidents resulted in 38 fatalities. Also reported were 550 incidents of near miss occurrences (unintentional aircraft separations of less than 500 ft.). Although there were only 18 mid-airs in the United States last year, the subject is one that always evokes high emotional response. Mid-airs not only result in fatalities to occupants of the aircraft involved, but often inflict damage to property, or cause injuries or death to persons on the ground. Notable mid-air accidents were: The collision of two airliners over the Grand Canyon (6/30/1956, 128 killed); collision of commercial sight-seeing aircraft in the Grand Canyon (5/19/86, 25 killed); The San Diego collision of a PSA 727 and a light twin (9/26/78, 136 killed); The collision of an Air Mexico DC9 and a light aircraft over El Ceritos (8/31/86, 67 aboard the aircraft killed, 24 killed on the ground, 10 houses destroyed); The collision of a commuter turboprop and light aircraft over Salt Lake City (1/15/87,10 killed). Heavy press coverage of mid-airs have excited the electorate to pressure their legislators who in turn have enacted legislation requiring the Federal Aviation Agency (FAA) to initiate a solution to the mid-air collision dilemma. The FAA responded in two ways. One was the implementation of the Terminal Control Area (TCA) and "Mode C" transponders, and the other was a new requirement that all aircraft carrying 30 or more passengers be equipped with collision avoidance instrumentation by the end of 1991.

A TCA is a designated block of restricted airspace around congested metropolitan airports for the purpose of identifying and controlling all traffic operating within that airspace. A schematic representation of a TCA is presented in figure 2.

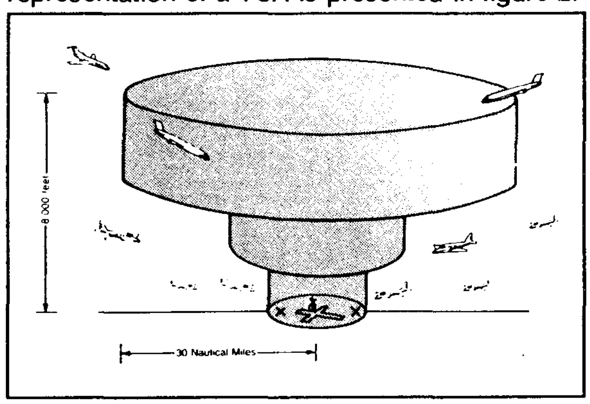

Figure 2

Entry into the TCA is restricted to permission from a ground controller only. Unfortunately, the controller, radar systems, air traffic control (ATC) computers and software are often unable to cope with the increased activity in many of these congested areas.[4] During busy times, many low priority aircraft are prohibited from entering the TCA or are channeled into narrow corridors and compressed vertically to fit underneath the controlled airspace. The complexity of this problem may be better understood by examining a map of the Los Angeles TCA which is presented in figure 3.

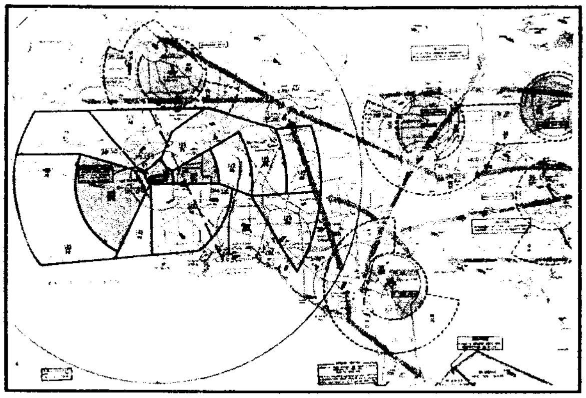

Figure 3
In this congested airspace, non-participating aircraft are often given no guidance or traffic information from the radar traffic controller. Thus, in addition to avoiding other aircraft, the pilot must also navigate complex airspace without ATC assistance. This places a heavy workload on the pilot.

One FAA approved collision avoidance system is designated as: Traffic Alert and Collision Avoidance System (TCAS). TCAS operates by detecting transponder replies of nearby aircraft that have responded to interrogations coming from ground based radar, or in the case of TCAS II, interrogations by other TCAS units. TCAS II senses the position of transponder replies by using directional antennas for determining a bearing and measures signal return time to compute distance. The primary advantage of the TCAS system is that all aircraft operating within 30 nautical miles of an airport in either a TCA or Airport Radar Service Area (ARSA) are required to have transponder and altitude encoder equipment installed and operating. Disadvantages include: 1) a potential overload of the TCAS system when there are too many target aircraft operating in one area, 2) bearing accuracy is dependent on complexity of an expensive directional antenna system, and 3) the extreme high cost of the system. Cost estimates range from a low of $40,000 for a simple TCAS I system to as much as $250,000 for a fully implemented TCAS II system. This prices the general aviation pilot out of the market when one considers that his entire capital investment in his aircraft may be less than $25,000. Another privately developed collision avoidance system is the Ryan TCAD system. This unit is strictly passive, eavesdropping on transponder replies elicited from ATC or other TCAS transponder interrogations. It locates distance to intruder aircraft by measuring transponder reply signal strength (which may vary considerably) and determines altitude by receiving transponder message signals originating from the intruder's encoding altimeter. The TCAD unit provides no directional information of the intruder, only a warning of its presence, altitude (if the intruder's transponder is coupled to an altitude encoder), and relative distance. Cost for this system is approximately $7,000.

The SCAN Collision Avoidance System

Our approach to collision avoidance is to use a navigation source such as Loran C (or GPS) to determine the position of both the primary aircraft and potential intruder (target) aircraft. Each aircraft intermittently broadcasts its position over an air to air radio link. Data received by the primary aircraft is then used to compute the positions and headings of each target craft relative to its own position. An onboard computer identifies each aircraft by its own unique "N" number which has been pre-programmed into Read Only Memory. A block of latitude, longitude, altitude data and any other transmitted information associated with that "N" number (such as aircraft type, error warning flags, a communications frequency, or other messages) is stored. Each aircraft's position is updated continuously on a display as various algorithms are used to compute vectors, possible collision occurrences, and to trigger pilot warning devices.

At present, **SCAN** consists of a Loran C receiver, an altitude encoder, a radio transmitter/receiver, a computer system and a display. Any Loran C receiver which supports data output in ASCII format may be used. Output of latitude, longitude (and optionally error codes to indicate Loran malfunction) are required. The radio link is a computer controlled high frequency transceiver designed to exchange data in ASCII format at extremely high baud rates. A "polite transmit" algorithm is implemented to minimize data channel collision. Transmission power limits reception to a reasonable distance (30-50 miles). The computer system will initially be based on the Intel 80386-SX (DOS compatible) with a numerical co-processor, chosen for its wide use, speed, reliability and availability of standard software tools. The custom computer is being designed as a "single card solution" with an onboard keyboard interface and VGA display controller. A schematic of the **SCAN** system is presented in figure 4.

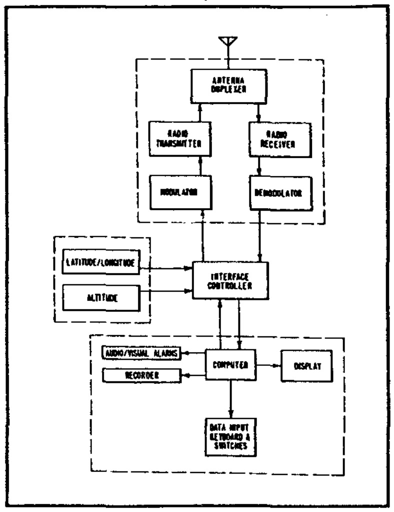

Figure 4

SCAN has been programmed in the ANSI compatible "C" language utilizing standardized code for ease of documentation and code maintenance. All computer functions (operating system, data base, application software) are presently memory based to provide a rugged and maintenance free system. The computer and radio portion of **SCAN** can be mounted in a remote location of the aircraft. The **SCAN** display will consist of a color LCD display mounted on the control yoke or on the instrument panel to provide a close proximity to the pilot. Later, a head up display may be incorporated.

A major advantage of an independent aircraft based system such as **SCAN** is that it requires no ground control intervention. Only operational Loran transmitters, GPS, or equivalent systems are required. Nor is data output interrogation dependent. Latitude, longitude, and altitude provide the pilot with complete collision avoidance information in a three dimensional environment. To help the pilot navigate and competently avoid mid-air collisions, one of our chief design goals is aimed at simple and concise information management. To do this, we present most of the data to the pilot in graphic form, displaying alphanumeric data only when required or requested. **SCAN** is designed to automatically display the following information for the primary and all intruder aircraft: aircraft positions, types, headings, speeds, true north, and imminent collision threat vectors and alarms. Altitudes, projected flight vectors, aircraft identification numbers, a zoom feature and other message displays are functions available to the pilot upon input request. Target aircraft automatically change color and intensity as they approach within a set dimension (at present, 1000 feet) of the same altitude as that of the primary aircraft. In the event of a predicted intrusion of an aircraft within some preset window of airspace (such as .5 mile distance and 500 feet vertical), **SCAN** will display a timely warning to the pilot of the imminent collision possibility. The display is designed to encourage the pilot to respond well in advance of, and intuitively, to intruder threats. Since the pilot in command is the person ultimately responsible for the safety of the aircraft and its passengers, it is imperative that he have the maximum amount of information available on which to base his decisions.

SCAN is designed with computer capability and channel bandwidth adequate to handle up to 100 intruder aircraft simultaneously. Sufficient capability has been reserved to allow the implementation of other messages such as weather data, emergency, or flight control advisory information.

Development

The **SCAN** prototype system was developed using available off the shelf components. This quickly provided us a with a "proof of concept" model with which we could concentrate on the development of function and software algorithms. In turn, with developed software we could then specify the required hardware to run the code and design the complete system package. The computer used for the prototype was a Mitsuba laptop portable[5], chosen for its display quality and portability. Loran RS-232 output was taken from either an ARNAV R-50 or ARNAV R-21[6] Loran receiver depending on the particular aircraft installation. Altitude input was taken from an ACK Technologies[7] blind encoder. Prototype radio communication was performed with an ICOM[8] hand held aircraft radio operated at 123.45 Mhz (an aircraft band frequency for use in aircraft flight testing). Inter-connection was accomplished using an Enduratek Data-V-Com[9] to provide serial and digital I/O capabilities and onboard conversion of altitude encoder data. A photograph of the prototype system is presented in figure 5.

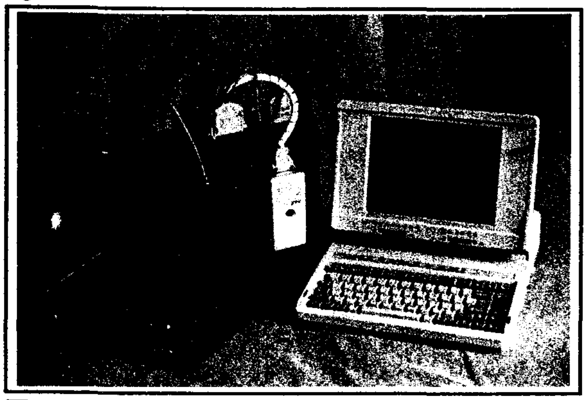

Figure 5

Results

Early in our development, we observed that data acquired from the Loran indicated a certain amount of dither from point to point. Some of that data was charted to show what happens when turns of varying rates are made compared to straight flight (figure 6).

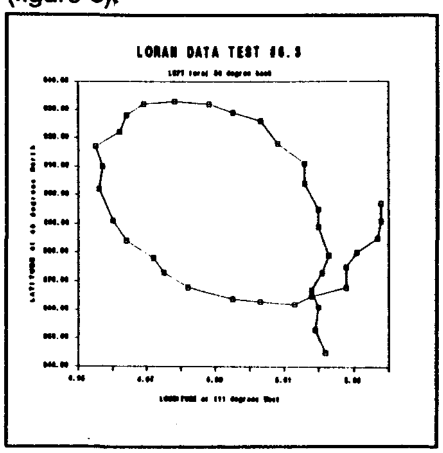

Figure 6

The LORAN used in this test was an ARNAV-R50. It appeared to track well, even when extremely tight 60 degree turns were attempted. At most, a deviation of 120 feet was the maximum potential dithering error. Tracking lag error was not noticeable. **SCAN** lag accuracy will always be dependent upon aircraft speed minus the sum of Loran acquisition and data dump and **SCAN** processing times. We perceived a total time lag of 4 to 6 seconds in the reporting of the true position.

It appeared that the LORAN knew immediately where it was whenever a sharp maneuver was made. Our initial conclusion is that LORAN is highly reliable for this specific application and would provide acceptable safety margins for helping the pilot locate and avoid other traffic. The slight dithering of data was overcome by using a data smoothing algorithm in the calculation of headings and vectors.

The first prototype **SCAN** was successfully flown on June 6, 1990. As we flew collision avoidance missions with two aircraft, we were able to detect each other by first glancing at our onboard computer displays and then visually searching the airspace indicated. In nearly every case, the "other" aircraft was easily detected. Distance measurements were extremely accurate and consistent on each craft. Altitude measurements were constantly verified and always fell within 100 feet of those vocally reported. At one point, the other aircraft was located visually from as far away as 16 miles. In most cases, detection could be quickly established at a distance of eight miles.

A typical output display of the **SCAN** system is shown in figure 7.

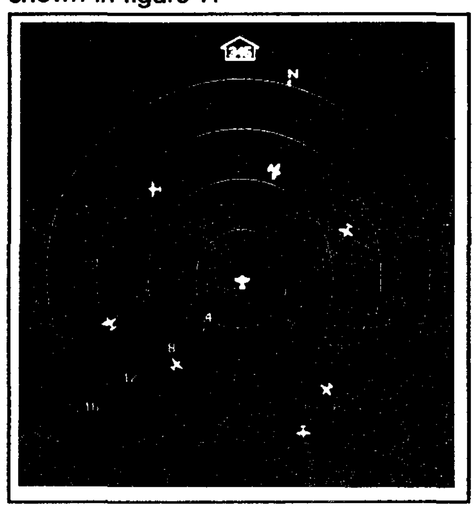

Figure 7

The primary aircraft is shown at the center, with its true ground vector indicated in the heading box at the top of the display. Concentric rings portray increments of distance in nautical miles. Other **SCAN** equipped aircraft are plotted in their relative positions on the screen with their aircraft symbols oriented to their appropriate headings. The user can request additional display items as shown in figure 8.

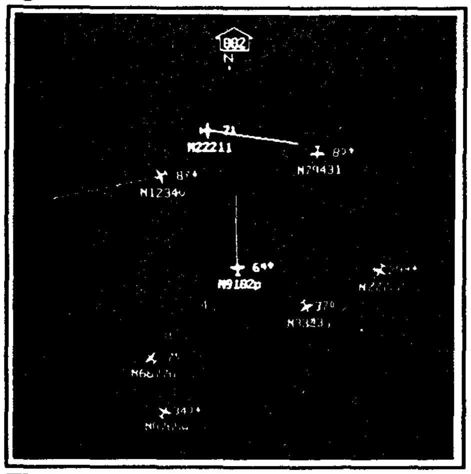

Figure 8

These include identification or "N number" of the aircraft, altitude display (postscripted arrow indicates aircraft that are climbing or descending) and projected flight vectors.

The advantages of providing each aircraft operator a **SCAN** system are obvious. Not only is he able to monitor his own airspace, but additional benefits accrue to the Air Traffic Control (ATC) system in general. Implementation of **SCAN** eases the burden for ground based facilities to provide aircraft position information to the pilot if it is known that the aircraft is **SCAN** equipped. This in turn relieves unnecessary pressure imposed on communication frequencies because each pilot knows where to look for interfering aircraft. In addition, the passive monitoring of **SCAN** communications by ATC could act as a source of aircraft position information independent of the radar based ATC system. This passive monitoring system can be implemented at low cost for use in developing nations who cannot afford to implement a radar based ATC system.

The largest obstacle to general acceptance of **SCAN** is the lack of other compatible units in the field. All aircraft must have a **SCAN** unit for the collision avoidance system to work. In order to overcome this problem, we intend to incorporate other desirable features such as flight planning, weather mapping, or moving map displays to show such items as VOR and NDB radio navigation aids, airports, prominent lakes, rivers, mountains and other natural or man made features useful in navigation.

Additional Applications

SCAN would be a useful tool in the marine environment for navigating under adverse weather conditions, especially when piloting through narrow or shallow passages, while conducting docking and mooring maneuvers, for collision avoidance, and for emergency location service. Since LORAN is so widely used today for both marine and aircraft navigation, an overlapping of communication frequencies would allow interoperability for emergency pilot to pilot advisories, "help and rescue" aid, or for a wide range of advisory services.

Future Implementations and Considerations

With deployment of the **SCAN** system, it becomes possible to passively track and record all flights. In cases where aircraft are missing or ships are lost at sea, one only need scan the accumulated data base for the last known position of the missing craft to establish a search area. It is possible that the Emergency Location Transmitter (ELT), a source of many false alarms for search and rescue, could ultimately be phased out. Once GPS is fully deployed, it can serve as an alternate or additional input to **SCAN**. If the acquisition signal is not dithered, GPS may also provide accurate altitude information that is not subjected to atmospheric pressure changes, an important consideration in the flight environment.

It is imperative that a standard data output format be put into place for both Loran C and GPS receivers. We recommend that manufacturers form a LORAN/GPS interoperability coalition to develop a standard for data communication protocols.

We also propose adoption of an international communication frequency allocation for collision avoidance service and the specification of a regulated data exchange format for its use.

Acknowledgements

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We also want to recognize the work of Philip H. Berger for his initial creative efforts and his staff at Enduratek Corporation for retrofitting their Data-V-Com to our "proof of concept" package which allowed us to gather the valuable information included in this publication.

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LONARS - Extracting the Maximum Performance from Loran-C

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The Loran Navigation Receiving System (LONARS) is a highly accurate Loran-C position reference system developed for the U.S. Navy by The Johns Hopkins University Applied Physics Laboratory. The system supports Demonstration and Shakedown Operations on Fleet Ballistic Missile submarines off the east coast of Florida. The ship transmits position information generated by LONARS to shore so range safety radars can acquire the missile as it broaches the water. LONARS displays the ship's current position and its predicted position at a future time on two monitors on the ship. It also records the Loran-C measurements on magnetic tape for post-mission analyses to determine the weapon systems' position and velocity error conditions at the time of missile launch. Accuracies are better than 150 ft in real time and 50 ft error in post-mission analysis. A pattern monitor system on shore tracks Loran-C signals during the mission, and this data is used to remove Loran-C biases and transmitter fluctuations. Other techniques remove noise that limits the accuracy of Loran-C performance, including the use of strong editing algorithms and tracking of non-navigation loran stations.

THE LONARS MISSION

The Johns Hopkins University Applied Physics Laboratory (APL) designed the Loran Navigation Receiving System (LONARS) to fulfill a need to independently determine the position of U.S. Navy submarines during Demonstration and Shakedown Operations (DASOs) off of the east coast of Florida. The Navy conducts DASOs after initial construction of a Fleet Ballistic Missile submarine or after it has been overhauled. These operations demonstrate the submarine's ability to perform its primary function and determine the level of readiness of all of the subsystems on the ship, culminating in the launch of a missile. The Navy installs LONARS on the submarine during the DASO to:

1. Provide a display of projected position that is transmitted to shore so range safety radars can acquire the missile immediately when it broaches the water.
2. Provide a readout of current position throughout the at-sea operations to monitor real-time ship inertial navigation system performance and provide precise ship navigation.
3. Record loran data about once a second on cartridge tape to allow post-mission processing for precise determination of the error conditions of the Polaris/Poseidon/Trident weapon systems at the time of missile launch.
4. Provide loran and navigation data on paper printout for ready position reference and backup data processing.

During a DASO, one LONARS system is installed on the submarine that has a loran antenna mounted on a 150-ft test instrumentation mast. A second system is installed at the Pattern Monitor System (PMS) on shore, and a third system is installed on the supporting surface ship. The magnetic data tapes from the submarine and the PMS are processed after the mission to determine the ship's precise position and velocity at the time of launch. Accuracies realized by LONARS are 150 ft in real time, and using the PMS data improves system accuracies to better than 50 ft in post-mission analysis.

The U.S. Coast Guard cooperates with the Navy so that maintenance and transmitter shift schedules for the southeast chain do not coincide with DASOs. The data demonstrates that we do much better than 50 ft, and part of that good performance is due to the cooperation of the Coast Guard.

LONARS HISTORY

APL participated with the Air Force in the precision use of Loran-C in southeast Asia and a study of accurate loran navigation systems in 1972; however, no equipment design resulted from that effort. The experience gained from that study and improvements in the loran coverage in the Florida region convinced the Laboratory to propose a precise loran navigation system for the Navy for strategic submarine test and evaluation. Approval and funding were granted by the Navy in 1977, and the Laboratory built three ship systems and one shore system (the PMS). The first of these systems was tested and calibrated in 1978, it became operational in 1979, and final area calibration of the Loran-C signals was completed in 1980. LONARS I has been used during the 1980s for precise navigation during DASOs.

The passage of time has brought about the situation that the scarcity of parts makes maintenance of LONARS I very difficult. LONARS II was begun with the objectives of developing a system that would carry on to the end of the century and possibly beyond and making the software easier to maintain and upgrade compared with the original system. APL began developing LONARS II in 1987 and delivered the system to the Navy in the spring of 1990.

UNIQUE DESIGN FEATURES OF LONARS

Many problems limit the accuracy of loran navigation, and LONARS has attempted to systematically address and solve them. These issues were addressed and implemented during system development for LONARS I, and the concepts were carried over to LONARS II. They include:

1. Using a PMS on shore that tracks Loran-C signal biases and variations during the mission.
2. Measuring the timing for the tracking point to a 1-nanosecond (ns) resolution.
3. Setting the gains dynamically for each station being tracked.

4. Searching for and tracking non-navigation stations to eliminate data that would be corrupted by colliding stations.

5. Using a median filter of the measurements on all eight pulses in the Loran-C transmission to reduce the error due to atmospheric disturbances.

6. Synchronizing time on all receivers so that pattern monitor variations can be removed by subtracting data points that are known to have occurred at identical times.

7. Tracking the A and B phases as independent signals.

The PMS uses the same components as the LONARS system on the submarine and tracks Loran-C signals during the mission, recording the data on a cartridge magnetic tape recorder. The tapes from the ship and the PMS are used during post-mission processing to determine the ship's position and to remove the biases and fluctuations from the ship's data. This post-mission processing reduces navigation errors from about 150 ft to 50 ft.

LONARS tracks the zero crossing of the third cycle of the Loran-C pulse to a 1-ns resolution by using a high-quality crystal oscillator, a linear receiver, dynamic gain control, and a 12-bit A/D converter to make measurements of the loran signal output from the receiver.

The high-quality crystal oscillator preserves the 1-ns measurement accuracy over the Loran-C chain's GRI interval. LONARS II uses an SC cut oscillator that has a short warm-up period, a low-frequency drift rate, and excellent stability.

The linear receiver preserves the shape of the loran pulse through the receiver system. This allows the system to sample the analog waveshape with a 12-bit A/D converter to determine the time of the track point to a 1-ns resolution. The computer tracks the zero crossing of the third cycle by taking A/D measurements at several locations about the zero crossing and uses a fitting process to determine the timing of the zero crossing point. The computer also measures the maximum and minimum peaks about the third-cycle zero crossing to continually verify that the third-cycle track point remains valid. As the track point moves as a result of ship velocity or oscillator drift, the tracking point can be adjusted in 100-ns increments.

To realize the full resolution of the A/D converter for every station being tracked, the receiver includes attenuators so that the gain can be changed dynamically for each loran station as its signal arrives at the receiver. The operator sets the overall gain of the receiver during system initialization, and this does not change during the mission because changing the gain stages would change the time delay of the signal through them. Gain changes while tracking are achieved by changing the amount of attenuation that is set for each station as its signal arrives at the receiver. Since the signal delay through the attenuators can be matched to + or - 1 ns when the attenuator is on or off, minimal degradation of timing is incurred. LONARS I has an attenuator resolution of 6 dB, and LONARS II has a resolution of 3 dB.

Another problem when working with loran is the noise generated by cross chain interference. As data is collected on the stations in the desired navigation chain, the measurements can be contaminated by the simultaneous receipt of loran pulses from other chains. LONARS eliminates this source of noise by actively tracking non-navigation stations, called "nuisance" stations, that are stronger than 15 dB weaker than the weakest navigation station. The tracking loops for the navigation stations are coasted through those intervals of time when collisions might contaminate the measurement for a navigation station. The system is so data rich that this does not degrade the navigation results. To detect new "nuisance" stations as propagation changes occur, LONARS actively searches at the times when the known "nuisance" stations should appear to determine if any of them have increased enough in amplitude to cause a degradation of the desired stations. When they do, these stations are put into the track list. When the signal amplitude for these stations decreases below the 15-dB threshold, they are removed from the track list. Eliminating measurements that are contaminated by cross-rate stations is a large step in reducing the noise generated in loran data.

LONARS tracks the A and B phases of each loran station independently, which gives a quick indication of when an anomaly occurs and is also useful in acquiring the third-cycle signal. LONARS I can track a maximum of 8 different loran stations, 16 when both phases are counted, and LONARS II tracks a maximum of 9 loran stations, 18 stations when both phases are counted.

Lightning is a predominant source of noise for Loran-C. Its nature is impulsive and it typically will interfere with one or two consecutive pulses, but not all eight. Some systems use an average of the data of the eight pulses to remove this kind of effect. LONARS uses a median filter that determines the value of the signal at a specific point by arranging all of the data readings for a specific measurement in numerical order. The middle value is used if there is an odd number of data points, or the average of the two middle values is used if there is an even number. This technique removes the contaminated data better than using the average because an average always introduces some contamination error.

SYSTEM DESCRIPTION

LONARS I

The LONARS I receiving system was designed using commercial components as much as possible and uniquely designed items only if commercial units were not available or did not meet the requirements. The purchased items included an HP 2109 minicomputer, a CRT with keyboard and integral tape unit, a remote CRT monitor, a cartridge tape recorder, a printer, and an Austron 2082 linear receiver that was modified to include computer-controlled signal attenuators. APL designed and built the sensor, which included the necessary digital logic, a 12-bit A/D converter, and an electronic interface to the minicomputer. APL also designed and built the antenna that is mounted on the test instrumentation mast on the submarine. Notch filters were included because of the proximity of the Laboratory to the Navy's low-frequency transmitters at Annapolis. The software for LONARS I was written in HP 2109 assembly language.

LONARS records data on tape, prints data on paper, and displays real-time data on a terminal and a remote monitor. LONARS I records time of day, time of arrival of the loran pulses, and a status word on the cartridge magnetic tape about once a second. Every 15 seconds, LONARS I prints the time of day, the status word, the two time differences (TDs), the navigated latitude and longitude, and the calculated velocity north and velocity east. One terminal and a remote monitor display the loran information and graphically depict the location of the ship with respect to the harbor at Cape Canaveral or the launch operational area.

The post-mission analyses use the data on tape to generate plots of the TDs after they have been corrected by the pattern monitor and to generate corrections for the submarine's internal navigation system. Although the real-time navigation mathematical model uses a flat-earth projection that was carefully calibrated, post-mission processing uses a full-up earth model ellipsoid.

LONARS II

LONARS II retains the functionality of LONARS I with technology upgrades that improve system performance and operation. The system design again followed the philosophy of purchasing as many items as possible, including an HP 2439B computer, a touch screen CRT for operator control of the computer, a remote CRT monitor, a cartridge tape unit, and a printer. APL designed the sensor that includes the receiver electronics, the A/D converter, and a microprocessor. The microprocessor controls the receiver settings and collects data autonomously once the collection parameters have been supplied by the HP 2439B computer. The tracking loops, navigation, data display, and storage are all performed by the HP 2439B computer. APL programmed the HP 2439B in the Pascal language, which enforces good programming practices and should allow a better way to correct and update software in the future. The data recorded on tape and printed have the exact same format as that of LONARS I to make full use of the established analysis programs. Figure 1 shows the LONARS II equipment in the ship's stack configuration.

The improvements made in LONARS II compared with LONARS I include:

1. The ability to track 18 stations compared with 16 for LONARS I.
2. The sensor tracks the stations independently once the HP 2439B has supplied the tracking parameters.
3. The operator interface is via a touch screen CRT.
4. Parallel acquisition of the stations in three chains allows the system to boot up and track in 2 to 5 minutes, as opposed to 15 minutes or more in LONARS I.
5. The computer language is Pascal, as opposed to HP 2109 assembly language.
6. The real-time earth model is the WGS 84 ellipsoid, as opposed to a planar approximation.
7. The display on the LONARS II terminal is color compared with black and white for LONARS I.
8. The gain change resolution is 3 dB compared with 6 dB for LONARS I.
9. The notch filters are controlled by microprocessor, not manually.
10. Time is carried internally in the sensor with a battery-backed clock so the operator does not have to insert it every time the system is operated.
11. Time synchronization from loran uses stations that are dual rated into two other loran chains, requiring the real-time clock to only be within 1.1 hours for correct time synchronization, instead of 13 seconds for LONARS I.

LONARS II displays three pictures on the video monitors, one of which is shown in Figure 2. The top of each display shows the time of day, navigated position, calculated velocity, current TDs, time of launch, predicted position at launch, and loran tracking status. The middle part shows the position of the boat pictorially in relation to the port or the operational area at sea. Figure 2 shows a closeup of the port area with the channel and the buoys marked, which lets the ship's navigator know, pictorially, exactly where the ship is with respect to navigation hazards. The ship's current position is marked by a square, and its projected position at the time of launch is marked by an asterisk. As the ship moves, the screen changes automatically. The operator can zoom in or out by touching the Access Command block at the bottom of the display.

The LONARS II system has the limitation that the current version of software only allows it to work in the U.S. Northeast chain (9960) and the U.S. Southeast chain (7980), but the software was written so that it can be easily expanded.

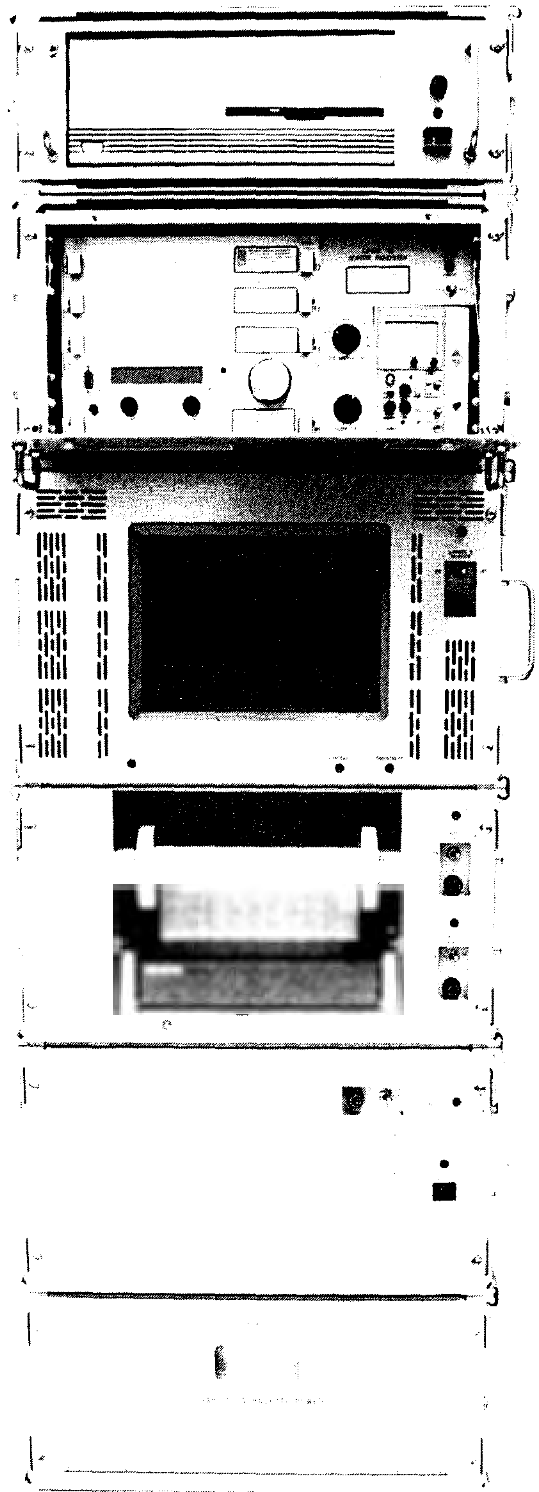


Figure 1 LONARS II ship's stack configuration.

Signal Environment in the Chesapeake Bay Region

As a prelude to showing tracking data collected at APL and for those who may be interested in looking a the signal environment in the Chesapeake Bay region, Figure 3 shows the spectra about 100 kHz. The Navy operates its low-frequency communication

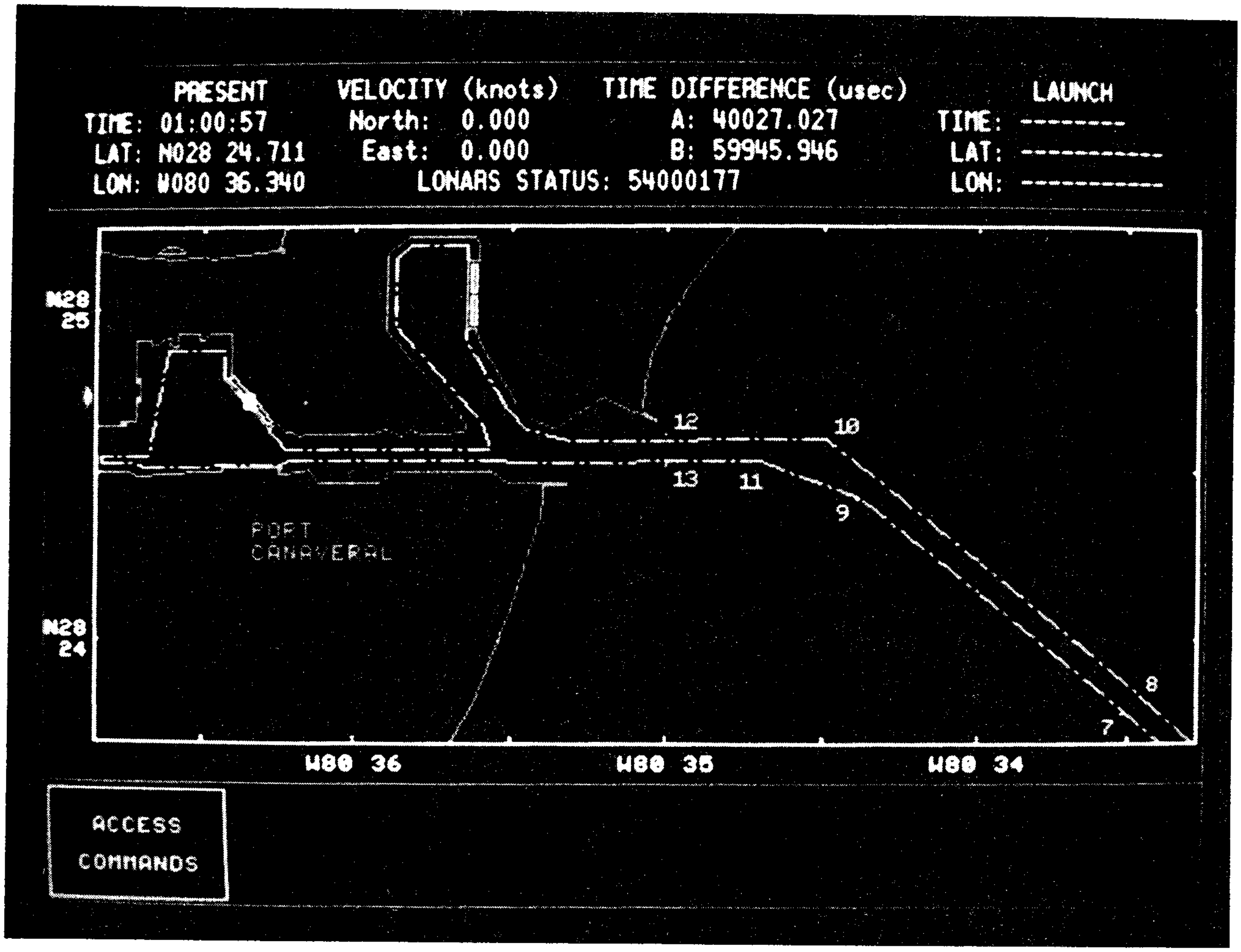


Figure 2 CRT display for Port Canaveral.

system at Annapolis, MD, which is 30 miles from APL and typically has three to five stations transmitting simultaneously with a combined power sufficient to bury the loran signals if a receiver does not use notch filters. We use five notch filters but other stations occasionally come on the air and induce more noise into our system.

The loran band of 90 to 110 kHz is in the center of each picture in Figure 3, and since the loran signals are pulsed, they do not show up as solidly as the CW communication signals. Display (a) shows the signal spectrum at the antenna with four signals visible at 58, 78, 88, and 135 kHz. Displays (b) and (c) show the signals after they have gone through the bandpass filter of the LONARS II receiver; no notch filters are on. Display (b) is 20 kHz per division and Display (c) is 10 kHz per division. The 58-kHz signal is severely attenuated by the bandpass filter alone, the 88-kHz signal is barely attenuated at all, and the other two are attenuated but still are large enough to cause timing problems. Displays (d) and (e) show the effect of setting one notch filter on the 88-kHz signal. Display (d) is 20 kHz per division and display (e) is 10 kHz per division. The signal at 88 kHz is still too large, and now a signal at 115 kHz is becoming visible. Displays (f) and (g) show the spectrum after five notch filters have been activated, two of them on the 88-kHz signal. Display (f) is 20 kHz per division, and display (g) is 10 kHz per division. The spectrum looks fairly clean but the loran signal on an oscilloscope still shows some residual baseline noise.

This problem does not exist at Cape Canaveral and, typically, very clean signals can be received there without using notch filters.

RESULTS

The tracking noise of the LONARS receiver is less than 10 ns, and the navigational accuracy achieved by the system is less than 150 ft in real time and 50 ft in post-mission analyses. Tracking data from APL with two receivers establishes the tracking noise of the LONARS II receiver, tracking data from Cape Canaveral at the PMS and on board the U.S.N.S. Range Sentinel demonstrate that LONARS I and LONARS II perform similarly, and navigation results from DASOs compare LONARS navigational accuracy to that of the GPS.

For computational noise considerations, LONARS uses stations other than the normal one as the master station. This means that the Loran-C TDs derived from LONARS and plotted here will not correspond to the TDs that are on navigational charts.

LONARS II Tracking at a Stationary Location at APL

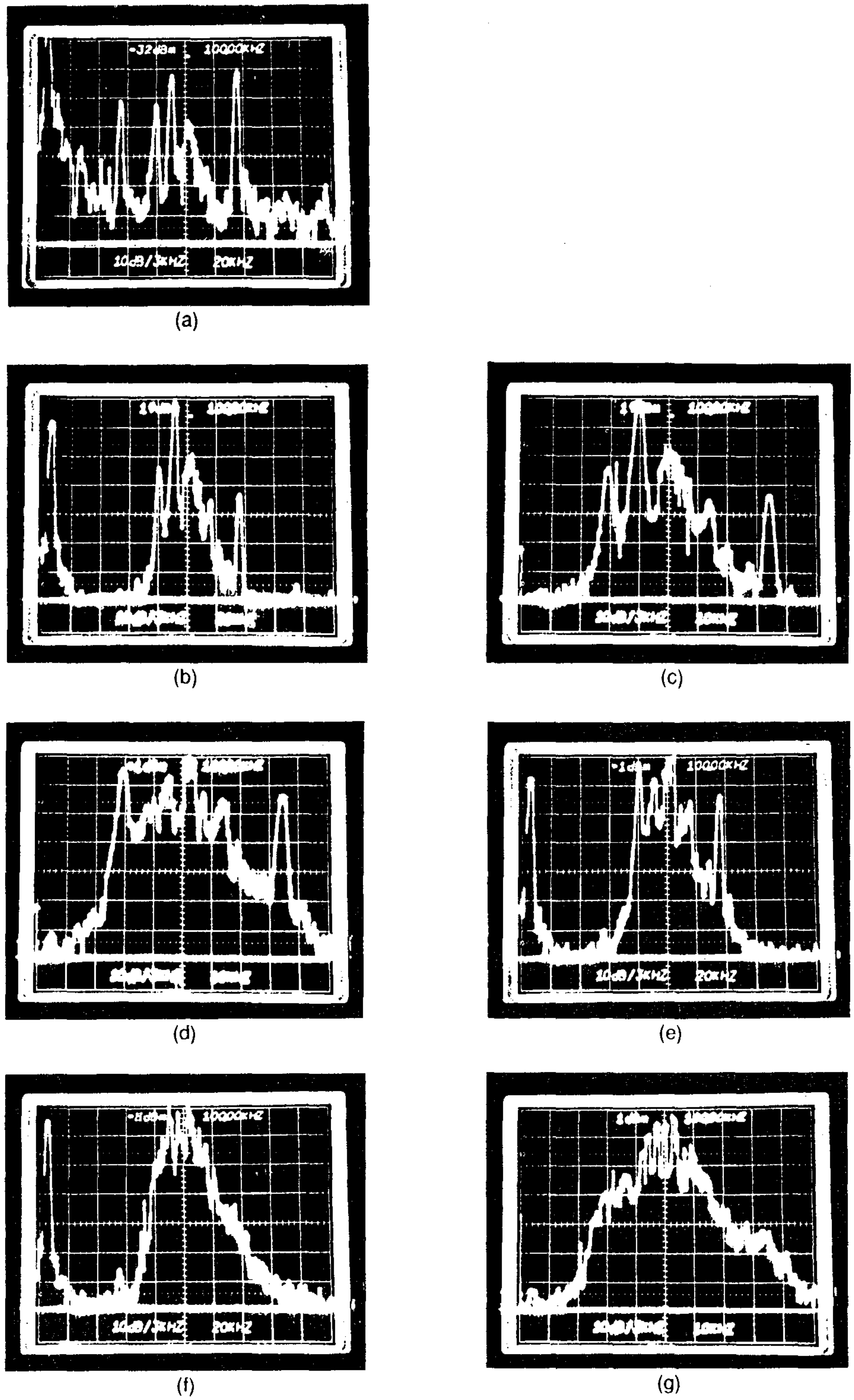
To determine the noise contribution of the LONARS II receiver, a 24-hour experiment was conducted at APL with two LONARS II systems tracking the same antenna signal. Figure 4 is a plot

Spectrum at the antenna

Spectrum at output of receiver with no notch filters; effect of the bandpass filters

One notch filter on the 88-kHz signal

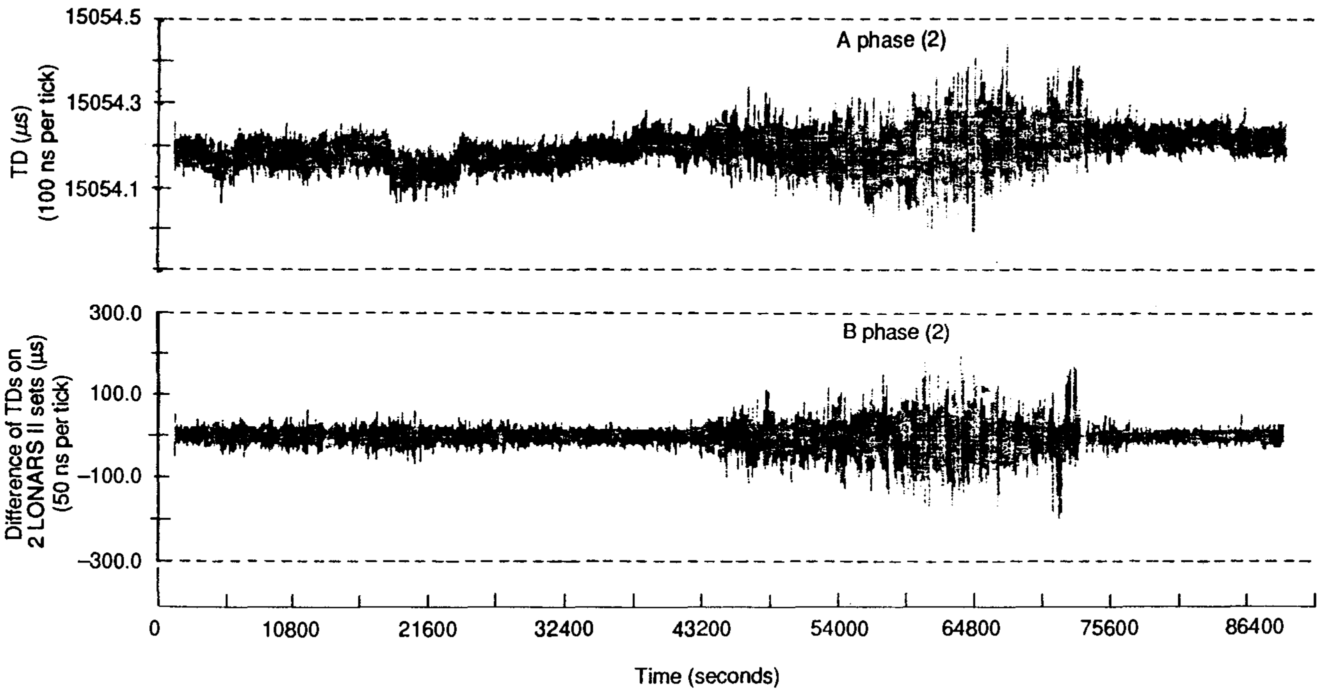
All five notches used, two on the 88-kHz signal



20 kHz per division

10 kHz per division

Figure 3 Spectrum of loran signals at APL.



Delta time differences

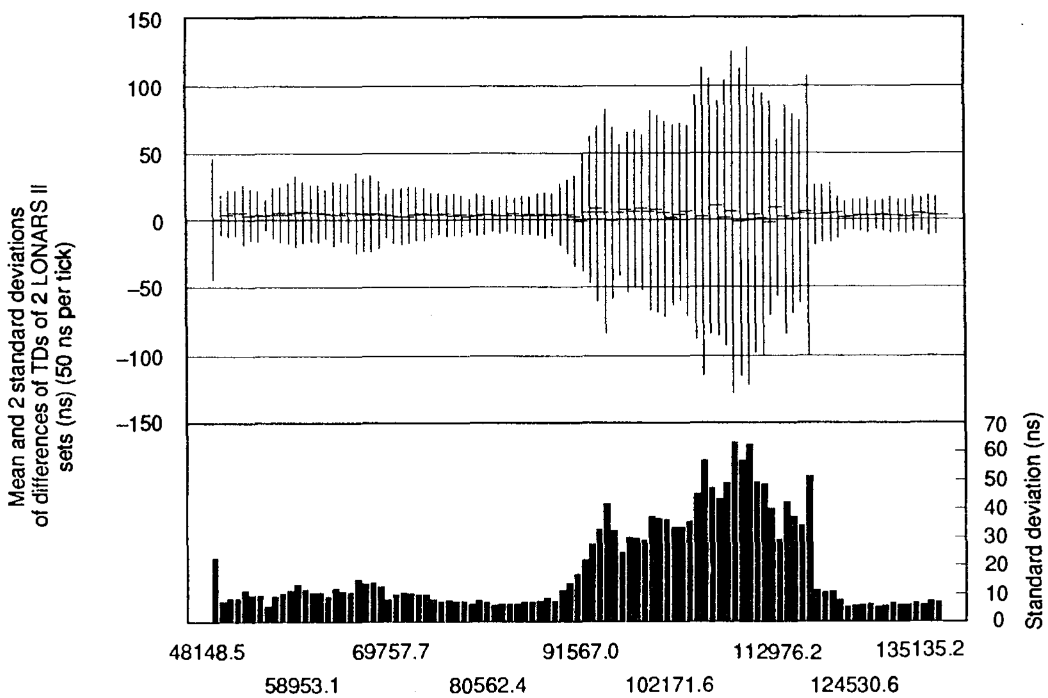


Figure 4 Differences in TDs between two LONARS II systems at APL tracking the same signal.

of data from that experiment. The X axis is time in seconds from the start of the data run, which was at 1321Z on day 162/1990. The top plot of Figure 4 shows one of the raw time differences, TDA, for one of the two systems for the entire experiment. The Y axis is in units of microseconds, with each tick mark equal to 100 ns. The thick portion is caused by the nighttime signal conditions. The second plot shows the time differences between the TDAs of the two receivers. The Y axis is time difference in nanoseconds, with each tick mark equal to 50 ns. The third plot shows the mean of the differences of the TDAs and the two standard deviation points on either side of the mean. The average has a bias of about 5 ns between the two receivers. The lower plot is the plain standard deviation of the differences of TDA for the two receivers. Each tick mark on the third plot is 50 ns and each tick mark on the last plot is 10 ns.

By tracking the same signal and taking the difference of the two TDs, we remove some of the effects of the incoming signal and can determine the noise being introduced by the receiver itself. During the daytime, when the external noise effects are minimized, the standard deviation is less than 10 ns. Assigning a noise value of 10 divided by the square root of 2 to each receiver gives a noise value of 7 ns for each receiver.

The noise induced during the evening hours creates a standard deviation that goes as high as 50 ns which implies that the nighttime noise induced in each receiver is on the order of 35 ns. This noise level increase during the evening is due to sky waves and other low-frequency interference such as the communication signals from Annapolis. Typically, three to five stations are transmitting simultaneously with a combined power sufficient to bury the loran signals if the receiver does not use notch filters. Even with this aggravation, the noise induced is still only 35 ns.

The basic conclusion is that the receiver hardware does not induce more than 7 ns of noise, even though it is switching gains dynamically.

Reference (1) documented that the noise characteristics of LONARS I was less than 10 ns.

LONARS II vs. LONARS I at a Stationary Location at Cape Canaveral

A similar experiment was conducted at Cape Canaveral, Florida, with LONARS I and LONARS II tracking the same antenna signal at the PMS. The results are plotted in Figure 5. As can be seen, the character of the signal is similar to the results achieved at APL, but the size of the nighttime disturbance is smaller. During the day, the standard deviation is on the order of 10 ns, again indicating a 7-ns system. At night, the standard deviation increases to 25 ns, which gives a noise character of 17 ns to each system. This is consistent with APL's past experience with the cleaner environment at the Cape compared with that of the Chesapeake Bay region. This data indicates that both receivers perform similarly in a fixed location.

LONARS I vs. LONARS II on a Moving Platform

Table 1 compares the tracking and navigation results of LONARS I and LONARS II aboard the Range Sentinel on April 30, 1990. Figure 6 plots the mean of the TDs for that exercise and the two standard deviation points. Figure 7 plots the differences in latitude and longitude for the same time period. The data that is the basis of these statistics was collected as the Range Sentinel accompanied the U.S.S. Kamehameha on the missile firing part of the DASO from 1530Z to 2230Z. Both systems used the same antenna signal for this exercise. The data from both systems was stored on magnetic tape and used in the post-mission analyses to determine the statistics shown in Table 1. The processing steps were:

1. Remove the pattern monitor variations from the data of both system
2. Calculate and plot the difference of the resulting TDs (see Figure 6).

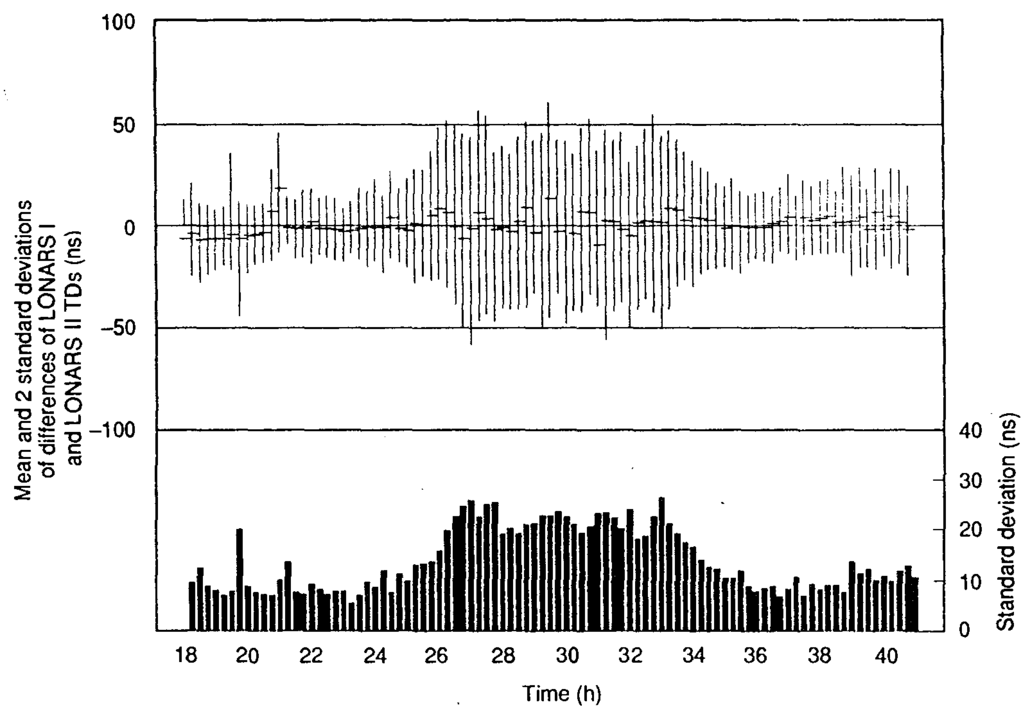


Figure 5 Differences in TDs between LONARS I and LONARS II systems at Cape Canaveral tracking the same signal.

TABLE 1
Position and Velocity Difference between LONARS I AND LONARS II
Post-Mission Analysis, Pattern Monitor Corrected Data
Date - April 30, 1990; Time - 1530Z to 2230Z
U.S.N.S. Range Sentinel

	CB/J TD (nsec)	M/J TD (nsec)	Latitude (ft)	Longitude (ft)	Vel North (kn)	Vel. East (kn)	Radial (ft)
Mean	20	24	-1.9	-1.8	-0.0001	-0.0004	
Std Dev	10	7	2.9	4.5	0.0011	0.0197	
RMS			3.5	4.8			
Radial (RSS)							6.0

Note: CB/J indicates TD for Carolina Beach - Jupiter and M/J indicates TD for Malone - Jupiter.

3. Calculate the mean and standard deviation of the TD's for both systems (see Table 1).
4. Navigate both systems.
5. Calculate and plot the differences between the navigated positions of the two systems (see Figure 7).
6. Calculate the mean and standard deviation of the navigated positions of the two systems (see Table 1).

The plots and statistics show a 20-ns bias between the two systems, but the standard deviation being less than 10 ns again shows that both receiving systems have noise better than 7 ns. The RMS difference in the latitude and longitude of the two systems is 3.5 and 4.8 ft, respectively, and the RSS difference in the radial error is 6.0 ft. This ensures that both versions of LONARS also perform similarly on a moving platform.

LONARS vs. GPS

Table 2 presents the navigation results of comparing LONARS and GPS on two different experiments. The first was aboard the submarine U.S.S. Tennessee on November 29, 1989. The post-mission LONARS I data, which had the pattern monitor corrections applied, was compared with precise GPS position data for a period of 19 minutes during the trip. The differences between the two are 2.0 ft for latitude, and 5.6 for longitude and 9.2 ft for the RSS radial error, which is rather amazing for two 30-ft navigation systems.

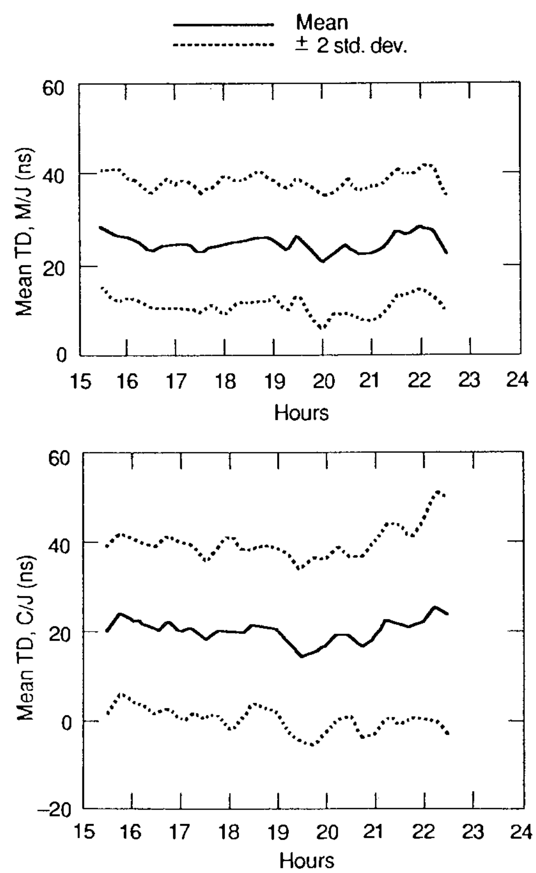


Figure 6 Differences in TDs between LONARS I and LONARS II systems on the U.S.S. *Range Sentinel* tracking the same signal on day 120, April 30,1990.

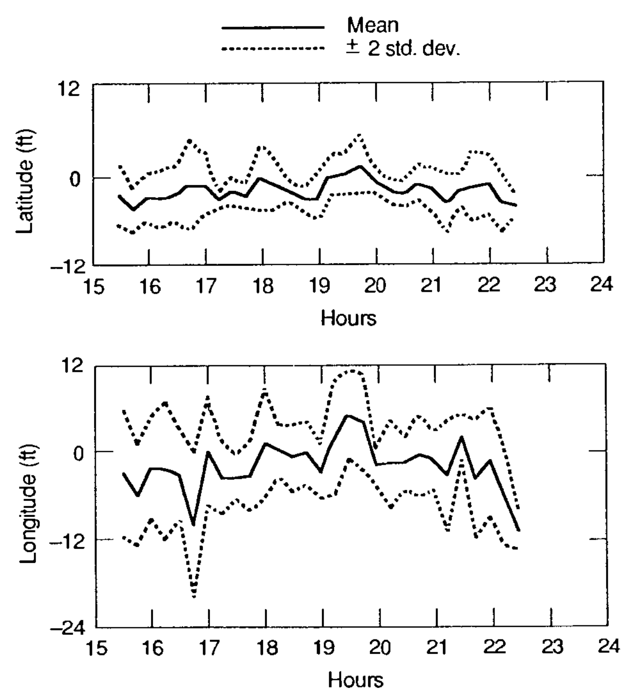


Figure 7 Differences in position between LONARS I and LONARS II systems on the U.S.S. *Range Sentinel* tracking the same signal on day 120, April 30, 1990.

TABLE 2
Position Difference between LONARS I and GPS

Post-Mission Analysis, Pattern Monitor Corrected LONARS I Data
November 29, 1989

Time Dur. (min)	Latitude (ft) Mean	Latitude (ft) Std.Dev.	Longitude (ft) Mean	Longitude (ft) Std.Dev.	Radial (ft)
19	2.0	5.1	5.6	5.1	9.2

Real-Time Comparison between LONARS II and Precise GPS
September, 1989

Time Dur. (min)	Latitude (ft) Mean	Latitude (ft) Std.Dev.	Longitude (ft) Mean	Longitude (ft) Std.Dev.	Radial (ft) Mean	Radial (ft) Std.Dev.
33	21.0	10.0	-33.1	13.7	40.9	12.2

NA - not available

An exercise conducted on board the U.S.N.S. Redstone on September 1989, provided the opportunity to evaluate LONARS II and GPS while compensating for the selected availability clock dithering on the GPS signal. The data from this exercise was analyzed to characterize the real-time performance of LONARS II vs. GPS; Table 2 tabulates those results. The mean of the real-time error between the two systems is 40.9 ft with a standard deviation of 12.2 ft. Since the systems have no inherent similarities, except for the planet they inhabit and the fact that they are both radio navigation systems, there is no rationale for how to partition the error between them. I do believe, however, that this will support the statement that LONARS II provides real-time accuracies better than 150 ft.

LONARS I vs. SATRACK

Table 3 is a tabulation of the results from 12 different DASO operations comparing LONARS I post-mission results with those of a system called SATRACK that uses GPS to track the missile during its flight. The SATRACK data for the missile's position as it broached the water and the pattern monitor

TABLE 3

LONARS I Post-Mission vs. SATRACK
Initial Position Comparison

C4 DASO Test #	Latitude (ft)	Longitude (ft)	RSS Difference (ft)
01	-6.0	-6.7	9.0
03	14.4	-3.9	15.0
04	-0.9	17.3	17.3
05	-14.6	11.2	18.4
07	26.0	-40.5	48.1
09	32.2	19.2	37.8
10	-20.9	36.8	42.3
14*	-21.1	-83.9	86.5
15	-26.1	16.7	31.0
18	-33.9	-20.8	39.8
19	-10.0	4.0	11.0
20	-41.3	5.4	41.7
Statistics of all the data:			
Mean	-8.5	-3.8	33.1
Standard Deviation	23.0	32.3	21.7
Radial (RSS)			40. 7
Statistics with DASO #14 Removed:			
Mean	-7.4	-3.5	28.3
Standard Deviation	23.8	21.1	14.4
Radial (RSS)			32. 8

*Pattern Monitor Time Synchronization Inaccurate.

CURRENT MARINE RECREATIONAL LORAN-C PRACTICES

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Abstract: Today's Loran-C receivers have the potential of providing the recreational boater with an excellant navigational capability and are now priced for this market. However, all too often the purchaser assumes that installation of the receiver is all that is required before setting out for the open seas. This paper gives an insight with examples, as to the educational challenges facing manufacturers, retailers, and end-users, to provide the recreational boater with a navigational capability and not just a show piece of electronic hardware.

Last year I was invited by our Secretary, John Beukers, to give a paper at the Institute of Navigation in Washington, D.C. on "The recreational Boaters' Use - or Mis-Use of Loran-C". These remarks are an update of that paper.

There has been an unprecidented growth in recreational boating in the United States in the past 10 years. With the increase in the personal disposable income of the 2 salary family, and the increased leisure time, Americans have turned to boating for both family and personal recreation.

This explosion in recreational boating is significantly different from the pre-World War II Yachting of the ultra rich - normally done with the assistance of paid professional crews - and the boating boom of the Post War Era - where people bought comparatively smaller and slower boats which they cruised locally during fair weather.

Today's recreational boater is a different breed. They are more impatient to go places - usually fast - and do not have the time nor inclination to spend the "apprenticeship" learning basic seamanship, navigation, and marine weather, to become accomplished seamen or seawomen. I should also point out that many of these new sailors also did not have the opportunity and/or advantage of growing up around the sea and hence could not assimilate much of the background knowledge while growing up.

While the "Old Salts" among us decry the new developements in recreational boating such as Fibreglass boats (real boats are made out of wood - toys are made out of plastic), marine sanitary devices, and electronic navigation: These same developements have enabled more people to enjoy and afford boating activities than ever before. The real question to be answered is: How do we encapsulate 20 years of seafaring experience into one video tape or easy-to-read book so that these neophyte boaters will not become a burden to the already overloaded U. S. Coast Guard and Marine Police Units; or worse, become a negative statistic?

Part of the answer has come in the form of technology: Fibreglass boats do not require the seemingly endless hours of spring preparation and eternal summer maintenance; Engines have become more efficient and much more reliable; and Electronic Navigation - specifically Loran-C - has simplified the task of determining a vessel's position and finding the way home.

However, with this increased simplicity and ease of operation comes the danger of complacency and the increased probability of "getting into water over our head": Failing to do the necessary preventive maintenance to ensure safe operation - because the boat was sold as "turn the key and go", and hence there seemed to be no need to learn mechanics; Assuming that because the salesman said the boat would do 50 Knots, that weather is not important; and that because Loran-C is supposed to be "foolproof", that there is no need for charts and old fashioned navigation techniques.

I believe that some illustrative examples of actual boater attitudes that I have witnessed - both as a professional navigation instructor, and as the proprietor of a non-electronic navigation retail store - Landfall Navigation of Greenwich, Connecticut - will be enlightening:

I recently picked up a 47 ft. Ketch in St. Johns, New Brunswick, Canada and returned her to Newport, Rhode Island - a 300 N.M. trip. What amazed me was that there was not a single pencil mark on any of the charts! Yet this deep draft yacht was well up inside the Bay of Fundy, one of the foggiest places in the world with 30 ft. Tides and strong currents!

Obviously, the ease of "Waypoint Navigation" makes coastal piloting much less traumatic and corrected LONARS data for the ship's position at the time of launch, corrected for antenna-to- missile-tube displacement, were used in this comparison. The statistics of all 14 tests give a difference of -8.5 ft for latitude, -3.8 ft for longitude, and 40.7 ft for RSS radial. There were known problems in the LONARS I data for test 14. If that data is removed, the differences are reduced to -7.4 ft latitude, -3.5 ft longitude, and 32.8 ft RSS radial. This data indicates that LONARS is indeed a precise navigation system with accuracies of better than 50 ft.

POTENTIAL APPLICATIONS

We have demonstrated a 150-ft real-time loran system without the use of collocation data. We believe that this system performs as well as loran can. In fact, it performs as well as any type of radio navigation system. A system such as this with an antenna on the bow and stern of large cargo ships could tell the crew exactly where the ship was in the channel, its heading, and where it would be at some future point in time using the known velocity. The system could include maps of many ports, such as the one we used for Cape Canaveral, to show the operator graphically his position with respect to the navigation channels. This system could be put into a very small package that could provide economically valuable navigation information. One area of development that would be required to make this a viable year-round system would be to include changes in propagation according to seasonal variations. Obviously, this is not a problem in Florida, but for a general-purpose system, some type of calibration and data storage or computational algorithm would be needed.

The Laboratory has been involved with precise navigation since it developed the Transit Navigation System, we have been actively involved in using GPS for the navigation of missiles during test flights, and we have been involved in precise loran developments. As an institution, we are still involved with precise navigation developments.

LONARS demonstrates that precise navigation using Loran-C is a reality, not just a theory, experiment, or paper analysis. This capability could be provided to the navigational community at a modest cost and in a small chassis.

ACKNOWLEDGMENT

I would like to acknowledge the people who developed LONARS I: John Berg, Glen Bolls, John Boyd, Tim Criss, Leo Fehlner, Gene Gick, Lynn Hanson, Tom Jerardi, Tom McCarty, Jim Perschy, Bill Peters, Ron Roll and Kermit Sanders. I would also like to acknowledge the people who developed LONARS II: Ray Bateman, John Berg, Dean Blazie, Stan Cooper, John Goldsten, M. J. Hermes, Lynn Hanson, Lyle Hoard, Bill Innanen, Jeff Love, Ed Mengel, Al Mobley, Bill Peters, Ron Roll, Damon Rutherford, Will Schneider, Lisa Segal, Dick Smith, Phil VonGunten, Dick Yost, and Kevin Zemejda.

REFERENCE

(1) W. J. Peters III, "LORAN Navigation Receiving System LONARS," in Proceedings of the 1978 Wild Goose Association

Edwin E. Mengel

Edwin E. Mengel was born in Baltimore, MD in 1941. He received a Bachelor of Engineering Science degree in Electrical Engineering from The Johns Hopkins University in 1963 and a Master of Arts degree in Numerical Science from The Johns Hopkins University in 1972. In 1966, he joined The Johns Hopkins University Applied Physics Laboratory as an electronics engineer specializing in digital electronics for both ground and flight systems for the Transit Satellite Navigation System. He worked on various digital and microprocessor design projects for the U.S. Navy, the U.S. Coast Guard, NASA, and SDI. For the past two years, he has been a lead engineer on the development of a second-generation LONARS receiver for the Navy. For the past eight years, he has been the supervisor of a section of electronics engineers and since 1984 has taught a class on microprocessor systems development in the graduate school at Hopkins. He is a senior member of the IEEE.

risky with the simple feature now found on virtually every Loran-C receiver: Range & Bearing to Waypoint. However, alittle old fashioned Plotting during this trip would have been prudent.

Last year at the Norwalk In-Water Power Boat Show, a customer who had just purchased a 30+ foot Power Boat came into our booth and started looking through our selection of Waterproof Charts. As he was about to purchase one covering his local area, his "knowledgable friend" came rushing up and told him to "forget about those (Charts) - all you need are these Waypoint Directories".

What this "experienced" sailor was referring to was a series of booklets which list all the major Navigation Aids in a given area and their psotions in T-Ds and Lat/Long. When planning a trip, the Navigator can save considerable time by merely looking up the Nav Aid's position in the Directory, instead of having to plot each one - before entering it's position as a Waypoint in the Loran-C receiver.

A dangerous practice growing out of this method of navigation is the setting of a course to a destination using the Range & Bearing Function of the Loran-C receiver - without ever establishing the vessel's present position on the chart - and hence never really knowing where you are.

The fallacy of the above example obviously is that no prudent mariner will leave the dock without the appropriate up-to-date chart coverage for the intended voyage. Not only does one require a backup to the electronics, but vessels rarely stay on the rhumb line during passages - either due to wind, sea, and tidal action and steering errors, or due to intentional divergences from the planned route.

In the same vein, I recently instructed a new boat owner and his wife in the use of their Loran-C receiver onboard their boat - a 30 Ft. Tiara. We spent the morning plotting courses, reviewing Magnetic versus True Headings, and Plotting Routes and Waypoints. The, after a lunch break, we put to sea to practice what they had learned.

After a few trips out into Long Island Sound and back to the harbor entrance "finding the Waypoints", I realized that my students had forgotten completely about their charts and were merely following whatever their Loran-C receiver suggested! My solution was to direct them to take us to a destination that was hidden behind a point of land and which would require steering a 2 leg course. Naturally, my students loaded the Destination Waypoint into their Loran-C receiver, selected the "Range & Bearing" Function, and off we went at 20 Knots.

After a short while, I could see my students looking alternately at the approaching headland, their Loran-C receiver readout of Course and Distance to Waypoint, and their Compass. Finally, one of them turned and looked at me rather sheepishly picked up the chart and said "oh, now I get it"!

If it had been dark or thick fog, or the point had been a partially submerged reef, things could have truned out quite differently for these people - who, by the way, were well-educated and afluent business owners.

Also, remember that even if the courses had been previously plotted on the chart, letting the Loran-C receiver plot Range & Bearing to the Waypoint from "Present Position" - as a Course - will effectively negate the Cross Track Error Function - something that Capt Hazelwood of the EXXON VALDEZ and most of the State of Alaska, may wish he had been using in Prince Willaim Sound.

Another facit of today's new boaters is an impatience with "bothering to learn the basics". Acouple of years ago at another Boat Show, a man in his late 40'swearing a U. S. Coast Guard sweat shirt, and his wife came into our booth to complain in a loud voice that the Loran-C Course that I had taught him had been a waste of time and that too much time had been spent "selling Loran-C Receivers" (something I never do at my seminars).

I knew from his description of the course that he was not referring to one of my seminars - but to a local competitor's - so I tried to see if I could explain the goals of my course of study, suggest that it had, in fact, not been my seminar that he had attended, and see if I could help him with his navigation problem at a later time and place.

Unfortunately, when I suggested that all any Navigation Instructor can do is to provide the student with the tools to navigate - and that it is up to each apprentice navigator to practice and to raise his or her proficiency - our Sunday Sailor announced to the world that practicing navigation got in the way of partying - and that there was simply not enough time for both in a weekend!

At that point, I gave up, turned to his wife, and suggested that they hire a professional Captain to run their yacht. That way, he would have all the time he needed to party, and she would get home safely.

For this particular problem, I am not certain that there is a simple solution - but B.W.I. (Boating While Intoxicated) Enforcement and a general change in the image of and attitude towards the "Drunken Sailor" would help.

A final example comes from two students - one a retired dentist and the other a young salesman: Both were given private navigation instruction in thier homes. I attempted to teach them basic chart reading,course plotting, bearing taking, and Magnetic versus True compass headings. Neither student had any interest in learning to manually plot a course, visually fix a position with cross bearings, or concern themselves with the potential for errors in the Loran-C System. They continually kept telling me that once they got onboard their boat, with their Loran-C receiver that everything would work itself out - because they "would let the Loran do it".

In both these cases, they had been sold Loran-C receivers on the premise that this magic box would do all their navigating and would alleviate them from having to do anything but turn on the set and relax. Not, in my opinion, a prudent way to operate any vessel.

Now that I have defined the problem of the new boater and his Loran-C venturing out onto "unknown" waters with his new "yacht" - what can we, the professionals, do to make their endeavor as safe, simple, and enjoyable, as possible.

A lot has been said and written, and a lot more will be said and written about Licensing Boat Operators. The Pro- Licensers say that there should be training, education, and responsibility before someone is allowed to go out on potentially dangerous water with an even more potentially dangerous boat. What they say is true, and only a fool will intentionally take himself and his loved ones where they will get hurt or worse.

On the other side, the Contra Licensers say that it is everyone's birth right to go boating if they choose; that this is one more attempt to install "Big Brother" to watch over us - at our expense; and that licensing certainly did not help the EXXON VALDEZ and Prince William Sound. This is also true.

As is usually the case, the best solution will probably lie somewhere in the middle between these two positions. However, Government Regulation is not my subject today.

On a realistic basis, more education of and interest by the new boater in the mysteries and techniques of coastal piloting, including the basics of course plotting, bearing taking, and dead reckoning navigation will be part of the solution.

Since 1983, I have been teaching a 6 Hour Loran-C Navigation Seminar with very favorable results. In fact, this seminar was so popular that I made it into a 90 Minute Video Tape entitled - LORAN-C A NAVIGATOR'S APPROACH. This tape was produced by my company, Landfall Navigation, shot by a Hartford, Connecticut company, and is distributed by Bennett Marine Video of Marina del Rey, California. In 3½ years, over 9,000 copies of this marine education program have been sold, and there appears to be no slackening in demand.

What this seminar and tape do, is to explain - in non-technical terms - what the Loran-C System is all about: how the Chains are set up, what the potential problems with the System are, what effects the geographical accuracy and reliability of the position fix, and most importantly, how to use those "funny numbers" that appear on the screen.

My tape is 90 minutes long, but only 55 minutes are devoted to my "lecture" about the system. The balance of the time is spent giving navigation problems, telling the student to stop the tape and work out a solution, and then reviewing the answers that should have been obtained.

I teach all my seminars the same way: I spend the majority of the time having the students work out navigation problems - Courses, Distances, Estimated Times of Arrival, Tidal Current Set & Drift, and Position Fixes - and then discussing the solutions and explaining what happened. Navigation is taught by doing - not watching - and I might add that I have rarely had a dissatisfied student.

I believe that if people are given a reasonable oppotunity to obtain a <u>simple</u> understanding of the weather, common sense rules of the road, minimum saftey equipment requirements, and shown how to read a chart, take a pair of cross bearings, and plot a course, that we will have gone a long way to achieving Safe Boating.

I also believe that there will always be a few who will try to ruin it for the rest of us by being discourteous, reckless, irresponsible, and stupid. The answer to this problem is for severe penalties to be established, violations to be prosecuted, and harsh judgements rendered - regardless of the race, creed, wealth, or political influence of the perpitrator.

Hopefully, if we achieve a "kinder and gentler nation", some of the Rambo style machoism will dissappear and it will not be "wimpy" to ask how to operate a boat safely. In my Junior Navigation Classes, I always find the girls to be better students, and more fun to teach. They tend not to "know all the answers before the question is asked", and they are not afraid to ask questions if they do not understand.

On a related tack, if a sea-going chapter of M.A.D.D. (Mothers Against Drunk Drivers) could work at dispelling the popularity of the Drunken Sailor Image, we would all be better off. Even the Royal Navy has stopped the Grog Ration as no longer prudent in this age of high speeds and modern technology. In today's recreational boating environment, there is no place for an intoxicated kamikaze pilot.

It is our responsibility as professionals. to aid in the developement of these new boaters by producing simple, stimulating, and interesting programs that will stress not only the latest space age navigational technology, but also, the old fashioned "basics" - upon which foundation to base modern electronic navigational practices. If we set the example - and borrow from the U. S. Coast Guard and the Boy Scouts of America - Semper Paratus - and use the motto as a standard for all good sailors, I believe that we can interest the majority of the boating public in learning to do it right.

The Marine Electronics Dealers also share some of this responsibility to the new boater to see that he or she is prepared to operate safely. In my experience, far too few Marine Electronics Salespersons have sufficient navigation knowledge or off-the-dock experience.

Naturally we are all in business to sell our product lines - these sales pay the bills and more importantly, our salaries. However, it is irresponsible to advise a customer that it is safe and prudent to enter a Waypoint 100 Nautical Miles offshore at a "fishing hole", and set sail - without cautioning about weather patterns, and how to navigate back home if electrical problems arise. The Loran-C receiver may be waterproof, but very few small vessel electrical systems are.

We actually had a customer come into Landfall to buy a chart and ask: "What are those (Plotting) tools"? When we demonstrated a pair of parallel rules snd dividers, he said: "Oh Richie said to let the Loran do that". My next question to him - which went unanswered - was: "If you have an electrical short or the system goes down while you are out at the canyon (approximately 100 N.M. Offshore), how do you plan to get home?

I seriouly doubt, on the other hand, that a single sale would be lost if the salesperson took a more balanced approach: If he or she were to demonstrate a D. R. Course Plot and a Visual Bearing Fix, and then show the new customer how the Loran-C receiver verifies these results (a safety check), and finally accesses all the other time saving and useful information that the set can provide - wouldn't he significantly raise his credibility with the customer? In our experience, this technique results in repeat business and lots of referrals of the customers' friends - because we helped them understand it.

I have also found a tendency among electronics salespeople to over-sell the simplicity of the Loran-C System. "Just put this receiver onboard and forget about having to navigate". No mention is made of the flourescent lights at the Nav Station (Why do Boat Builders do that?), or what happens when your wife turns on the color television set to watch her favorite soap opers - just as the fog closes in! Loran-C is great, but it does have its moments, and unless the customer/user has been fore-warned - he may be in for some anxious and/or expensive moments.

Full Service Electronics Dealers are - in most cases - much better at sending their customers out to sea prepared, than are the Discounters. At least with a Full Service - Factory Trained Rep, the set is properly installed, grounded etc., and probably initialized to the proper G.R.I. and pair of Secondary Stations. Where the Full Service Dealer "fails" his customer is, in not spending that extra few minutes after the installation with him - to go over the set's operation. Keep in mind that many of these new boat owners do not know enough about boating and navigation to ask the needed questions.

It is very important for the novice boater to operate his new equipment on his boat - ie: in familiar surroundings. Until this happens, it will all remain a mystery to our new sailor/navigator. We at Landfall Navigation spend many hours each year on customers' boats teaching them - for a fee - how to operate equipment that other marine dealers have sold them.

Why do boaters come to a store that does not sell electronics for help with their electronic equipment? Simply b ecause we have a hard earned reputation for being navigators and seamen - and for taking the time to explain things.

The Discount Electronics Dealer, on the other hand, gives his customers nothing except a low price. In most cases, all the sales staff are capable of doing is giving the customer a carton containing the item requested. There is very little installation, operational instruction, or product knowledge available from the clerk - and if you have a warrantee problem, you are on your own with the manufacturer.

A case we saw a few years ago involved a discount purchased Loran-C receiver which did not work after installation. The owner had purchased the set at a discount store and hired a kid on the dock who said he could install it. Naturally, our "learning as we go" technician blew the protective diode. When the unit was returned to the manufacturer, the warrantee claim was denied. Naturally, our "technician" insisted he had done the installation correctly and that it was the set which was defective. Unfortunately for the owner, this could not be verified.

By saving acouple of hundred dollars at the discount store, this boater ended up paying two installers over $100.00 each, plus a $75.00 Factory Service Charge - and was without the use of the set for most of the summer. Was it worth it?

Another suggestion that I make to new boaters: Today's "yachts" have alot of electronic equipment onboard. Given the harshness of the marine environment, something is always going to need attention. When you "buy discount" and need a technician the week before a holiday weekend - who do you think is going to the head of the service list? You or the dealer's regular customer who buys all his electronics gear from this Full Service Dealer?

Once again, my solution for the above "Dealer Problem" is Education - for both the Full Service and Discount Dealer. During the slow periods, send your sales staff to Navigation School. There are many opportunities in your local areas - Power Squadron, Coast Guard Auxiliary, Seamen's Institutes or Maritime Academies, and Correspondence Courses. Yes educating your employees is another "investment" for your business- but how else can you keep up with progress?

There are also opportunities for local marine businesses to sponsor Navigation Seminars for their customers, generate community good will, make a contribution to safe boating, and generate some new customers - at little cost and possibly a small profit. For a moment imagine yourself as a marine electronics or boat dealer: During your slow season - winter in the Northeast, for example - you arrange, advertise, and put on a Navigation Workshop or Loran-C Navigation Seminar. Hire a local Power Squadron or Coast Guard Auxilary Instructor, or make a deal with a local boating school. You will receive "credit" for promoting Safe Boating in the community, you will attract some new/potential customers to the seminar, and you should be able to charge enough to pay for the entire program.

I have been presenting a series of Navigation and Marine Safety Seminars for local boating clubs and organizations for the past few years. For the "commercial organizations" that charged admission, I know that they recouped my charges and in most cases were over-subscribed by attendeees.

There is also something that the Loran-C Manufacturers can do to h elp the new boater and first time Loran-C receiver purchaser: Write the Operations Manuals in simple English - not roughly translated Japanese - so that a non-computor oriented novice will understand it.

Although Loran-C receivers have become simpler to operate and considerably more user friendly - the Owners' Manuals still leave a lot to be desired. An example of misleading instructions comes from my own Furuno L/C 80 Instruction Card:

To enter a Waypoint: Depress the "CL" (Clear Left) Key, enter 1st Coordinate, depress "CR" (Clear Right) Key, enter 2nd Coordinate, and depress "Enter" Key. Almost Correct!

The Correct Steps are: Depress "CL" Key, enter 1st Coordinate, depress "Enter" Key, depress "CR" Key, enter 2nd Coordinate, depress "Enter" Key. Not an obvious difference in instructions, but very significant when trying to operate the set.

A further indication that the Operating Manuals provided by most Loran-C receiver manufacturers are inadequate, are the series of short video tapes coming on the market - see attcahed brochure. What these tapes do - for $29.95 - is show a close-up of the Loran-C receiver in question. Then as the narrator describes a function, the student sees the buttons on the set depressed in proper sequence. Again, not very dramatic, but we sold over 100 copies of these tapes at the New York Boat Show - to people who obviously could not operate their Loran-C receivers.

I hope that my experiences with the boating public as a Navigation Instructor and as a Retailer of Charts, Navigation Tools and Supplies has provided some insight into the world of the amateur recreational boater. I would be happy to discuss any of this with you in detail and will be here for theentire symposium. Also, please feel free to call me at Landfall Navigation during regular business hours - 203-661-3176.

Thank you,

Capt. Henry E. Marx

Biography

Capt. Marx received his B.S. in Economics & Finance from the University of Hartford (CT.), and his M.B.A. from the University of Connecticut. He started sailing Long Island Sound in 1946 and has since seen duty with the U. S. Navy in diesel submarines, with the Norwegian Merchant Marine in an Oil Tanker, and holds a 50 Ton Auxiliary Sail License from the U. S. Coast Guard. Capt. Marx took over Landfall Navigation in 1982 and has since built it into one of the leading nautical chart agencies, and marine navigation and safety equipment retailers in the country. In 1986 he produced the well-received marine instructional video - LORAN -C - A NAVIGATOR'S APPROACH - which explains the Loran-C System and how to use it to navigate. In addition, Capt Marx teaches a number of Navigation Seminars each year, gives numerous personalized navigation classes to boaters both onboard their yachts and in the classroom, and when time permits, he delivers yachts along the U. S. East Coast. He was also appointed a Director of the Wild Goose Association for 1990.

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Measurement Techniques for Narrowband Interference to LORAN

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U. S. Coast Guard Academy, New London, CT 06320

Abstract

This paper represents follow-on work to our previous paper [1], where we primarily considered the problems of cross-rate and skywave interference. Here we also discuss the issue of interference to LORAN, but now we specifically address the problems associated with narrow band interference such as power line carrier (PLC) and Navy FSK interference, and we present theory and measurement techniques for detection. Specifically, we introduce a model that simplifies the exact calculation of the LORAN spectrum and predicts the effects of interference on observed Time Delay (TD) or Time Of Arrival (TOA). We derive equations that relate amplitudes of interference relative to LORAN signal strength to peak variations in observed TD and TOA (for synchronous or near synchronous interference), and to rms variations (for non-synchronous or wideband interference). Furthermore, we consider various techniques in detecting interfering signals within the LORAN band in the presence of strong LORAN signals, and we present methods to determine if the interference is synchronous, near synchronous or non-synchronous. Such methods include use of analog analyzers, Fast Fourier Transform (FFT) analyzers, SSB audio, time averaging, and odd/even strobe dropping. We also introduce a measurement system that integrates a SSB receiver with an FFT analyzer. Such a system allows very fine detailed time and frequency domain measurements from VLF to HF , and we compare this system to recently announced fine resolution spectrum analyzers. Finally, we give examples showing analysis methods for typical types of existing narrowband interference sources, including Naval communications stations, time dissemination signals, and power line carriers (PLC's).

Introduction

The expansion of LORAN to the aviation community in CONUS (where narrow band interference such as PLC interference is more common), coupled with the continued growth of LORAN throughout the world (where inband carriers are much more common), has generated renewed interest in the question of interference and its effect on the received LORAN signal. What effect does that interference have on either a navigational or a monitor grade receiver? Certainly interference cannot improve performance, and when picking locations for monitor receivers, perhaps a reasonable goal is to choose a location in the desired area that is relatively "quiet," i.e., experiences "little" interference at that location. Now the question remains, how little is "little," and how can we make interference measurements in order to guarantee we have enough sensitivity to see any interference that could cause us problems?

Fine Spectrum of LORAN

To fully understand the effects that interference has on the received signal, we must know about the coarse and the fine spectrum for LORAN. It is well known that the LORAN signal format has a period of one Phase Code Inverval (PCI), which is equal to two Group Repetition Inverval (GRI). Fourier analysis says that the spectrum of such a signal contains lines at integer multiples of 1/(2 GRI). For example, in the case of rate 9960 this spectral line separation is 5.02 Hz, and for rate 5930 this line separation is 8.432 Hz. Since all existing GRI's are multiples of 100 μsec, all existing PCI's are multiples of 200 μsec, thereby implying that every LORAN rate has spectral components at integer multiples of (1/200 μsec) or at 5 kHz intervals. Of course this represents synchronous cross rate interference, and the predominant interfering lines occur at 95 kHz, 100 kHz, and 105 kHz on all rates.

Calculation of Fine Spectrum

So far we know the location of the fine spectral lines, but we do not know the relative strengths of each line. To see the actual structure of the LORAN fine spectrum, we propose the model shown in Figure 1. We model the LORAN signal format as the output of a linear, time invariant, continuous-time filter, that has been "driven" by a periodic impulse train. More specifically, the LORAN signal format over one PCI can be expressed as

$$x(t) = \sum_{i=1}^{16} Pc(i)\,\delta(t-t_i)\,, \tag{1}$$

where Pc(i) is ± 1, depending on phase code. The Fourier transform is then

$$X(\omega) = \sum_{i=1}^{16} Pc(i)\exp(-j\omega t_i) = \sum_{i=1}^{16} Pc(i)\{\cos\omega t_i - j\sin\omega t_i\} \tag{2}$$

In Figure 2 we show a plot of $\frac{|X(\omega)|}{16}$ in the region of the 100kHz spectral line for a GRI of 9960. Although the line spacing of 5.02Hz was expected, we should comment on the relative amplitudes of the spectral lines.

Note that the spectral lines in Figure 2 vary in amplitude from about 0.12 to 0.33 with a nominal value of .25. There are several physical interpretations for these values. One interpretation for the value of .25 at 100 kHz is that the LORAN harmonic at 100 kHz is .25 what it would have been had all pulses been of the same phase code. That is,

$$\frac{10 \text{ positive pulses} - 6 \text{ negative pulses}}{16 \text{ total pulses}} = 0.25\,. \tag{3}$$

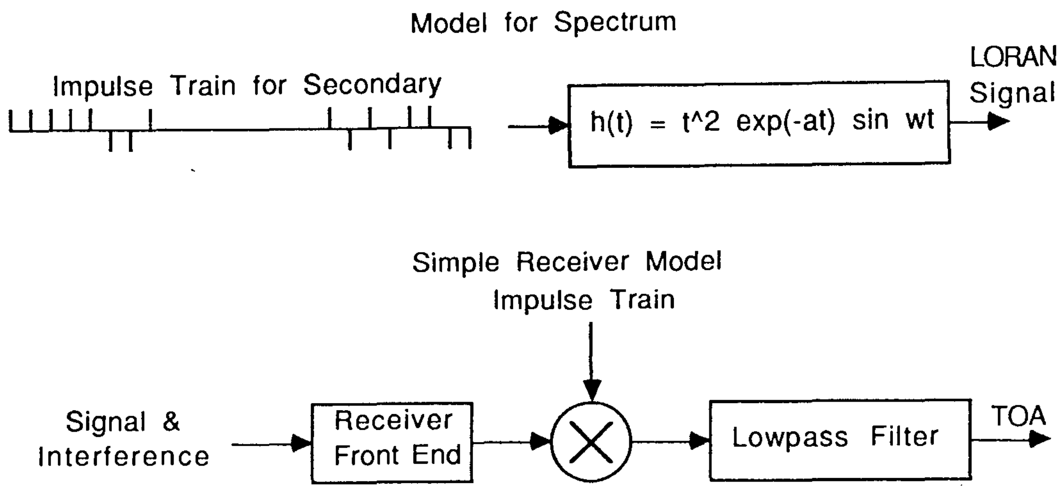

Figure 1. Model of for Calculation of LORAN Spectrum and Analysis of Interference.

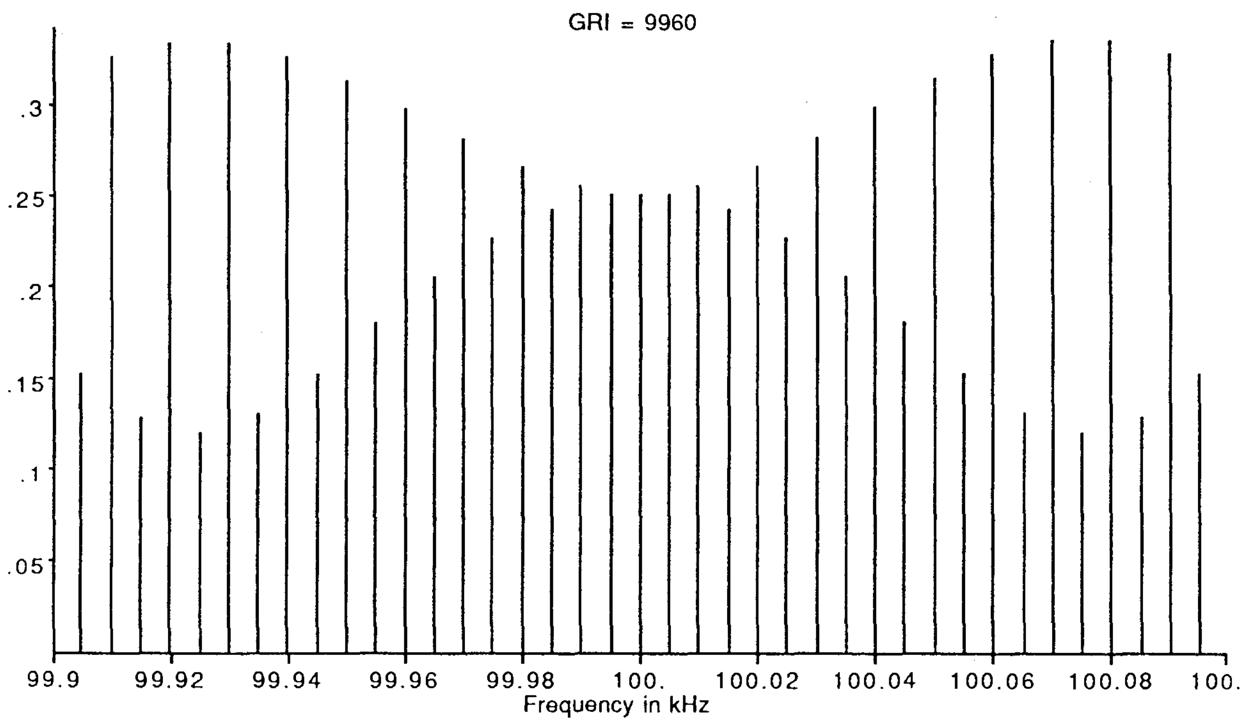

Figure 2. Plot of |X(w)|/16 showing the spectral line structure in the region of 100kHz.

A second interpretation lies in the expected movement in time of the average of the zero crossings of all 16 pulses relative to the movement of the zero crossings of any single pulse, due to synchronous or near synchronous interference. More specifically, for interference at or very near the line at 100 kHz, the zero crossings of all 16 pulses move by the same amount, but zero crossings of positively phase coded pulses are shifted in the opposite direction from zero crossings of negatively phase coded pulses. The shift of the average is exactly 1/4 the shift of any individual pulse.

Effect of Interference on TOA

Certainly the maximum shift in zero crossing time (or in radians) occurs when the interference peaks in the vicinity of the LORAN zero crossing (shown in Figure 3), and is given as

$$\text{Phase shift (rad)} = \sin^{-1}\left(\frac{A_{Int}}{A_{Lor}}\right) \cong \frac{A_{Int}}{A_{Lor}},$$

$$\text{for } A_{Int} < \frac{A_{Lor}}{2}, \tag{4}$$

where A_{Int} is the amplitude of the interference, and A_{Lor} is the amplitude of the Loran envelope at the sampling point. Therefore for a single pulse, the shift in microseconds is given as

$$\Delta t \cong \frac{10\, A_{Int}}{2\pi A_{Lor}}\ \mu\text{sec} = 1.59\left(\frac{A_{Int}}{A_{Lor}}\right)\ \text{msec}, \tag{5}$$

and for the average of 16 pulses the shift is

$$\Delta t \cong 1.59\left(\frac{A_{Int}}{A_{Lor}}\right) R\ \mu\text{sec}, \tag{6}$$

where R represents a "relative line strength," or just the amplitudes between 0.12 and 0.33 plotted in Figure 2.

Example 1. What must the strength of an interfering line near 100 kHz be relative to LORAN signal strength to result in 100 ns peak to peak variations in observed TOA? Assume the difference frequency is well within the receiver bandwidth.

Solution:

Since the zero to peak variations would be 50 ns, we set

$$0.05\ \mu\text{sec} = \Delta t \cong 1.59\left(\frac{A_{Int}}{A_{Lor}}\right) R\ \mu\text{sec} = (1.59)\left(\frac{A_{Int}}{A_{Lor}}\right)(0.25)\ \mu\text{sec}$$

so

$$\left(\frac{A_{Int}}{A_{Lor}}\right) \cong 0.126, \text{ or } \boxed{-18\text{ dB}}.$$

Perhaps a more fundamental question to address is, can we detect an interfering line 18 dB below LORAN signal strength? To accomplish this we often look for lines or narrowband "spikes" in the spectrum (as displayed either on an analog or digital spectrum analyzer), or we listen to the output of a receiver. In any case, the ability to detect interfering spectral lines is not so much a function of the line strength relative to LORAN signal strength (defined by the envelope at the sampling point), but rather it is a function of the line strength relative to LORAN power within the resolution bandwidth of the instrumentation. Therefore we must express the strength of individual LORAN lines (or the total power in adjacent lines in a specified bandwidth) as a function of LORAN signal amplitude.

The Relationship Between Signal Amplitude and Individual Spectral Line Strength

This calculation is somewhat tedious, but it is based on the principle that average power in the time domain is equal to the sum of the power in the spectral lines in the frequency domain (Parseval's theorem). If we numerically integrate the power in a single pulse of peak amplitude A_p volts, and multiply by 8 (for a secondary) the result is energy in one GRI.

If we represent a single pulse as

$$v(t) = \frac{A_p\, t^2\, e^{-t/32.5\ \mu\text{sec}} \cdot \sin(2\pi \times 10^5 t)}{(65\ \mu\text{sec})^2\, e^{-2}} \tag{7}$$

then the energy per pulse (in units of V^2 seconds) is given by

$$\int_0^\infty v^2(t)\, dt = 4.16 \times 10^{-5} A_p^2. \tag{8}$$

Therefore the total power, P_T, in units of V^2 for a secondary is

$$P_T = \frac{8 \times 4.16 \times 10^{-5} A_p^2}{GRI} = \frac{3.33 \times 10^{-4} A_p^2}{GRI} \tag{9}$$

where GRI is given in seconds.

Using Fourier techniques to derive the Fourier Transform for one LORAN pulse, we then numerically integrate the magnitude squared over all frequencies and compare the power per Hz of bandwidth at 100 kHz to the total power, with the following result:

$$\text{PSD at 100 kHz (in units of } V^2/\text{Hz}) = (1.73 \times 10^{-4})\, P_T.$$

To get the power spectral density (PSD) at any other frequency, we compare the coarse spectrum at that frequency to the spectrum at 100 kHz (and multiply by $1.73 \times 10^{-4}\ P_T$). Therefore the average line strength at 100 kHz is given by

$$\text{PSD at 100 kHz(in units of } V^2/\text{Hz}) \times \text{(Line Spacing in Hz)}$$

$$= \frac{1.73 \times 10^{-4}\, P_T}{2 \times GRI} = \left(\frac{1.73 \times 10^{-4}}{2 \times GRI}\right)\left(\frac{3.33 \times 10^{-4} A_p^2}{GRI}\right)$$

$$= \frac{2.88 \times 10^{-8} A_p^2}{GRI^2}. \tag{10}$$

This relationship between individual line strength (near 100kHz) and pulse amplitude may be expressed in dBv as

$$\boxed{L_{dBv} = \text{Line in dBv} = -75.4\text{ dB} + 20\log(A_p) - 20\log(GRI)} \tag{11}$$

where A_p is peak pulse amplitude in volts, and GRI is given in seconds.

The actual strength of a particular line anywhere in the spectrum (say at frequency f_i) may be calculated by

$$\boxed{L_{dBv} = C(f_i)_{dB} + F(f_i)_{dB} - 75.4\text{ dB} + 20\log(A_p) - 20\log(GRI)} \tag{12}$$

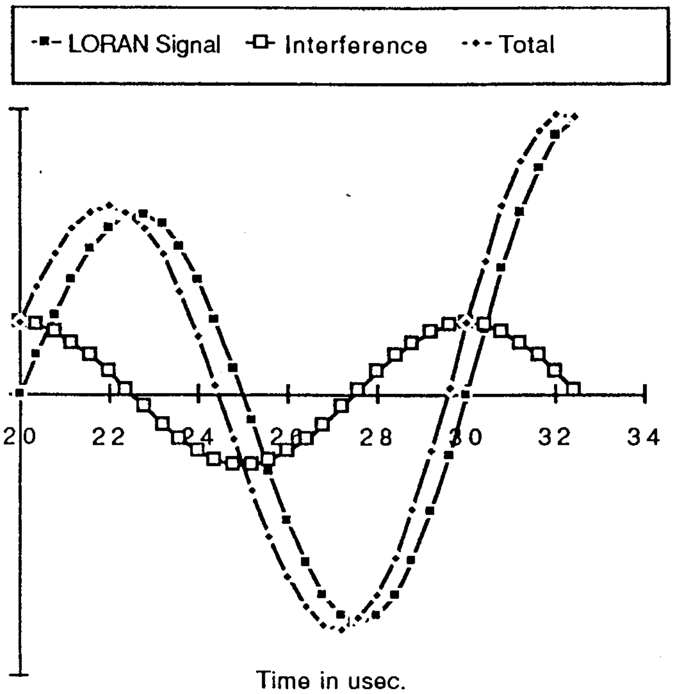

Figure 3. Shift in zero crossing due to sinusoidal interference.

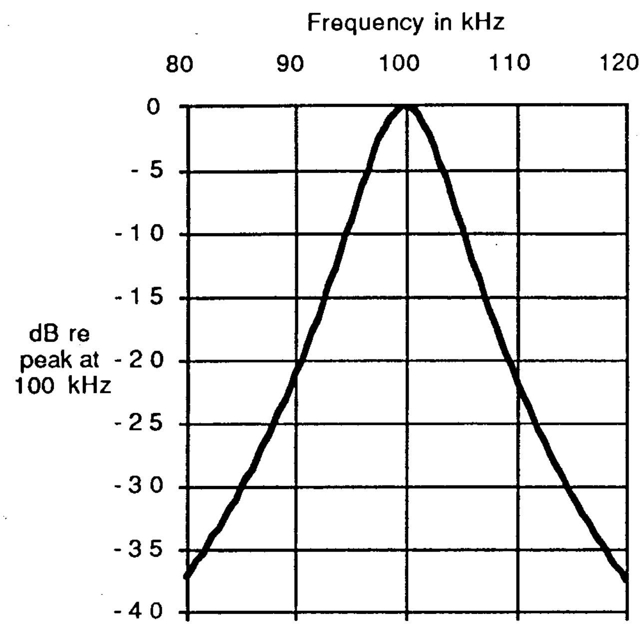

Figure 4. Coarse spectrum of LORAN.

Figure 5a.
192 Hz
resolution
bandwidth.

Figure 5b.
6 Hz
resolution
bandwidth.

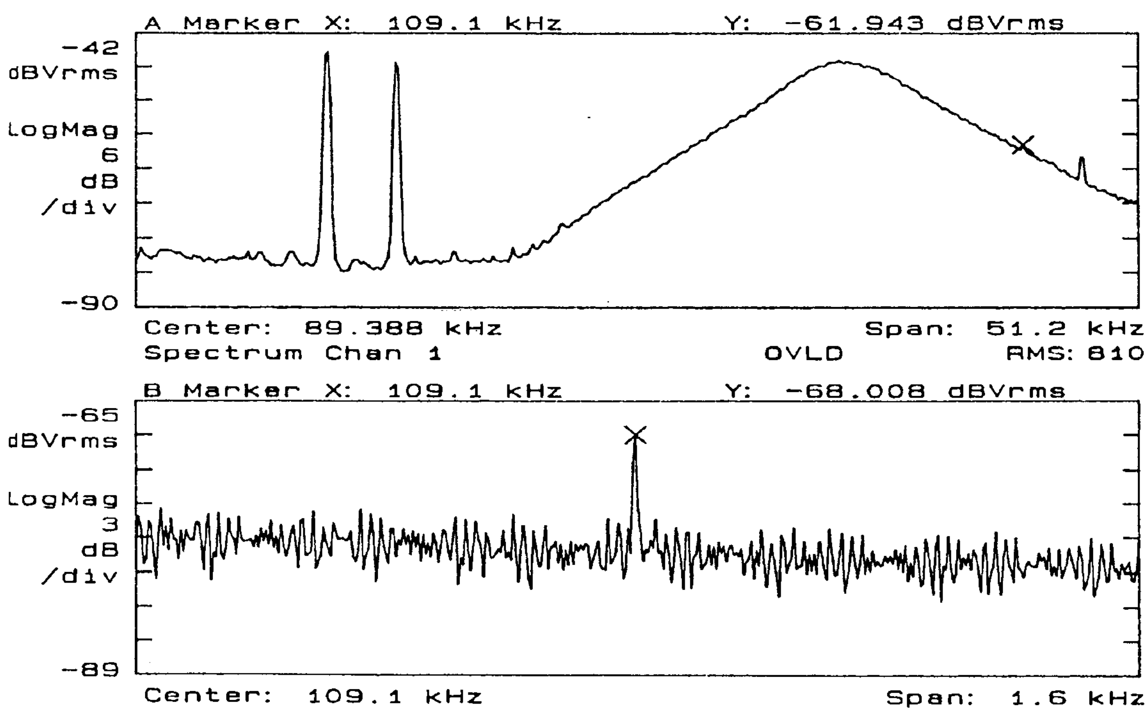

Figure 5. Resolution bandwidth comparison for PLC detection.

where

$C(f_i)_{dB}$ - represents a correction due to the coarse spectrum roll-off characteristic- (As shown in Figure 4, 0dB occurs at 100kHz, with negative values for other frequencies), and

$F(f_i)_{dB}$ - represents a correction due to the fine spectrum characteristic (shown for example in Figure 2). This correction will be $20\log(S_i/0.25)$, where S_i represents a Fourier amplitude value from 0.12 to 0.33.

Inversely, the peak pulse amplitude as a function of line strength (L_{dBv}) is given by

$$\boxed{A_p = 5{,}888 \times GRI \times 10^{(L_{dBv}/20)}} \,. \tag{13}$$

If we define Loran signal strength (S_{30}) as the rms value at the 30 μsec. sampling point, another useful relationship is that between this value and individual line strength near 100 kHz. More specifically,

$$S_{30} = 20\log(A_p/\sqrt{2}) - 20\log\left(\frac{A_p}{\text{envelope amplitude at 30 } \mu\text{sec.}}\right)$$

$$= 20\log(A_p) - 3\text{dB} - 4\text{ dB},$$

and from Equation (11) this implies

$$\boxed{S_{30} = L_{dBv} + 20\log(GRI) + 68.4\text{ dB}} \,. \tag{14}$$

Example 2: Suppose we receive pulses in New London, CT from LORAN Station Nantucket with peak amplitudes of 37 mV on rates 5930 and 9960. Calculate the individual spectral line strengths for each of the two rates near100 kHz.

Solution:

From equation (11), we know the line strength in dBv for rate 5930 (near 100kHz) is given as

$$\text{Line in dBv} = -75.4\text{ dB} + 20\log(0.037) - 20\log(0.0593)$$
$$= -79.5\text{ dBv},$$

and the 9960 line strength is

$$\text{Line in dBv} = -75.4\text{ dB} + 20\log(0.037) - 20\log(0.0996)$$
$$= -84.0\text{ dBv}.$$

Example 3. Could we expect to detect an interfering line near 100 kHz that we suspect is causing a 100 ns peak to peak variation in our observed TOA? Assume the difference frequency is well within the receiver bandwidth. (The information given is the same as for Example 1, however we are considering a different question.)

Solution:

As we saw in Example 1,

$$\left(\frac{A_{Int}}{A_{Lor}}\right) \cong 0.126, \text{ or } -18\text{ dB}.$$

Now the question is, can we detect this interfering line which is18 dB below LORAN signal strength? Observe that a line -18 dB relative to the LORAN signal strength at the 30 μsec. sampling point (S_{30}) from Equation (14) is given as

$$\begin{aligned} S_{30} - 18\text{ dB} &= L_{dBv} + 20\log(GRI) + 68.4\text{ dB} - 18\text{ dB} \\ &= L_{dBv} + 30.4\text{ dB} \quad \text{for 9960} \\ &= L_{dBv} + 29.4\text{ dB} \quad \text{for 8970} \\ &= L_{dBv} + 25.9\text{ dB} \quad \text{for 5930} \\ &= L_{dBv} + 28.4\text{ dB} \quad \text{for 7980 and 7930} \end{aligned}$$

Therefore if the resolution bandwidth for our analyzer is on the same order as the line spacing (5-8 Hz), lines of this strength should be clearly visible above the LORAN spectrum. If instead, the resolution bandwidth is larger than the line spacing, this may not be true. For instance, when using an analog spectrum analyzer with a resolution bandwidth of 1 kHz, we need to calculate the line strength relative to the LORAN power in 1 kHz. This is given by

$$\text{LORAN power in 1 kHz} = \frac{\text{LORAN power in single line x 1 kHz}}{\text{Line spacing in Hz}}$$

For 9960 this difference corresponds to 7 dB, and the interfering line may be only marginally detectable. For wider bandwidths, it probably could not be detected. When listening to the audio output of a SSB receiver with a few kHz bandwidth, a line of this strength would be clearly audible.

Detecting Interference In the Presence of Strong Local LORAN Stations

When tracking the TOA of distant LORAN stations in the presence of strong local stations, significant interfering lines within the LORAN band can be buried in the spectrum of that local station. For example, in New London, CT, signal strengths for stations at Dana and Caribou are at -36 dB and -24 dB relative to Nantucket, respectively. This implies that interfering lines of sufficient strength to interfere with Dana and Caribou could be undetectable because of the local LORAN station. Now using instrumentation with resolution bandwidths of 100 Hz or more will not work to detect the interfering lines. To illustrate this, Figure 5 compares resolution bandwidths of 192 Hz (Figure 5a) and 6 Hz (Figure 5b) when trying to examine a power line carrier (PLC) spectral line at 109.1kHz. In Figure 5a the PLC at 109.1 kHz is below the LORAN spectrum and is undetectable. In Figure 5b the LORAN spectrum is 10 log(192/6) = 15 dB lower, and the109.1 kHz line is easily detectable. Now we consider other techniques to improve detection of interfering lines in the presence of strong local stations.

In areas where only one rate is received, it is possible to trigger and look at data in the "quiet" part of that single GRI in order to improve interference detection. Unfortunately, most stations are dual-rated, and the more typical situation is that we receive interference on two rates from a local station. This is exactly our case in New London, where we have a strong local dual rated station (Nantucket) located approximately 100 miles away. Here the technique of triggering in the quiet part of a single GRI improves detection by only 3-4 dB, so we propose a simple solution whereby we take data only during the quiet periods of both 9960 and 5930 GRI's. To accomplish this, we generate timing waveforms, periodic at one GRI (for each GRI), with a 20% duty cycle. These waveforms are slewed so that the leading edge of the pulse occurs at the beginning of a quiet period, whose duration is at least the pulse width plus the data vector length. For example, for 9960, Dana is very weak and the last significant signal is Carolina Beach with a TD of 44 msec. This implies that there is 48 msec of quiet between Carolina Beach and Seneca. For 5930, Cape Race and Fox Harbor are weak, and there is 41 msec of quiet after the last pulse of Nantucket. This means we are assured that any time both waveforms are high, there will be at least 28 msec of quiet in both rates to collect data. (The number 28 msec comes from the minimum of 48-20 and 41-12, where 20 msec represents a 20% duty cycle on 9960 and 12 msec represents a 20% duty cycle on 5930.) The logical AND of the two waveforms is used to trigger the data collection as shown in Figure 6. For our application we use a 16 msec data vector length, multiplied by a Hanning window, for a resolution bandwidth of 96 Hz.

Figure 7 compares results of different methods for detecting low level power line carrier (PLC) interference. The top curve shows the result of continuous triggering, the middle curve shows a 4 dB improvement by triggering in the quiet part of 5930, while the bottom curve shows the increase of 17 dB in sensitivity by using our circuit to trigger in the quiet part of both 9960 and 5930. The remaining LORAN signals (Carolina Beach on 7980 and Seneca on 8970) could be eliminated with additional logic hardware. We should note that this represents 3-6 dB more sensitivity than that achievable if we could employ resolution bandwidths of comparable size to spectral line spacing. Additionally, triggering in quiet periods allows us to search wider portions of the spectrum more quickly (because of larger resolution bandwidths), but this is achieved at the cost of additional hardware and set-up time. In this location (New London, CT), triggering in the quiet part of only one GRI is counterproductive. Because the data vector can be no longer than the quiet part of the GRI, resolution bandwidths narrower than 8-20 times LORAN line spacings are not achievable, and the 3-4 dB increase in sensitivity relative to continuous triggering is more than offset by the increased resolution bandwidth due to the limited data vector length.

If looking only for synchronous or near synchronous interference, another possibility is to trigger in a quiet part of the GRI and to average in time. Effectively this implements a comb filter with passbands centered at the LORAN spectral lines, with widths of 1/(averaging time). The resulting spectrum contains the synchronous cross rate lines at multiples of 5 kHz for co-prime rates. For rates not co-prime, there are other lines as well. For example, for 9960 and 8970, there is synchronous interference lines at multiples of 1666 2/3 Hz. For a more detailed description of these measurement techniques, we refer the interested reader to [1].

Synchronous/Near-Synchronous/Non-Synchronous Interference: Obtaining Additional Information

Once a line has been detected, there are a number of methods for determining its relative proximity to a LORAN harmonic, for determining the interference class as synchronous/near-synchronous/non-synchronous, or for learning just a bit more about the interfering line. These techniques include:

1. Isolate the line using a narrowband bandpass filter, trigger an oscilloscope at the Phase Code Interval, and watch for drift in the sinusoid. This can be accomplished with several types of hardware. For example:

   a. The restored output of an HP 310 Wave Analyzer-

   b. A general purpose, high Q, variable bandpass amplifier (EG&G Model 189)-

   c. The CW or SSB output of a receiver, when the mixing frequency is an integer multiple of 5 kHz, and all local oscillators are referenced to a single highly accurate oscillator- Now a difference frequency will be observed, whose phase (not zero crossing in time) will drift at the same rate as the original line.

2. Measure its frequency directly. Generally speaking it takes 1/(Frequency Resolution in Hz) seconds to measure frequency. For example, to measure to the nearest mHz takes 1000 seconds. If using a quartz oscillator as a reference, we may also need to use the 100 kHz LORAN for calibration.

3. Notch out the line and see if the problem is corrected. This method can be time consuming. Also, it does not automatically follow that if we observe a TOA offset after notching out an interfering line, the line was synchronous. The notch will have introduced a phase shift at 100 kHz, and a TOA offset is expected, regardless of interference.

4. Custom software for monitor grade receiver. A customized version of the Austron 5000 software, developed for internal use by engineers at the Coast Guard Electronics Engineering Center (EECEN), performs odd/even strobe dropping to help engineers classify whether an interfering line occurs at an "even" or "odd" harmonic. In this method, only every other pulse is processed. When using only the even pulses, the phase codes of GRI B are opposite those of GRI A, and the receiver response to synchronous or near synchronous interference at even multiples of 1/PCI goes to zero. Similarly, when using only the odd pulses, the phase codes of GRI B are the same as those of GRI A, and the response of the receiver to synchronous or near synchronous interference at odd multiples of 1/PCI goes to zero. For examle, if use of even strobe dropping stops a TOA "sinewaving" problem, there is reason to suspect that a near-synchronous line has been identified, and it occurs at an even multiple of 1/PCI.

Sources of Interference

Power Line Carriers: These are low power signals that can exist within the LORAN band. Because of mid-continent expansion and expanded aviation use, these sources of interference are getting much more attention. Figure 8 shows the spectrum as measured using an FFT analyzer, radiated from power lines near the Coast Guard Academy in New London, CT. Figure 9 shows these amplitudes as compared to LORAN signal strength, as a function of distance from the suspected radiating lines. Note that the lines fall off as $1/r^2$ as we move away from the suspected power line, with the exception of the single line at 108.6 kHz. Clearly this spectral line is being radiated from another source. We have observed that power line carriers are quartz oscillator based, and could possibly drift over LORAN spectral lines. Since their amplitudes go as 1/(distance squared) they are only a problem near (< 1 mile) power lines. Because so many lines exist, however, notching is not a feasible alternative.

Local CRT's. One of the problems of recent technology is the increase in raster scan displays on computers and test instruments. Frequently harmonics of the horizontal scan frequency fall within the LORAN band. For example, the HP35660A Dynamic Signal Analyzer and the HP54501A Digital Oscilloscope have horizontal scan frequencies of 25.16 kHz and 24.09 kHz respectively. These frequencies are quartz based and quite stable. If we suspect that a raster scan display is a problem, methods to isolate the culprit include turning off each of the suspected devices one by one, and listening to the audio output of a receiver, or using an EMI probe and looking for highly localized fields.

Naval Communications Stations. These are typically frequency shift keyed, 50 baud, with a 50 Hz shift in frequency (as shown in Figure 10 for the 77.15 kHz Driver signal). In some cases, each time the station transmits one of its FSK frequencies, it is phase coherent with

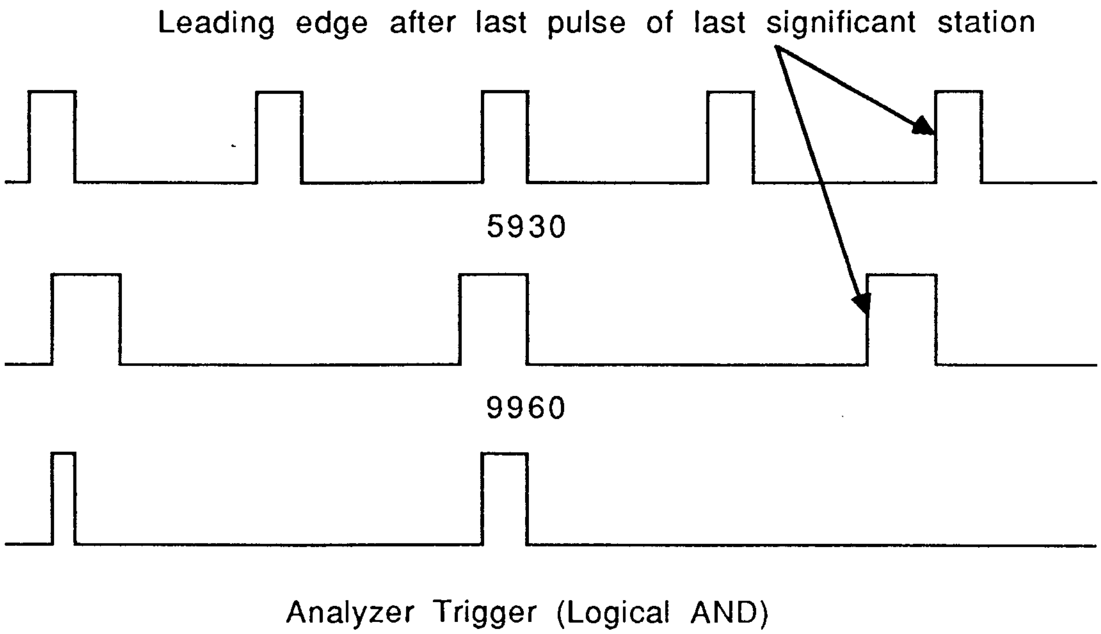

Figure 6. Timing diagram of circuit to trigger in quiet of both GRI's.

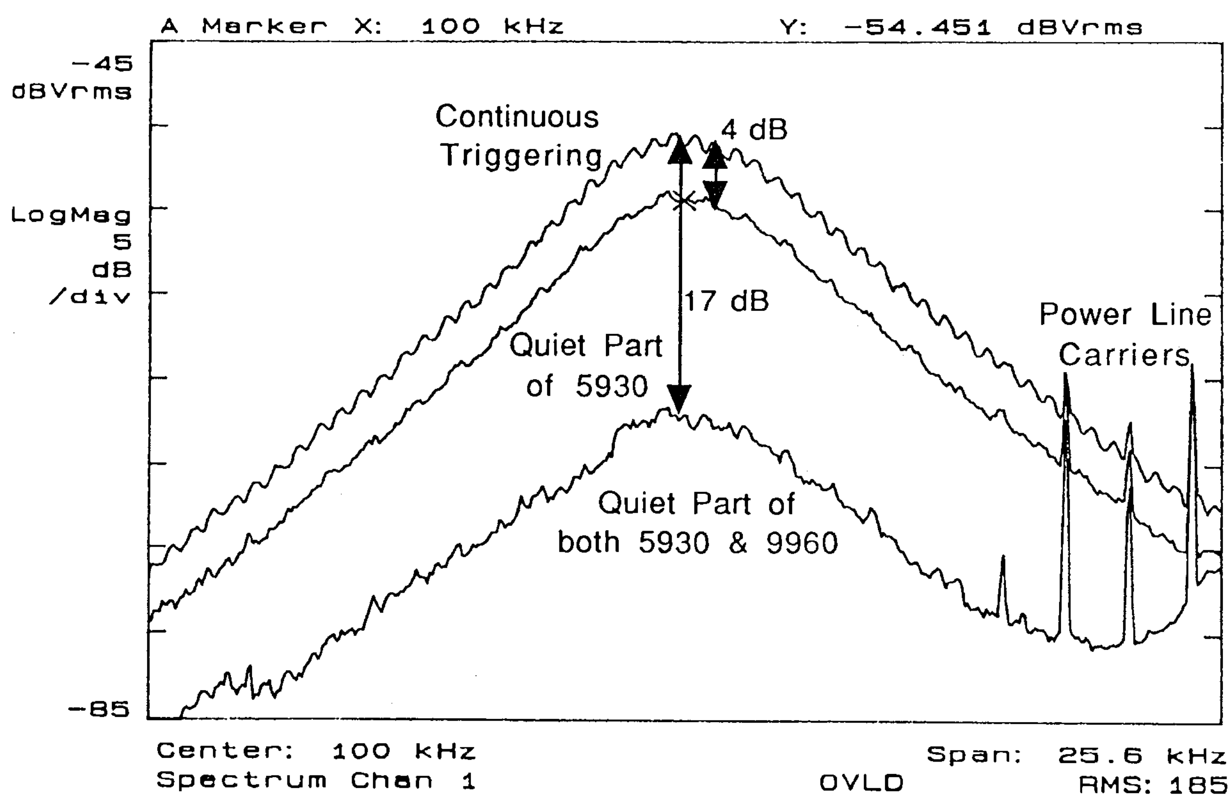

Figure 7. Effect of triggering in quiet part of GRI

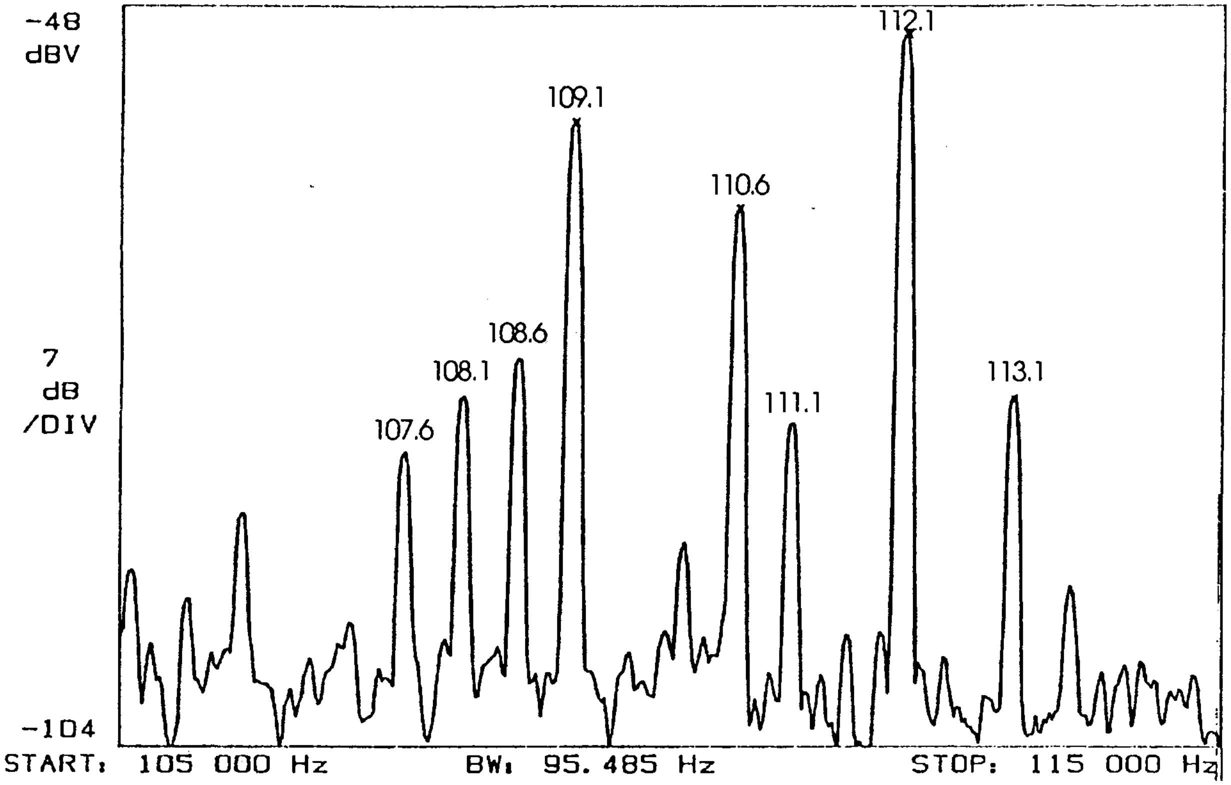

Figure 8. Typical Spectrum of Power Line Carriers.

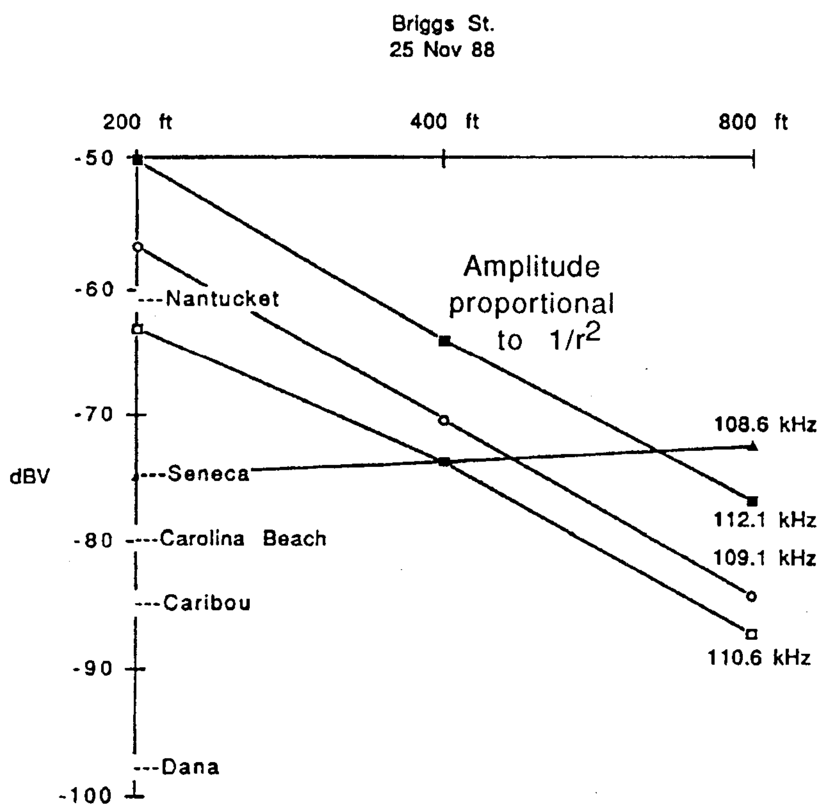

Figure 9. Power Line Carrier Strength vs. Distance and Relative to LORAN Signal Strength.

previous transmissions at that frequency. This implies that two discrete lines in the frequency spectrum exist (as shown in the phase vs time plot of the 77.15 kHz Driver signal, Figure 10). In other cases (as in the VLF station at Cutler, ME), the signal is 200 baud with only 100 Hz of frequency shift, resulting in no pure spectral lines, because the signal may return 180° out of phase. In general, we can model the process as the superposition of two AM signal generators with carriers at the two instantaneous frequencies, with a modulating signal of 'ones' and 'zeros'. Therefore the average amplitude of each of these carriers is one half that of the signal amplitude or one fourth of the total power. The signal can be divided into parts and these parts are treated as either deterministic or random noise, when considering the effects on TOA.

Analysis of Navy FSK Interference

As described earlier, we consider the FSK interference as the sum of two processes. The two "spikes" are treated as deterministic sinusoids, each at a level of -6 dB relative to the total signal, and the analysis of effect on TOA (assuming the interfering "spike" is within the servo bandwidth of the receiver) can be considered exactly as before. Since 50 Hz equals 100 GRI times the line spacing, (7.98 lines for 7980, etc.) if one spike is near synchronous, typically the other is as well. The random portion of the power, which represents the remaining one half of the signal, is treated as an addition of random noise at -3 dB relative to the total signal. This analysis is similar, but the final result is dependent on receiver time constant. If the noise plus random interference power is σ_n^2 and the rms signal power at the sampling point is $(A_{Lor})^2/2$, the signal to noise (plus interference) ratio (SNR) is given by

$$SNR = \frac{(A_{Lor})^2}{2\sigma_n^2} \tag{15}$$

From Equation (5), movement of a single zero crossing is

$$\Delta t \cong \frac{10\,A_{Int}}{2\pi A_{Lor}}\ \mu sec, \text{ and} \tag{5}$$

since the LORAN signal is deterministic, the standard deviation of a single zero crossing is

$$\sigma_t \cong \frac{10\,\sigma_n}{2\pi A_{Lor}} = \frac{1.125}{\sqrt{SNR}}\ \mu sec. \tag{16}$$

If we use 8 pulses per GRI and a time constant of N GRI, the standard deviation of our TOA estimate is reduced by

$$\sqrt{\text{number of pulses averaged}} = \sqrt{8N}$$

or

$$\sigma_t = \frac{0.4}{\sqrt{(N)(SNR)}}\ \mu sec\ . \tag{17}$$

This result is summarized in Figure 11. Assuming the independence of the noise in master and secondary, the standard deviation of a TD is given by

$$\sigma_{TD} = \sqrt{\sigma_m^2 + \sigma_s^2} \tag{18}$$

Referring to Figure 5a, we can now estimate the maximum possible effect due to the interference at 77.15 kHz. We recognize that the LORAN peak at 100 kHz (in 192 Hz noise equivalent bandwidth) is approximately 0 dB relative to the peak at 77.15 kHz, and that Nantucket on 9960 is -4 dB relative to total LORAN. The individual Nantucket 9960 line at 100 kHz is therefore

$$-4\ dBv - 10\log(192/5.02) = -19.8\ dB$$

relative to the line at 77.15 kHz. Using Equation (14) derived earlier, the LORAN signal strength is

$$\begin{aligned} S_{30} &= L_{dBv} + 20\log(GRI) + 68.4\ dB \\ &= -19.8\ dB - 20\ dB + 68.4\ dB \\ &= 28.6\ dB \text{ (relative to the total signal at 77.15 kHz),} \end{aligned}$$

or 31.6 dB relative to the random part of the 77.15 kHz signal and 34.6 dB relative to the individual spikes in the 77.15 kHz signal. Therefore, even ignoring any possible attenuation of 77.15 kHz in the receiver front end, and even if we assume we have a fast time constant receiver, neither the random nor the deterministic parts would cause any significant problems in the tracking of Nantucket. For Caribou at -24 dB relative to Nantucket, there is potential for variations of up to 120 ns (zero to peak) due to the deterministic part, but the random part will not significantly affect the overall signal to noise ratio.

It should be noted that the spikes in the fine spectrum of the Naval FSK signals are far from infinitesimally narrow. In [1] the 88 kHz signal from Annapolis was seen to vary over tenths of a Hz, as does the 134.9 kHz Annapolis signal. The 77.15 kHz signal jumps 0.5 Hz higher momentarily at 30 sec intervals and is not a pure tone exclusive of these jumps. Therefore, while the interference could be considered and analyzed as near synchronous, it would not produce sinusoidal TOA traces.

LF-HF High Resolution Spectral Analysis

Nominally the Dynamic Signal Analyzers we use (HP3561A and HP35660A) are limited in frequency to 0-115 kHz. To extend this frequency range we use a VLF-HF receiver (in CW mode) to frequency translate high frequency signals to frequencies within the analyzer's range. (See Figure 12.) The system was originally developed to measure near field LORAN HF interference to Air Force OTH-B radar at Tok, AK, but it is useful as a precise analysis tool over the entire LF, MF and HF bands. While this concept is possible with virtually any synthesized HF receiver, the following receiver features make the approach much more feasible:

a. All carriers referenced to a single internal or external reference-
b. Ability to disable AGC- Precise control and knowledge of gain-
c. Selection of IF bandwidths- (We use six from 300 Hz to 16 kHz.)
d. Externally controllable via IEEE-488 or serial port-
e. Has highly linear, low noise analog mixers, amplifiers and filters-

The system will work without the cesium beam frequency standard, but averaging in time would not be possible due to the loss of coherent phase information. Recently spectrum analyzers that combine analog and digital technology have become available, (HP3588A for example), that have frequency resolution to within a factor of five of that of the low frequency Dynamic Signal Analyzers, and that have an upper frequency limit in the VHF. However, we find that in most cases we need phase measurements, or we require the ability to trigger and average in time, so we find our system to be much more versatile than recently introduced spectrum analyzers for purposes of interference measurement.

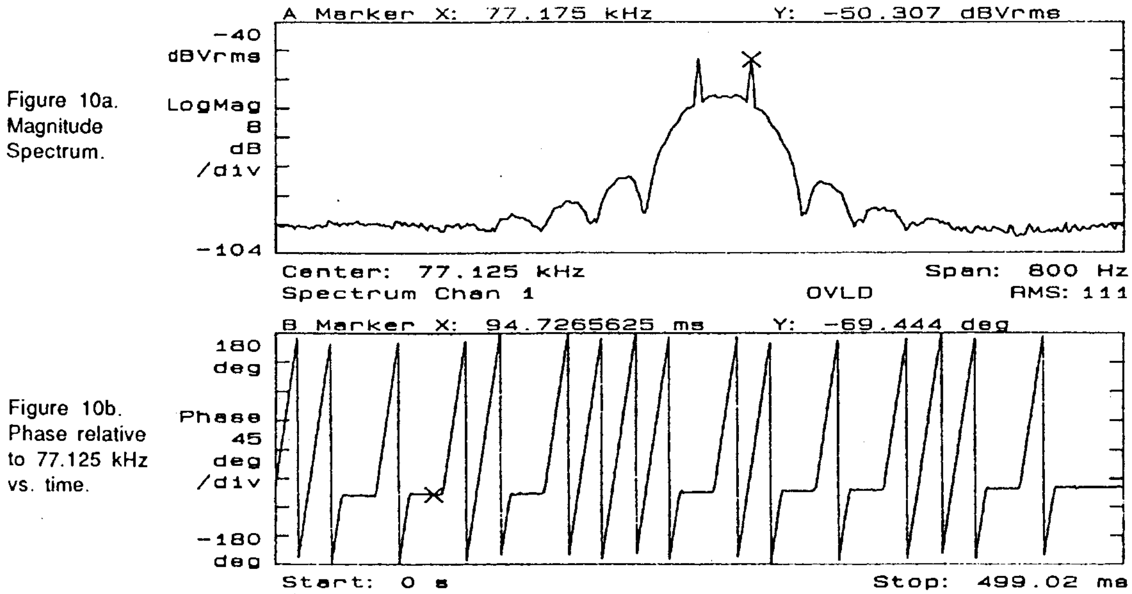

Figure 10. Frequency Shift Keyed (FSK) Signal from Driver, VA.

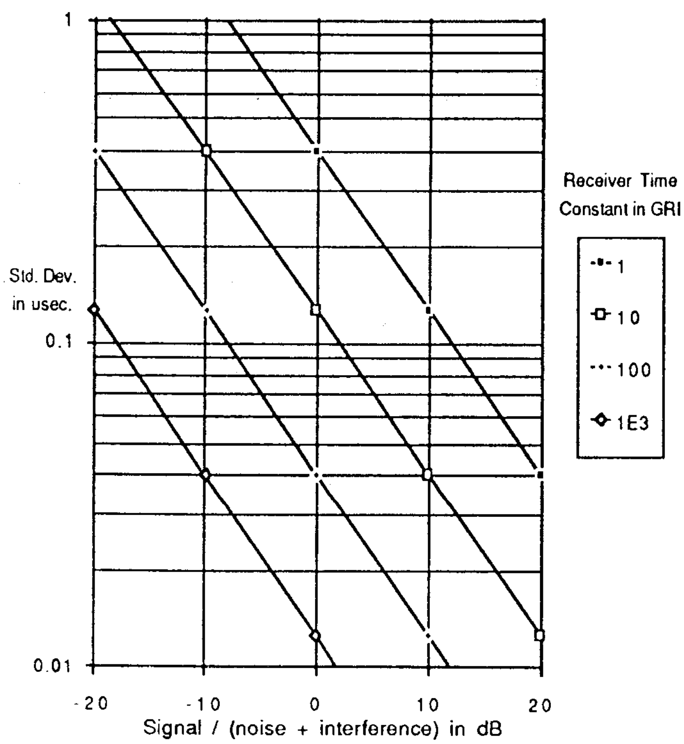

Figure 11. Phase noise vs. signal / (noise + interference).

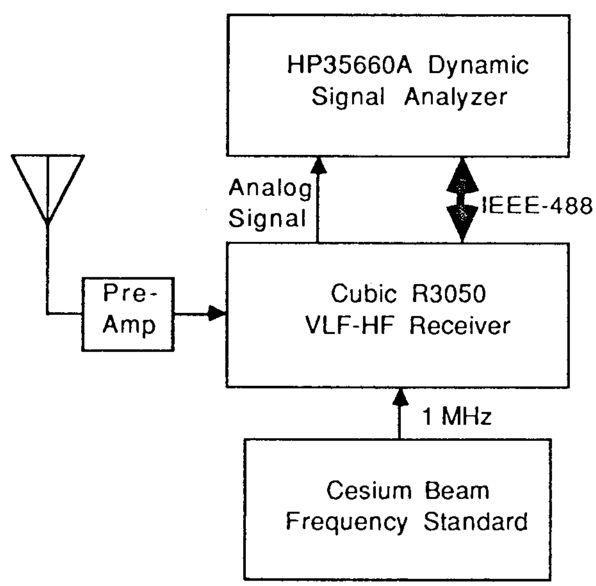

Figure 12. Spectral Analysis System for 0.01-30 MHz.

Summary

Our contributions in this paper are as follows:

1) We derived relationships that relate signal amplitude and individual spectral line strength.
2) We derived relationships that relate shift in TOA to interfering sinusoidal amplitude and LORAN envelope at the sampling point.
3) We proposed some "smart methods" for LORAN interference measurements, and we showed the effects of:

   a) Instrumentation resolution bandwidth-
   b) Triggering in quiet part of one GRI-
   c) Triggering in quiet part of two GRI-
   d) Triggering in quiet part of GRI's and average in time [1]

4) We presented a summary of methods commonly used to gain more information about synchronous/near-synchronous/non-synchronous interference.
5) We outlined some common sources of narrowband interference.
6) We developed the theory to analyze the effect on TOA from Navy FSK transmitters-
7) We introduced a system that we use to translate LF, MF, and HF signals into the frequency range of existing Dynamic Signal Analyzers, so we can take advantage of current FFT technology (high frequency resolution, ability to average in time, etc.).

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Biographies

CAPT Benjamin B. Peterson received the BS degree from the U. S. Coast Guard Academy in 1969 and the MS and Ph.D. degrees in Electrical Engineering from Yale University in 1978 and 1983 respectively. He has been a member of the Coast Guard Academy faculty since 1973. He is presently Chief of the Electrical Engineering Section within the Department of Engineering, and is the Director for the Center for Advanced Studies at the Academy. He is presently co-authoring with LCDR Richard Hartnett a text entitled Analog and Digital Filter Design, to be published by Saunders College Publishing division of Holt, Rinehart and Winston. His research interests include system identification and control, digital signal processing, and electronic navigation systems.

LCDR Richard J. Hartnett received the BSEE degree from the U. S. Coast Guard Academy in 1977, the MSEE degree from Purdue University in 1980, and is currently completing Ph.D. research at the University of Rhode Island. He holds professional engineering registration in the State of Connecticut. LCDR Hartnett has contributed several WGA papers over the last six years, and received WGA's "Best Paper Award for 1984-1985" for his paper (submitted with LCDR Ron Hewitt) entitled "The U.S. Coast Guard's Loran-C Remote Operating System," Proceedings of the 13th Annual WGA Tech. Symposium) . LCDR Hartnett has been on the Coast Guard Academy faculty since 1985, and was selected for the permanent commisioned teaching staff (PCTS) in 1987. He is presently co-authoring with CAPT Ben Peterson a text entitled Analog and Digital Filter Design, to be published by Saunders College Publishing division of Holt, Rinehart and Winston. His general research interest include digital filtering, digital signal processing, communications sytems, and electronic navigation systems.

Interference Detection and Suppression Methods for Loran-C Receivers

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ABSTRACT

Reliability is a parameter which becomes more and more important in today's general navigation systems like Loran-C: positioning data obtained from such systems is used increasingly in safety-critical applications like air transport or transport of dangerous cargo. Therefore, methods have to be found to increase reliable operation of general navigation systems.

In the case of Loran-C, several threats to reliable operation do exist. One of those in the Northern and Western European environment is the presence of a large number of Continuous Wave Interference (CWI) signals. The problems caused by these signals to proper Loran-C operation, can be solved in several ways. This paper will deal with solutions to be implemented in Loran-C receivers.

1. INTRODUCTION

Much has been written about Carrier Wave Interference to Loran-C [1], [6], [7], [9]. In these papers, the different types of CWI interference have been discussed and their effects on Loran-C operation are shown. The most important issue is the distinction between a-synchronous, near-synchronous and synchronous CWI signals (discussed in depth in [1]), which is determined by the bandwidth of the tracking loops used inside a Loran-C receiver.

The deterioration that can be expected from CWI signals, has also been analyzed in several papers [1], [9]. According to these publications it is quite clear that especially synchronous and near-synchronous signals can have a disastrous influence on the reliability of Loran-C operation. Once this conclusion has been drawn, two questions have to be asked:

1. How many harmful (near-)synchronous signals can be expected in the operational area of a Loran-C chain? The answer to this question is important in determining what counter-measures are necessary.
2. What counter-measures are needed to combat all harmful CWI signals? The answer to this question of course depends on the severity of the problem. Basically, two methods for dealing with CWI can be distinguished:

i. The system approach. In this method for dealing with CWI, the GRI of a Loran-C chain is selected for minimum (near-)synchronous interference. A suitable algorithm is described in [6].

ii. Proper receiver design. In this method, a receiver is fitted with hard- and software to automatically detect and filter those signals harmful to Loran-C operation. A first description of a suitable receiver architecture is found in [7].

In the following paragraphs of this paper, several possibilities for the implementation of automatic CWI filtering in Loran-C receivers will be presented.

2. CWI - DEFINING THE PROBLEM

The distinction between synchronous, near-synchronous and a-synchronous signals [1] is caused by the sampling pattern employed by Loran-C receivers. In this pattern one sample per burst is taken, and the sample is multiplied with the phase code (+1 or -1). The Master sampling pattern is shown in fig. 1. The lowest repetition rate is $1/(2\,\mathrm{GRI})$.

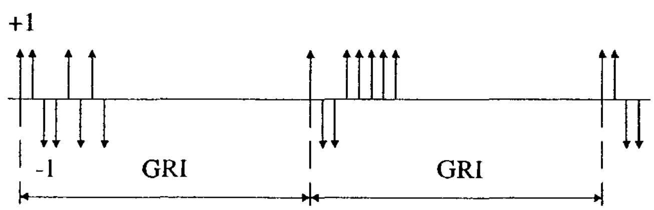

Fig. 1. Sampling pattern for Master station.

By fourier transforming the sampling pattern for Master or Secondary stations, it is found that a Loran-C receiver folds back all antenna signals into a small frequency band between $-1/(4\,\mathrm{GRI})$ Hz and $+1/(4\,\mathrm{GRI})$ Hz. This is illustrated in fig. 2.

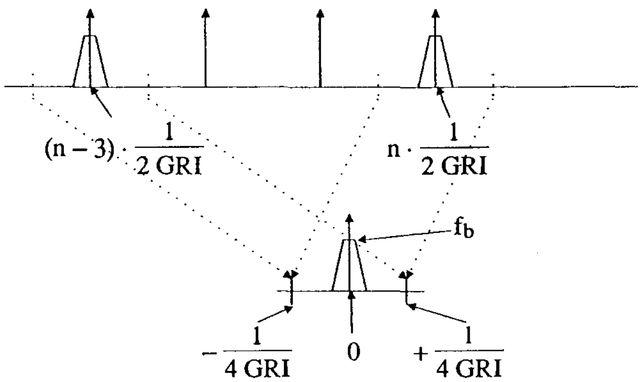

Fig. 2. Spectrum fold-back due to sampling pattern.

In principle, all signals from 0 to infinity are folded back into the small band between $-1/(4\,\mathrm{GRI})$ Hz and $+1/(4\,\mathrm{GRI})$ Hz. The bandpass filter present in the front-end of Loran-C receivers, is the component limiting the range of this fold-back action. The mathematics behind these principles of Loran-C receiver operation, are described in detail in [4] and [6].

After all incoming signals are folded back in a Loran-C receiver, they are filtered in the loops present in Loran-C receivers:

- The cycle identification loop determines the proper cycle to be used for phase measurements. It usually has a bandwidth of less than 0.01Hz.
- The phase tracking loop is used to get phase measurement data. Its bandwidth depends on the application of the receiver: typical values are 0.01 Hz to 0.1 Hz.

These loops in fact implement low-pass filters; stylized low-pass transfer functions are therefore shown too in fig. 2.

The tracking loop bandwidths are useful in getting an estimate of the risk that a CWI signal is (near-)synchronous, assuming randomly distributed CWI frequencies (as is the case with a transmitter with a drifting oscillator). GRIs can range from 40 to 100 ms; this means that the band from $-1/(4\,\mathrm{GRI})$ Hz to $+1/(4\,\mathrm{GRI})$ Hz is 5 to 12.5 Hz wide. With a tracking loop 0.01 Hz wide, the risk of a signal becoming (near-) synchronous is $\frac{2\cdot 0.01\text{ Hz}}{5\text{ Hz}} = 0.4\ \%$ worst-case.

In Northern and Western Europe, many CWI signals are present [1], [3], [6]. All signals between 50 kHz and 150 kHz are considered particularly dangerous to Loran-C operation. Measurements described in [3] have found a total of 68 CWI signals, of which 43 probably are not controlled by atomic standards; this means that their exact frequency can be considered random due to oscillator drift. Another source [6] reports several hundred possible CWI signals found in the official ITU list of transmissions [5], without separating stable signals from DECCA or time reference stations and other, less stable signals.

If 43 CWI signals exist with assumed random frequency, the chance that none of these signals is (near-) synchronous is $(1-0.004)^{43} \approx 84\ \%$. So, if no counter-measures are taken (and realizing that almost all near-synchronous and synchronous signals have disastrous effects), the reliability of Loran-C receiver operation in Western and Northern Europe is limited to 84 %! Clearly, this is not acceptable.

As stated in the introduction, this paper will deal with receiver designs optimized for the detection and suppression of CWI signals. In [7] a detailed justification can be found for using special receiver architectures in areas with many CWI signals, as well as reasons why today's traditional receiver architectures do not perform very well in such areas.

First a description of bandpass filters is given, which can be used to remove part of the CWI spectrum. It will be shown that such filters alone are not sufficient to remove all CWI. Therefore, attention will be paid too to control of dedicated notch filters, which are used to remove specific harmful CWI signals.

3. BANDPASS FILTERS - A FIRST ATTEMPT TO REMOVE CWI

At first sight the CWI problem could be solved easily: all CWI signals are found either below 90 kHz or above 110 kHz, so a bandpass filter from 90 to 110 kHz with very steep slopes should be sufficient to filter out all interference. The European CWI spectrum (demonstrating the location of CWI signals) is shown in fig. 3, a suitable bandpass filter in fig. 4.

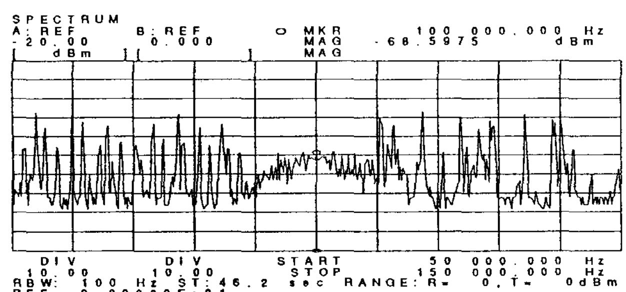

Fig. 3. European CWI spectrum from 50 to 150 kHz.

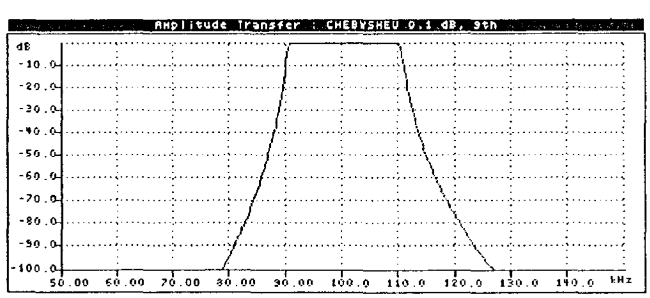

Fig. 4. A filter with steep slopes used for removing CWI.

The problem arising with this approach is a deterioration of the immunity to skywaves. This can be explained by looking at a Loran-C pulse filtered with the filter of fig. 4.

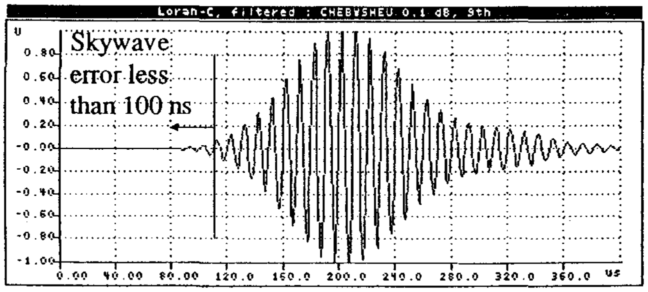

Fig. 5. Loran-C pulse filtered with the filter of fig. 4.

As fig. 5 shows, the rising edge of the Loran-C pulse is delayed and slowed down considerably. This means that the signal early in the pulse (where skywaves are not yet present) is very small and therefore the Signal-to-Noise Ratio is very bad.

The filter shown in fig. 4 does not have a linear phase transfer function, as shown in fig. 6 (this picture, as well as all other analog bandpass filter pictures, was generated with the program described in [8]). Non-linearities in the phase transfer function of bandpass filters are one reason for the envelope distortions in fig. 5.

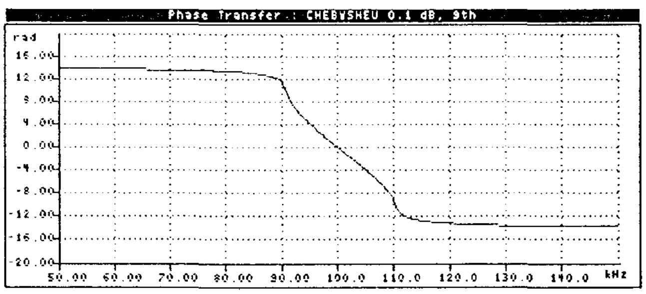

Fig. 6. Phase transfer function of the filter in fig. 4.

Non-linear phase transfer functions are found with all analog filters. Because of this property of analog filters, receiver designers are faced with a fundamental choice:

1. An analog filter with relatively little phase distortion can be used. Such a filter has a very gentle amplitude transfer function. An extreme example of such a filter is shown in

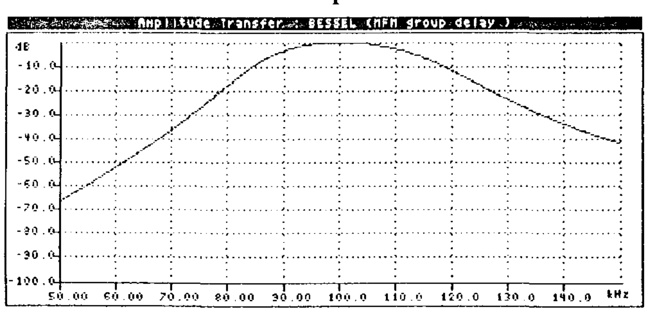

Fig. 7. Example of a filter with gentle slopes.

figs. 8 and 7 and and the corresponding filtered Loran-C pulse is shown in fig. 9.

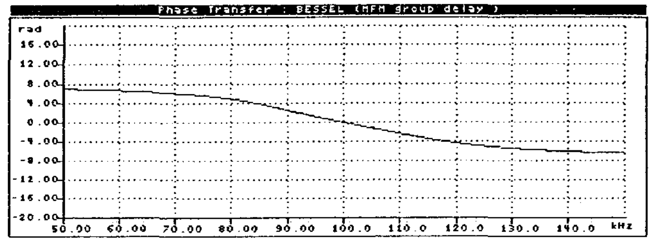

Fig. 8. Phase transfer function of the filter of fig. 7.

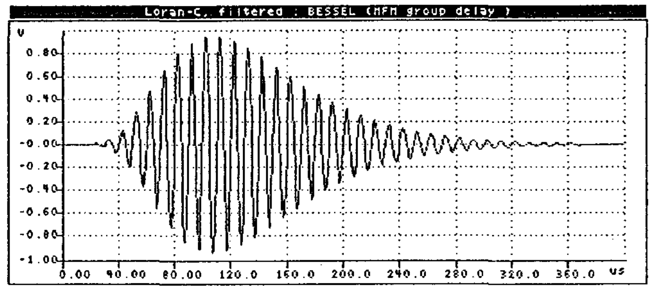

Fig. 9. Loran-C pulse filtered with the filter of fig. 7.

With a filter as shown in fig. 7, CWI signals are not removed sufficiently to prevent problems to Loran-C operation. Therefore, notch filters have to be used in addition to the filter of fig. 7 to remove harmful CWI signals. Note, however, that the design of such a filter system always includes a difficult trade-off between skywave-rejection and CWI rejection. This difficult trade-off is described in more detail in [2].

2. A filter with a linear phase transfer function can be used. Such a filter will not distort the pulse envelope, as long as it has a constant amplitude transfer in the Loran-C band from 90 to 110 kHz. Using such filters will therefore lead to optimum skywave-performance, independent of the CWI rejection obtained. Linear phase filters can be made with digital signal processing techniques only, so this means a complete redesign of receiver architectures. A suitable architecture is shown in fig. 10.

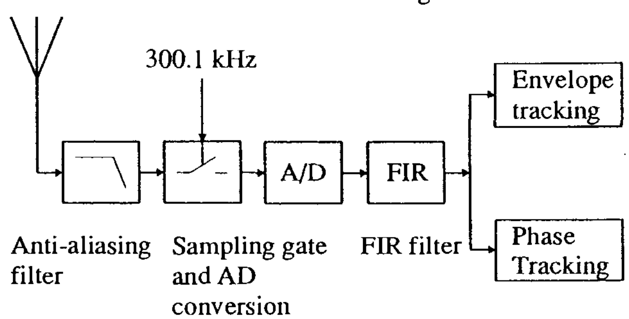

Fig. 10. Receiver with a FIR bandpass filter.

In order to be able to use digital signal processing, the incoming antenna signal must be A/D converted first. Then a Finite Impulse Response (FIR) filter, which can be designed to have a linear phase transfer function, must be used to rid the Loran-C signal of all CWI. Finally the filtered signal enters envelope- and phase-tracking loops. Note that the design of simple phase tracking loops is much easier if the sampling frequency for the tracking bandpass filter is not a multiple of the Loran-C carrier. Therefore, a sampling frequency of 300.1 kHz is chosen in fig. 10. This choice, however, is still under review.

The first option of using an analog bandpass filter and a set of notches is the traditional method. It has been proven to work, but suffers from problems with flexibility: if the receiver is to be used in a different area, the notch filter settings must be different too. In [7] the problems with this method are described in detail.

The second option of using linear-phase FIR filters to prevent pulse distortion, looks very promising. However, one important constraint is the amount of processing power needed for a filter with steep slopes. The principles and implementation techniques of FIR filters will not be described here; the interested used is referred to [11] for more information about such filters. Here only an indication of the relation between filter properties and necessary processing power given.

In order to get an idea of the processing power needed, it is assumed that the FIR filter is implemented on a general purpose signal processor. Such a processor will minimally need (N + 2) instructions per incoming sample for the filter operation, with N being the filter order. With a sampling frequency f_S in MHz, the signal processor has to have a performance in MIPS (Mega Instructions Per Second) of:

$$\mathrm{MIPS} = f_S \cdot (N+2) \qquad 3.1$$

With a processor with given performance, the maximum obtainable filter order N is:

$$N = \frac{\mathrm{MIPS}}{f_S} - 2 \qquad 3.2$$

A state-of-the-art Texas Instruments DSP320C30 signal processor has a performance of 16.7 MIPS. With a sampling frequency of 300 kHz as is used in fig. 10, the maximum filter order N is then 53. It is assumed that with such a filter all unwanted signals should be suppressed more than 90 dB. Fig. 11 shows the amplitude transfer function of a filter with such properties.

Fig. 11 shows that a rejection of 90 dB is obtained below 60 kHz and above 140 kHz. However, in the frequency bands between 60 kHz to 90 kHz and 110 kHz to 140 kHz CWI signals are insufficiently suppressed. Notch filters are still needed to remove harmful CWI signals in these frequency bands. Note, too, that in the example of fig. 11 the bandpass filter uses up all performance available from the signal processor. In practical designs, the signal processor will be used for other tasks too, so the maximum possible filter order will be lower than 53. Such an implementation severely limits the usefulness of FIR filters in Loran-C receivers.

Two approaches can be used to improve the performance of FIR bandpass filters in Loran-C receivers:

1. The Loran-C spectrum, though located around its carrier of 100 kHz, is only 20 kHz wide. Sampling theory states that with proper processing techniques, a sampling frequency of 40 kHz (twice the information bandwidth) is sufficient to reconstruct the Loran-C signal. In a practical design the information bandwidth will be larger: this bandwidth is equal to the -90 dB bandwidth of the filter. Fig. 12 shows the transfer function of a filter with order 128; this filter has a -90 dB bandwidth of 45 kHz. According to formula 3.1, this filter can still be implemented

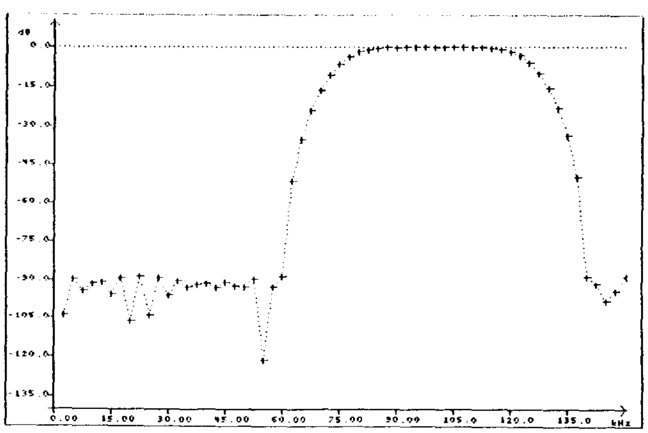

Fig. 11. A FIR bandpass filter with order 53.

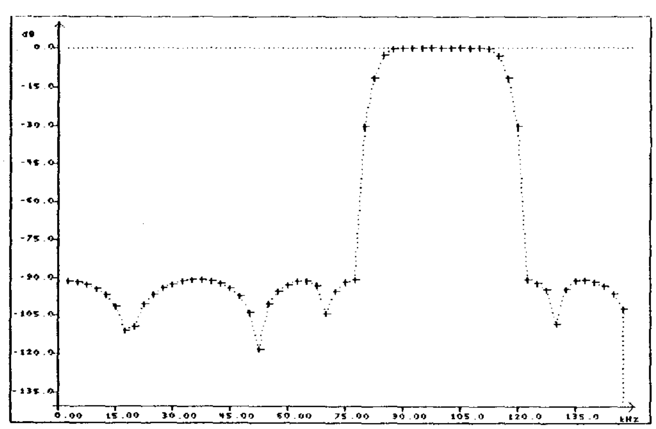

Fig. 12. FIR filter useful for bandpass sampling.

on a TMS320C30 with a sampling frequency of 90 kHz and processing power to spare.

Note that even with the filter of fig. 12, notches are still needed in the spectrum bands from 77.5 to 90 kHz and from 122.5 to 110 kHz. A receiver architecture incorporating digital notches, is shown in fig. 13.

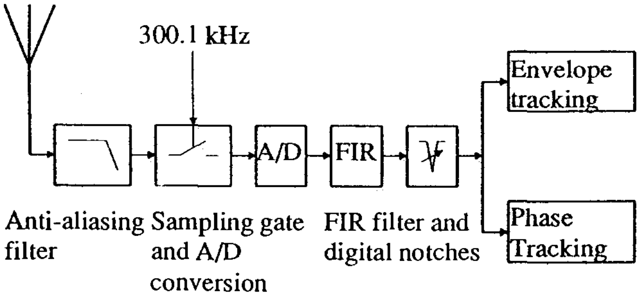

Fig. 13. Receiver with FIR filter and digital notches.

2. A second possibility is to use special hardware to increase the amount of instructions available per sample interval. If such hardware is available, then the filter order N can be increased drastically. Two limits do exist in such a case:

   - The filter order N is still limited by formula 3.2. With a performance of e.g. 400 MIPS, a maximum filter order of 1331 is found.
   - Increasing the steepness of the filter slopes means an increase in the required calculation accuracy. With very steep slopes this leads to wide data bus structures in the filter hardware.

Receiver designer will have to choose between three possibilities:

1. Use a straightforward FIR filter as shown in fig. 11 with a large number of notches. Implement the filters on a general-purpose signal processor.
2. Use more complicated algorithms like e.g. bandpass sampling to reduce the sampling frequency and increase bandpass filter performance. Implement the filter system on a general-purpose signal processor.
3. Use special hardware to implement a FIR filter with very steep slopes.

The available hardware facilities will be a very important criterion:

- For good filter performance with limited processing power, a combination of FIR filter and dedicated notches as shown in fig. 13, is the optimum. Notch filters can be designed as low-order Infinite Impulse Response filters [11] with high notch attenuation and little necessary processing power. Since these filters are used outside the Loran-C band, skywave rejection will not be deteriorated appreciably. Such filters have to be set to the most harmful CWI signals; algorithms to find these signals are described in the next paragraph.
- If no constraints are present regarding the amount of dedicated hardware, a FIR filter with very high order is technically the best solution. It is straightforward: no notch filters with or without automatic control have to be used.

With today's VLSI technology, the choice between these possibilities is not clear-cut. In many cases there will be a continuing need for notch filters. The design of such filters is not covered in the remainder of this article, since much has been written about that subject. Attention will be focused on algorithms which automatically obtain optimum settings for notch filters and which can be implemented in Loran-C receivers. The next paragraph will deal with such algorithms.

4. CWI DETECTION IN LORAN-C RECEIVERS

As shown in the previous paragraph, there is still a need for notch filters to filter out harmful CWI signals. With state-of-the-art digital bandpass filters, the spectrum in which harmful CWI signals can be found, is limited (see fig. 12). Within these limited bands, a technique is needed to detect harmful (mostly synchronous or near-synchronous) signals.

In [7] the principles of detection of harmful CWI signals in Loran-C receivers have been described. In [7] it is assumed that harmful CWI can be found in the spectrum from 50 to 150 kHz. This spectrum has to be analyzed first with digital signal processing techniques (FFT and FFT-derived algorithms). The resolution of this spectrum analysis must be sufficient to distinguish between (near-)synchronous CWI signals and a-synchronous signals. With tracking loop bandwidths of 0.1 Hz or less, this implies a resolution of better than 0.1 Hz.

All signals found with this spectrum analysis are then multiplied with a weighting function, which has a high value around multiples of ½ GRI and low values between multiples of ½ GRI. The spectrum is now searched for those signals with highest amplitudes, and these signals are filtered with notch filters. By using a weighting function, attention is focused mainly on (near-)synchronous signals, while very strong a-synchronous signals (which will cause performance degradation) are also detected and filtered. Fig. 14 show an example of a weighting function.

In [7] a receiver architecture is proposed (see fig. 15) which folds back the spectrum between 50 and 150 kHz to a spectrum between -50 and 50 kHz. This is made possible by taking two samples of the antenna signal 2.5 μs (= 90° at 100

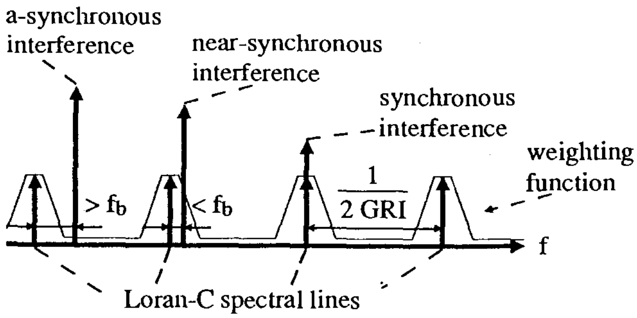

Fig. 14. Example of a weighting function.

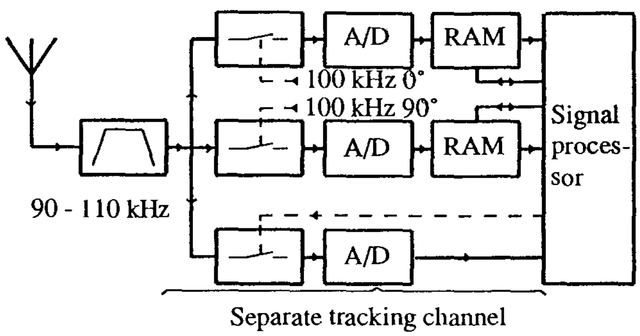

Fig. 15. An architecture useful for spectrum analysis.

kHz) apart. The two samples are then treated as one complex number; this complex number is saved in an array to be used later in a complex FFT.

The receiver architecture of fig. 15 takes a large amount of samples and then calculates the spectrum between 50 and 150 kHz with one complex FFT. The amount of complex samples needed is determined by the resolution and sampling frequency [7]:

$$N = \frac{f_s}{f_r} \qquad 4.1$$

with:

- f_s the sampling frequency;
- f_r the resolution;
- N the amount of samples.

With a sampling frequency of 100 kHz as shown in fig. 15 and a resolution of 0.1 Hz, the amount of samples is 10^6. Each sample contains two values, which must be stored in double-precision floating point format in order to prevent round-off errors in the FFT from ruining the spectrum analysis [7]. Each double-precision floating point value consists of 8 bytes, so the total amount of memory needed is $2 \cdot 8 \cdot 10^6$ = 16 Mb. For Loran-C receivers such a large memory area is clearly not practical. Therefore, the most important problem to be solved is to reduce the amount of samples needed for the spectrum scan from 50 to 150 kHz.

A first reduction in memory size has already been obtained in the previous paragraph. By using a sharp FIR filter, the spectrum containing potentially harmful signals, is reduced considerably (in the example of fig. 12 the spectrum is limited to 77.5 to 122.5 kHz: a reduction of 55 %). With the architecture of fig. 15, this means a total memory size of 7.2 Mb.

For further reductions, two approaches can be used:

1. First a spectrum analysis can be made with a resolution of e.g. 100 Hz. For such an analysis only little memory is needed. Then the frequencies on which peaks are found, are analyzed again with a much finer resolution, <u>but only around the peak detected in the first scan</u>. This implies the use of a zoom-in FFT algorithm as the Chirp-Z transform [10]. Fig. 16 shows a suitable receiver architecture; fig 17 illustrates the proposed zoom-in mechanism.

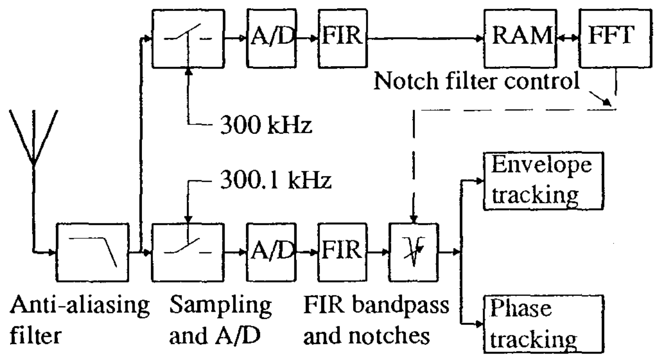

Fig. 16. Receiver architecture for zoom-in FFT.

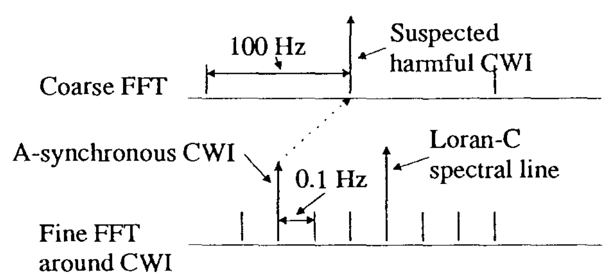

Fig. 17. Zooming in on an area with suspected harmful CWI.

Note that in the architecture of fig. 16, two sampling clocks are used. As stated before, the sampling clock used for tracking should not be a multiple of the Loran-C carrier. However, according to [7] the sampling clock used for FFT, should be locked to the Loran-C carrier, in order to be able to relate the measured CWI spectrum to the Loran-C spectrum.

2. A second possibility to reduce the amount of RAM needed, is found by comparing the operating principles of a spectrum analyzer and the FFT algorithm:
   - A spectrum analyzer does a serial scan of the spectrum to be analyzed. It needs much time to determine the presence of a signal on any particular frequency, but uses no storage to do so. Detection time goes up with decreasing resolution.
   - The FFT algorithm does a parallel scan of the spectrum to be analyzed. It needs little time to determine whether a signal is present on any particular frequency, but uses up storage in order to do so. Storage goes up with decreasing resolution.

   It should therefore be possible to trade in speed for a reduction in data storage. In the case of Loran-C, this means that the spectrum containing harmful CWI is divided into several segments of e.g. 5 kHz wide. Each segment is then analyzed separately with one FFT. This is demonstrated in fig. 18 (with the filter of fig. 12), where the spectrum segments are called FFT 1 to FFT 6. Note that the Loran-C spectrum from 90 to 110 kHz does not have to be analyzed, since it does not contain any CWI signals.

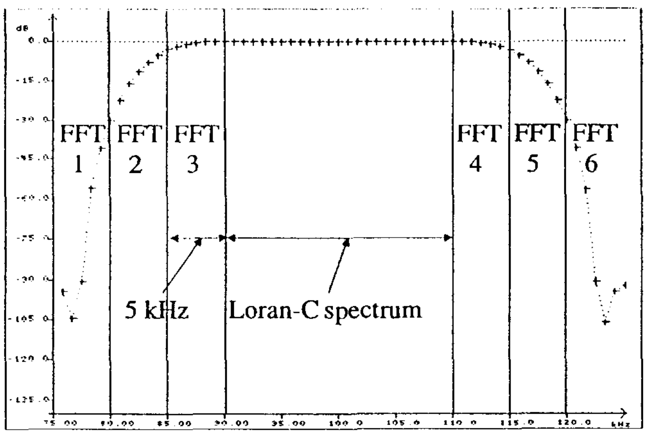

Fig. 18. Breaking up the CWI spectrum into segments.

According to formula 4.1 the amount of samples is now reduced to 50,000 and the required storage space to 800 kb. By selecting a different width for the spectrum segments (e.g. 1 kHz), the necessary amount of RAM can be reduced even further.

Breaking up the CWI spectrum into segments can be done with two methods:

i. Digital bandpass filters can be used to filter out the spectrum segments. One tunable filter is sufficient, since the segments are analyzed consecutively. A suitable receiver architecture in shown in fig. 19.

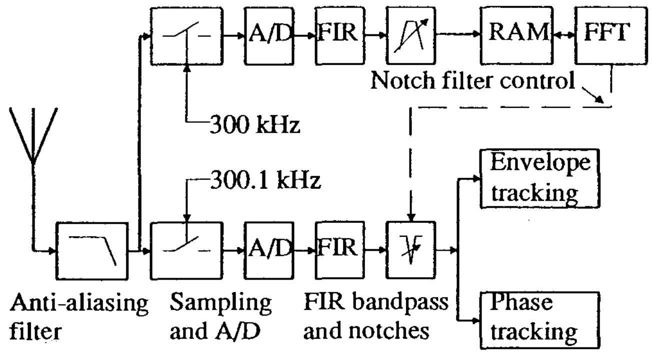

Fig. 19. Receiver with tuneable bandpass filter and FFT.

   For each segment a new set of samples has to be collected, because in the RAM in fig. 19 only information about the segment currently being filtered, is stored. The time necessary to collect samples is the inverse of the FFT resolution, so for a resolution of 0.1 Hz a sampling time of 10 seconds is necessary. If the spectrum to be analyzed, is divided into 6 segments (as shown in fig. 18), total sampling time is 60 seconds or one minute. This is a clear disadvantage of the architecture in fig. 19, compared with the method described in [7].

ii. The Chirp-Z transform [10] can be used to analyze one spectrum part at a time, without using a bandpass filter to separate the spectrum parts. According to [10], the amount of samples needed is still only determined by the width of one spectrum part of 5 kHz. The same set of samples can be used for all spectrum parts, so sampling time is considerably less than with the receiver shown in fig. 19.

The Chirp-Z transform is both easier to implement and faster than an FFT with a tunable bandpass filter as shown in fig. 19. It has therefore been chosen for further research into segmented spectrum analysis for Loran-C receivers.

Both the zoom-in method of fig. 17 and the segmented spectrum analysis of fig. 18 are being investigated at the Delft University of Technology. Up until now, no clear-cut preference for one of these methods has been found.

5. CONCLUSIONS

While CWI interference can endanger reliable Loran-C operation, it is has been shown that with suitable counter-measures in receivers, proper Loran-C operation can still be obtained. These counter-measures are based heavily on digital signal processing.

The most promising method for solving the CWI problem, uses a mixture of bandpass- and notch-filtering to remove all harmful CWI signals. The problems that can be expected with this method have been described and solutions have been given.

Further research will be necessary to get a functioning Loran-C receiver with automatic CWI filtering. Two important topics are:

- Choice and implementation of special FIR filter algorithms for bandpass filters.
- Implementation of a spectrum analysis method with high resolution, low processing power requirements and little execution time.

Research into these problems is currently carried out at the Delft University of Technology.

6. ACKNOWLEDGEMENTS

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About the author

Martin Beckmann was born in 1964. He studied Electrical Engineering at the Delft University of Technology, and completed his masters thesis in 1987 concerning software for an OMEGA navigation receiver. He is still with the Delft University of Technology, working on Loran-C.

Terrestrial Navaids - Critical Stepping Stones To Satellite Navigation

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Biography

Mr. Beukers graduated from London University in 1954 with a degree in Electronics and Telecommunications. In 1957 he immigrated to the United States taking a position with the Avionics Division of IT&T. In 1960 he joined Servo Corporation of America where he developed Doppler Direction Finders and was responsible for the development of the Doppler VOR.

In 1963 Mr. Beukers formed his own company Beukers Laboratories, Inc. and became dedicated to Loran-C and Omega technology. He pioneered Navaid retransmission technology which has been applied to a wide range of applications, in particular, meteorological systems for monitoring the atmosphere.

Following the sale of his company in 1984, Mr. Beukers formed Beukers Technologies and is currently devoting his time to the expansion initiative of the Wild Goose Association - the International Loran Radionavigation Forum. He is a senior member of the Institute of Electrical and Electronics Engineers, a member of the Institute of Navigation, the Royal Institute of Navigation, the International Omega Association and the American Meteorological Association.

Abstract

Several independent studies have shown that for a constellation of satellites to meet the stringent requirements of aviation, an adequate number of satellites must be visible at one time, and some form of signal integrity monitoring and communication to the user must be in place. Several possible methods have been proposed, all of which are in the study phase with no single contender being adopted at present. The probability of having twenty-one healthy Global Positioning System satellites in orbit within the next two years poses a significant challenge to operational system designers to incorporate this new radionavigation capability into the National Airspace System. The author suggests that the completed United States Loran-C coverage offers an immediate solution to the signal integrity and selective availability problems which otherwise might have to wait until the end of the decade to be resolved.

Introduction

The Institute of Navigation (ION) held its third Global Positioning System (GPS) Technical Meeting last month (September 1990). Of the ninety-six papers listed in the program, more than eighty were presented to an attendance that exceeded one thousand people. The papers were of a high standard and covered a wide range of GPS topics. The author delivered a paper at this meeting entitled "*Developing a Commercial Market for GPS Receiving Equipment.*" The paper being presented today, while standing on its own, may be considered as a sequel to the one given at the GPS meeting and reflects the author's overall conclusions reached from the material presented at the technical sessions.

A report, assessment and analysis of the ION GPS meeting provides an appropriate introduction and sets the stage for a forward thinking discussion of radionavigation system interoperability.

It may come as no surprise that the majority of the GPS community has its eyes focused in space and does not recognize or understand - or may not want to - the assets represented by terrestrial radionavigation aids. This is illustrated by two examples of conversations with well known and respected professionals. In one instance the author was chided for his continued involvement with Loran-C with the statement, to quote "*I just don't understand why you continue to endorse an obsolete system - all terrestrial navaids will have been phased out by the turn of the century.*" And in the second example, when the author questioned a strong GPS advocate whether it was prudent to put all one's navigation eggs in the space basket, the advocate, seeing that the author was wearing a Wild Goose lapel pin, remarked "*No wonder you ask, you are with the WGA!*" Apparently questions regarding the validity of GPS philosophy result in one being labeled anti-GPS. One further example of this myopia occurred at the Navtech Seminar on Loran-C/GPS interoperability. A class member, seemingly genuinely puzzled, asked "*Why even consider such an inaccurate and unreliable system as Loran-C as a candidate for aiding GPS.*"

So rampant is the misinformation and lack of understanding of Loran-C that we should all be concerned and make every endeavor to correct the situation. A strong GPS lobby and an over zealous GPS community are not in the best interests of an enlightened radionavigation policy and need to be balanced by those with their feet on the ground.

Two aspects of the GPS meeting serve as a backdrop for this paper. The first is an analysis of the affiliation of those attending and serves to emphasize where the financial support and special interests lie. This is shown in figure 1. The DOD, DOD contractors, government and large corporations dominated the attendance. Universities and study groups were well represented as were participants from overseas. A few small companies with a large representation were present, and the remainder was made up from committees, associations such as the Aircraft Owners and Pilots Association (AOPA) and the Radio Technical Commission for Aeronautics (RTCA), state representatives, survey companies and those with unidentified affiliation.

Loran-C prematurely in favor of GPS, the military has no Loran-C hardware. To make matters worse, military GPS equipment is virtually non existent. As a result, commercial Loran-C receivers and commercial GPS receivers are being shipped into the area. Further, in order that commercial GPS receivers can operate, selective availability, the coding that is to be in effect in times of national conflict, has had to be turned off!

To compound this hiatus, the 1991 defense bill approved by the House Appropriations Committee on October 9, 1990 denied $47.6 million requested by the Army, Navy and Air Force to purchase receivers. The basis for the denial was that

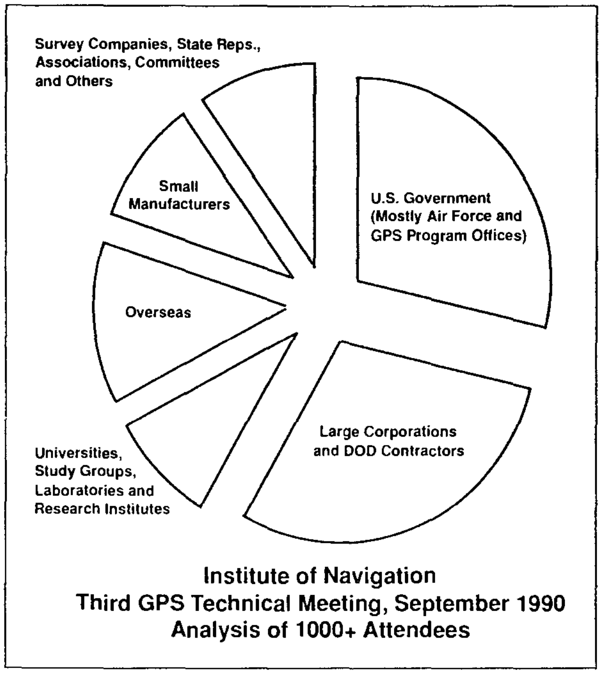

Figure 1. Analysis of Attendees

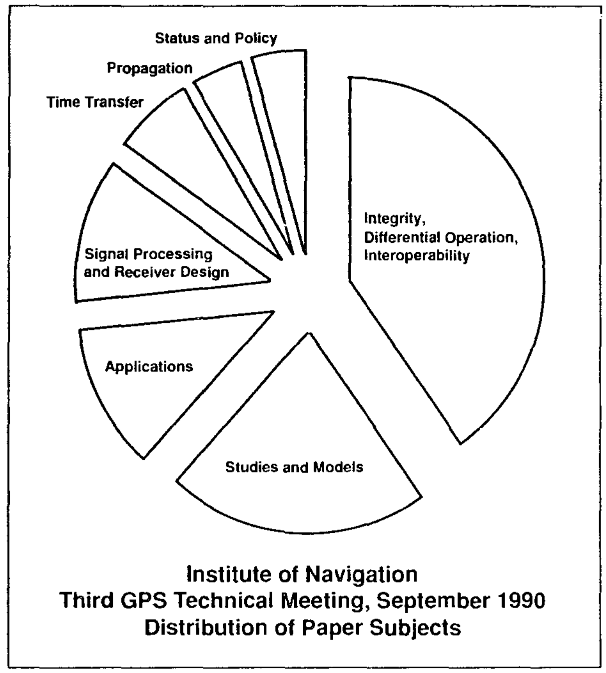

Figure 2. Distribution of Paper Subject Matter

The second aspect serves as an important indication as to where the technical concerns lie. An analysis of the subject matter of the papers presented is shown in figure 2. It is quite clear that the issue of interoperability, integrity and the schemes to beat selective availability are foremost in the minds of the GPS community. Conspicuous by their absence from the agenda are the subjects of operational procedures and other issues of GPS implementation.

U.S. Global Radionavigation Policy

That the United States Global Radionavigation Policy is in disarray is dramatically brought into focus by the inexcusable situation in the Persian Gulf. There are two Loran-C chains in Saudi Arabia, a northern chain and a southern chain. These are shown with the corresponding coverage of the area in figure 3. The fully operational northern chain provides excellent coverage over most of the Desert Shield theater of operation. But, because DOD was persuaded to abandon

GPS program delays make the funding unnecessary. Without this procurement the military will continue to have to rely upon commercially available receivers which cannot decipher the encrypted precision code.

How did we get into this confused mess? A clue can be found in a report to the Secretary of Transportation from the General Accounting Office (GAO) dated September 18, 1981. This fifteen page dissertation has the title *"DOT Should Terminate Further Loran-C Development And Modernization And Exploit The Potential Of The Navstar/Global Positioning System"* and is a follow up review of a March 21, 1978 report entitled *"Navigation Planning — Need for a New Direction* (LCD-77-109)." The 1978 report cautioned against further investment in Loran-C and recommended that the Department of Transportation turn its attention to GPS. The 1981 report castigates the Coast Guard for continued improvement of Loran-C and for considering operation of Loran-C beyond 1990. It further states that any refurbishment of transmitting equipment is unnecessary. The reason

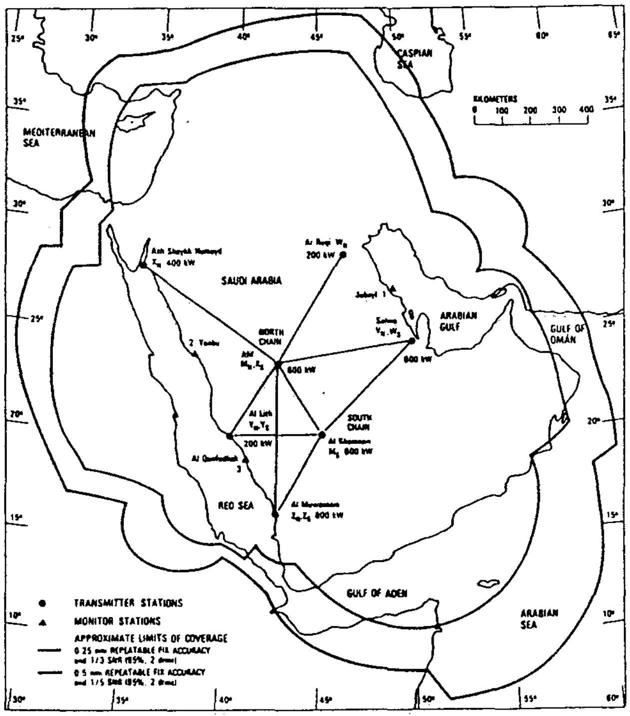

Figure 3. Saudi Arabia Loran-C Coverage

given for this position is that "....*GPS is currently scheduled to provide, in 1986, accuracies equivalent to Loran-C for oceanic and coastal navigation.*" The first paragraph of the Conclusions and Recommendations states "*In our opinion, the Coast Guard's plan to operate Loran-C until at least the year 2000 is based on questionable assumptions and the Coast Guard could potentially phase out Loran-C by the early 1990's. By announcing in 1983 its tentative plans to phase out Loran-C by the early 1990's, the Coast Guard can ease the transition for the user community as well as avoid the high future operating costs of Loran-C.*"

What was going on behind the scenes to provoke these recommendations that history has shown were so far off base? The GPS lobby led by the Department of Defense needed funding for a $25 billion program and used the argument that once GPS was operational, all other radionavigation aids would be obsolete and could be phased out, thereby saving the country the running costs of multiple systems. VOR/DME, Loran-C, Omega, TACAN, MLS and others were all cited as candidates for the ax.

In these reports, which are a must reading for anyone in the radionavigation planning business, The Department of Transportation must be given the credit for presenting the real world situation and being totally opposed to the GAO's recommendation. Fortunately for us the better judgement prevailed. Unfortunately, this confusion and these politically motivated policies find their way into the U.S. Federal Radionavigation Plan (FRP). If one studies these documents and searches for the consistency, or lack thereof, from one issue to the next, it is not difficult to identify the tug of war between the various government agencies. The civil community, especially those from overseas, should take heed of this and check the stated plans and policies with current and projected practice. We should also bear in mind that the FRP is generated by the Government for the Government and, as such, tends to be self serving.

GPS Implementation

Funding

Using the ION GPS Meeting as the basis for current GPS thinking and the history of GPS advocacy, we can turn our attention to the orderly implementation of a satellite-based radionavigation system. First let us consider funding. Figure 4 depicts life funding for radionavigation systems. Loran-C and GPS were conceived to satisfy a military requirement and their development was funded by the Department of Defense. After expenditure on development and procurement, funding is directed towards operation, and appropriations for development are curtailed. As time goes on, pressure builds to cut the operational budget resulting in reduced support capability and lack of on-going refurbishment. Figure 4 shows that this cycle takes several decades and that Loran-C precedes GPS by about 15 years. (The author's paper, "Developing a Commercial Market for GPS Receiving Equipment" elaborates on the impact of reducing operational funding during the mature phase of the life of radionavigation systems.)

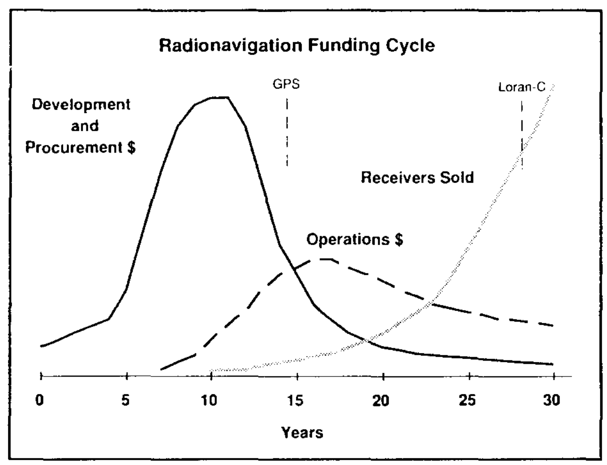

Figure 4. Radionavigation Funding

Meaning of Operational

Next we need to define the term "Operational." Depending on whom you ask, "operational" has different meanings. For those responsible for establishing a satellite constellation, operational status means satellites in orbit, positioned and transmitting to a determined specification. This is equivalent to siting a terrestrial transmitter, turning power on and delivering a signal to its antenna. From the user's standpoint, a great deal more is entailed than simply throwing a switch for a system to be declared operational. The signal in space is just the tip of the iceberg. Some of the non-technical requirements for a system to be pronounced truly operational are:

1. Defining policy for system technical longevity.
2. Obtaining funding commitment for long term operation.
3. Clarification of user fee policy.
4. Publication of system specifications.
5. Publication of administrative control authority, system responsibility and operational procedures.
6. Communication of system status to all user communities.
7. Establishment of national interagency agreements.
8. Establishment of international agreements.
9. Obtaining agreements on legal issues of liability.
10. Establishment of user procedures in mixed navigation systems.

It is not until all of these issues have been addressed and appropriately dealt with that a system can be pronounced operational.

GPS System Design

The status of GPS system design can be described with the aid of figure 5. If the current launch schedule of fifteen additional Block 2 satellites into the required orbital planes is maintained, and the satellites are declared healthy, the Air Force will declare the GPS system operational by mid-1993. This definition of operational is a healthy constellation of twenty-one satellites and is depicted by the short dots line in figure 5. With only two years before the twenty-one satellite constellation is to be available, attention is being turned towards the challenges of using the system in traditional navigation scenarios. Signal reliability and availability, and all the non-technical operational issues that have been neglected, are coming to the surface. A sort of after-the-fact system design!

Integrity and Interoperability

Of all the concerns, it appears that signal integrity and interoperability are getting the most attention. In order to use GPS for aviation it is necessary to be able to detect signal failures, to isolate the faulty satellite and to communicate this change in status to the user's platform within a specified time. Using GPS alone, five satellites having good geometry are required for fault detection, and six or more are required for both detection and isolation. This self monitoring scheme known as Receiver Autonomous Integrity Monitoring (RAIM) was proposed in the mid 1980's and has received a great deal of attention. Several studies have concluded that RAIM schemes will be marginal at best and require a twenty-four satellite constellation to meet aviation requirements. For a twenty-one constellation alternative, integrity methods are being explored to aid RAIM in meeting these requirements. R. Grover Brown in his draft report to the RTCA SC159 Working Group on GPS Integrity Implementation notes that "*...near term RAIM systems will have to be aided with outside measurement information.*" He also observes that there are as many such schemes as there are authors! One of these is SatZap, a new approach which, as its name sounds, zaps a satellite transmission when the ground determines that its signal is out of specification.

This is the reason for exploring all forms of interoperability available today and in the future. One proposal is to use GPS in conjunction with GLONASS the Soviet satellite navigation system. This requires a joint working agreement to be in place having the DOD's blessing. It also raises the question of reliability of Soviet satellites which has recently been disappointing. Two out of the three satellites from the last launch, while exhibiting superior oscillator performance, failed after just two years and the GLONASS system is currently down to five satellites. There have been no launches for over two years giving rise to speculation that the reasons for the failures are being corrected before further launches are made. Putting more satellites into the system does nothing for RAIM if the overall system reliability is degraded. It would appear, therefore, that interoperability with GLONASS, if pursued, will not be available until the end of the decade.

A second set of proposals is to use geosynchronous satellites as an overlay. INMARSAT has been suggested, as has GEOSTAR. These schemes require the launch of additional satellites with new capabilities not yet designed. This solution would also appear to have a long gestation period and require significant additional funding. There are also proposals for new satellites specifically designed for GPS integrity monitoring. It goes without saying that any commercial additions to GPS will have to be paid for by the users.

Use of differential GPS has wide support but requires communication channels. This requires international agreements on the methods and frequencies to be employed - again a lengthy process that will probably not result in a solution with hardware before the end of the decade.

The point to this discussion should be self evident. The all satellite navigation system for aviation is still in the debate stage and its realization would seem to be a long way off. Further it requires additional substantial expenditures. There are other factors that must also be considered. The current confused policy regarding selective availability has to be resolved, as have the non-technical issues previously listed.

Solar Activity

Another aspect of GPS system performance that has received little attention is the effect of solar activity both on satellite performance and signal propagation from satellite to receiver. This topic is the subject of a paper being delivered at this Technical Symposium by Joe Kunches from the Space Environment Services Center, Space Environment Laboratory, NOAA in Boulder, Colorado. Suffice it to say here that severe magnetic storms can have irreversible effects on spacecraft and temporarily perturb signal propagation.

User Procedures

The loran community knows only too well the time it takes and the frustration that is encountered when introducing a new navigation system into an existing operational scenario. Loran-C is an area navigation system unlike the traditional

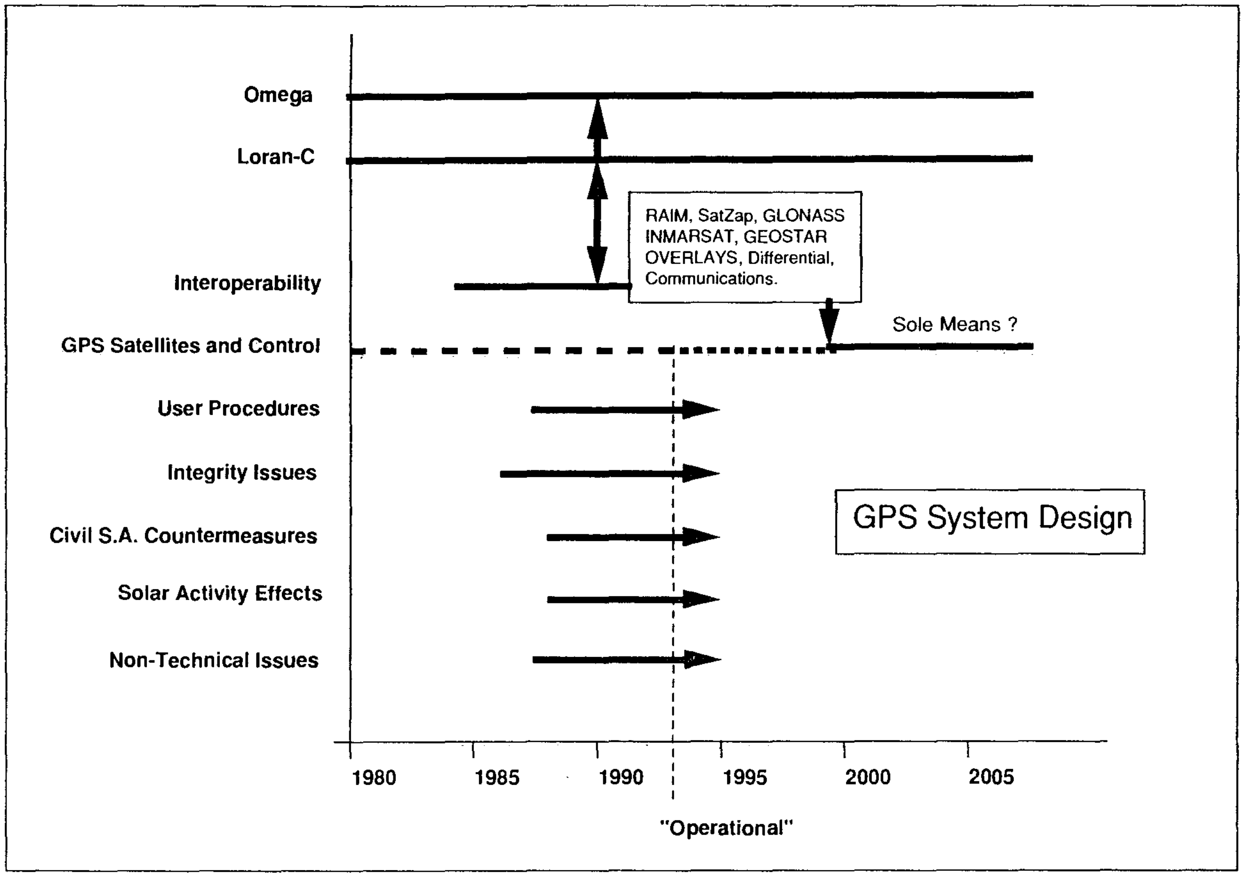

Figure 5. GPS System Schedule

Rho-Theta, VOR/DME air lane radionavigation aid. This has required a change in thinking for the National Airspace System and the development of new procedures. Implementation of these changes takes a long time and requires additional financial resources. The non-precision approach is a good example. First demonstrated in 1979 using Loran, it has taken eleven years to get the program off the ground. The reasons we are told have nothing to do with the Loran-C system. It requires people and money to drive the program, and these are slow in being assembled. GPS must also go down this path but it will have the advantage of Loran-C paving the way. Many of the procedures and mapping will be directly applicable.

Selective Availability Issues

Perhaps the easiest but seemingly impossible issue to resolve is the availability of the inherent accuracy of GPS to the civilian community. While the DOD maintains its current policy of degrading the performance of GPS without defining what this actually means in terms of 99.99% positional accuracy, system design is a gamble at best. 100 meter 2D rms is too loose for the aviation community. Not to be outdone, the civilian community is busy devising all sorts of ways to defeat the intent of the DOD. This is somewhat analogous to the police radar and radar detector business that results in an endless counter-countermeasures game.

Non-Technical Issues

The non-technical issues previously listed speak for themselves and all are important. The one common element is that papering the issues and obtaining agreement is a lengthy process, especially if it involves the international community.

The Case for Loran-C

It is time to draw an interim conclusion. Based on the current flurry of integrity and interoperablity activity as evidenced by the papers presented at the ION GPS Technical Meeting and an analysis of the message that they carry, GPS has a long way to go until it can be assessed as being acceptable to the aviation community, probably to the turn of the century. But why wait? This is where the terrestrial radionavigation aids Loran-C and Omega can provide an immediate interim if not a long term solution. Loran-C appears to be the radionavigation aid of choice for coastal waters and land masses. We are witnessing a move toward international agreement on this as evidenced by (a) the drafting of a proposal by the European Economic Council recommending member nations adopt Loran-C, (b) the funding of the North European study group, (c) solidarity in the Far East shown by Japan, China, the Soviet Union and Korea, and (d) countries like India and Venezuela that are going ahead with their own Loran-C chains.

Combining GPS with Loran-C

North America is poised to benefit from GPS interoperablity within the next few months. Completion of the mid-continent transmitters and the timing of master stations to UTC using GPS (the transmissions have always been exact as to frequency, but their time of transmission has not been synchronized to UTC), provides additional stations and makes possible cross chain operation. For example, projections show that in Denver, Colorado, sixteen Loran-C stations of excellent signal quality will be available at all times. Secondary phase factor calibration for positions derived from this North American (U.S. and Canada) network of transmitters, using GPS, will yield a self-contained radionavigation system of high accuracy, reliability, and redundancy, that will be totally immune to the activation of selective availability.

By using GPS and Loran-C as complementary systems, the basic problem of GPS integrity is solved and the combined system will meet the requirements of the National Airspace System with no further expenditure on additional satellites. Taking this one step further, by using international Loran-C and Omega, the area of satisfactory integrity operation can be extended over most of the world.

If this makes sense, why is it that there is a complete absence of Loran-C and Omega interoperability discussions and proposals in Future Air Navigation Systems' panel (FANS) of the International Civil Aeronautics Organization (ICAO)?

Omega has been available worldwide for over a decade and Loran-C coverage is expanding each year. The near term worldwide Loran-C coverage diagram is shown in figure 6.

Filling in the Mid-Continent Gap

The United States Loran-C network of transmitters will be complete and all transmitters on the air for use by April of 1991. (Should *network of transmitters* be a new term since, once master stations are time synchronized, the term *chain* is meaningless except to identify a group repetition interval?) Four new stations, funded by the Federal Aviation Administration, have been added as shown in figure 7. The added transmitters are Boise City, OK (Master); Gillette, WY; Havre, MO; Las Cruces, NM (all Secondaries). As of the date of this conference the Office of Navigation Safety of the U.S. Coast Guard provides the following information regarding the status of the stations: Boise City has been on air from mid August. Gillette's transmitters have been installed and the station is complete. Transmissions from Gillette should have started last week. At Havre, the transmitters are to be

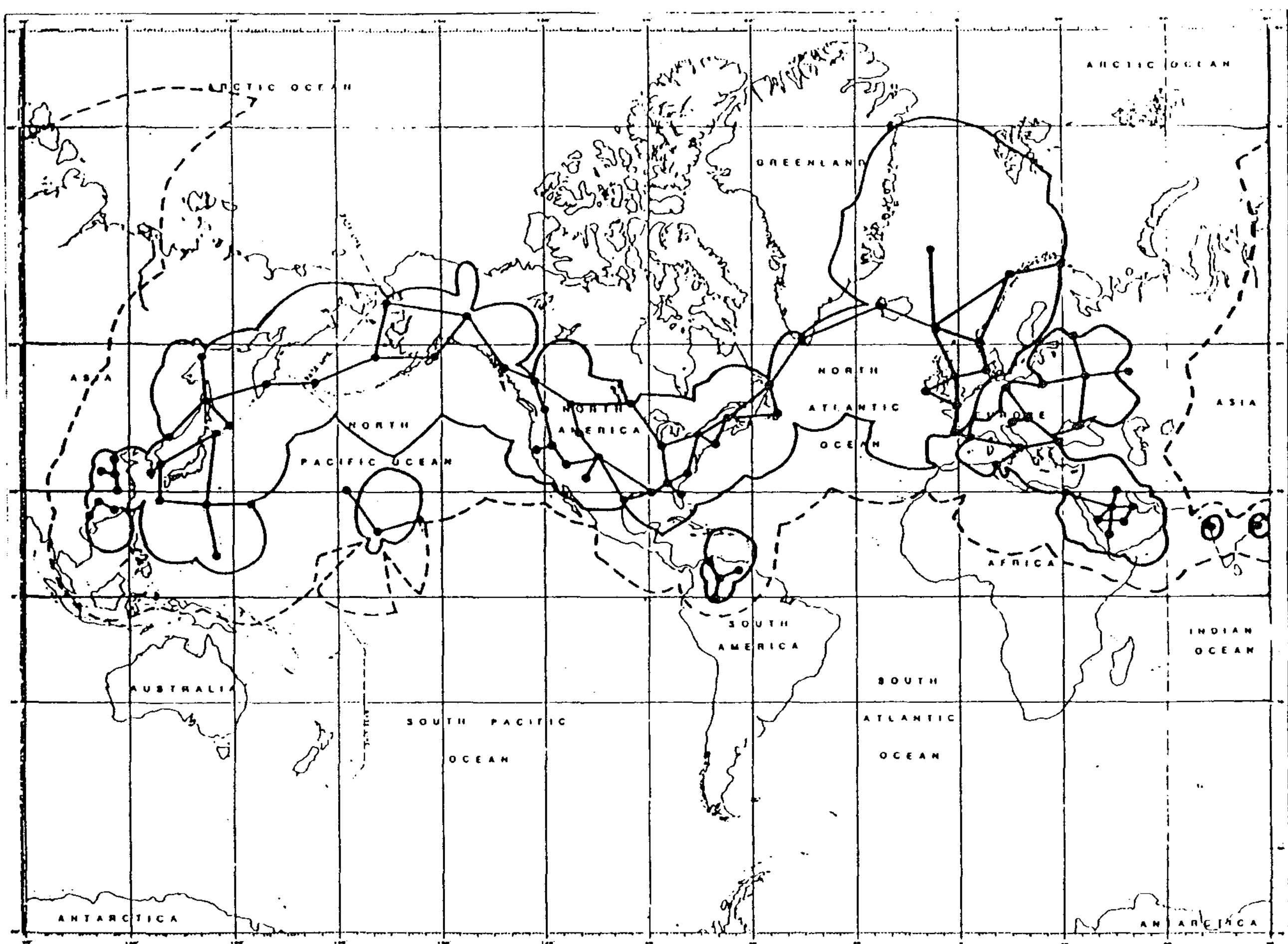

Figure 6. Projected Loran-C Coverage for the early 90's

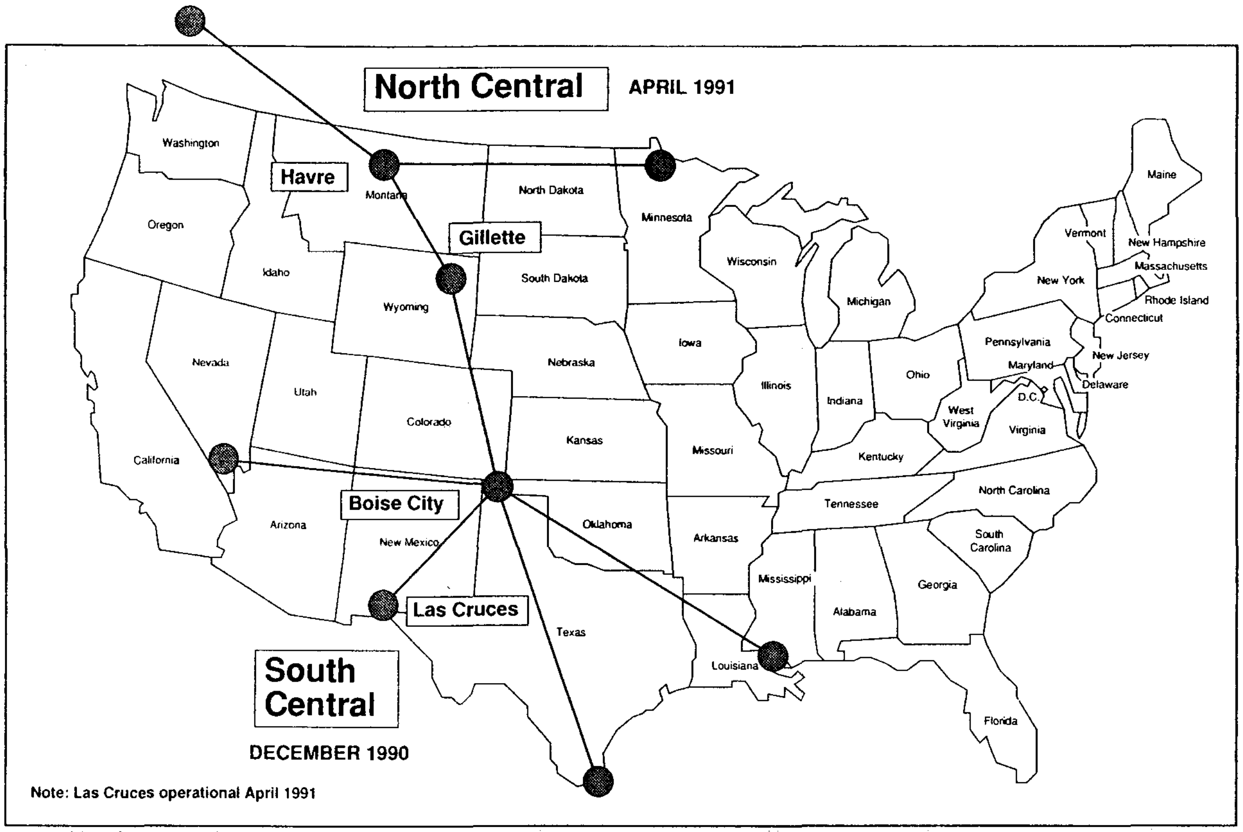

Figure 7. New Mid-Continent Loran-C Stations and Chains

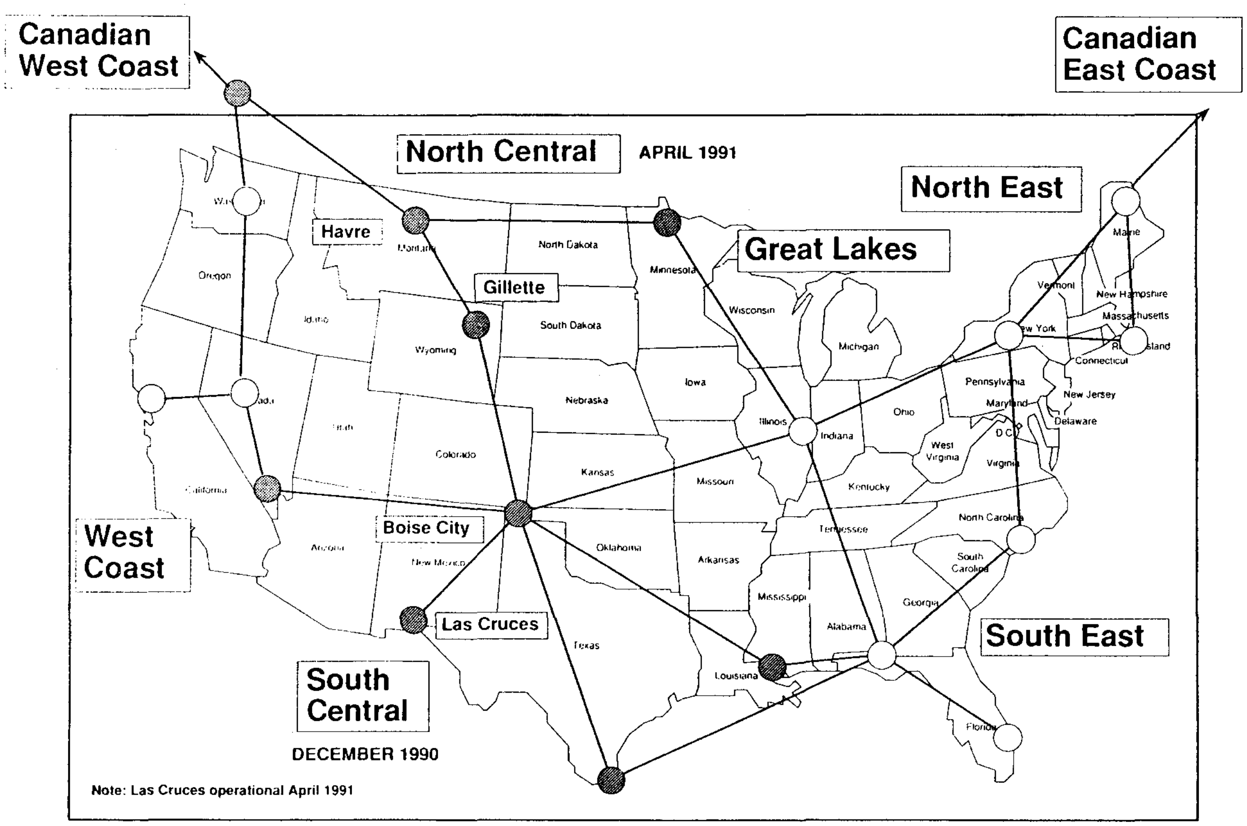

Figure 8. Completed United States Loran-C Network

installed shortly and the station will be on air in mid November. The last station to be completed is Las Cruces. The building will be complete next month and transmitters will be installed later this year. These four new stations together with existing stations create two new chains - South Central United States (SOCUS) and North Central United States (NOCUS). It is anticipated that SOCUS will be declared usable in December of this year (without Las Cruces) and that NOCUS will be declared usable (along with Las Cruces) in April of 1991. Further details may be obtained from CDR Tom Gunther, Office of Navigation Safety and Waterway Services, Radionavigation Division, United States Coast Guard. Phone: 202-267-0282, Fax: 202-267-4427

April of 1991 will see the completion of the United States Loran-C network. At this time the there will be eighteen transmitters within the mainland as shown in figure 8.

Master Timing - Cross Chain Operation

The synchronization of master station clocks to UTC has a major impact on signal availability and interoperability. No longer is one restricted to a single chain to obtain navigation information. A receiver that has both GPS and Loran-C receiving capability can use any Loran-C or GPS transmitter as an input to the navigation equation. Over the continental United States this can double or triple the number of usable signals available from GPS alone This redundancy has been shown to satisfy the aviation requirement for signal availability and reliability. Presentations on the master synchronization and Loran/GPS interoperability that go into these subjects in detail are to be given at this WGA Technical Symposium.

Conclusions

1. It is clear to the author that for GPS alone to qualify to enter aviation service as a sole means radionavigation system, significant system changes must be made. These are not short term fixes but require careful design, planning and the expenditure of significant amounts of money. It is estimated that *if* embarked upon, this program will take many years and not be ready for implementation until at least the turn of the century.

2. All the elements for a high quality national Loran-C/GPS system exist today and can be implemented with little incremental cost.

3. A worldwide terrestrial/GPS system can be deployed within a short time frame, at substantially less cost than a satellite system alone.

4. If the DOD continues with its policy of denial of GPS precision code to the civil community then a worldwide terrestrial/GPS system will exhibit equal, if not better, performance than that of GPS alone and provide built in redundancy.

5. The author questions the wisdom of relying completely on a space radionavigation system from the standpoint of achieving the required reliability and signal availability at an acceptable cost.

6. At the very minimum we should not abandon terrestrial systems until an all space system has been proven over *at least* one complete sunspot cycle.

7. The prudent navigator should not rely upon one system of radionavigation alone. Should we abandon this maxim?

8. Terrestrial systems should be used as Stepping Stones to space.

For Further Reading

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4. 1988 Federal Radionavigation Plan, Department of Transportation. DOD-4650.4, DOT-TSC-RSPA-88.4.
5. Fact Sheet for the Chairman, Committee on Armed Services, House of Representatives by the General Accounting Office. Military Space Programs, An Unclassified Overview of Defense Satellite Programs and Launch Activities. GAO/NSIAD-90-154FS, June 1990.

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Synchronous Interference to Loran-C and its Influence on Cycle Identification.

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ABSTRACT

As the plans for Loran-C expansion in Northern and Western Europe will very probably succeed, the problems which are typical for Loran-C operation in Europe must be understood. One of these problems is the presence of many non-Loran-C signals on frequencies adjacent to the Loran-C band. These signals do cause all kinds of problems for Loran-C operation.

In previous papers, attention has been focused on the influence of these interfering signals on Loran-C phase tracking. However, before a Loran-C receiver can perform phase measurements, it first must find the correct cycle on which to do so. Analysis shows that this Cycle Identification process is influenced as least as severely as phase tracking by interference. This paper describes a method to analyze the influence of interfering signals on Cycle Identification.

1. INTRODUCTION

Over the past few years, several reports have appeared on the development of plans for the expansion of Loran-C in Northern and Western Europe [1], [2]. The efforts described in [1] and [2] will undoubtedly lead to an operational European Loran-C system. However, for such a system to become widely accepted, it is necessary to provide solutions for the problems future European Loran-C users are likely to encounter.

One of the typical European problems reported before [3], is the problem with interference from signals transmitting in frequency bands adjacent to the Loran-C spectrum. These signals are commonly called Continuous Wave Interference (CWI), and come from data transmission stations, time reference transmitters, other navigation systems (notably DECCA) and many other, often unidentifiable, sources. These signals are found on frequencies close to the Loran-C band between 90 and 110 kHz. Fig. 1 gives a good idea of the amount of signals found in the bands from 50 to 90 and from 110 to 150 kHz.

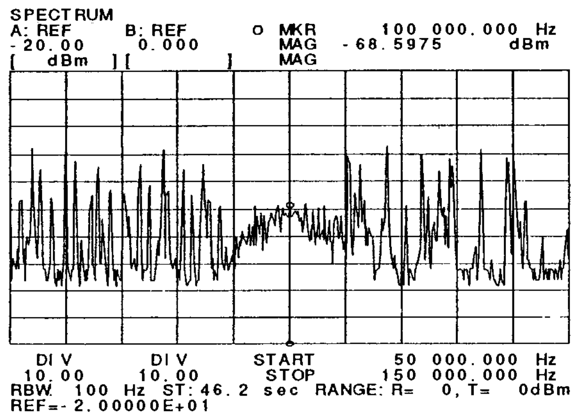

Fig. 1. Typical spectrum from 50 to 150 kHz in Delft.

The effects of CWI signals on Loran-C phase tracking have already been discussed in [3]. There it has been shown that a Loran-C receiver is sensitive to all frequencies on multiples of $1/(2\,GRI)$ Hz. All CWI signals falling exactly on such a multiple are called synchronous CWI signals; signals with frequencies very close to such a multiple are called near-synchronous signals and all other signals are called a-synchronous [3]. Synchronous signals will cause an offset in the phase tracking loop present in all Loran-C receivers, which cannot be distinguished from normal changes in tracking data due to receiver movement [3]. In [4] and [5] methods have been introduced to combat synchronous and near-synchronous interference.

Though much effort has been put into understanding the influence of CWI on phase tracking, little attention has been paid to the distortion caused to the Loran-C envelope by CWI until now. The envelope is at least as important to proper Loran-C receiver operation as proper phase tracking, since the envelope is used by the Loran-C receiver to determine the proper carrier cycle to be tracked. Errors in this Cycle Identification (CI) process immediately yield errors in range measurements of multiples of 3 km. A CWI signal does always distort the envelope of a Loran-C burst, as is shown in the example of fig. 2.

For a-synchronous signals, the envelope distortion will be different for every pulse, with an average distortion of zero.

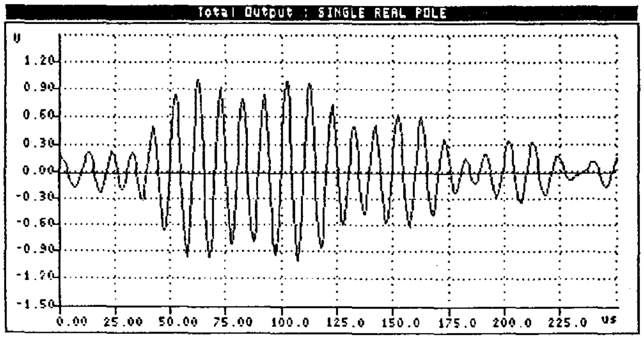

Fig. 2. Envelope distortion caused by CWI.

These signals are therefore removed with the long integration times that are used for Cycle Identification anyway. However, the distinguishing feature of synchronous signals is that the relative phase between the CWI signal and the Loran-C pulse is equal for all pulses spaced 2 GRI apart, as demonstrated in fig. 3.

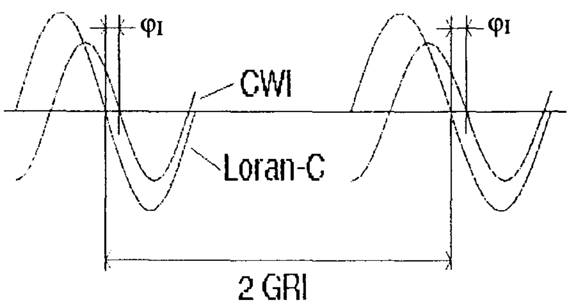

Fig. 3. Phase relation of synchronous CWI and Loran-C.

This means that after 2 GRI seconds, the receiver will see exactly the same signal (consisting of a Loran-C pulse and CWI signals) again. Integration can only remove randomly changing signal components with an average of zero, such as noise or a-synchronous signals. It does not help against synchronous CWI, which does not change randomly [3]. This is valid for Cycle Identification as well as for phase tracking.

Analysis of the deterioration of Cycle Identification due to synchronous CWI has been limited to describing particular cases of synchronous interference signals. However, for reliable prediction of the deterioration of Cycle Identification due to synchronous CWI signals, a generally valid method is needed. In the next paragraphs, such a method will be described. First, however, the two most-used Cycle Identification methods will be described briefly and it will be shown, that both methods work on the same principle.

2. CYCLE IDENTIFICATION - THE TWO MOST COMMON METHODS

In the previous paragraph, it has been shown that CWI signals influence the Cycle Identification abilities of a Loran-C receiver, and that a general model describing the deterioration, is needed. In order to be able to develop such a model, first attention has to be focused on Cycle Identification mechanisms.

Receivers use phase tracking loops in order to get Time-of-Arrival data from the received Loran-C signal. These loops find and track a zero crossing of the incoming signals, i.e. the moment in time when the incoming signal changes from positive to negative or vice versa. Within each Loran-C cycle of 10 μs there is one positive and one negative zero crossing (see fig. 4). Receivers usually use either the positive or the negative crossing. Therefore, one Loran-C cycle has one zero crossing useful to the receiver.

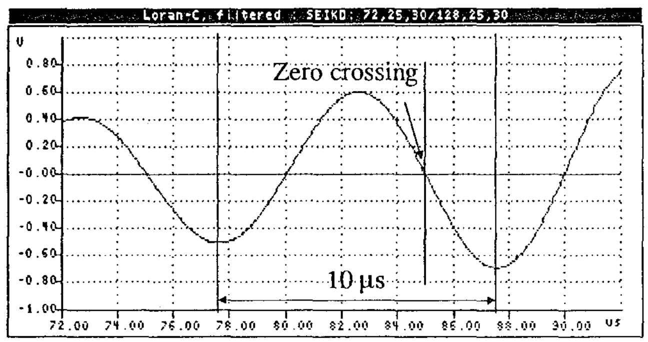

Fig. 4. Loran-C pulse with zero crossing for tracking.

Cycle Identification will be defined here as the mechanism by which the receiver finds the cycle of the Loran-C carrier it wants to use for TOA or TD measurements. Note that this definition does not fix the cycle to be used: this could be the third cycle as well as the seventh in the Loran-C burst.

Traditionally, Loran-C receivers have found the cycle to be used for tracking by internally generating a 5 μs delayed and slightly amplified version of the incoming antenna signal (see fig. 5).

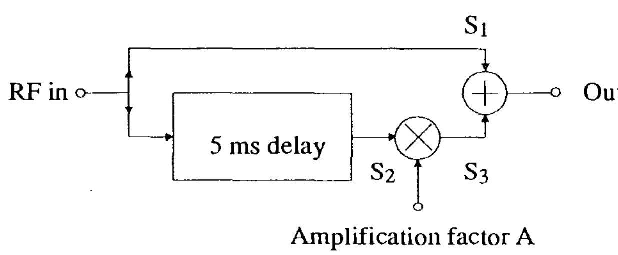

Fig. 5. Traditional Cycle Identification circuit.

The non-delayed and the delayed signals are then added; this addition will result in a phase reversal at one moment in the combined signal, as shown in fig. 6. This moment of phase reversal can be detected easily, since it is the only time interval in the burst where two samples taken 2.5 µs before and 2.5 µs after the zero crossing (i.e. on the signal peaks) will have the same sign. This method works well for linear and hard-limiting receivers.

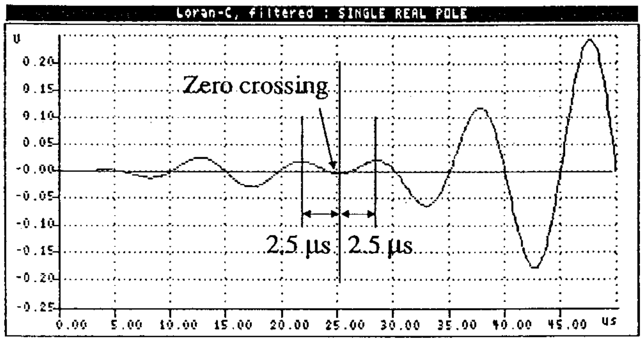

Fig. 6. Combined signal in a traditional CI circuit.

A second method useful for cycle identification in linear receivers is shown in fig. 7. Here, two samples are taken: one 2.5 µs before and another 2.5 µs after a zero crossing of the incoming signal.

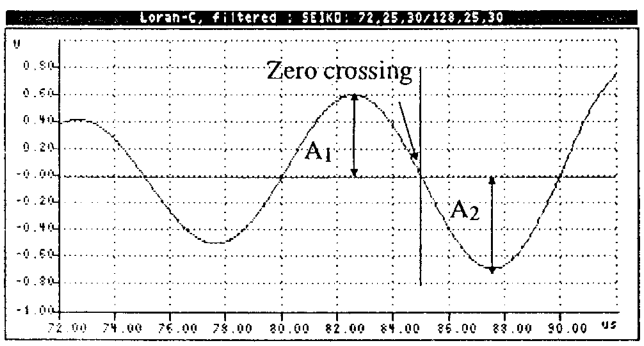

Fig. 7. Cycle Identification in linear receivers.

The amplitudes of the two samples are then used to form an amplitude ratio R_{amp}:

$$R_{amp} = \frac{A_2}{A_1} \qquad 2.1$$

A table can be calculated, giving the amplitude ratio R_{amp} for every zero crossing of a loran-C burst.

A loran-C receiver in its initialization phase will track a zero crossing found at random. It then uses the following mechanism for its Cycle Identification:

1. determine R_{amp} for the zero crossing being tracked at the moment;
2. look up the position of the zero-crossing in the table;
3. calculate the time difference between the zero crossing that is tracked and the zero crossing that should be tracked;
4. and finally jump to the correct zero crossing.

Table 1 shows an example of a ratio table.

Filter	: SEIKO Industrial	
Center Frequency	: 100 kHz	
Bandwidth	: 18 kHz	
Zero number	Position of zero	Ratio
1.	7.2119 µs	21.91
2.	11.7227 µs	7.81
3.	16.3362 µs	4.58
4.	21.0507 µs	3.29
5.	25.8384 µs	2.62
6.	30.6773 µs	2.22
7.	35.5518 µs	1.96
8.	40.4519 µs	1.78
9.	45.3706 µs	1.64
10.	50.3033 µs	1.54

Table 1. Example of a ratio table.

Basically, the Delay-and-Add method makes use of amplitude ratios:

- In a traditional CI circuit as shown in fig. 5, the output signal represents the difference between the non-delayed signal S_1 and the delayed and amplified signal S_3. This is due to the delay time of 5 µs, which inverts the carrier and the sign of the envelope and therefore converts the addition of the signals into a subtraction.
- The phase inversion shown in fig. 6 takes place at the moment that S_1 and S_3 have equal amplitudes (difference zero). This phase inversion is used to mark the proper zero crossing to be tracked.
- Since the delayed signal S_2 in fig. 5 is amplified with a factor A, the phase inversion will occur at that moment where signals S_1 and S_2 have an amplitude ratio A. Since S_1 and S_2 represent the same signal with a time difference of 5 µs, the phase inversion in fact marks a zero crossing with a pre-defined amplitude ratio $R_{amp} = A$.

Since the Cycle Identification methods shown in figs. 5 and 7 are both based on finding the position on the Loran-C pulse with a fixed ratio R_{amp}, it is interesting to analyze the change of a ratio R_{amp} due to synchronous CWI. This will be done in the next paragraph.

3. CALCULATING AMPLITUDE RATIOS WITH CWI PRESENT

For the calculation of a ratio with CWI interference present, the following assumptions were made:

- We are interested in the worst-case ratio error, i.e. the worst-case difference between the ratio belonging to a zero-crossing <u>with</u> CWI interference and the same ratio <u>without</u> CWI interference present. Since the ratio without interference is known and independent of CWI parameters, we can also look first for the ratio with interference present, and then subtract the ratio belonging to the pure Loran-C signal.
- The Loran-C signal is built up as shown in fig. 8.

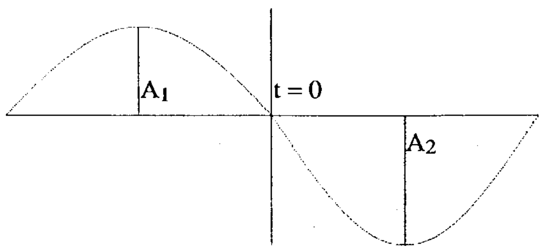

Fig. 8. Definition of a Loran-C signal for analysis.

It consists of two half cycles around a negative going zero crossing, with two different amplitudes A_1 and A_2 (note: this is in fact an approximation of a Loran-C signal). The zero crossing of the pure signal in fig. 8 provides the time reference $t = 0$ for the calculations. The Loran-C signal can then be written as:

$$S_{Loran} = \begin{cases} -A_1 \cdot \sin(\omega_L \cdot t) & t \leq 0 \\ -A_2 \cdot \sin(\omega_L \cdot t) & t \geq 0 \end{cases} \qquad 3.1$$

- The CWI signal is shown in fig. 9.

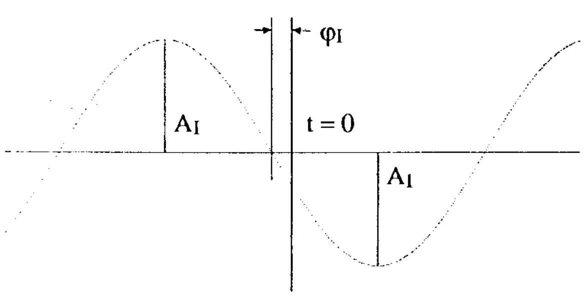

Fig. 9. Definition of a CWI signal for analysis.

It is a pure sine wave with a negative going zero crossing with a phase difference φ_I between the Loran-C signal and the CWI signal:

$$S_I = A_I \cdot \sin(\omega_I \cdot t + \varphi_I) \qquad 3.2$$

- The phase difference φ_I is assumed to be random. This corresponds with real-world conditions: due to propagation effects and position shifts the phase of a received CWI signal is impossible to predict. The ratio found with a CWI signal present, can be smaller or larger than the ratio of the pure signal depending on phase shift φ_I. Therefore, both the maximum and minimum ratios as function of φ_I should be found.

In order to be able to calculate the maximum and minimum ratios as function of φ_I, the following steps have to be made:

1. First the phase tracking error due to the CWI signal has to be calculated. This is necessary since a Loran-C receiver determines ratios by taking samples 2.5 µs <u>before</u> and 2.5 µs <u>after</u> the zero crossing it is tracking. This implies that if a tracking error is made, the sampling moments used for ratio determination will be shifted in time too; this alone will already cause an error in the measured ratio.
2. Then the measured ratio $R_{measured}$ belonging to the tracked zero crossing has to be calculated. This ratio is a function of the Loran-C parameters as defined in equation 3.1 and of the CWI signal parameters as defined in equation 3.2, <u>including</u> φ_I.
3. Next the first derivative $\frac{dR_{measured}}{d\varphi_I}$ has to be found and set equal to zero. This will yield all values of φ_I where $R_{measured}(\varphi_I)$ has a local maximum or minimum.
4. For all values of φ_I where $R_{measured}$ has a local maximum or minimum, that maximum or minimum has to be calculated and the overall highest maximum and lowest minimum have to be found. This yields the maximum and minimum ratios and, by subtracting the constant ratio of the pure signal, also the maximum and minimum ratio errors.
5. For ease of interpretation it was decided to include a possibility to recalculate a ratio found with CWI present, into an apparent zero-crossing. In order to be able to do so, the ratio table calculated for the pure Loran-C signal (which will be similar to table 1) is converted into a continuous function

$$R_{amp} = f_{ratio}(t). \qquad 3.3$$

This function is then inverted to find an apparent zero crossing belonging to a ratio found with CWI present:

$$t_{zero,\ apparent} = f^{-1}_{ratio}(R_{amp,\ CWI}). \qquad 3.4$$

Note that the signal will probably not have a real zero crossing at position $t_{zero,apparent}$. However, by subtracting the zero crossing of the pure signal used for tracking, from

$t_{zero,apparent}$, it is possible to calculate the apparent shift of the envelope due to CWI (see the example of fig. 10). This shift is called the apparent ECD due to CWI.

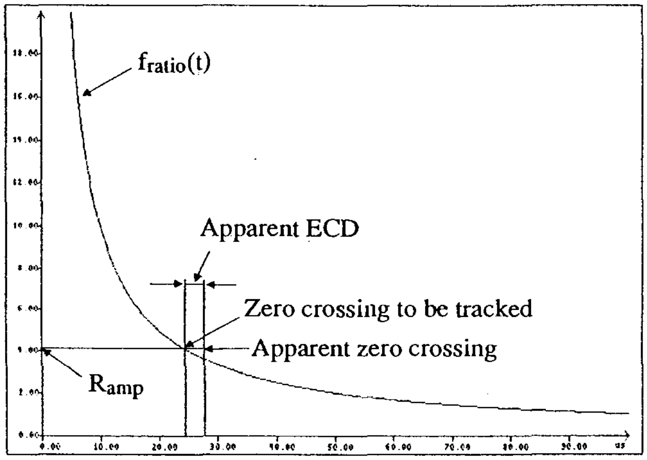

Fig. 10. Calculation of the apparent ECD.

For the calculation of the tracking error the phasor diagram method described in [3] has been used. Fig. 11 shows the phase relations between a Loran-C signal (with zero crossing at t = 0), a CWI signal and the combined signal.

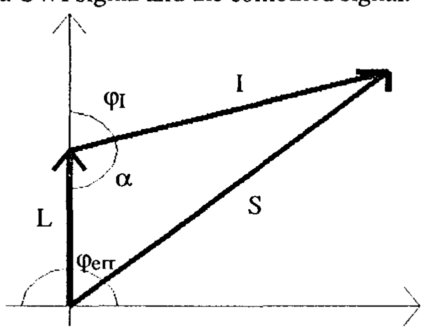

Fig. 11. Phasor diagram used for analysis.

The phase difference φ_I and therefore the angle α, as well as the Loran-C and CWI amplitudes L and I are known. First the amplitude of the combined signal is calculated:

$$S = \sqrt{I^2 + L^2 - 2 \cdot I \cdot L \cdot \cos(\alpha)} \qquad 3.5$$

The angle α is written as: $\alpha = \pi - \varphi_I$, and so equation 3.5 becomes:

$$S = \sqrt{I^2 + L^2 - 2 \cdot I \cdot L \cdot \cos(\pi - \varphi_I)}$$
$$= \sqrt{I^2 + L^2 + 2 \cdot I \cdot L \cdot \cos(\varphi_I)} \qquad 3.6$$

Angle φ_{err} (the phase tracking error angle) can then be calculated with:

$$\frac{I}{\sin(\varphi_{err})} = \frac{S}{\sin(\alpha)} \rightarrow \sin(\varphi_{err}) = \frac{I}{S} \cdot \sin(\varphi_\alpha) \rightarrow$$

$$\varphi_{err} = \sin^{-1}\left(\frac{I}{S} \cdot \sin(\alpha)\right)$$
$$= \sin^{-1}\left(\frac{I}{S} \cdot \sin(\pi - \varphi_I)\right)$$
$$= \sin^{-1}\left(\frac{I}{S} \cdot \sin(\varphi_I)\right) \qquad 3.7$$

This tracking error angle can be converted into a time shift error:

$$t_{err} = \frac{T_L}{2 \cdot \pi} \cdot \varphi_{err}$$
$$= \frac{T_L}{2 \cdot \pi} \cdot \sin^{-1}\left(\frac{I}{S} \cdot \sin(\varphi_I)\right) \qquad 3.8$$

and S in equation 3.8 can be calculated with equation 3.5. For simplicity's sake we will write equation 3.8 often as:

$$t_{err} = t_{err}(\varphi_I) \qquad 3.9$$

Samples for the measurement of the ratio are now taken at $t_1(\varphi_I) = -2.5\ \mu s - t_{err}(\varphi_I)$ and $t_2(\varphi_I) = +2.5\mu s - t_{err}(\varphi_I)$. The corresponding amplitude ratio is:

$$R_{amp}(\varphi_I) = \frac{A_2 \cdot \sin(\omega_L \cdot t_2) + A_I \cdot \sin(\omega_I \cdot t_2 + \varphi_I)}{A_1 \cdot \sin(\omega_L \cdot t_1) + A_I \cdot \sin(\omega_I \cdot t_1 + \varphi_I)} \qquad 3.10$$

and of course t_1 and t_2 are functions of φ_I in equation 3.10 too.

As φ_I is randomly and evenly distributed between $-\pi$ and π, the first derivative $\frac{dR_{amp}}{d\varphi_I}$ has to be calculated and set to zero to find all local minima and maxima:

$$\frac{dR_{amp}}{d\varphi_I} = 0 \qquad 3.11$$

Getting an expression for $\frac{dR_{amp}}{d\varphi_I}$ is complex but standard mathematics, which will not be shown here. The result of this mathematical exercise is that the following equation has to be solved:

$$\left(A_2 \cdot \frac{dt_2}{d\varphi_I} \cdot \cos(\omega_L \cdot t_2) + A_I \cdot (1 + \frac{dt_2}{d\varphi_I} \cdot \cos(\omega_I \cdot t_2 + \varphi_I))\right) \cdot$$

$$\left(A_I \cdot \sin(\omega_L \cdot t_I) + A_I \cdot \sin(\omega_I \cdot t_I + \varphi_I)\right) -$$

$$\left(A_I \cdot \frac{dt_I}{d\varphi_I} \cdot \cos(\omega_L \cdot t_I) + A_I \cdot (1 + \frac{dt_I}{d\varphi_I} \cdot \cos(\omega_I \cdot t_I + \varphi_I))\right) \cdot$$

$$\left(A_2 \cdot \sin(\omega_L \cdot t_2) + A_I \cdot \sin(\omega_I \cdot t_2 + \varphi_I)\right)$$

$$= 0 \qquad 3.12$$

with t_I and t_2 functions of φ_I. Equation 3.10 has a local maximum or minimum at all zeros of equation 3.12. These zeros can be found with well-known numerical methods.

From the set of local maxima and minima the global maximum and minimum ratios can be selected. The maximum and minimum ratios can be converted into maximum (positive) and minimum (negative) apparent ECD shifts with the method shown in fig. 10 and equation 3.4.

The next paragraph will describe the implementation of such an algorithm.

4. THE DELFT CWI ANALYSIS SOFTWARE

Equation 3.12 is too complex to be solved analytically. Therefore, it was decided to use the Bisect method [8], which numerically calculates the roots of an equation with a single variable, to solve equation 3.12.

In order to get results, the following Loran-C and CWI signal parameters have to be known:

- A_I and A_2: the amplitudes of the Loran-C half cycles just before and after the zero crossing of the pure signal which is tracked;
- A_I: the interference signal amplitude;
- ω_I: the interference signal angular frequency.

The amplitudes of the Loran-C and CWI signals can be found easily when it is assumed that these signals are not filtered. This, however, is rather unrealistic, since every Loran-C receiver uses a bandpass filter system in its front-end. This filter system influences the Loran-C burst envelope (and thereby the amplitudes A_I and A_2) even though it usually has no attenuation in the Loran-C band. It also changes the CWI signal amplitude A_I.

For the calculation of A_I and A_2, algorithms for the simulation of bandpass filtering of Loran-C pulses have to be available; such algorithms are described in [6]. In their original form, these algorithms only calculate the filtered Loran-C pulse $S_{Loran-C,\ filtered}(t)$. With numerical methods the zero-crossings of $S_{Loran-C,\ filtered}(t)$ can be found, and by calculating the signal values at 2.5 µs before and 2.5 µs after the zero crossing, the amplitudes A_I and A_2 are found. Suitable algorithms are incorporated into LOSP.

Once filter algorithms are available, calculating the filtered CWI amplitude A_I is easy:

$$A_I = \left|H_{BPF}(\omega_I)\right| \cdot 10^{\left(\frac{SIR}{20}\right)} \qquad 4.1$$

where

- SIR is the Signal-to-Interference Ratio of the CWI signal as defined in the Minimum Performance Specifications [7];
- ω_I is the angular frequency of the CWI signal;
- $\left|H_{BPF}(\omega_I)\right|$ is the amplitude transfer of the filter system at frequency ω_I.

It was decided to include equations 3.10 and 3.12 and the Bisect method for numerically solving them, into the existing receiver simulation program LOSP. This program has been described in detail in [6] and includes facilities easing the implementation of equations 3.10 and 3.12:

- Calculation of zero-crossings, amplitudes and ratios of filtered Loran-C bursts, for a wide selection of different bandpass filter systems.
- Calculation of amplitudes of filtered CWI signals.
- Easy conversion of ratios into zero-crossing positions, as defined in equation 3.4 and fig. 10.
- A good user interface and a program structure which enables easy and fast adaptation.

The output of the calculations in equations 3.10 and 3.12 is given in graphics representation. Three functions are defined:

1. Calculation of apparent ECD as function of variable SIR, with the CWI frequency and the zero crossing to be tracked, having fixed values.
2. Calculation of envelope shift as function of the zero-crossing, with the CWI frequency and the SIR having fixed values.
3. Calculation of envelope shift as function of the CWI frequency, with the SIR and the zero crossing having fixed values.

Fig. 12 gives an example of a typical screen output of the calculations in equations 3.10 and 3.12 in LOSP. It shows that apparent ECD shift is represented in LOSP as a filled area. This area contains all possible ECD shifts that can be found as a function of the CWI phase φ_I, between the maximum positive and the minimum negative shift found with equations 3.10 and 3.12.

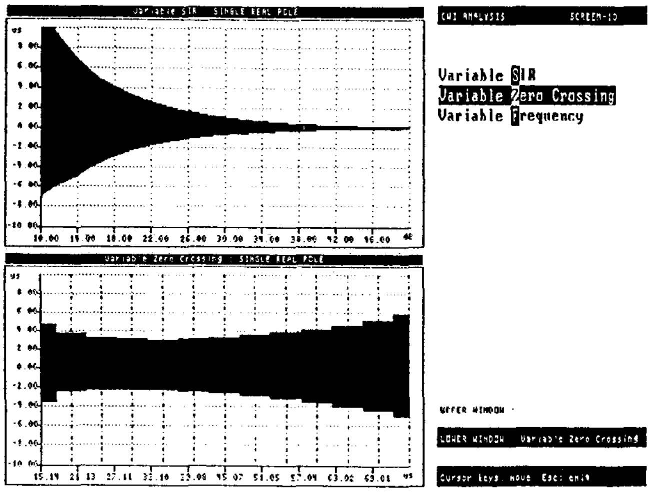

Fig. 12. Typical screen output of CI analysis in LOSP.

The next paragraphs will discuss examples and limitations of the analysis capabilities now provided with equations 3.10 and 3.12 and their implementation in LOSP.

5. AN EXAMPLE

An interesting question to be answered is whether synchronous interference causes more harm to Cycle Identification or to phase tracking in a Loran-C receiver. An analysis was carried out in order to find an answer to this question under the following conditions:

- a GRI of 8940, which belongs to the French Loran-C chain;
- a synchronous interference signal at 85000 Hz, which comes from one of the UK DECCA chains;

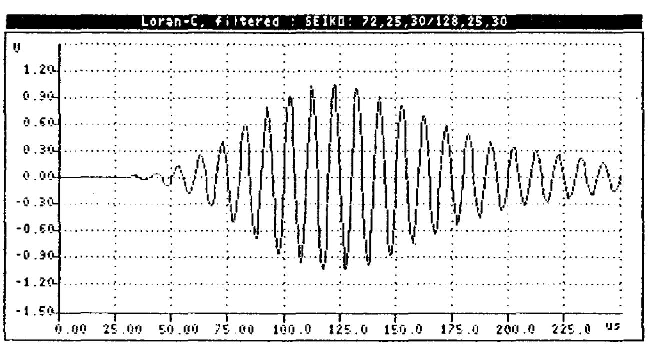

Fig. 13. Loran-C burst filtered with SEIKO filter.

- a SEIKO bandpass filter with a bandwidth of 20 kHz with an amplitude transfer function as shown in fig. 14, and a filtered Loran-C burst as shown in fig. 13.

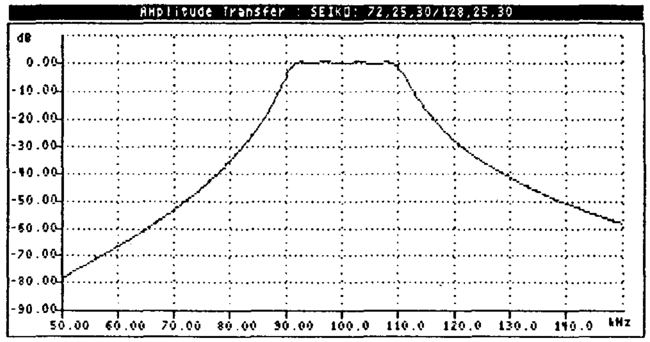

Fig. 14. Amplitude transfer function of SEIKO filter.

- a zero-crossing as far up in the pulse without having a phase tracking error due to skywaves of more than 100 ns.

First the appropriate zero-crossing has to be found. LOSP can calculate the zero-crossings of signals with and without skywaves. By comparing the generated lists, the last zero-crossing with an error less than 100 ns can be found easily. Two lists, one calculated with and the other without skywaves, are shown in table 2.

Bandpass filter: SEIKO
Bandwidth: 20 kHz
Center frequency: 100 kHz

Zero of pure signal	Zero with skywave
40.4242 μs	40.4242 μs
45.3419 μs	45.3416 μs
50.2739 μs	50.2709 μs
55.2168 μs	55.2047 μs
60.1683 μs	60.1365 μs
65.1269 μs	65.0614 μs
70.0914 μs	69.9760 μs
75.0607 μs	74.8787 μs
80.0344 μs	79.7690 μs
85.0119 μs	84.6474 μs

Table 2. Zero's of pure and skywave-contaminated signals.

From table 2, it can be seen that the last zero crossing without skywave contamination is found at 65 μs. This zero crossing was used in the rest of the analysis.

The next step is to generate a picture containing the maximum and minimum envelope shift due to CWI under the chosen conditions, as a function of the (unfiltered) SIR. This was done again with LOSP and the results are shown in fig. 15. With increasing SIR the envelope shift decreases towards zero.

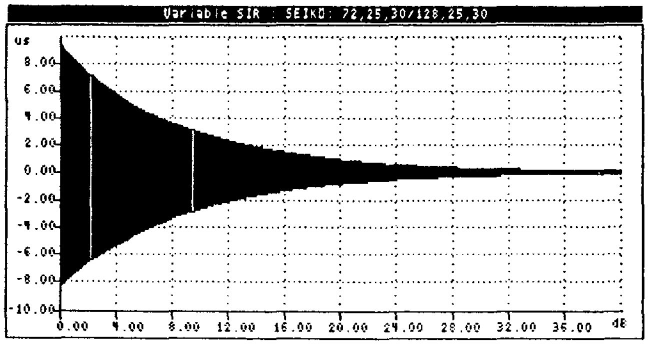

Fig. 15. Envelope shift as function of SIR - an example.

We can define a synchronous CWI signal to be harmless if the tracking error it causes, is smaller than 100 ns. With the phasor method described in [3], it is possible to calculate the worst-case tracking error due to a synchronous CWI sugnal. The equation to be used is:

$$t_{err} = \frac{1}{4} \cdot T_L \cdot \left(\frac{2}{\pi} \cdot \arcsin\left(\frac{A_I}{A_l}\right) \right) \qquad 5.1$$

where:

- T_L is the Loran-C carrier cycle time of 10 ms;
- A_l is the Loran-C signal amplitude before the zero crossing (this amounts to worst-case conditions);
- A_I is the filtered CWI signal amplitude.

Equation 5.1 can be converted to calculate the filtered CWI signal amplitude A_I as function of the tracking error t_{err}:

$$A_I = A_l \cdot \sin(2 \cdot \pi \cdot \frac{t_{err}}{T_L}) \qquad 5.2$$

With equation 5.2 and the maximum allowable t_{err}, we can then calculate the corresponding amplitude A_I:

$$A_I = A_l \cdot \sin(2 \cdot \pi \cdot \frac{0.1\ \mu s}{10\ \mu s}) \approx 0.064 \cdot A_l$$

LOSP gives an amplitude A_l (relative to the Loran-C pulse peak) for a SEIKO filter at 65 µs of 0.25, so the maximum permissible A_I is 0.016 (also relative to the Loran-C pulse peak). With the amplitude transfer of the SEIKO filter at 85 kHz, this amplitude can be recalculated into a Signal-to-Interference Ratio as defined in the MPS [7]. This simple calculation yields a SIR of 7 dB; this SIR should not get lower if the tracking error caused by the CWI signal on 85 kHz is to remain below 100 ns.

In fig. 15, we can see that a CWI signal at 85 kHz with a SIR of 7 dB, will cause an apparent ECD shift between 4 µs maximum and -4 µs minimum. This is already much more than specified in the MPS [7]: the MPS require a receiver to lock onto the proper zero crossing with a maximum ECD of ± 2.4 µs. In principle Cycle Identification is possible with ECD up to ± 5 µs, but with the presence of noise and "real" ECD (due to propagation effects), the chance of detecting the proper cycle with an apparent ECD shift of 4 µs due to synchronous CWI, are quite slim. This illustrates that synchronous CWI signals are potentially more dangerous to Cycle Identification than to phase tracking.

6. CONCLUSIONS

A model has been presented describing the effects of synchronous CWI interference on Loran-C Cycle Identification. The Loran-C receiver simulation program LOSP has been shown to be a good tool for implementation of the model on a computer. An example has been given of the usefulness of the implemented model in analyzing the problems synchronous CWI can cause.

The model presented here, is certainly not perfect. Some possible improvements are:

1. Due to the Loran-C transmission sequence with its irregular phase coding pattern, the relative phase φ_I of a synchronous CWI signal has a different value for each of the 16 Loran-C pulses within a cycle of 2 GRI. After 16 pulses (2 GRI seconds), φ_I has the same value again. Since Cycle Identification uses long integration times, this effect probably can be modeled as a reduction in the interference amplitude A_I.
2. Equations 3.10 and 3.12 are valid if one CWI signal is present. As fig. 1 shows, this is not the case in Western Europe, even if only synchronous signals are selected from all signals present. Therefore, an expansion of equations 3.10 and 3.12 is necessary to include the effects of more than one synchronous CWI signal.
3. Equations 3.10 and 3.12 are developed for pure Loran-C bursts without ECD. Future versions of the model can include "real" ECD (due to propagation effects) and skywaves, to see the total envelope shift under real-world conditions.

Another future development is the inclusion of the model presented here, into the coverage prediction software described in [9]. This should lead to a further improvement in real-world coverage prediction, especially under European conditions.

7. ACKNOWLEDGEMENTS

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About the author

Martin Beckmann was born in 1964. He studied Electrical Engineering at the Delft University of Technology, and completed his masters thesis in 1987 concerning software for an OMEGA navigation receiver. He is still with the Delft University of Technology, working on Loran-C.

THE RAYMONDVILLE GHOST
Loran-C Signal Reflections

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ABSTRACT

In 1979, eight months after declaring the new Southeast U. S. (7980) chain operational, the U. S. Coast Guard issued a Notice to Mariners message warning of a low-level unidentified interference source affecting Loran-C navigation in the Port Isabel/Brownsville, Texas area. Receivers from several manufacturers acquired the interference signal in place of the Raymondville (7980X) groundwave. The interference was in the form of low-level signal bursts with Loran-C characteristics delayed by about 1500 microseconds from the Raymondville secondary signal and became known as the Raymondville Ghost. This paper characterizes the interference signal, recounts the search for the cause of the interference, describes the interference source, and identifies in the coverage area of the new Mid-Continent transmitters some potential signal reflectors with characteristics similar to the Sierra Madre Oriental escarpments that are the source of the Raymondville Ghost.

INTRODUCTION

The Southeast U. S. Chain (7980) was declared operational in October, 1978. The Loran-C signal interference problem, here called the Raymondville Ghost, was first noticed by shrimp fleet captains in the area of the Brownsville ship channel and the Port Isabel area in southern Texas, on the coast of the Gulf of Mexico [Figure 1]. The Loran-C receivers of several manufacturers attempted to lock on to (and in some cases tracked) a low-level interference signal delayed in time by some 1500 microseconds after the arrival of the Raymondville secondary signal. The result was improper acquisition and in some cases position errors of hundreds of kilometers.

In December of 1978 a major manufacturer reported the problem to the Coast Guard Chain Commander of the Atlantic Area [Reference 1]. An unsuccessful search for the interference source was conducted by both manufacturers and U. S. Coast Guard personnel. In 1979 a team was contracted by the Coast Guard to locate the source of the signal. The source was finally located in Mexico. Manufacturers made modifications to eliminate the problem, but the Raymondville Ghost signal still exists.

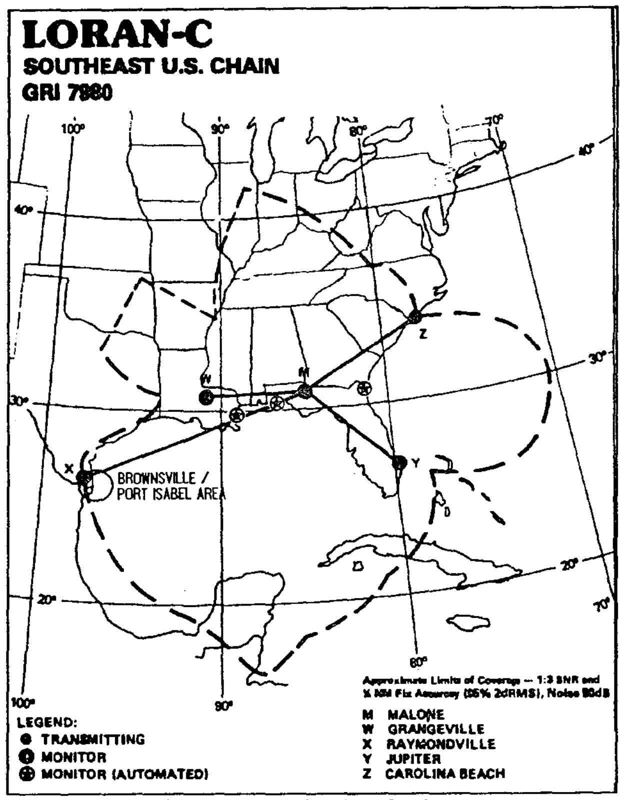

Figure 1. Southeast U. S. Chain (7980)

The Southern Mid-Continent Chain, using the Raymondville transmitter on another rate, may increase the use of the Raymondville signals, particularly in avionics receivers. New Mid-Continent Chain transmitters are coming on the air and some are located in places where similar "Ghost" signals could occur.

The purpose of this paper is to record the history of the Raymondville Ghost, to suggest that other Ghosts may occur, and to remind a new generation of Loran-C designers that some of the best acquisition schemes of major manufacturers were spoofed by the Raymondville Ghost.

THE INTERFERENCE PROBLEM

The Raymondville Ghost signal was often acquired, and in sometimes tracked, by some Loran-C receivers in the South Texas Gulf of Mexico area. The problem was of serious concern in early 1979.

The shrimp boat fleets were then the largest user of Loran-C sets in the area. These boats used Loran-C, particularly for its repeatable accuracy, to locate hazards and fishing areas. The Ghost signal caused the receivers to occasionally report time differences (TDs) with 1500 microsecond errors on the Raymondville 7980X secondary signal. While this most often occurred during initial acquisition in port, making the problem noticeable, it was not a simple matter to force correct acquisition by any other method than to continuously re-acquire until the TD was correct. In addition to the noticeable, in port, acquisition, boats entering the Raymondville service area from other areas of the Gulf of Mexico could unknowingly acquire the Ghost signal, introducing large position errors (200-300km) in receivers tracking three stations, and smaller, less noticeable errors in multiple station receivers.

This was a period in which the expansion of the Loran-C system with the installation of the Southeast U. S. Chain was accompanied by the introduction of new and inexpensive (then <$1,000.00) receivers. The appearance of the Ghost caused both an operational problem for users and a serious product image problem for several manufacturers attempting to make large numbers of sales in the area. In addition, the phasing out of Loran-A transmitters was being met with criticism from the same fleet owners that were having these Loran-C problems.

INTERFERENCE PARAMETERS

The Raymondville Ghost signal is a low-level set of eight Loran-C like pulses that occur at one millisecond intervals, delayed (in the problem area) by some 1500 microseconds from the Raymondville groundwave. Early investigations by manufacturers resulted in some characterizations of the Ghost.

Signal Characteristics

The Ghost signal can be seen in the area on an oscilloscope. Figure 2 shows the first five groundwave pulses and the first three Ghost pulses. In addition to the groundwave and main Ghost pulses, other interference bursts can be seen.

The Problem Area

The Raymondville Ghost problem area appears to be a local one, with the interference problem only noticeable in the Southeast Texas area.

Phase Code

The signal maintains the secondary phase code of the Raymondville groundwave signal.

Time Differences

The relative time difference between the Master (at Malone, Florida) and the Raymondville groundwave changes from location to location. This is an indication that the Ghost is not present on the signal when transmitted by the Raymondville antenna.

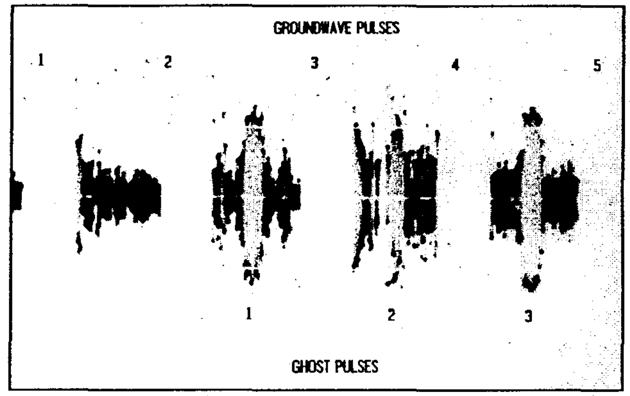

Figure 2. Raymondville Ghost: First Three Pulses

Amplitudes

The amplitude of the Ghost signal often changes by more than 10db over a short distance (<20km) while the amplitude of the Raymondville groundwave changes by less than one decibel (db) over the same distance. The Ghost signal varies in amplitude relative to the Raymondville groundwave from -40 to -55db [Reference 2].

Receiver Effects

Several well-known manufacturers, using different receiver techniques, experienced similar problems in acquisition and tracking of the Ghost. It seemed unlikely that similar interference was caused by different receivers.

Skywave

In the locations affected by the Ghost, the range to the Raymondville transmitter is around 80 kilometers. Multiple-hop skywaves can be detected out to around 900 microseconds, but none appear between the end of the second groundwave pulse and the start of the Ghost. Early efforts [Reference 1] showed that while these skywave pulses shifted amplitude and delay during the diurnal shift, the Ghost amplitude and phase remained relatively constant.

Early attempts at source location

Initial attempts to locate the source of the Ghost signal were based on the assumption that the source was in the Brownsville/Port Isabel area. Both manufacturers and the Coast Guard made field strength measurements in the area. In every case the largest amplitude readings were observed at the eastern end of the Brownsville ship channel near Port Isabel. Coast Guard personnel made initial attempts to locate the source with a loop antenna and a Loran-C timing receiver. The measured bearings showed a tendency to point parallel with the ship channel, but no conclusive results were obtained.

Many theories were advanced. Power line retransmission, power line carrier interference, retransmission from satellite television systems or decommissioned Loran-A transmitters, and even buried rail lines were suspected as possible sources.

COAST GUARD SPONSORED INVESTIGATION

The Broadcast Warning appeared in the June 23, 1979 Notice To Mariners [Reference 3]. In December of 1979, a team from Austron Navigation, Inc. was contracted by the Coast Guard to find the source of the Raymondville Ghost.

First measurement trip

The first Austron measurement trip to the area was in February, 1980. The Austron Navigation, Inc. measurement van was equipped with a three-kilowatt generator, an Austron 5000M Loran-C Monitor (an eight-station, four-chain receiver), both whip and loop antennas, an Austron 1250 Crystal Frequency Standard and an Austron 6030 Loran Assist Device (latitude, longitude converter).

Tracking the Ghost

All of the reported characteristics of the Ghost signal were confirmed during the first few hours in the area.

During acquisition the 5000M searches over several seconds for Loran-C energy occurring at the Group Repetition Interval (GRI). A table is constructed with approximate arrival times of phase coded 100kHz energy. To track the Ghost, the 5000M was manually instructed to track the interference signal after its approximate time of arrival was found following the Raymondville groundwave in the acquisition table.

Tracking points were selected at approximate delays of 500, 1500, and 2500 microseconds after the Raymondville groundwave signal. Phase code errors occurred at both the 500 and 2500 microsecond delays. The 5000M would occasionally attempt to lock onto the Ghost signal if the receiver happened to start looking for Loran-C energy at the Ghost position in the acquisition table.

The shape of the signal was difficult to characterize. The 5000M did not automatically track the signal because no envelope shape was found that satisfied the criteria for third-cycle tagging.

Measurement Sites

During this first trip, an attempt to locate the source was conducted using field strength and bearing measurements. Measurement sites were chosen for convenience and proximity to intersections that could be located on U. S. Geodetic Survey (USGS) 7.5 minute quadrangles. Positions were located to an accuracy of about one second (about 30 meters).

Field Strength Measurements

Field strength was measured in db above one microvolt per meter using the 5000M signal strength parameter. Because this parameter assumes a specific envelope shape, the reading can vary by six db with different manually selected tracking points near the start of the Ghost pulse.

Figure 3 shows the measured field strengths at measurement sites from this first trip. These measurements confirmed the earlier reports of high signal strength near the east end of the ship channel.

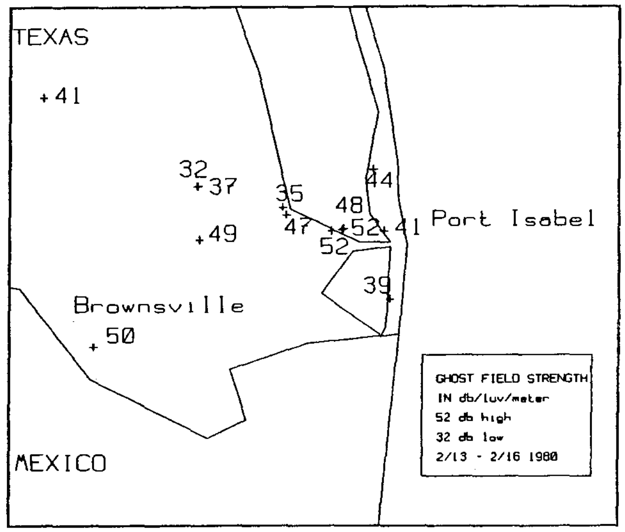

Figure 3. Local Area Ghost Field Strengths

Bearing Measurements

Bearings to the source were measured by adjusting a loop antenna until a minimum Ghost field strength was measured. The bearing were adjusted by the local magnetic variation and for the 90 degree offset in null measurements. The resulting bearings and their reciprocals were plotted [Figure 4].

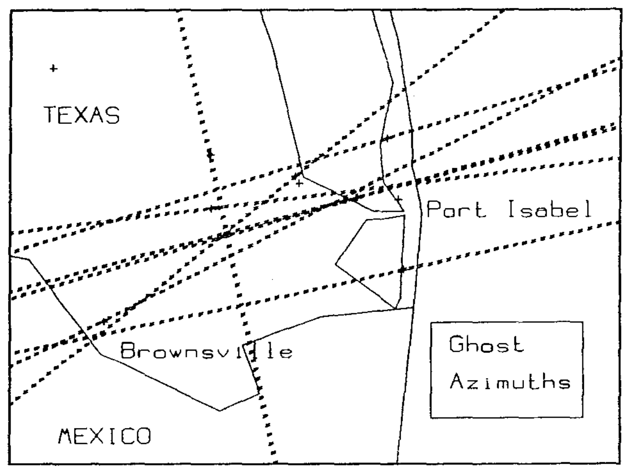

Figure 4. Local Area Ghost Bearings

Time Difference Measurements

Ghost time differences were recorded at each site. Because no attempt was made to maintain cycle lock between measurement sites, the TDs are only approximate indicators of Ghost arrival times with respect to the Master. Table 1 shows the first trip measurements.

First Trip Results

The results of this first trip, other than to confirm the existence of the Ghost and to verify the measurements made by previous investigators, were inconclusive. The source was not located.

Table 1. Trip One Data

#	Date	Time	Name	Lat	Long	α	db	TD
1	2/13	1720	FCC Monitor	27:28:00	97:51:30	218	40	25030.0
2	2/14	1013	PI Marina	26:04:30	97:12:47	254	48	25053.0
3	2/14	1045	San Roman	26:03:56	97:23:53	263	49	24947.7
4	2/14	1120	100 & 510	26:05:37	97:17:09		47	25012.0
5	2/14	1112	48 & 100	26:04:24	97:13:37		52	25044.0
6	2/14	1132	2480 & 510	26:07:43	97:23:55		37	24952.0
7	2/14	1340	802 & 281	25:56:17	97:32:07	243	50	24826.0
8	2/14	1529	Boca Chica	25:59:47	97:09:07	258	39	25066.0
9	2/15	1300	Wright's	26:04:34	97:12:39	255	52	25085.3
10	2/15	1400	Padre South	26:04:22	97:09:29		41	25116.2
11	2/15	1555	Laguna Vista	26:06:07	97:17:26	231	35	25034.0
12	2/15	1800	Andy Bowie	26:08:43	97:10:17	253	44	25094.0
13	2/16	1330	Bay View	26:07:42	97:24:01	348	32	24969.9
14	2/16	1500	1420 & 508	26:13:59	97:35:48		41	24873.3

Second Measurement Trip

A second field trip was made from June 23 to June 28 of 1980. Plans were made for a second trip to attempt source location by time of arrival phase tracking measurements and to test the power line carrier theory.

Power Line Carrier

Several people had suggested that Power Line Carrier (PLC) might be related to the Ghost interference. Power Line Carrier is the generic name for communications equipment that is used by power companies to send data and control information over power lines using low frequency transmitters and receivers. Much of this equipment transmits at 100kHz. One theory proposed that a PLC system might receive and retransmit the Raymondville signal, accounting for the 1500 microsecond delay by transmission over a 450km round-trip path length.

With the assistance of an official of the local Central Power and Light Company, the 100kHz PLC equipment was shut down for 25 minutes at noon on June 24. Prior to the shut-down the 5000M was set up to track the Ghost using the loop antenna adjusted for maximum gain. No change in amplitude or signal phase was notice during the shutdown so the PLC interference source theory was rejected.

Time of Arrival Measurements

The other planned measurements were time of arrival (TOA) measurements. By phase locking to an arbitrary cycle of the Ghost signal, travelling slowly along the roads, avoiding power lines and urban areas, it was possible to maintain phase lock on the Ghost signal. By returning to the starting point and observing time difference measurements within one microsecond of those measured at the start, phase lock was confirmed. Two sets of phase-locked time of arrival data were measured.

Measurement Sites

Measurements were made at sites with positions that could be located on the 7.5 minute quadrangles, but because the van was moving continuously along the road, the accuracy of the positions may be in error by as much as 5 seconds of latitude and longitude (about 150 meters).

Clock Drift

The 5000M records both TDs and TOAs. Because the TOAs are measured with respect to the frequency standard driving the 5000M, an attempt was made to rate this clock. TOAs on the strong Raymondville groundwave were measured at the position that was used as the start and the end for the data sets. Multiple time and TOA measurements were made on this signal. Mean start time and start TOAs were subtracted from mean end times and TOAs to arrive at a linear oscillator drift estimate for the clock during the measurement period. The drift was then used to adjust each measured TOA to produce an adjusted TOA for each measurement site.

TOA Data Set 1

The first data set was taken in the primary problem area. Table 2 shows the first set of phase-locked data.

Table 2. Set A (Oscillator drift= .002662 μs/s)

1	Time	Name	Lat	Lon	db	TD	TOA	Adj TOA
1	11:04:46	802 & 281	25:56:17	97:32:07	50	24815.8	31504.6	31504.6
2	11:13:02	1421 & 281	25:59:37	97:36:09	52	24801.8	31492.2	31490.9
3	11:34:16	Int & 4	25:54:03	97:29:14	39	24836.0	31523.8	31519.1
4	11:38:46	4 & 1419	25:54:37	97:28:27	39	24851.1	31531.8	31526.4
5	11:43:29	511 & 1419	25:53:25	97:26:15	38	24858.9	31533.0	31526.8
6	12:04:16	4 & 511	25:55:00	97:24:25	37	24888.2	31552.3	31542.8
7	12:07:09	802 & 511	25:56:19	97:24:25	37	24892.9	31552.6	31542.6
8	12:08:46	48 & 511	25:57:05	97:24:33	37	24893.3	31554.3	31544.0
9	12:28:09	100 & 48	26:04:24	97:13:38	55	25045.8	31632.4	31619.1
10	13:24:07	510 & 100	26:05:37	97:17:09	53	25013.6	31623.8	31601.5
11	13:41:27	1847 & 100	26:04:17	97:28:33	45	24889.9	31563.6	31538.6
12	13:46:16	1847 & 511	26:00:50	97:28:52	48	24871.7	31557.1	31531.3
13	13:52:03	1847 & 802	25:56:54	97:29:13	53	24848.8	31548.0	31521.2
14	11:51:46	3068 & 1419	25:51:57	97:24:27	38	24874.0	31543.3	31535.7

TOA Data Set 2

Because of the difficulty in maintaining phase lock for any distance, a second set of TOA data was taken in an area north and west of the Brownsville area. The data from that set is presented in Table 3.

Table 3. Set B (Oscillator drift=.001258μs/s)

1	Time	Name	Lat	Lon	TD	TOA	Adj TOA
1	14:54:20	Rest Area	26:29:59	99:04:09	24636.5	45844.1	45844.1
2	15:00:50	2098 & 83	26:31:55	99:05:22	24645.3	45853.5	45853.0
3	15:03:20	Power Line	26:32:49	99:06:31	24646.8	45859.9	45859.2
4	15:05:20	2098 & 46	26:33:54	99:07:30	24649.3	45865.9	45865.1
5	15:11:20	Falcon Dam	26:33:10	99:08:38	24636.9	45861.3	45860.1
6	15:19:50	Salinas Rd	26:31:40	99:05:19	24643.5	45855.4	45853.4
7	15:23:50	Salinas Sq	26:30:57	99:06:44	24629.9	45851.2	45849.0

Preliminary Data Analysis

The data from the second trip measurement sets were used to estimate the position of the Ghost source.

TOA Analysis

The times of arrival were interpreted as if the Ghost was a signal re-transmitted from a single point. A computer program was developed that used the relative arrival times from these two sets of sites to locate the probable position of the source.

The program used pairs of TOAs from each set of sites as lines of positions in a reverse navigation process. Several sets of data pairs were used and the results averaged to estimate the position of the source. The geometry of the measurement sites and the estimated measurement noise was used to predict the position error.

The program indicated a source at 25:22:10 North latitude and 99:20:50 West longitude, with a 48km circular error of position. This is a position south and east of Monterrey, in northern Mexico.

Bearing Analysis

When re-plotted at a smaller scale [Figure 5], the bearing data from the first field trip was now seen to support the possibility of this position as the source of the Ghost.

Flight Over Mexico

In July, 1980, the Austron team made a flight to Mexico in a twin-engine Cessna, equipped with an ONI 711 Loran-C avionics receiver and an oscilloscope. The Ghost did not appear on the screen until about 40km from Brownsville in the direction of the probable source position.

During the flight, the delay of the Ghost signal with respect to the Raymondville groundwave decreased. As the plane flew along the azimuth toward the predicted position the delay was reduced from about 1400 microseconds to a few hundred microseconds. As the interference signal delay went from 1200 to 1000 microseconds, it passed through the Raymondville groundwave second pulse and re-appeared with a delay of less than 1000 microseconds.

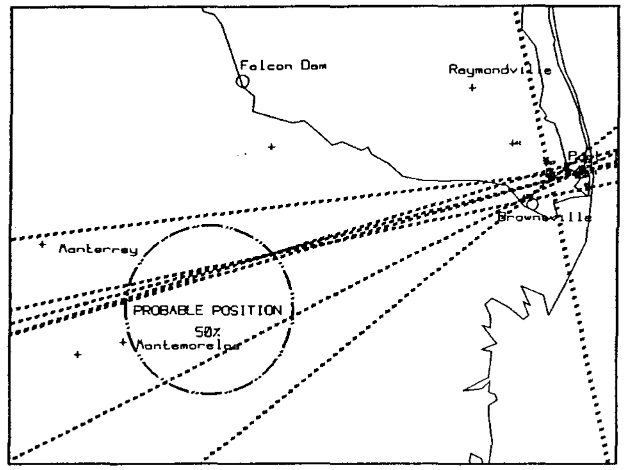

Figure 5. Probable Ghost Position and Bearings

When the aircraft reached the predicted area there was still a delay of around 300 microseconds. At the predicted point the Ghost amplitude was large, with an amplitude of -30db with respect to the groundwave. While continuing to fly along the predicted azimuth, the signal delay decreased and was still just visible behind the groundwave at the town of Montemorelos. Beyond Montemorelos, the eastern escarpments of the Sierra Madre Oriental climb from an elevation of a few hundred meters to almost 3000 meters in a short distance. As the aircraft approached the steep face of these mountains the Ghost signal disappeared into the groundwave pulse. The Ghost signal did not reappear west of the ridge.

Investigation Results (1980)

It seemed possible that the Ghost signal was the Raymondville groundwave reflecting off the face of the steep escarpment of the Sierra Madre. If the mountain ridge near Montemorelos was modeled as a flat reflector, an incident ray path angle from Raymondville would result in an equal angle of reflection toward Brownsville [Figure 6]. Field strength magnitudes could be explained by the 450km path from Raymondville to Montemorelos and back to Brownsville, and a directed beam could account for the high field strength readings directly in the center of the beam at Port Isabel.

A report [Reference 4] was issued to the Coast Guard in July, 1980 and was circulated by Coast Guard Headquarters to interested parties. No further action was taken by the Coast Guard because the Ghost was seen as primarily a receiver problem. Careful design can reduce the chance of locking up on a signal some 1500 microseconds late and with a -40db field strength relative to the desired signal. Manufacturers were quick to change their acquisition techniques (rumor has it that one manufacturer installed "Texas Mod" software). The operational problem disappeared with receiver re-design, but the Raymondville Ghost signal is still there.

Figure 6. Sierra Madre Oriental Near Montemorelos

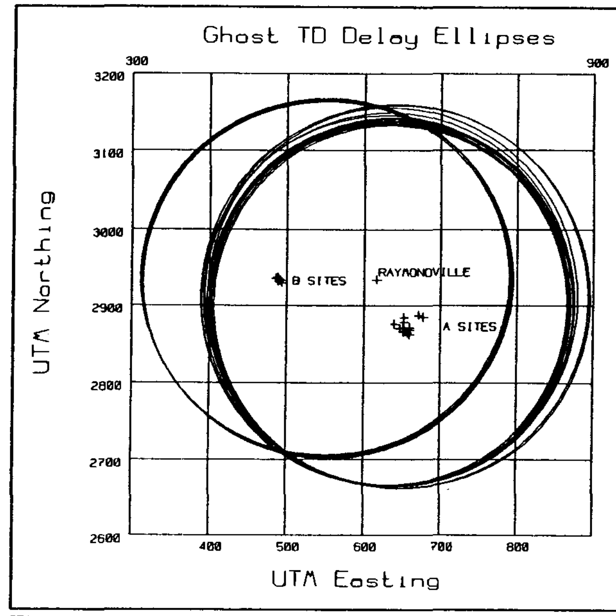

Figure 7. TD Delay Ellipses

GHOST SIGNAL REFLECTION ANALYSIS (1990)

The Raymondville Ghost continues to exist. The Raymondville transmitter has been dual rated for the new South Central Chain. The Ghost now is being transmitted on two GRIs. New avionic receivers are being designed and additional areas of the country will soon be within the coverage area of the new Mid-Continent Chains.

Because some of the new transmitters will be located near the eastern edge of the Rocky Mountains, and the Raymondville transmitter will be utilized in areas not previously covered with good Loran-C, a new look at the Ghost source in Mexico is appropriate.

TD and TOA Analysis

The data presented in Tables 2 and 3 can be used in several ways to point to the Ghost source.

Delta TD Ellipses

Each measured TD from the Ghost signal can be converted to delays from measured or predicted Raymondville groundwave TDs. These delta TDs can be interpreted as ranges over the path from the transmitter, to the Ghost source, and back to the measurement site. For both sets of phase-locked TD measurements the ellipses can be plotted on a grid representing the possible Ghost source locations. Figure 7 shows these ellipses plotted in Universal Transverse Mercator (UTM) Northing and Easting. Because the entire area covers only a few hundred kilometers, all of the analysis assumes that ranges and bearings computed from UTM coordinates are close enough to ellipsoidal earth computations that the differences are far less than the noise in the initial measurements. The datum for this UTM system is the North American Datum of 1927.

The Ghost signal, if it were a single source, would be located near the area in which the ellipses intersect.

Function Minimization

For this report, a program was written that iteratively solves for a single source position, minimizing the residuals between the predicted and observed TOAs for both set of sites. The directional derivatives for TOA errors from the two sets of sites are used together by assuming two different clock bias offsets for the two sets of sites. Equation 1 shows the method used to move a predicted position to a minimum residual error point. The program, imprecise because of the poor geometry (GDOP>22), measurement noise (around 2μs), and the dubious assumption of a single point source, predicts a source location at 25:23:42N latitude and 99:15:53W longitude (473375 East, 2808546 North).

Δ*Easting*, Δ*Northing*, *and range*
from predicted position to each measurement site

$$A = \begin{vmatrix} (\Delta Easting/range \;\; \Delta Northing/range \;\; -1.0 \;\; 0.0)_{TOA\ SET\ 1_i} \\ (\Delta Easting/range \;\; \Delta Northing/range \;\; 0.0 \;\; -1.0)_{TOA\ SET\ 2_i} \end{vmatrix}$$

Δ *TOAs = measured TOA-predicted TOA*

Δ *position* $= (A^T * A)^{-1} A^T * \Delta$ *TOA*

new position = predicted position + Δ *position*

(1) Iterative Source Prediction from Two TOA Sets

Grid Correlation

Another way to look at the TOA data is to compute TOA residuals at 10km grid points over the area. A residual grid was produced for each set of TOAs. By multiplying the grids together, a new grid is formed that graphically displays the correlation between residuals from both data sets [Figure 8]. The minimum contours center on the area in which the source should be found.

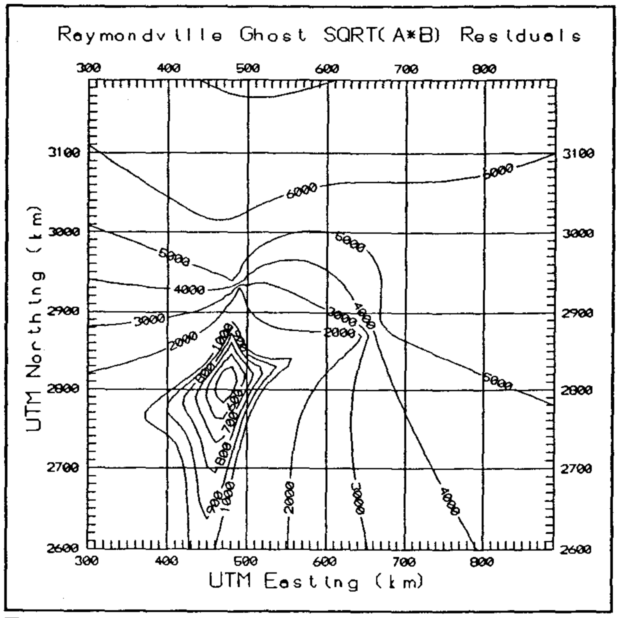

Figure 8. Correlation of Both TOA Residual Sets

Reflection Source

The Sierra Madre Oriental is a thrust fault, with limestone layers from the Lower Cretaceous period standing on edge [Reference 5]. A digital terrain model [Figure 9] of part of the ridge near Montemorelos was produced from topographic maps [Reference 6]. Viewed from the direction of the Raymondville transmitter, the mountains present a considerable reflecting surface. The cross section through the ridge center shows the steepness of the slope, shown with a vertical exaggeration of five.

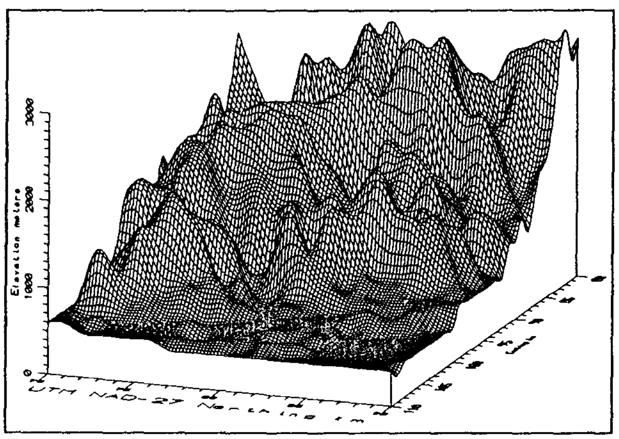
Figure 9. Montemorelos Area Sierra Madre Ridge

Ground Reflections

Loran-C ground reflections are usually associated with the ground reflections of multiple-hop skywaves. The skywave ground reflection coefficient is related to ground conductivity and incidence angle [Reference 7]. For the skywave case where a vertically polarized signal reflects from a surface perpendicular to the plane of polarization, the effect of incidence angle on both attenuation (3 to 15db) and phase shift (10 to 180 degrees) is significant.

The case here, in which a vertically polarized signal is reflected from a surface in the same plane as the polarization, the incidence angle has a minimal effect on both attenuation (<3db) and phase shift (<10 degrees) [Reference 8].

Roughness

The Rayleigh criteria [Reference 9] defines a surface as smooth if the height of surface features is less than the value given by Equation 2. It is not clear that this expression holds true for very large wavelengths such as the 3000 meter Loran-C wavelength. If the criteria is applicable, a ridge over an eighth of a wavelength high could reflect the groundwave and the surface of the ridge facing the incident ray (at 83 degrees) would have to have average surface variations of less than 378 meters. Both requirements are met by the uplifted-sedimentary layers of the Sierra Madre Oriental near Montemorelos.

$$h < \frac{\lambda}{8*\sin(\gamma)}$$

where h = surface relief height
λ = wavelength
γ = angle of incidence

(2) Rayleigh Smoothness Criteria

Models of the Ghost

It seems reasonable to assume that although the Montemorelos area ridge is a prime candidate for the source of the Ghost, many reflections from other ridges along the escarpment may combine to form complex interference patterns in the South Texas area. The following simplified models can assist in an understanding of the Raymondville Ghost.

Beam Forming

Antenna beam forming techniques can be used to model the reflection pattern from the ridge. Figure 10 shows the result of applying Equation 3 [Reference 10] to a ridge 30 kilometers long, centered at 390km Easting, 2780km Northing, and angled at the 152.24 degree azimuth of the Montemorelos ridge. This pattern was generated by assuming 30 antenna elements at one kilometer spacing along the ridge. Phase shifts at each element are computed from the range to the Raymondville transmitter. The resulting narrow beam is directed in the azimuth that points to the Brownsville/Port Isabel area.

$$E(\Theta) = a/n_e * \sum_{n=0}^{n=n_e} e^{(j*\phi_n - j*k*de*n*SIN(\Theta))}$$

where E = beam field
Θ = azimuth
a = field strength of emitters
n_e = number of emitters
ϕ_n = phase shift of emitter n
de = distance between emitters

(3) Antenna Beamforming Equation

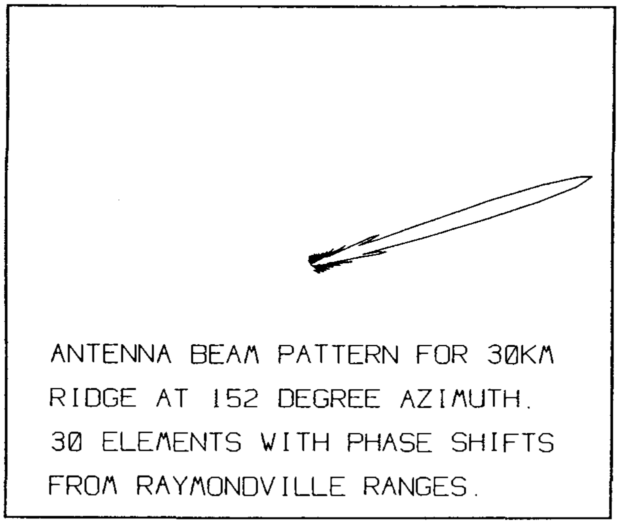

Figure 10. Antenna Beam Pattern

Ghost Simulation

The Ghost reflection pattern can also be modeled through a simulation. Figure 11 shows the results of a simulation in which the 30 source elements along the same ridge described above are used to compute at each grid point the phase and amplitude of the resulting signal. In this simulation, attenuation from ground conductivity is included in the computations. The resulting pattern matches the direction of the beam pattern, but includes predicted field strengths for the Ghost signal. When examined in the area of the field measurements, the pattern shows a remarkable ability to predict Ghost field strengths [Figure 12].

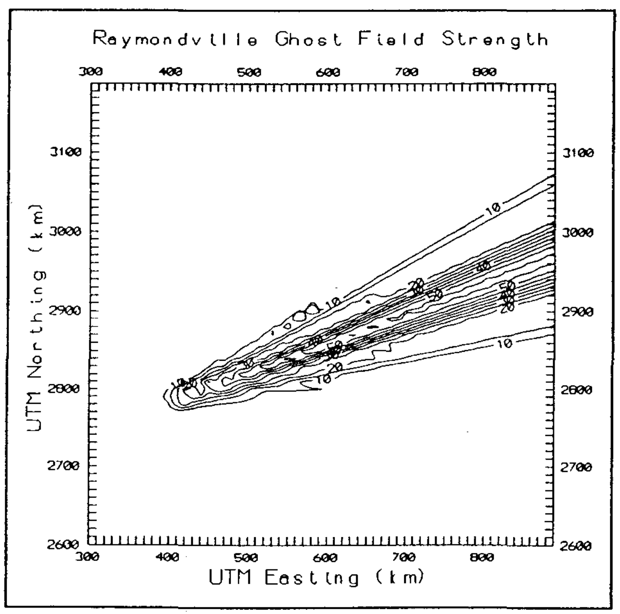

Figure 11. Ghost Field Strength Simulation

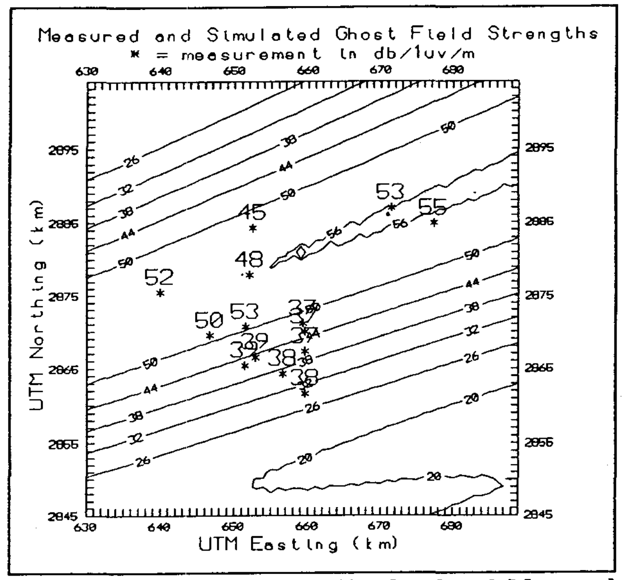

Figure 12. Brownsville Area Simulated and Measured Ghost Field Strengths

MID-CONTINENT CHAIN IMPLICATIONS

The new Mid-Continent Chains [Figure 13] will use the Raymondville signal on two GRIs. New transmitters are coming on-line east of the Rocky Mountains. In those areas where reflections might occur with sufficient amplitude to be seen by a receiver, careful receiver acquisition design and the ability of the Loran-C phase code to minimize tracking errors caused by one pulse (1ms) delays can solve most Ghost-like problems. But near reflectors where Ghost delays are small, errors in phase tracking of the groundwave can occur.

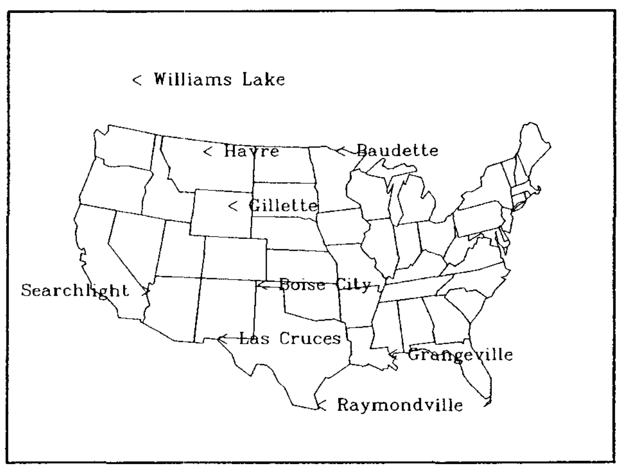

Figure 13. Mid-Continent Transmitters

Figure 14 is a view of the eastern edge of the Rocky Mountains, as seen from a vantage point just above the new transmitter at Boise City, Oklahoma. The ridges of the mountains east of Pueblo, Colorado share many of the characteristics of the Sierra Madre Oriental. For example the Greenhorn Mountain ridge is a sedimentary uplift, and has steep slopes rising to half wavelength heights above flat ground in the direction of a transmitter less than 200 kilometers away. While the particular geologic features of the Sierra Madre Oriental near Montemorelos may be unique, the possibility exists for new Ghosts along the eastern edge of the Rocky Mountains.

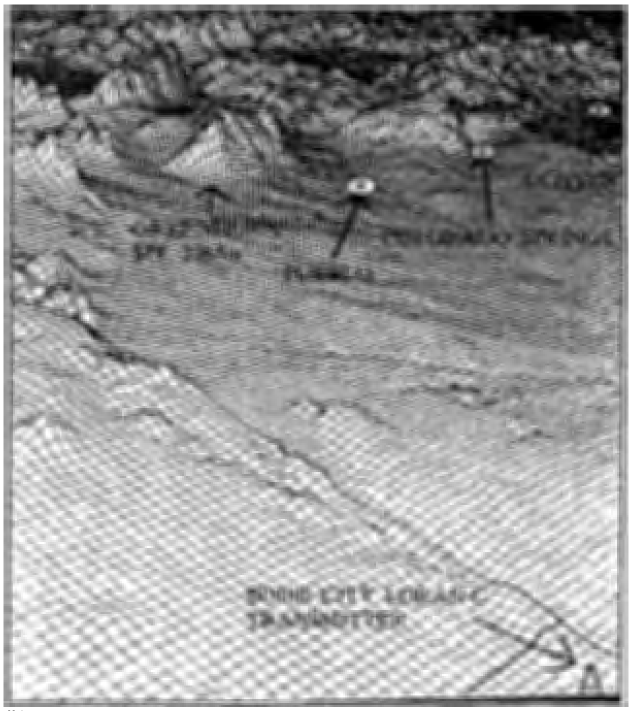

Figure 14. Eastern edge of Rocky Mountains

[Adapted from "The Rockies, the High Plains and the Intermountain West." Computer image copyright © Dynamic Graphics, Berkely, CA.]

SUMMARY

The Raymondville Ghost caused problems in a small area of the Gulf of Mexico for both users and manufacturers when the Southeast U. S. Chain came on the air in the late 1970s. The signal interference source was identified as reflections from the escarpments of the Sierra Madre Oriental in Northern Mexico. Manufacturers implemented receiver changes to avoid the problem.

The Raymondville transmitter will soon be used in new areas as a dual-rated station in the Mid-Continent chain configurations. New transmitters are being constructed and brought on-line near the eastern edge of the Rocky Mountains. New avionics receivers are being designed and deployed in wide areas that may see a re-occurrence of the Raymondville Ghost. The possibility exists for new Ghosts, resulting from reflections of signals from the new transmitters.

Early identification of Ghost reflections and awareness of the potential for Ghosts in new receiver designs can prevent problems in the Loran-C avionics environment of the 1990s.

ACKNOWLEDGEMENTS

This paper draws on the Austron Navigation, Inc. report issued to the Coast Guard in 1980 [Reference 2]. Bill Schorr was helpful then and now with details about the Raymondville Ghost. Bruce Francis, then program manager for the Raymondville Interference Signal Investigation project, shared in all the field and office work but kept the difficult political and team management tasks for himself.

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THE STATUS AND FUTURE OF GPS/LORAN-C INTEROPERABILITY

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ABSTRACT

Recent studies have shown that the interoperability of the Global Positioning System (GPS) and Loran-C may satisfy the requirements for a sole-means navigation system. A sole-means navigation system requires accuracy, coverage, availability, and integrity. While both of these systems have the potential to satisfy requirements for supplemental navigation, it is unlikely that either GPS or Loran-C, operating independently, will meet these requirements.

INTRODUCTION

GPS/Loran interoperability refers to the cooperative use of both the Global Positioning System (GPS) and Loran-C navigation systems in order to achieve a level of performance that cannot be obtained from the use of either system alone.

GPS is a satellite-based radionavigation and positioning system currently being deployed by the U.S. Department of Defense. While GPS was developed primarily for military purposes, it has the capability to satisfy civil needs as well. When fully operational in 1993, GPS will provide worldwide navigation to both military and civilian users. Loran-C is a well-established navigation system whose coverage is being extended to include the interior of North America. The mid-continent chains are expected to be operational in the spring of 1991.

In 1987, a Congressional mandate known as Public Law 100-223 directed the synchronization of Loran master stations to within 100 nanoseconds of universal time. It also required the study of methods to coordinate the time references of Loran and GPS to within approximately 30 ns for the purpose of making the interchange of data between the two systems possible. The law further required the FAA to establish minimum standards under which a radionavigation system can be certified for sole-means operation within the NAS. As a result of this law, a study was conducted by VNTSC for the FAA, which examined the interoperability of GPS and Loran, as well as the navigation performance which can be achieved by combining these two systems.

This paper presents a history of the work performed on the interoperability of GPS and Loran-C, specifically pertaining to air navigation. This work was performed in response to a Congressional mandate, known as Public Law 100-223. The paper also provides an update on current work on GPS/Loran interoperability, which involves flight testing of a hybrid GPS/Loran receiver. Finally, considerations for future analysis in this area are discussed. This paper is based largely on studies conducted by VNTSC in response to Public Law 100-223.

LORAN-C

Loran-C is a land-based radionavigation system consisting of transmitters which are grouped into chains. Each chain consists of one master station and two to four secondaries. The exception to this is the new South Central U.S. chain which will have five secondaries. Loran operates in the 90 to 110 kHz frequency band.

In 1974, Loran-C was selected as the federally provided navigation system for civil marine use in the U.S. coastal areas. There are 14 operational transmitters located around the coast of the United States. The shaded areas denote regions where currently there is no Loran coverage. Just a few years ago, the aviation community became interested in this system and aviation use of Loran grew rapidly. Consequently, the FAA has responded by sponsoring four additional Loran stations. These stations, now under construction, will cover this mid-continent gap, expanding the Loran coverage to include all of the conterminous United States. The four new stations will be located in Havre, MT; Gillette, WY; Boise City, OK; and Las Cruces, NM. The expected operational dates are December 1990 for the South Central U.S. Chain and April 1991 for the North Central U.S. chain.

Loran was designed to be used in a hyperbolic mode of operation. In this mode, each master-secondary pair defines a hyperbolic line-of-position based on the time difference between the reception of master and secondary pulses. The receiver is located at the crossing of two or more lines-of-position, requiring a minimum of three transmitters.

Problems with Loran involve its susceptibility to high atmospheric noise, precipitation static, transmitter synchronization errors, and receiver measurement errors.

GPS

The Global Positioning System, known as GPS, is a satellite-based radionavigation system currently being deployed by DOD. When GPS becomes fully operational, scheduled to occur early in 1993, it will provide worldwide navigation and timing information through a 21-satellite constellation with three additional spares. The constellation consists of six planes, with four satellites per plane, and is at an altitude of 20,000 km with approximately a 12-hour orbit. The satellites are monitored by five ground stations, including a master control station at Colorado Springs. There are currently nine Block II fully operational satellites in orbit, as well as six Block I test satellites.

Each satellite continuously transmits at center frequencies of 1.57542 GHz (L1) and 1.2276 GHz (L2). There will be two levels of service from GPS. The standard positioning service (C/A code) which is for civilian users, will provide accuracies of 100 meters, while the precise positioning service (P-code) which is for military use will provide an accuracy of approximately 17 meters.

However, GPS, even when fully operational, will not provide complete 24-hour coverage. There will be 21 satellites operational 98% of the time, but there will be 24 satellites only 72% of the time. The "outages," or places where there will not be GPS coverage, will be few and last only a matter of minutes if there are no satellite failures. GPS is also affected by ephemeris and clock errors, propagation errors, receiver measurement errors, and Selective Availability.

MOTIVATION FOR GPS/LORAN-C INTEROPERABILITY

The interoperable use of GPS and Loran is motivated by a number of factors which have emerged over the last few years. With each new launch, the GPS coverage increases significantly. The constellation is scheduled to become fully operational in early 1993. Meanwhile, Loran will provide coverage over the entire CONUS when the mid-continent chains are completed early next year. Moreover, the potential benefits of direct routing and additional routes which can be provided by RNAV are increasing in importance.

Although minimum standards for a sole-means radionavigation system have not yet been defined, criteria gathered from FAA Advisory Circular AC 20-130, RTCA DO-194, and the 1988 Federal Radionavigation Plan, references [1,2,3], show that position accuracies should be 0.3 nautical miles for nonprecision approach, 1.7 nautical miles for the terminal area, and 2.8 nautical miles for en route operations. Also, a pilot making a nonprecision approach must be warned within 15 seconds if the position error is greater than 0.3 nautical miles. This time to alarm is 40 seconds for terminal area operations and 60 seconds for en route. Ideally, the system should be able to provide positioning and integrity with an unavailability of only 2.5×10^{-8}. It can be seen from the description of both radionavigation systems given above that neither GPS nor Loran will be able to satisfy these guidelines for a sole-means navigation system.

PUBLIC LAW 100-223

The study of GPS/Loran interoperability was prompted by Section 310 of Public Law 100-223, the Airport and Airway Safety and Capacity Expansion Act of 1987. This act required the Secretary of Transportation to synchronize all master Loran transmitters to within 100 ns and to study the impact of synchronizing all Loran stations to within 100 ns. It also required the Secretary to study methods of coordinating the time references of Loran and GPS to within approximately 30 ns for the purpose of making the interchange of data between the two systems possible. The law further requires the FAA to establish minimum standards under which a radionavigation system can be certified for sole-means operation within the NAS.

In response to this law, VNTSC, through NAVCOM Systems Inc., conducted a study for the FAA on GPS/Loran interoperability. The study focused on methods of combining GPS and Loran into an interoperable system and determining the navigation performance which could be achieved, concentrating on applications for air navigation. In particular, the GPS/Loran hybrid system was examined, in which a single receiver uses signals from both systems simultaneously to compute a single navigation solution.

KEY ASSUMPTIONS

There are several key assumptions which were made in the study of an interoperable GPS/Loran navigation system [4]. For the hybrid system, the mid-continent gap must be filled. Also, all Loran stations must be virtually synchronized, within 50 ns 2-sigma. This is done using Loran to broadcast the time offsets or having the user equipment calibrate the time offsets. For the nonprecision approach case, it is assumed that monitors are at or near the landing sites and that the user has received a calibration factor which is incorporated into his receiver. This technique should reduce the additional secondary factor (ASF) to less than 100 ns. One hundred nanoseconds (1-sigma) is included in the NPA error budget to account for this. The peak seasonal effect in New England is about 1.2 nanoseconds per kilometer. This drops to about 0.4 nsec/km in the Southeastern U.S. One nsec/km of error in the Loran pseudorange standard deviation is allowed for the en route ASF to account for this effect. The other assumptions include a probability of failure for Loran stations of 0.001 and a 30-meter (1-sigma) error for Selective Availability.

INTEGRITY

One of the most important factors in the use of a navigation system for aviation is the issue of integrity. Integrity refers to the ability of a system to provide a timely warning to the user, in this case the pilot, when the system is out of tolerance and should no longer be used for navigation. Integrity requirements include a low total alarm rate, perhaps as low as one alarm per 5,000 hours of flying time. The system must also have an extremely low probability of missed detection, perhaps on the order of 10^{-10}. If a navigation system is to serve as a supplemental system, which requires that a sole-means system be on board and operating, then simple fault detection is adequate. In the case of a sole-means system, both fault detection and fault isolation are required. This is a significantly more difficult problem.

Two approaches to solving the integrity problem for aviation are currently under discussion. The first involves the use of ground-based monitors and a communications link (integrity channel) to the pilot. Several levels of integrity information are provided, ranging from a use/don't use message, to detailed information on the health of each satellite. The second method, called receiver autonomous integrity monitoring (RAIM), depends upon the use of redundant measurements and is completely contained within the cockpit.

GPS/LORAN-C INTEROPERABILITY

Five different approaches for forming an interoperable GPS/Loran system were examined in the interoperability study [4]. The five methods are:

1. Loran as the GPS Integrity Channel (GIC)
   In this method, the aircraft does position fixes using GPS alone, but the communications capability of Loran is used to communicate GPS health information.

2. Latitude/Longitude Comparison
   This method requires that the aircraft contains a GPS receiver and an independent Loran receiver. Both receivers develop estimates of latitude and longitude, and if these estimates disagree by more than a certain distance the pilot is alerted. If the estimates are close, no integrity alarm is sounded.

3. GPS Pseudoranges with Loran Pseudoranges
   In this method, the receiver combines data from the two systems before a latitude/ longitude estimate is made. It combines GPS pseudoranges with Loran pseudoranges, both

referenced to a common clock. Although few existing Loran receivers use pseudoranges, the idea is not difficult to implement. The hybrid receiver may use some of the available Loran pseudoranges, or it may use all the available pseudoranges. The receiver uses GPS to calibrate the Loran propagation uncertainties. This calibration can be done in real time, during periods when GPS is capable of guaranteeing its own integrity, or the calibration can be performed offline, with the resulting database installed in the receiver.

4. GPS Pseudoranges with Loran Time Differences
   In this method the aircraft also combines the lines of position from the two systems before a latitude/longitude estimate is developed. However, the receiver combines GPS pseudoranges with Loran time differences. This receiver uses the Loran information in the same form as most existing Loran receivers.

5. Loran Direct Ranging Using GPS Time Transfer
   This method uses direct ranging Loran and then uses GPS to provide the required time synchronization. The receiver clock is very accurately synchronized to the Loran transmitter clocks so that the range can be measured directly. The clock synchronization is achieved by using the time transfer capability of GPS. GPS timing receivers would then be used at the Loran transmitter and at the user receiver.

The study concluded that the two strongest approaches for combining GPS and Loran in an interoperable system were the combination of GPS and Loran pseudoranges and using Loran as the GPS Integrity Channel (GIC). The study demonstrated that combining the GPS/Loran pseudoranges in a full hybrid system will most likely not meet the unavailability requirement of 2.5×10^{-8}, however it provides a great improvement over either system alone. The addition of the Loran information to GPS is shown to decrease the unavailability by a factor of 1000. Using Loran as the GPS Integrity Channel gives a probability of unavailability between 2.1×10^{-3} and 4.0×10^{-4} due to the high atmospheric noise conditions. If the flight can be flown with the Loran GIC or GPS RAIM, the aircraft would be without integrity for approximately 0.003 percent of the time. This is two orders of magnitude better than either system alone, but still several orders of magnitude worse than the sole-means guideline.

FLIGHT TESTS

Since the completion of the GPS/Loran interoperability study in May 1989, much of the work has concentrated on field testing of an interoperable GPS/Loran system in real time. Many manufacturers are now providing low-cost aviation grade GPS and Loran receivers, and several manufacturers including Trimble, Datamarine, and Micrologic are marketing a combined, or hybrid, GPS/Loran receiver. Currently, the FAA, through VNTSC, is sponsoring flight testing of a hybrid GPS/Loran receiver by Ohio University (Frank van Graas). The purpose of these flight tests is to operationally verify the performance of the integrity algorithm and demonstrate the performance and feasibility of a real-time hybrid GPS/Loran receiver. Also, a preliminary assessment of the flight technical error and the impact of failure modes are demonstrated [5].

A prototype hybrid GPS/Loran receiver, shown in Figure 1, was used for these experiments. A four-channel Motorola Eagle GPS receiver and an eight-station Advanced Navigation Inc. 5300 Loran-C receiver, both using continuous tracking, were used to collect GPS and Loran data. The two receivers were interfaced to a microcomputer through two serial communication ports. The microcomputer was also interfaced with a course deviation indicator (CDI), through a parallel port, to display guidance data to the pilot.

The navigation solution was a least-squares solution in which samples are taken once every 2 seconds. Equal weighting was given for GPS and Loran since the noise in each receiver was approximately the same. Therefore, the accuracy of the hybrid system will mostly be determined by the Loran measurements. The offset between GPS and Loran time was incorporated into the solution, however only the master station offset was used and the System Area Monitor was used to account for the secondaries. Standard Loran propagation models were used so that the achieved accuracies are repesentative of current Loran receivers. Due to this, however, the accuracy of the hybrid system will not be as good as GPS, but the availability and integrity of the hybrid system will exceed that of GPS alone by several orders of magnitude.

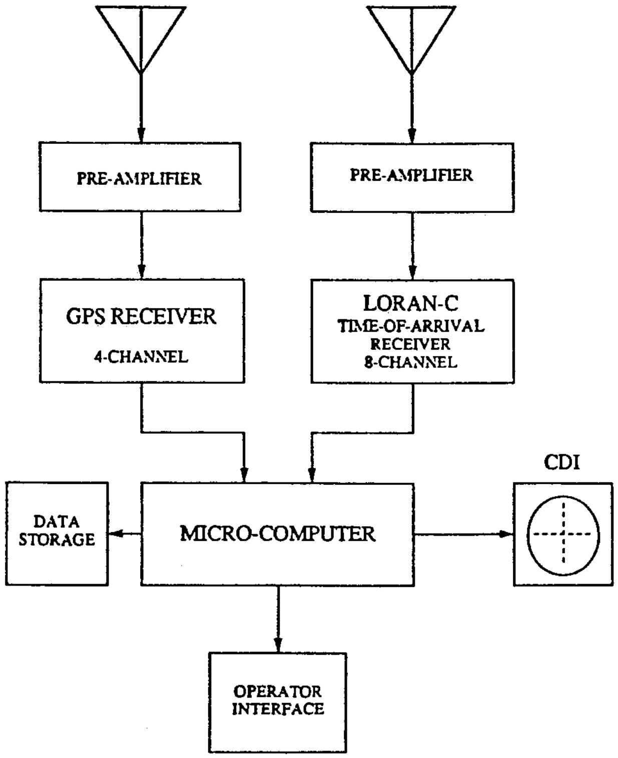

Figure 1

Prototype Hybrid GPS/Loran Receiver

The first flight test was performed on August 21, 1990. The prototype hybrid receiver was installed in a Piper Saratoga. The GPS microstrip antenna and preamplifier were mounted on top of the fuselage, approximately 4 feet from the front windshield. A 1-foot slanted Loran antenna is also mounted on top of the fuselage, approximately 8 feet back from the GPS antenna. Both antennas were connected to the corresponding receivers which were located in an equipment rack together with the microcomputer. The flight test was performed in Albany, Ohio which is in the vicinity of Ohio University. The duration of the flight was 34 minutes.

The second flight test was performed on August 23, 1990. This flight lasted approximately 52 minutes. The flight tests demonstrated that the hybrid GPS/Loran receiver performed in accordance with its design. The test pilots noted that the course deviation indicator is very responsive and that the indicated course compares favorably with those from other area navigation equipment. For en route navigation the flight technical error is 1 nmi 95% of the time. This is easy to achieve with GPS/Loran since cross-checks with VOR, DME, NDB, and the ILS localizer indicated that the GPS/Loran horizontal accuracy is on the order of 0.1 nmi. The error would be less than this, but the Loran was not calibrated which means that the biases (seasonal corrections) were not taken out in the propagation model. Loran, by itself, will provide an accuracy of at least 0.25 nmi.

A representative example of the GPS/Loran measurement geometry which was used in simulation work prior to the flight tests is shown in Figure 2. The four GPS satellites in view, and used by the receiver are SV-6, SV-9, SV-11, and SV-12. Transition to a different set of four satellites causes a sudden change in the magnitude of the two-dimensional error. The Loran stations used are Seneca as the master, and Dana and Carolina Beach as the secondaries.

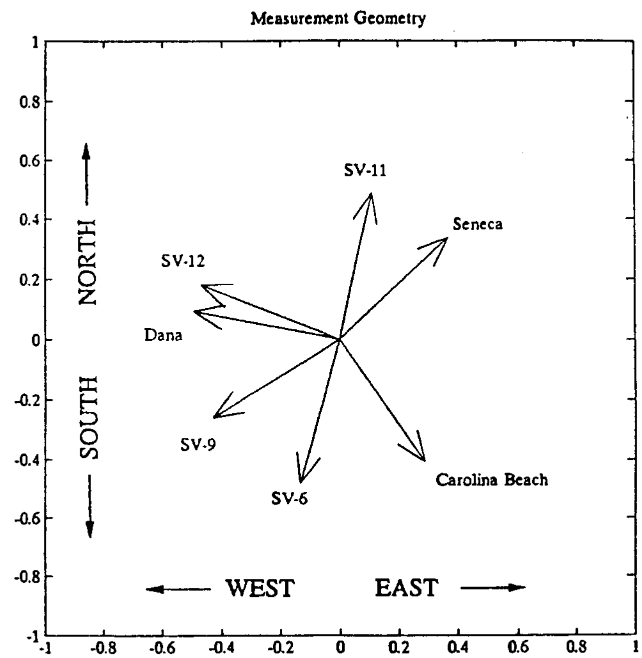

Figure 2

GPS/Loran Measurement Geometry

FLIGHT TECHNICAL ERROR

The analysis of the flight technical error (FTE) from the flight tests is preliminary [5]. Due to instrument meteorological conditions (IMC) during takeoff and landing, the intended GPS/Loran course could not be flown. The pilots were instructed to fly the CDI as closely as possible. The FTE represents the difference between the CDI (indicated

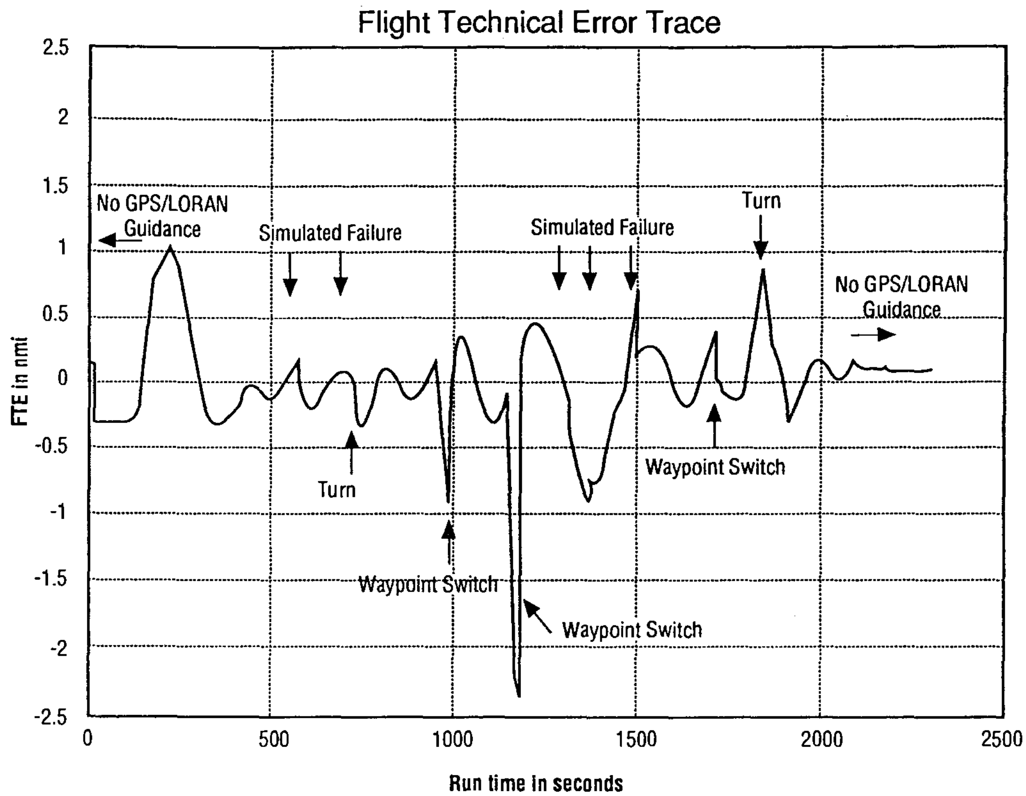

Figure 3 Flight Technical Error for Flight One

position) and the GPS/Loran position (actual position). The FTE for the first flight is shown in Figure 3. During the first flight, the CDI deflection was +/- 5 nmi en route and +/- 1.25 nmi for approach. The FTE plots display drifts which are unseen to the pilot; if the needle is off center by +/- 0.2 nmi the pilot is unable to notice a drift. To analyze the impact of signal malfunctions, a total of 15 simulated failures were injected into the measurement data during the two test flights. Both sudden errors (steps) and slowly increasing errors (ramps) were simulated; these are indicated by the small spikes. The large spikes indicate places where the system indicates to fly to a new waypoint.

The flight technical error trace for flight number 2 is shown in Figure 4. The CDI deflection for this flight is +/- 2.5 nmi en route and +/- 1.25 nmi approach. Both pilots utilized an ILS localizer to approach the runway at the end of the mission, so the latter part of the FTE trace is not representative of the GPS/Loran FTE. It is, however, a good indication of the GPS/Loran cross-track error. For both flights, the GPS/Loran cross-track error is approximately 0.1 nmi. Since the offset is the same for both flights, the error is most likely caused by an uncorrected Loran propagation effect. Flight number 1 used an integrity threshold of 300 m, while flight number 2 used an integrity threshold of 400 m. All signal malfunctions which would have caused unacceptable course deviations were detected by the integrity algorithm.

RECOMMENDATIONS

The future of an interoperable GPS/Loran system looks promising and it may one day become a sole-means navigation system. It is important that the FAA establish minimum standards under which a radionavigation system can be certified for sole-means operation within the NAS. Further analysis of the high atmospheric noise and precipitation static problems is needed. Also, field tests which examine the hybrid receiver under high dynamics should be performed. Another area of investigation is the integration of the hybrid receiver into the cockpit to examine how it operates with other instruments such as the altimeter and speed indicator.

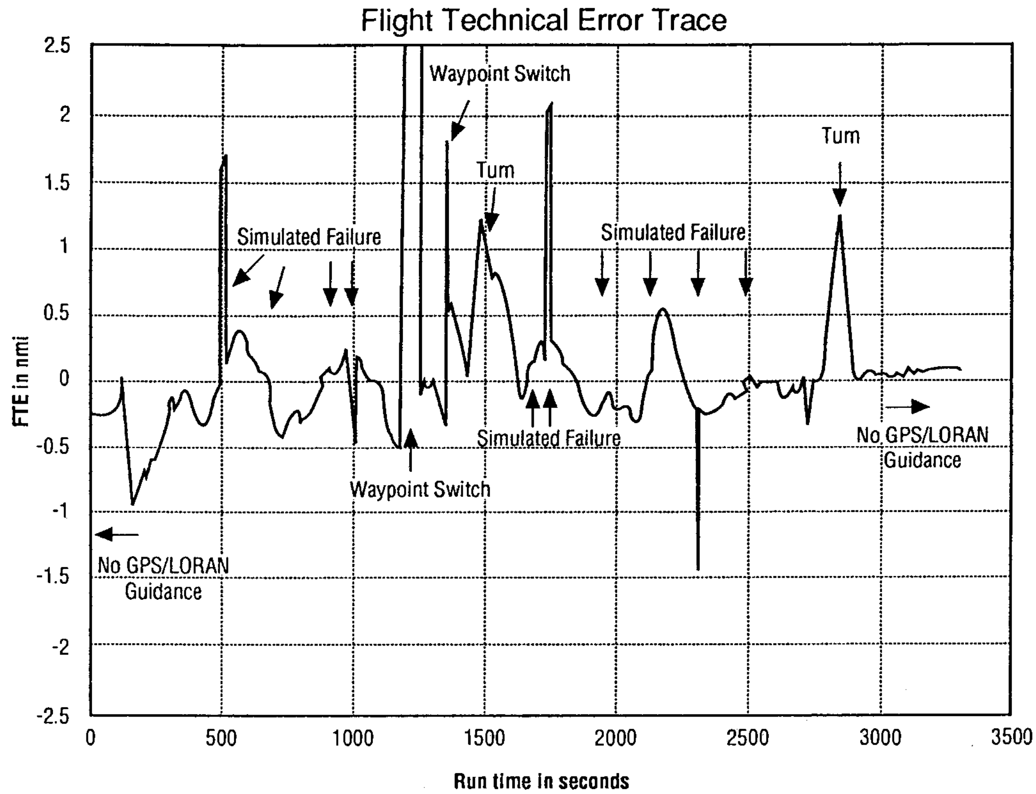

Figure 4 Flight Technical Error for Flight Two

As a result of the flight tests performed at Ohio University, continued integration of hybrid GPS/Loran into the National Airspace System in the future is recommended [5]. This includes continuing flight testing of the prototype GPS/Loran receiver to further address the flight technical error, as well as the impact of failure modes on en route navigation and nonprecision approach. Also, it is important to develop and evaluate criteria to be used for the certification of hybrid GPS/Loran receivers as well as criteria for the definition of a sole-means system. There should also be an evaluation of integrity and isolation schemes, which are not just based on the inconsistency of GPS/Loran measurements, but which also take into account information on:

1. The reasonableness of climb/descend rate as indicated by GPS/Loran
2. The rate of change and magnitude of the difference between barometric altitude and GPS/Loran altitude
3. The reasonableness of the GPS/Loran altitude
4. The rate of change and magnitude of the differences between the indicated GPS/Loran heading and the calculated heading, or indicated magnetic heading

CONCLUSIONS

The results of the GPS/Loran interoperability study for air navigation have resulted in several conclusions. The first is that neither GPS nor Loran will be adequate for sole-means navigation within the National Airspace System. A hybrid GPS/Loran system, however, will significantly increase the availability of position fixing relative to that of either system operating alone. A hybrid system may still experience outages which are caused by the combination of poor satellite geometry and high noise (poor signal-to-noise ratio). Finally, hybrid GPS/Loran will provide greater integrity by significantly increasing the availability of receiver autonomous fault detection and fault isolation. This was successfully verified by the Ohio University flight tests which demonstrated that the availability and integrity of the hybrid system exceeds that of GPS alone by several orders of magnitude.

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DUAL-RATE, AUTO-NOTCH COUPLER-LORAN

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ABSTRACT

Combining the latest in microcomputer capability with surface mount technology provides an antenna coupler sized (1.5" x 6") Loran-C receiver with a parts cost less than $50. The microcomputer processes up to six signals from each of two chains to provide dual rate tracking. Four processor tunable notch filters complement two fixed notches. Power requirements are just 25 mA at 9-15 volts ideal for marine, avionics, and AVL. This coupler-loran, or COUPLORAN, is the true black-box Loran-C receiver. An automatic GRI search program finds the best GRI(s) without operator/user intervention for independent operation, or, when the two-way interface is used, the COUPLORAN may be controlled by a processor that interfaces to the user, to a transmitter, or to other systems.

INTRODUCTION

Five years ago, advances in the level of microcomputer integration suggested that all the functions required to acquire and process Loran-C signals and convert the timing to numbers existed in single, off-the-shelf microcomputer chips. Numerous manufacturers offered promises of product that would do all.

The Motorola MC68HC11A8 was chosen over other implementations because (1) its data bus could be used as a parallel eight-bit read/write port with no external hardware, (2) it had an input pulse accumulator, and (3) its internal timing resolution was a half-microsecond. Ironically, the parallel bus ability was never used, and an unappreciated feature, *input capture,* became the heart of the MC68HC11 Loran-C receivers, eliminating the extra IC originally included and the need for the pulse accumulator!

Just five years later, the MC68HC11 has been used in far more than 100,000 Loran-C receivers representing more than a dozen different brands in countless models ranging from PCB receivers and very low-cost portables to full capability, combination Loran-C plotter-fishfinders.

The MC68HC11 in all these receivers is not the *Single-Chip Loran Transducer* described in my 1986 WGA paper (reference 1). In every production unit to date, the µC has been combined with RAM, ROM, and various control digital IC's (Figure 1) to make full function receiver/navigators. Additional programming

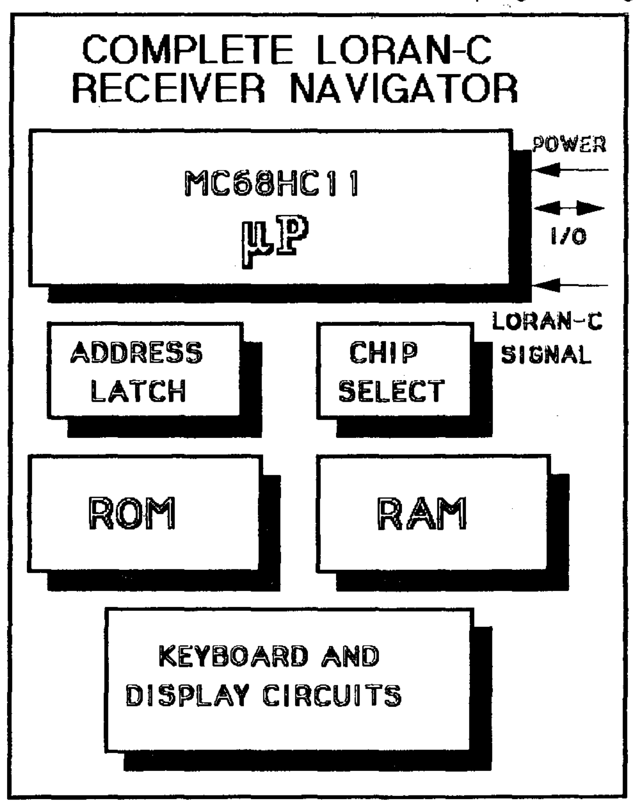

Figure 1

provided latitude-longitude conversion, waypoint management, navigation calculations, and, in some cases, a complete keyboard and display interface.

Perhaps because of its size (3" x 8"), the Single-Chip Loran Transducer proposed in the 1986 paper never came about. Although new microcomputer capacity and software capability allow enhanced operations that were inconceivable then, acceptance for the Single-Chip Loran Transducer lies in surface mount technology. By using SMT, the overall size can be reduced to just 1.5" x 6.0", small enough to be remoted with the antenna (Figure 2).

BENEFITS OF THE COUPLORAN

COST: Reducing the Loran-C receiver to a small antenna coupler sized printed circuit board allows the entire Loran-C function to be remoted and treated as a component. Thus manufacturers can increase their production quantity by using the common COUPLORAN component in a variety of products, and small volume users can obtain finished product from a high volume COUPLORAN manufacturer. Cost savings in the design result from eliminating the interface circuits between the two analog sections in traditional designs, compacting the analog design, simplifying testing with a single-piece unit, and using a dedicated loran processor, allowing any µP to do the other functions.

PERFORMANCE: With all the analog circuits together in a compact design away from multi-component digital processing systems, better signal-to-noise performance can be achieved. With gain, bandpass, and notch control present at the antenna, adjustment to the transmitters is possible at the input--not downstream after a fixed-gain, fixed-bandwidth coupler (reference 2).

LOW POWER: The single-chip microcomputer, without external RAM, ROM, and other digital components, uses very little power (<25 mA, reference 3) thereby contributing *less noise* to the measurement then would be the case with a complete digital system. With no external components, there are no external bus leads to radiate digital noise.

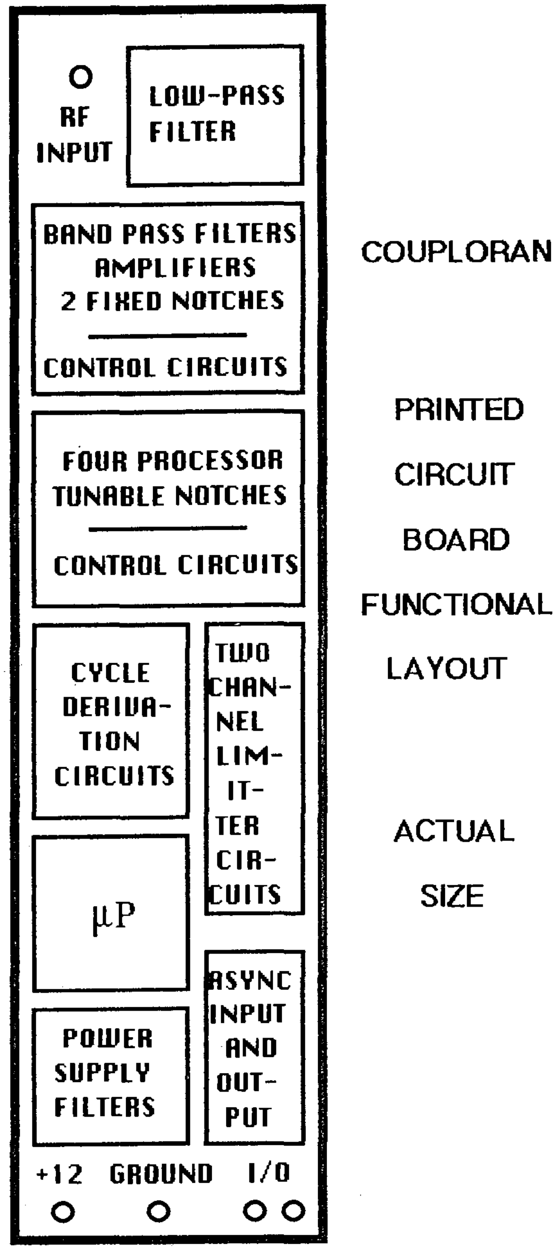

Figure 2

DUAL RATE: The single-chip microcomputer without the extra digital parts hasn't sufficient RAM and ROM to do latitude-longitude conversions, but this leaves it with considerable processor time for other functions that a fully loaded µP couldn't do, such as tracking a second chain. Two-chain tracking not only provides better handoffs when transiting from one chain to another, but in certain areas may provide a better position by using two stations each from two chains.

TRACKING NOTCH FILTERS: With the built-in analog-to-digital converter and available processor time, the µP can monitor the notch filters' rejection signals and tune for best performance, tracking aging and temperature variations in the components. With only a few inexpensive circuits, this low-cost receiver improves its performance.

INDEPENDENT OPERATION: Automatic GRI search algorithms are all subject to potential errors in selecting the absolutely correct rate because of overlapping coverage areas and local preferences. The ability to track two chains reduces the possible error.

FLEXIBILITY: By reducing the Loran-C receiver function to a component, flexibility is added to the product and system designer. Loran capability may be added to existing products, and different display units can use the same loran input.

SURFACE MOUNT TECHNOLOGY

Eliminating expensive digital parts reduces cost, but once the printed circuit board size is smaller than a display and keypad, further *size* reduction won't bring a smaller package for a *complete* receiver. The 1986 paper on the single-chip loran suggested a coupler-loran in a 3" x 8" package. A coupler this size has little utility for marine use and may be too large to tuck away for other applications; thus implementation has been as a complete receiver-navigator with the main PCB laid out 4" x 6" accomodating a large display and keypad. But surface mount technology (SMT) can shrink the analog circuits so that, when combined with only the single chip loran processor, the receiver is just 1.5" x 6.0" (Figure 3). Reducing a package to this size doesn't provide for much of a display. What is the use for a displayless, ultra-small receiver?

This question has two separate answers. One involves the traditional Loran-C receiver design and the other is for new applications.

First, traditional design involves two pieces: a pre-amp in an antenna coupler and the bulk of the receiver/control/display unit. Traditional products implemented with the COUPLORAN would also involve two pieces, but the functions are conveniently separated. Different display units with different markets can use the same front-end interchangeably. Without having to track loran signals in real time, the display µP can be more responsive.

For new applications, such as in *combination* products, the COUPLORAN is the perfect component. General purpose display units can take inputs from a variety of sources and display them individually or together. Thus combination Loran-C and GPS receivers can share the same display, or fishfinder plotters and autopilot controllers can have a Loran-C input.

Surface mount technology reduces loran to a component. Volume production of this component will reduce its finished cost. With a simple to use, low cost loran receiver, product designers need be no more concerned with loran technology than with any other component.

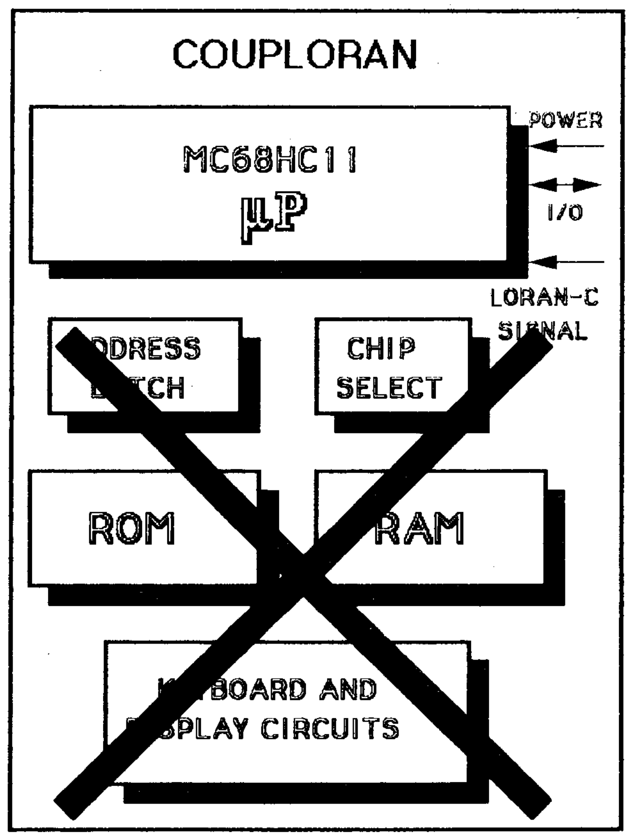

Figure 3

DESIGN

The design begun in 1985 has seen many changes resulting from µC enhancements and experience. The first design had a second digital IC, albeit an inexpensive counter chip, operating through the pulse accumulator input of the µC . After working with the MC68HC11 for a few months, it was realized that an inherent ability of the µC allowed it to time edges itself--which had been the function of the extra IC. This *input capture* feature, when properly implemented, eliminated the counter chip, and the true Single-Chip Loran-C Transducer was achieved. The pulse accumulator input capability also was not used.

The MC68HC11 µC had been chosen, in part, because it could be controlled serially *or* in parallel--both capabilities were built into the standard chip. With the loran function operating independently of a display µP, depending upon whether the µC was to be in the same module or not suggested both interfaces. However, every design that used a second processor interfaced through the serial channel, although most designs just used the MC68HC11 itself to operate the user interface. Since the COUPLORAN is designed to operate remotely, the parallel interfacing capability has been dropped.

The half-microsecond internal timing capability of the MC68HC11 was a factor of two better than earlier designs using the Intel8085. This improvement allowed more responsive tracking loops and less TD jitter.

Reduction of the Loran-C receiver to nine square inches of printed circuit board to be operated at the far end of cable brings problems as well as benefits. The primary problems are the ground and digital noise contamination.

Grounding is always a Loran-C signal problem. A large, stable ground plane enhances operation, ensuring that as much of the true (atmospheric) signal-to-noise ratio gets through the system as possible. Without a good ground, system noise can obliterate the signal and reduce performance significantly. On the other hand, removing all processing from local noise contributions can improve performance. Thus, there can be an overall improvement if the ground, and noise, can be controlled. This provides the greatest design challenge in the COUPLORAN.

Closely related, and obviously contributory, is the digital design's contribution to the noise. Again, an opportunity exists because reducing the number of digital components and their "noisiness" beyond what is necessary in a

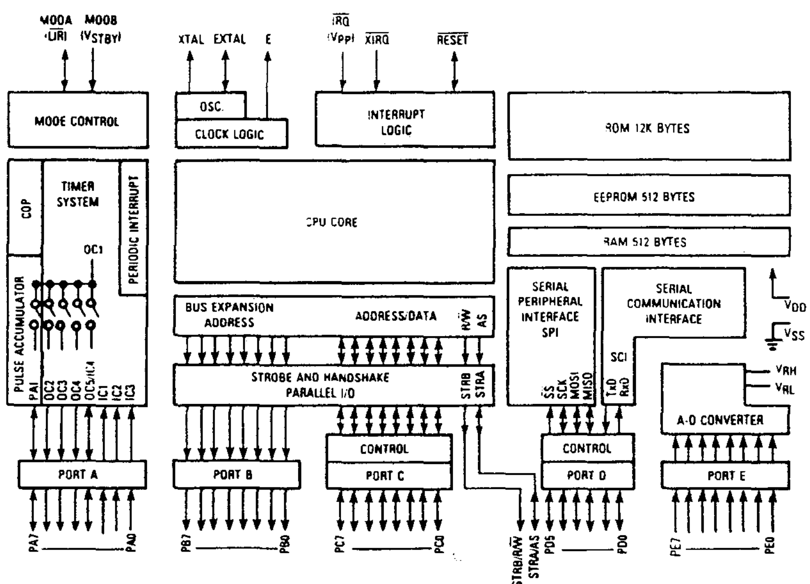

Figure 4 MOTOROLA MC68HC11E9 MICROCOMPUTER

complete Loran-C receiver/navigator can improve performance. In fact, the totally self-contained MC68HC11E9 μC (Figure 4) not only is a very low-power device, with **no** external components there are no radiating lines except for the microscopic connections on the chip itself.

Other design criteria involve just how much capability should be packed into the μC and how much engineering could be applied. After five calendar years of development with this remarkable chip, a number of opportunities have become apparent. Two years ago at this meeting (reference 4), I suggested that the oscillator requirements could be greatly reduced by using the μC's capability with a few cheap temperature sensitive parts to predict its oscillator frequency and reduce oscillator stability requirements by a factor of 5 or more (Figure 5). This has been implemented and is in use in a number of receivers on the market. Similarly, by using the μC's built-in analog-to-digital converter and some interesting algorithms, a very low-cost method of tuning notch filters not only improve performance but also reduce critical factory tuning.

Without external RAM and ROM, the MC68HC11 does not have sufficient internal capacity to do latitude-longitude conversions. With the original 'A8 version, just 256 bytes of RAM and 8K bytes of ROM made even tracking a master and five secondaries difficult. But without the lat-long conversion loading, the μP had considerable time to do something else. The new 'E9 version solves the problem. With double the RAM and 50% more ROM, sufficient resources are available to track two chains. But what does a single processor do when it is to take data from two stations at the same time? This problem has an obvious, simple solution, which allows the single-chip Loran-C processor to work.

Remoting the Loran-C receiver suggests hands-off operation. Programming to find the "best" GRI is useful to such applications, and, with dual rate capability, the chances of the algorithm being wrong are greatly reduced.

Although the MC68HC11 μC's 512-byte EEROM was too small for all the waypoints and other saved data of a complete receiver-navigator, it is more than sufficient for the COUPLORAN, and eliminating the battery is another plus.

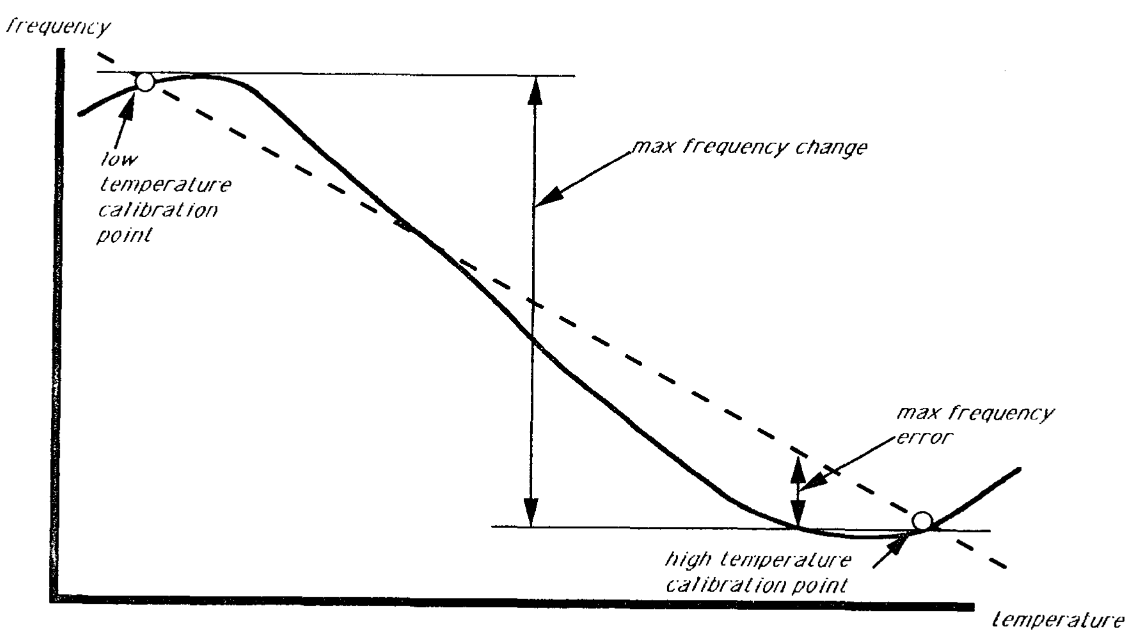

Figure 5 WORST CASE ERROR WITH STRAIGHT LINE PREDICTION

COST

All the parts for the COUPLORAN, except the μC, are very inexpensive, common devices. The variable inductors, the matching polystyrene capacitors, and a few other parts are leaded components; the remainder, representing the bulk of the COUPLORAN, are surface mounted parts. These components, in volume, cost less than $35. The MC68HC11E9 μC is a standard part with a custom, proprietary program. It will be available for approximately $15.

STATUS

By mid-September, 1990, the COUPLORAN has been breadboarded and is operating on a single GRI with through-hole components on a PCB considerably larger than 1.5" x 6". The tracking notch filters tune similarly to a PCB loran currently in production but with some enhancements. This engineering sample has proven the new parts of the design and the SMT circuit board is ready for layout, fabrication, and test.

Latitude-longitude conversion software has been rewritten to use five-secondary chains and is available in MC68HC11 assembly code. Similar programs to use the COUPLORAN TD outputs will be written in C.

CONCLUSION

The COUPLORAN offers many advantages to all Loran-C technology users, large and small. By treating Loran-C signal data as an input, products and systems can provide the user interface without the technical problems of acquiring and tracking the actual signals.

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BIOGRAPHY

Jesse Pipkin is a consultant specializing in Loran-C design. His introduction to Loran was as a user of Loran-A in the United States Air Force where he served as a Navigator and Instructor Navigator on hundreds of trans-Atlantic and trans-Pacific flights. He has been involved in Loran-C equipment design for the last twelve years, concentrating in cost and size reduction. His designs are used by more than a dozen companies involved in marine, avionics, and terrestrial applications. He has authored two papers for the Wild Goose Association (Single-Chip Loran-C Transducer, 1986, and Loran-C Oscillator Requirements, 1988). He received the BSEE from the University of Florida and did graduate electronic design work at the University of California, Berkeley.

A European Loran-C Coverage Prediction Model

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Abstract

The recent proposal to expand the LORAN-C system in North-West Europe has lead to an assessment of factors which limit coverage in that area. The high levels of carrier-wave interference and the lack of ground conductivity data present problems when predicting Loran-C coverage in Europe. In this paper existing coverage modelling procedures are reviewed and a method of implementing them under European conditions is demonstrated. The problem of carrier-wave interference is addressed and improved methods of combining interference with atmospheric noise are developed. The model also extends traditional coverage prediction techniques to introduce skywave interference as a coverage limiting criterion and includes a method of predicting Envelope-to-Cycle Difference (ECD).

1 Introduction

Proposals to expand the Loran-C system in North-West Europe have necessitated the examination of the coverage of various candidate configurations of stations, both theoretically and through field trials. The results obtained have clearly demonstrated the need for improved methods of Loran-C coverage prediction for application in Europe.

The inadequacy of existing techniques is principally due to their assuming that the dominant noise experienced by receivers is atmospheric in origin. It has been shown that the principal source of 'noise' in Europe is, in fact, the carrier-wave interference caused by the many other services with which Loran-C must share its frequency band [1]. A second problem is the lack of detailed ground conductivity data for this region which has sometimes encouraged producers of coverage diagrams to assume that all propagation paths lie over sea water.

This paper describes a research programme aimed at overcoming these limitations and producing a realistic Loran-C model for use under European conditions. The model is based on standard techniques developed by the US Coast Guard (USCG), modified and enhanced to reflect European conditions. This has entailed creating a detailed ground conductivity map using data assembled from a variety of sources. The problem of carrier-wave interference has been tackled in stages. First, an enhanced value of atmospheric noise was adopted which accounted for both atmospheric noise and carrier-wave interference. Currently, a more precise method of calculating atmospheric noise and carrier-wave interference separately is being developed, jointly with the Delft University of Technology.

In designing the model the opportunity has also been taken to extend the scope of coverage prediction to include the effects of changes of envelope-to-cycle difference (ECD) and of skywave propagation. The calculation of ECD is based on Sherman's method, which relates the rate of change of ECD with distance to the conductivity of the path. Skywave amplitude and delay values have been estimated by combining information from USCG sources with corresponding data from research on the Decca Navigator system. The paper will illustrate the reductions of coverage due to skywave propagation, assuming that receivers meet IEC Minimum Performance Standards.

Although designed to cope with the especially difficult conditions of North-West Europe, the coverage prediction model is also suitable for use in other areas of the world in which there is a need to predict the performance of LORAN-C chains.

2 Signal-to-noise ratio and geometrical factors

2.1 US Coast Guard method

The procedures for calculating the coverage area of a Loran-C chain have been established for decades [2]. The United States Coast Guard (USCG) employ two separate coverage-limiting criteria: signal-to-noise ratio (SNR) and geometrical dilution of precision. The USCG method estimates the field strength at the receiver from each of the three stations which constitute the Loran-C triad in use. The field strength of the noise, assumed to be atmospheric in origin, is also estimated and hence the signal-to-noise ratio is determined. A minimum SNR limit of -10 dB is set; it is assumed that, provided this SNR is exceeded, the receiver will be able to measure time differences with a standard deviation of less than 100 ns. The second limit restricts the dilution of precision to that value which would convert this uncertainty of time difference to an uncertainty of position of 0.25 nm, or 463m, $2d_{rms}$.

In implementing the USCG method it is customary to calculate the field strengths of the Loran-C signals at any point, knowing the transmitter power and the range of the point from the station, by reference to the CCIR attenuation curves which show attenuation as a function of ground conductivity [3]. Where the path is of inhomogeneous conductivity, the quasi-empirical Millington's method is employed, again in accordance with CCIR-recommended practice.

The atmospheric noise level is estimated by use of the data in CCIR Report 322-3 [4]. This provides a set of 24 values of field strength, appropriate to 4 seasons of the year and 6 periods of the day, which are combined to give a single 95 percentile value. In calculating the uncertainty of position resulting from the 100 ns uncertainty of time-difference measurements, the following equation is used:

$$2d_{rms} = \frac{2k\sigma}{\sin\gamma}\sqrt{\frac{1}{\sin^2\frac{\alpha}{2}} + \frac{1}{\sin^2\frac{\beta}{2}} + \frac{2\rho\cos\gamma}{\sin\frac{\alpha}{2}\sin\frac{\beta}{2}}}$$

where

k = 149.845581 m/μs,

α and β are the angles subtended by the lines joining the receiver to the master and to each of the secondary stations,

γ is the crossing angle between the two lines of position (LOPs), and

ρ is the correlation coefficient between the noise contributions to the two LOPs. A value of $\rho=0.5$ is employed when the position fix is derived from the customary master and two secondary stations, since the master time reading is common to the two. The correlation is zero if 4 stations are employed.

σ is the standard deviation of the time difference measurements, 100 ns. If the two LOPs have different standard deviation values, a more complex equation is employed.

2.2 Implementations of the USCG method

Initially the estimation of coverage by means of the USCG method was a pen-and-paper procedure. Now computers are used; indeed, the complexity of recent coverage prediction techniques makes computer modelling essential in the calculation of coverage.

The program COVERAGE [5], which automates the USCG procedure, is written in HP Basic and runs on HP9836C computers. The coverage boundary calculated is output to a plotter. In calculating field strength values, COVERAGE employs a polynomial representation of variation of field strength with distance for each value of ground conductivity. The program draws on a database of 10000 point values of ground conductivity which cover the continental United States and Canada. A second database contains the atmospheric noise values at 40 points covering the same area, calculated according to the USCG method. SNR and geometry limits are computed and output separately for individual triads; they must be combined manually by the user.

Recently, the Synetics Corporation has greatly improved upon this process in a program prepared under contract to the USCG [6]. This Synetics program is written in the high-level language Pascal and runs on IBM PC computers. Its user interface employs menus and a mouse. The coverage limit can be displayed, overlaid on a coastline map, on the screen or as hard copy on a plotter or laser printer. Ground conductivity data is stored as an array of values of elements each of 5° of latitude by 5° of longitude; that is, approximately 556x426 km at 40° latitude. Outside the US and Canada the source of ground conductivity data is the CCIR 'World Atlas of Ground Conductivities', Report 717-2 [3]. A single value of atmospheric noise, calculated according to the USCG method but employing the latest information from CCIR Report 322-3 [4], is employed for each Loran-C chain.

3 European coverage modelling

The two principal additional factors which must be considered when implementing the USCG coverage method in Europe are ground conductivity and carrier-wave interference.

At the start of this programme of work it was established that no sufficiently-detailed ground conductivity database of reliable values existed. Section 3.1 will describe how such a database has been constructed.

None of the models developed for predicting Loran-C coverage in the US and Canada are believed to take carrier-wave interference into account. This is understandable, since interfering transmissions there are relatively few. In Europe, in contrast, carrier-wave interference (CWI) is the dominant source of noise. It was decided to tackle the problem of modelling carrier-wave interference in two stages. First, an enhanced value of atmospheric noise was adopted. This value, 61 dB/μV/m, was the one recommended by the North-West European Loran-C Working Group [7]. It was chosen principally on heuristic grounds since it had been found that, when this value was used, the coverage area predicted by the USCG method for the existing Norwegian Sea chain corresponded with users' experience. Independently, and coincidentally, the United Kingdom Admiralty Research Establishment identified the same value by using a method which gives a much higher value than the USCG method.

Subsequently a method has been developed for modelling the carrier-wave interference independently of the atmospheric noise. This will be described in Section 6.

3.1 Ground conductivity database

The heart of any useful coverage prediction is the conductivity database from which the field strength of the Loran-C signals are calculated. It is also an essential component of any program to predict ECD values (see Section 4), carrier-wave interference levels (see Section 6.2) and even additional secondary factors (ASFs). For the coverage prediction model presented in this paper, the decision was taken to adopt a resolution which was sufficiently fine to ensure that detail in the data obtained from various sources would be preserved. The most detailed information was identified as that for Italy contained in CCIR Report 717-2. It required a resolution of the order of 0.1° of latitude by 0.1° of longitude, that is, typically, 11 km x 7 km for the North Atlantic area. This is believed to be a higher resolution than has been used in any previous model.

CCIR recommend that ground conductivity values be quantised according to a scale of the following values: 0.01, 0.03, 0.1, 0.3, 1, 3, 10, 30 and 5000 mS/m. Each of these figures is applied to a range of conductivity values; for example, 1 mS/m is to be assigned to any conductivity in the range 0.55-1.7 mS/m and 3 mS/m to the range 1.7-5.5 mS/m. We have complied with this recommendation.

The principal source of data was CCIR Report 717-2. However, although this contained detailed information for certain countries, on others there was either extremely scanty data or none at all! Representatives of all countries in North-West Europe were contacted and asked either to confirm that the CCIR data was the latest and best available or to provide alternative information. This was partly successful. However, the data for certain countries is still minimal (in the case of France, non-existent) and in this case we have been obliged to adopt values derived from examination of geological maps [8].

A program was written to allow conductivity values to be entered quickly and efficiently into the database by filling in squares on the computer screen corresponding to a map. The current version of the database contains the latest available conductivity data for the whole of North-West Europe.

3.2 The Bangor coverage model

The Bangor coverage model is embodied in a computer program which allows information on transmitter positions and power levels, ground conductivities, atmospheric noise and other parameters to be manipulated in a menu-driven environment.
An early decision in the development of the program was to employ a commercial computer-aided design package for all display functions. The package chosen, EASYCAD, is a derivative of FASTCAD, a three-dimensional computer-aided design system. EASYCAD provides a simple and structured environment for the manipulation of map data and other graphical information. Diagrams can be generated using a high level language, in the evolution exchange format (EXF) and imported, using an EASYCAD routine, onto the screen.

The model starts by regarding the coverage provided by a given group of transmitters as infinite. Limitations on the coverage area are then introduced individually or collectively. The limits include minimum signal-to-noise ratios, geometrical dilution of precision, and (as will be seen later in the paper) skywave contamination and ECD value. These factors are switched on, under menu control, by setting a flag or by means of a value in a program parameters file.

The model draws on the large database of conductivity values described earlier. The USCG method is used to calculate individual arrays of attenuation around each transmitter. The points which constitute these arrays are spaced at steps of 0.5° of latitude by 1° of longitude (typically, 56 km x 71 km). Each attenuation array is the set of values of the reduction in field strength, relative to the value at 1 km range, due to propagation of the signal. Each value is calculated by determining the Great Circle path between the point and the transmitter and so establishing the ground conductivity profile of the path. The total attenuation is then estimated by means of Millington's method. The array of such values is stored as a file which can be accessed when that transmitter is employed.

Note that attenuation values, rather than field strength values, are stored since the calculation of the array is is a time-consuming process. It is a simple matter to compute an array of field strength values for each station by reference to the attenuation array and a knowledge of the transmitter radiated power. Recalculation of the whole attenuation array is thus only required if a transmitter is moved or the ground conductivity database is updated.

A further array, of SNR values, is computed from the field strength array by using the assumed noise level of 61 dB/μV/m. Each value in this array is then tested against the USCG minimum of -10 dB. Fig. 1 shows those points in such an array for the transmitting station at Ejde on the Faeroe Islands which pass this test and are thus deemed to be within the coverage of this individual station.

In calculating the coverage of each Loran-C chain, the program checks at each array point whether the signals from the master station and at least two secondaries meet the USCG SNR criterion. The geometrical dilution of precision criterion is then applied. Points at which both criteria are met are deemed to lie within the coverage of the chain. The same technique is then extended to allow the composite coverage of a system of several chains to be determined; the program establishes whether each point is covered by any of the chains in the system.

The Bangor model is essentially geared towards the on-going analysis of the various coverage parameters. The more time-consuming features of coverage prediction such as attenuation and ECD are

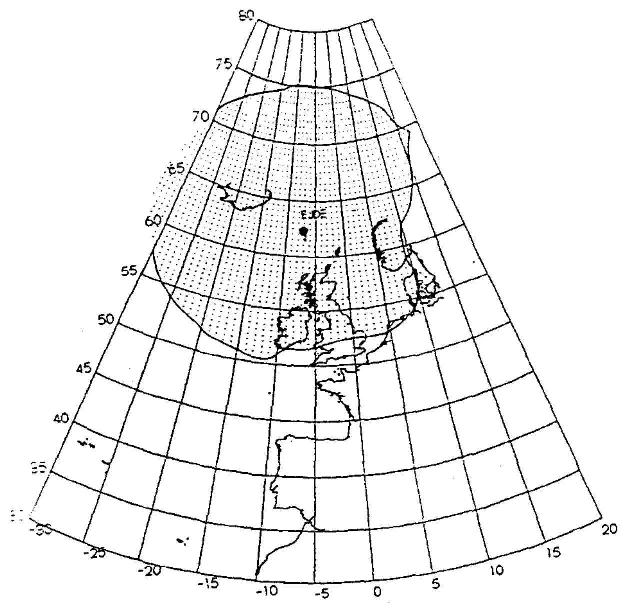

Fig. 1 Coverage of the Loran-C Transmitter at Ejde in the Faeroe Islands. Assuming a noise level of 61 dB $\mu V/m$

filed as arrays. This allows the continual manipulation of these factors in the model without the necessity for laborious and time-consuming recalculation for each coverage diagram.

In contrast, Synetics developed their program from the USCG tradition of plotting coverage limits. Hence, the approach of Synetics differs markedly from the Bangor model in that the generation of coverage limits is the priority rather than the analysis of the variation of coverage parameters within the coverage limits. Their program calculates the boundary of coverage in a novel and fast manner. The program effectively radiates out from the centre of coverage, calculating the signal strength and geometrical accuracy at each point. This is continued until the limit of coverage is reached and then the program 'walks around' this boundary plotting the contour of coverage limits.

The Bangor model has been extensively used by the North-West European Loran-C Technical Working Group in the planning of the proposed expansion of the Loran-C system. The resulting coverage area of one such proposal is shown in Fig. 2.

The model has now been extended to introduce additional novel features such as skywave and ECD into the coverage prediction process. The way these additional features have been implemented is described in Sections 4 and 5. In Section 6, the noise value is amended by calculating carrier-wave interference and atmospheric noise independently, then combining them in order to determine more precise SNR limits.

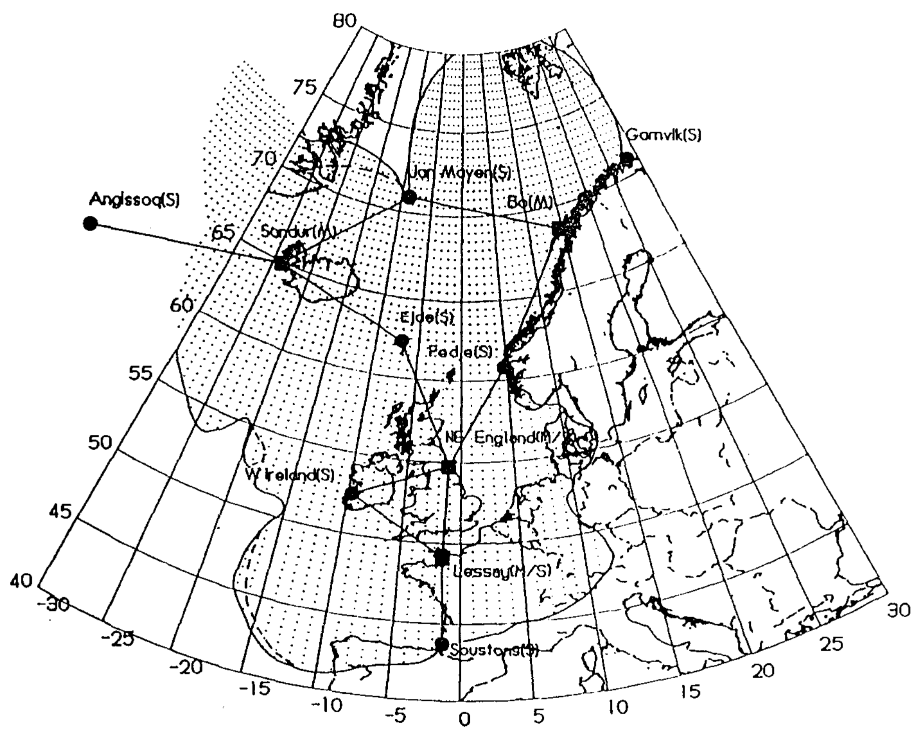

Fig. 2 Coverage of the proposed N.W.European Loran-C system. Within the solid contour the absolute accuracy is predicted to be 463m (95% confidence).

4 Envelope-to-cycle difference (ECD)

ECD is a potential coverage-limiting factor. Normally the ECD of the transmitted signal is adjusted so as to give a value of +2.5 μs in the near far field. The ECD value then falls as the signal propagates and, if the path lies over sea-water, reaches a value of approximately zero at the range of limiting SNR. This arrangement maximises range since, generally, receiver cycle-identification confidence is greatest at zero ECD and it avoids receivers having to cope simultaneously with poor SNR and high ECD.

The rate of change of ECD with range increases with falling ground conductivity when signals propagate over land. Also, receivers are only designed to guarantee reliable cycle identification when the ECD lies within a certain range, usually -2.4 to +2.4 μs [9]. It is important, therefore, to predict the ECD at all points in the coverage area so as to ensure that this condition is met. And even if the ECD is shown to be acceptable everywhere, predicting it allows the transmitter ECD value to be adjusted to the value which gives best cycle-identification performance throughout the coverage area.

The model employs the method described by Sherman to calculate ECD values [10]. Sherman established an empirical curve (Fig. 3) of rate of change of ECD with distance as a function of the conductivity of the land over which the signal travels. The model calculates the ECD of a signal at any point by first establishing the conductivity profile along the path from the transmitter and then summing the changes occasioned by each path section of uniform conductivity.

Fig. 4 plots contours of constant ECD around the station at Ejde. Comparison with Fig. 1 shows that the ECD lies within the allowed band of +/-2.4 μs at all points within the coverage area limit set by the SNR. Further, the contour of zero ECD does indeed coincide approximately with the SNR limit for the transmitter. We conclude that ECD is not a coverage-limiting factor for this station.

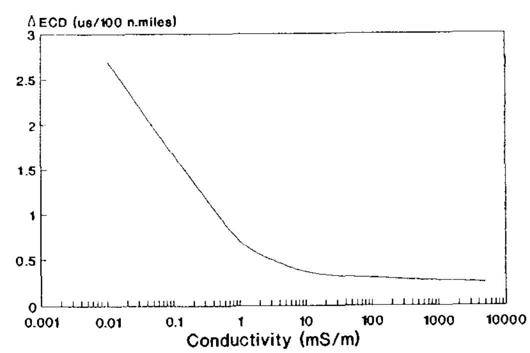

Fig. 3 Rate of change of ECD versus path conductivity. (After Sherman [10]).

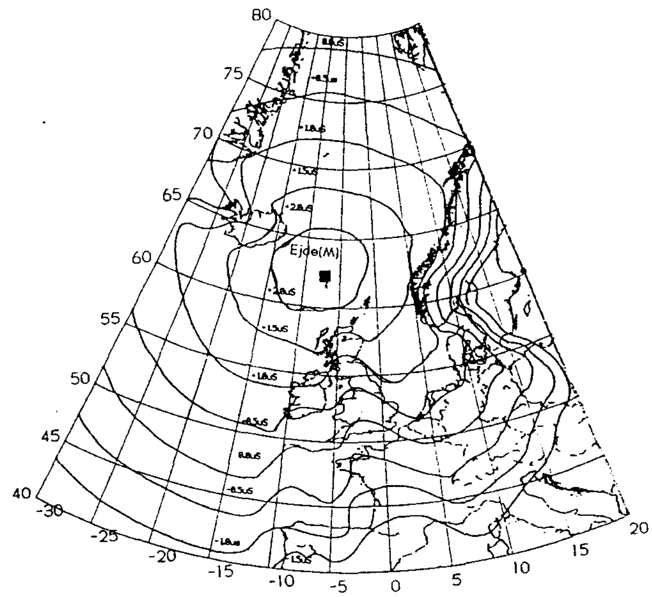

Fig. 4 ECD contours (in μs) for Ejde.

5 Skywave

Although Loran-C receivers are designed to identify the groundwave-propagated components of received signals and reject the skywave components, their ability to do so is finite and may be inadequate in certain circumstances. The minimum performance standard (MPS) for marine Loran-C receivers of the International Electrotechnical Commission (IEC) [9] requires *inter alia* that 'the receiver shall lock on in the presence of skywave interference with delays from 37.5 μs to 60 μs with relative skywave signal levels from 12 dB to 26 dB, respectively' (Fig. 5).

The model aims to check whether the conditions at each point allow receivers which meet this minimum performance standard to operate correctly. If not, a diagram showing the reduced coverage area is

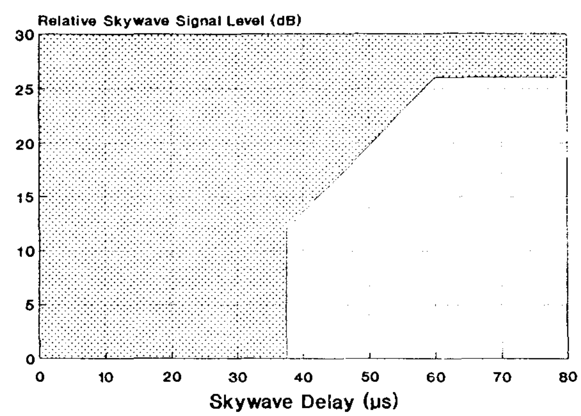

Fig. 5 IEC Skywave specifications [9]. Combinations of relative signal level and delay outside the clear area are out of limits.

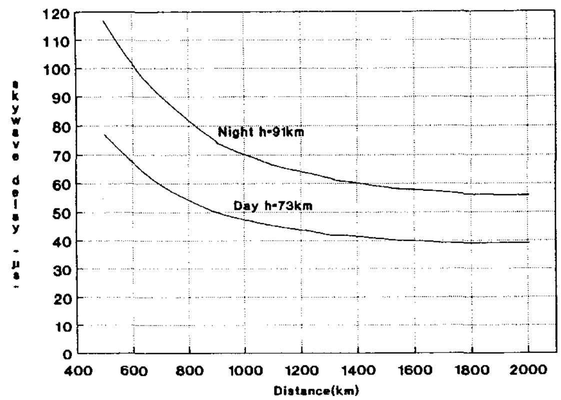

Fig. 6 Skywave delay from Loran-C rate tables [11]

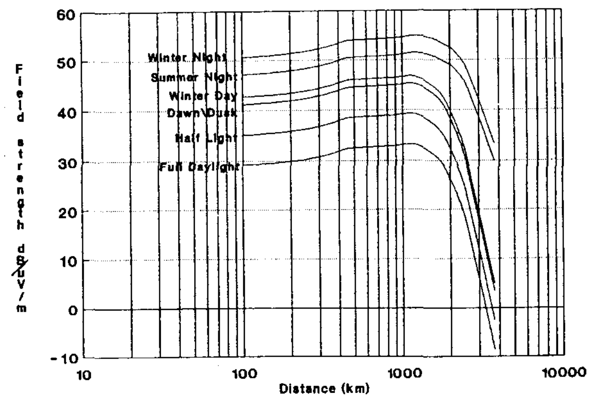

Fig. 7 99%ile skywave signal levels for various Decca Periods. Normalized for 1kW Radiator.

generated. This requires the model to be able to predict the skywave delay and relative signal level at each point in the coverage array. These two factors will now be considered separately.

5.1 Skywave delay

The U.S. Department of Transport Defense Mapping Agency publish tables which show the time differences between the arrivals of the skywave and groundwave signal components for each Loran-C master/secondary pair of stations [11]. Polynomial curves to describe the variation of skywave delay with range from the transmitter have been fitted to data extracted from such tables for use in the model. There are separate curves for daytime and nighttime conditions (Fig. 6).

5.2 Skywave field strength

The USCG publish curves showing the variation of the rms skywave intensity with range under average daytime and nighttime conditions for distances between 1000 and 3700 km (540 and 2000 nm) [12]. These curves agree well with other published figures and are believed to be reliable. Unfortunately, they do not illustrate seasonal variations of skywave intensity and they cannot be used for estimating skywave field strength at ranges of less than 1000 km.

These shortcomings have been overcome by reference to the extensive published data on skywave propagation for the Decca Navigator system (DNS) [13,14,15,16]. DNS signals are transmitted in the same frequency band as Loran-C and the skywave propagation characteristics of the two systems are very similar. Published skywave intensity information for the DNS covers ranges as short as 100 km and is broken down by season and time into 'Decca periods'. Where the Decca and USCG curves overlap agreement is satisfactory. The composite family of curves shown in Fig. 7 has been created by combining data from the two sources.

5.3 Skywave coverage limits

The coverage model employs the techniques described in Sections 5.1 and 5.2 to estimate the delay and the relative field strength of the skywave component at each point in the array. The values must fall within the IEC minimum performance specification for the point to be deemed to be within coverage.

Fig.8 shows the resulting coverage limits for the Norwegian Sea chain (GRI 7970) at various times and seasons. The Figure shows that skywave is a limiting factor to coverage during all periods except full daylight. As would be expected, skywave effects are least during 'Full daylight' conditions. Skywave has its most severe effect on coverage during daytime in the winter. This is a surprising result, at first sight, since skywave intensity is known to be greatest during winters' nights. The reason is that, although the skywave intensity is lower during winters' days than at night, the skywave delay is also much less as a result of the lower ionospheric height. The resulting skywave interference is consequently more severe, when judged against the IEC criteria (Fig. 5).

Lessons regarding transmitter power may also be drawn from this illustration. For example, the SNR limit of coverage for a transmitter of 400 kW over an all-sea path occurs at a range of 1370 km, assuming a noise level of 61 dB/μv/m. The coverage limit due to skywave interference on a winter's day is 1160km [17]. If the transmitter power is reduced the SNR limit falls, but the skywave limit remains the same. When the transmitter power falls to 126 kW the two limits coincide during the worst Decca period. Thus, there appears to be no point in employing transmitter power levels of much more than 126 kW over all-sea paths. This point is further illustrated by Fig. 8 from which it can be seen that the winter's day limitation of coverage from the 1500 kW station at Sandur in Iceland is much more severe than that of the lower-powered 275 kW station at Sylt in Germany.

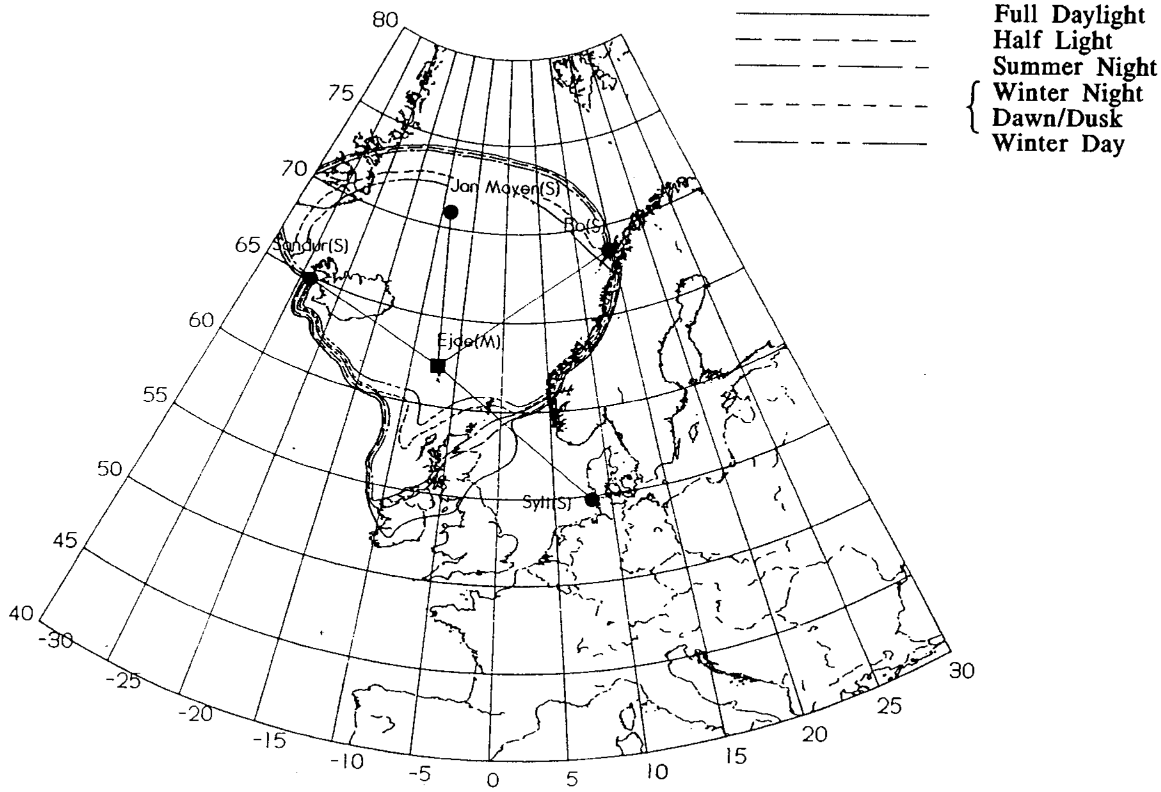

Fig. 8 Norwegian Sea chain coverage for various times and seasons showing skywave coverage limits.

The significance of the skywave limitations shown above should be seen in perspective. The MPS requires receivers to lock on correctly 99% of the time so the skywave signal strengths used are the levels which will occur for only 1% of the time in the period cited. Outside the skywave limits of coverage the receiver will not always fail but is likely to fail more than 1% of the time.

6 Noise and interference

The coverage diagrams illustrated so far in this paper, and those produced by several other workers, have been based on the assumption that the combined effects of atmospheric noise and carrier-wave interference in North-West Europe can be represented by a uniform noise field strength of 61 dB/μV/m.

A more accurate method of estimating atmospheric noise and carrier-wave interference is currently under development; the first stage of this work, which has already been incorporated into the coverage prediction model, will now be described.

6.1 Atmospheric noise

The field strength of the atmospheric noise is calculated according to the USCG method. The source of information is the most-recent issue of the CCIR data, Report 322-3. By calculating the atmospheric noise values at many points in Europe, it has been shown that the difference between adjacent points separated by 10° of latitude or 10° of longitude is less than 2 dB; consequently, this resolution has been chosen for the database of atmospheric noise values used in the model.

6.2 Carrier-wave interference

The task of modelling the carrier-wave interference is a daunting one: there are many actual and potential sources of interference; the intensity of the signal from each one varies geographically and temporally; and the effects of carrier-wave interference on receivers are complex and dependent on their design, construction and adjustment. So far, only the first stages in tackling this problem have been completed.

The approach has been to seek a representative set of conditions and develop an appropriate model. Subsequently, more exceptional circumstances will be explored. Beckmann and van Willigen, colleagues at the Delft University of Technology in the Netherlands, have advised and assisted in constructing this part of the model.

The effect of a cw interferer on the performance of a Loran-C receiver depends on the signal strength of the interferer, relative to that of the wanted Loran-C signal but also on its frequency, because of the filtering which is effected by the receiver. This filtering is generally of three kinds. Firstly, the response of the receiver can be represented by a comb filter, each passband of which is centred on a spectral line (Fig.9) of the Loran-C signal. Thus, interferers which are synchronous, or nearly synchronous, with Loran-C spectral lines have especially serious effects on receiver performance. Secondly, the receiver is normally fitted with a broad bandpass filter, centred on 100 kHz. Thirdly, Loran-C receivers customarily employ notch filters to eliminate the worst interferers close to the Loran-C frequency band.

The model contains descriptions of a comb filter (Fig. 10) and a bandpass filter (Fig. 11). The comb filter simulates the Loran-C receiver sampling function with a tracking loop bandwidth of 0.025Hz, which is typical for a marine-type receiver. The bandpass filter is also typical of that found in marine receivers. Notch filters have been omitted initially from the model so that it can be used to identify the most serious interferers. In the next phase of the work the effects of various notch filter settings will be investigated.

The database of interferers assembled by Beckmann [18] from International Frequency Registration Board (IFRB) sources, has been employed. This lists each transmitter by name, frequency, position and power. The model calculates a 'frequency-weighted power' for each interferer from its listed power by calculating the attenuation at its specific frequency due to the comb filter and bandpass filter. The spacing of the passbands of the comb filter, of course, depend upon the GRI of the Loran-C signal. The comb filter weighting process effectively eliminates interfering signals which are neither synchronous nor near-synchronous. The bandpass filter weighting process tends to eliminate signals at frequencies well separated from 100 kHz.

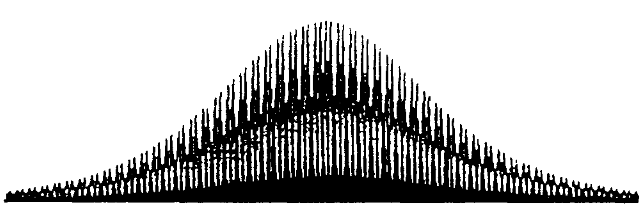

Fig. 9 Power spectrum of Loran-C transmission (After Beckmann [18]).

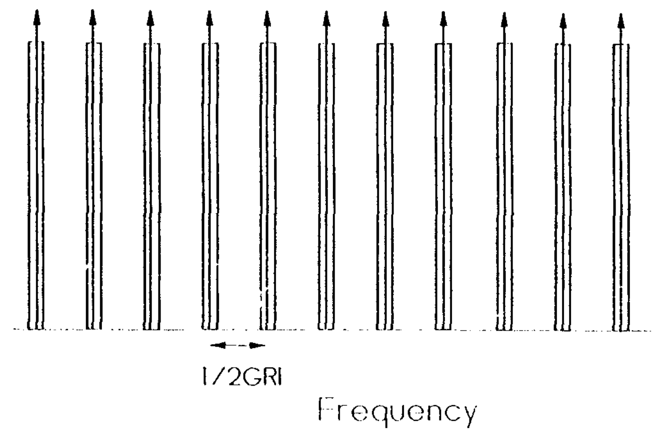

Fig. 10 Idealised comb filter transfer function.

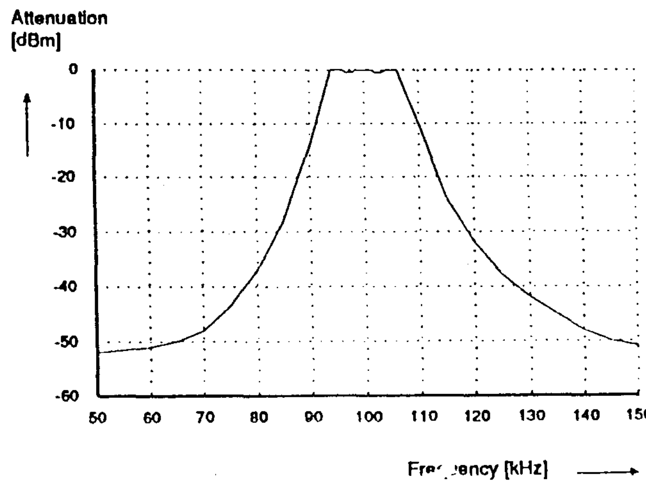

Fig. 11 Transfer function of the 'standard' bandpass filter (After Beckmann[18]).

An array of values of the field strength of the signal from each significant frequency-weighted interferer is now computed and stored. These arrays have the same point spacing, and cover the same area, as the array of ground conductivity values (Section 3.1). Both groundwave and skywave field strengths are calculated: the groundwave by reference to the ground conductivity profile of the path from the transmitter to the receiver and the use of Millington's method; and the rms skywave by means of the technique described in Section 5.2 and the curves of Fig. 7. At each point, the groundwave and rms skywave values are combined as a root of sum of squares.

The field strengths of the individual interferers are combined into a total interference value at each point by sum-of-root-of-squares addition. The model then adds the interference and atmospheric noise values together in the same fashion, so calculating a 'noise' value which can replace the 61 dB/μV/m figure employed previously.

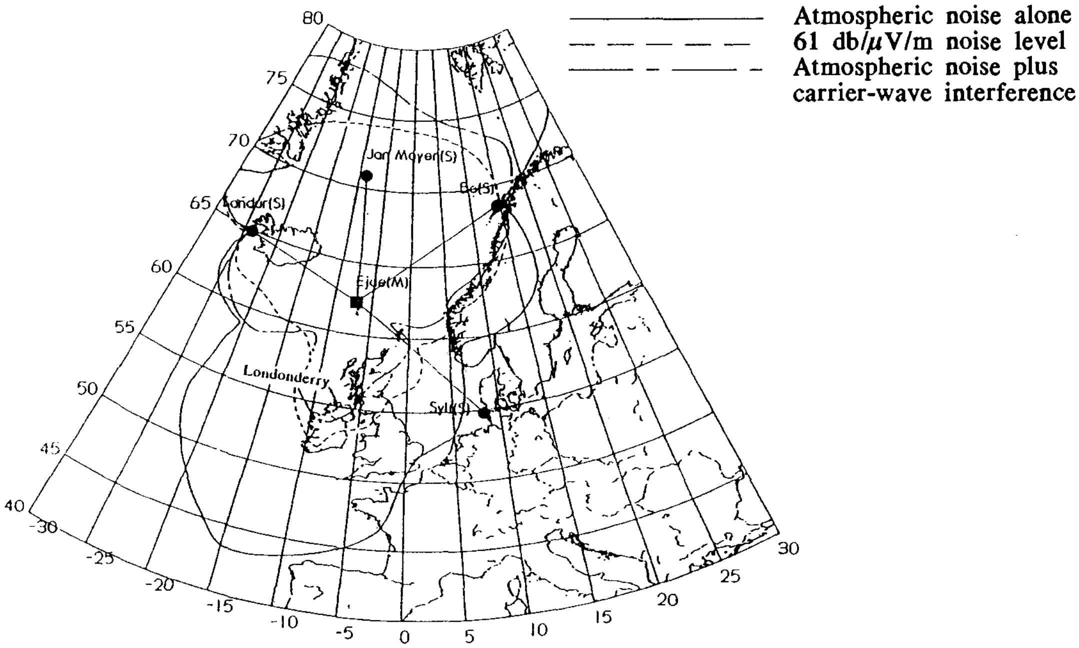

Fig. 12 Norwegian Sea Chain showing various coverage limits.

6.3 Effect of interference on coverage

Fig. 12 compares the coverage computed for the existing Norwegian Sea chain, assuming various limitations. The dashed line (- - - -) is the boundary of the coverage predicted when the noise level everywhere is assumed to be 61 dB/μV/m. The chain line (– —— –)is the coverage limited by atmospheric noise and carrier-wave interference calculated as described in Sections 6.1 and 6.2. The full line (———) shows the coverage limit due to atmospheric noise alone.

Incorporating the effects of actual interferers has reduced the coverage along the eastern boundary. Examination of the list of interferers shows that this reduction of coverage is entirely due to a single interfering station at a frequency of 105 kHz in East Germany. This station would clearly be a prime candidate for notch filtering in any receiver operating in the region. A much more localised, but important, effect is to be seen by examining closely the region around the transmitter station located in Ireland at 55°N and 7.467°W which is a synchronous interferer with this Loran-C chain. The frequency-weighted power of this station is only 1.5 x 10^{-3} kW. Nevertheless, the SNR falls below the USCG minimum within a radius of 7 km of this station. A notch filter tuned to the frequency of the station would be required in the locality.

Comparing either of the other two boundaries with that of the area limited by atmospheric noise alone shows the inadequacy of an atmospheric noise model for use under European conditions.

The techniques described in this Section for estimating the effective noise level due to

The techniques described in this Section for estimating the effective noise level due to
carrier-wave interference represent the first steps in a process of development of the coverage model. The coverage shown in Fig. 12 is illustrative of the operation of the model. It is not intended to represent coverage realistically; for example, the interferer which has the most severe effect on coverage, although it appears in the IFRB list, is no longer believed to be in operation [1]. A major task will be to develop a list of actual, operational, interferers to replace the IFRB list. That will then allow the model to show realistic limits for the operation of receivers of various types.

7 Conclusions

By assembling and using a database of ground conductivity values for Europe, the door has been opened to the creation of a coverage and performance model for Loran-C operation in the region. The coverage prediction techniques developed and tested by the USCG form a firm basis for this model. They are being enhanced by incorporating progressively more accurate estimates of the effects of carrier-wave interference, starting with an increased value of atmospheric noise chosen to reflect experience of Loran-C operation in the region.

The model also extends traditional coverage prediction techniques to include ECD effects and skywave interference. The examples presented show that ECD, as estimated by Sherman's model, should not prove a limiting factor to coverage. Skywave propagation, in contrast, needs to be considered carefully in system planning if the use of stations with power levels in excess of 250 kW is envisaged.

It should finally be stressed that the coverage prediction examples shown in this paper are all based upon relatively-conservative assumptions of receiver performance. Improvements in digital receiver design are already allowing operation at significantly-lower SNRs than are assumed here, overcoming the limitations due to skywave contamination and allowing carrier-wave interferers to be rejected by means of signal-processing techniques. As these advances continue to be introduced into our technology, the model will be adjusted to map their influence in extending the areas of Loran-C operation under European conditions.

8 Acknowledgements

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The accuracy and coverage of Loran-C and of the Decca Navigator System - and the fallacy of fixed errors

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Abstract

The proposal to develop an extensive North-West European Loran-C system, replacing many existing chains of the Decca Navigator System (DNS), has led to an intensive debate on the merits of the two navigation aids, especially in the United Kingdom. The paper reviews the principal sources of random and systematic position errors in the two systems. The wide range of DNS random errors, predominantly due to skywave interference, are compared with the Loran-C random errors, and typical coverage limits of acceptable repeatability are presented. The paper also identifies the factors which control the magnitudes of Loran-C and DNS systematic effects due to land paths. It demonstrates that differences between the two systems are substantially less than are predicted by simple models. Loran-C and DNS techniques for dealing with land paths are compared and the errors experienced by Loran users are shown to be reduced by modelling and publishing ASF values.

1 Introduction

The proposal to develop a Loran-C system for North-West Europe [1] triggered off an intensive debate. The key issue was that Loran would replace existing chains of the Decca Navigator System (DNS). Where the DNS was not already available, the advent of Loran-C was generally welcomed. But in those areas in which DNS was well-established, the advocates of Loran were required to justify removing a satisfactory operational system.

It was relatively straightforward to demonstrate that the costs of installing and running a Loran-C service were lower than the cost of maintaining the existing DNS service. This was true even though substantial capital equipment would be required to provide Loran-C coverage because the equipment installed at many DNS transmitting stations was nearing the end of its operational lifetime and would need to be replaced whatever the decision. The lower operational and maintenance costs of providing Loran-C coverage of the area meant that the Loran option was attractive to the Government Agencies charged with operating navigational systems.

Many of the users, in contrast, saw matters in a very different light. A change-over to Loran-C would mean that they had to scrap their DNS receivers and buy Loran equipment. They would also have to adopt new and different operational practices. And worst of all, especially for the fishermen, the records which they had built up over many years showing fishing grounds and the locations of wrecks and other hazards, would have to be amended. Extreme proponents of this view were vehemently opposed to the change and represented Loran-C as an old-fashioned system which had poorer repeatability than the DNS's, enormous fixed errors, and which would not work properly in Europe because of the high levels of carrier-wave interference.

The argument between the advocates of Loran-C and of the DNS was most intense in the United Kingdom. There the Department of Transport issued a Consultative Document [2] reviewing the issues and invited interested organisations to submit their views. This led to a vigorous public debate which obliged the participants on both sides to examine carefully the operation of their systems and exposed their claims to close scrutiny. The key technical issues concerned accuracy and coverage. In the course of this debate it became clear that, although the rivalry between Loran-C and the DNS is of long standing, recent developments in equipment and operational techniques justified re-examining these questions in detail. Moreover, the debate exposed significant differences in practice and terminology and frequent mis-understandings. It demonstrated the need for clarification of these key issues. That is the principal object of this paper.

Although the comparisons of the performance of the DNS and Loran-C systems were conducted within a European context, the results are of wider than just European interest. There are undoubtedly special factors obtaining in Europe: most notably the exceptionally high levels of carrier-wave interference. North-West Europe is also the region where the DNS is most widely established: 70 stations, grouped into 21 chains, serve possibly as many as 100,000 users. But these are secondary issues and the principal results of the paper will undoubtedly be of relevance in other areas of the World, such as the Indian sub-continent, in which the two systems are competing for dominance.

The paper will first describe the operation of the Decca Navigator System, the differences between Loran and the DNS, and their similarities - which are greater than is often recognised. The repeatabilities of the two systems will then be examined, the sources of random errors being identified and their magnitudes estimated. The paper will then discuss the factors which control the systematic effects due to signal propagation over land paths and compare the very different operational practices adopted to deal with the problems which arise. Finally, the question of absolute accuracy, allowing for both random and systematic errors, will be discussed.

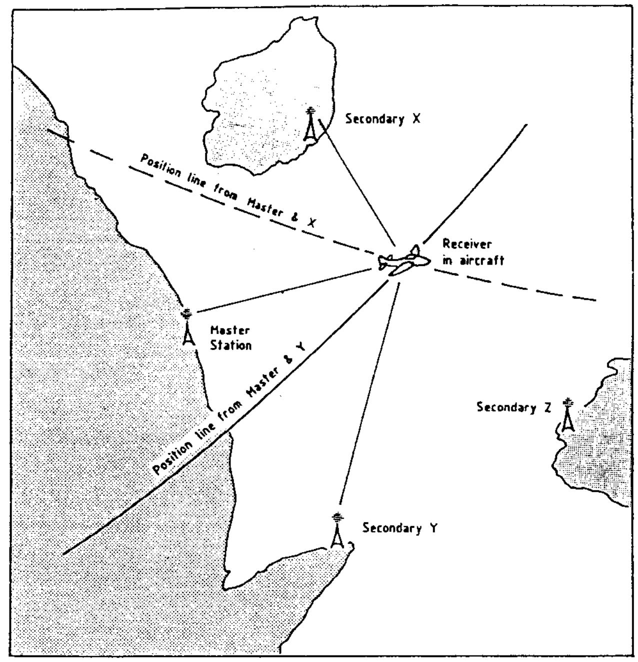


Fig. 1 The transmitting stations of both Loran-C and the Decca Navigator System radiate synchronised signals. The receiver (on the aircraft) measures time differences between their arrivals. The resulting lines of position fix the location of the aircraft.

2 Loran-C and the Decca Navigator System

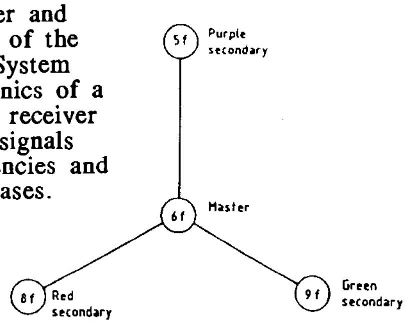
Loran-C and the Decca Navigator System are both hyperbolic, low-frequency radio-navigation systems which transmit in the 100 kHz frequency band. It is sufficient initially to take a relatively simple view of the operation of the two systems. Assume (Fig. 1) a chain of fixed stations which transmit pulses of radio energy simultaneously. The signals travel as surface waves from the transmitters to the receiver (in the aircraft) where time-of-arrival measurements are made. From these the receiver calculates the differences between the arrival times of the signals from pairs of stations. The corresponding differences of distance are then computed from knowledge of the velocities of propagation of the signals. Since we know the locations of the transmitters we can calculate the position of the receiver: it is at the intersection of the hyperbolic lines of position which correspond to the differences of distance (Master & X, Master & Y in Fig. 1).

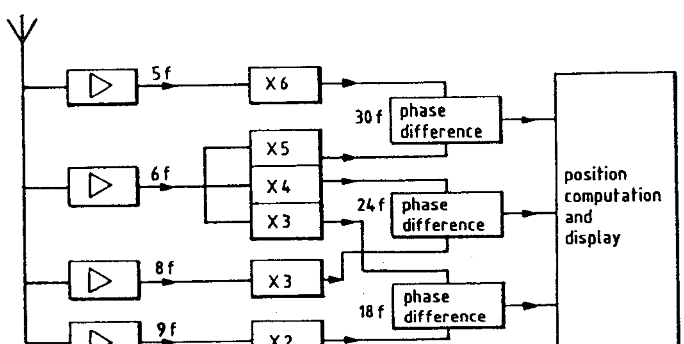
Particular systems, of course, elaborate on this simple model in specific ways. Loran-C pulses are transmitted at precisely 100 kHz. The signals radiated by the various Loran transmitters are distinguished from each other by being transmitted with fixed time intervals, which are subtracted in the receiver when the time difference values are calculated.

In the DNS the signals from the various stations are distinguished from one another by being transmitted at different frequencies. Each of the four stations of a normal DNS chain (Fig. 2) radiates on an individual frequency, between 70 and 130 kHz, that is a harmonic of a common frequency, f, which identifies the chain. The master station transmits at $6f$, and the secondaries at $5f$, $8f$ and $9f$. The principal difference between the DNS and Loran-C is that DNS transmissions are not pulses, but narrow-bandwidth, continuous-wave signals. The receiver determines the time differences between the signals it receives from the master and secondary stations by measuring their phase differences. To achieve this, the signals are converted to common frequencies: for example, the phases of the signals from the master station at $6f$ and those of the secondary at $5f$ are compared at their common multiple frequency of $30f$.

Measuring phase differences gives rise to cyclic ambiguities of time difference which must be resolved. This is done by the 'Multipulse' system in which each transmitter in turn periodically radiates a short burst of pulses, at the frequency f, whose times of arrival are measured and compared. The pulses are actually created in the receiver by Fourier addition of components transmitted by the stations at the four DNS harmonic frequencies.

Fig. 2 The master and secondary stations of the Decca Navigator System transmit at harmonics of a frequency f. The receiver converts pairs of signals to common frequencies and compares their phases.





At first sight, therefore, Loran-C and the DNS appear to be fundamentally different systems. Loran employs broad-band pulses while the DNS uses a narrow-band CW technique. But the essential similarity is that both are hyperbolic systems, operating in the 100 kHz band, in which fine time-difference measurements are made by the comparison of carrier phase, the cycles being identified by means of a pulsed transmission. And in matters of groundwave propagation the differences are trivial.

More significant differences appear when one identifies the effects of skywave propagation on the two systems. Loran-C is essentially immune to skywave signals at most times over most of its coverage area since receivers complete time-of-arrival measurements on the groundwave-propagated pulses before significant skywave energy is received. A Decca Navigator System receiver, in contrast, has no way of distinguishing between groundwave and skywave signals. Thus, in order to ensure that groundwave signals significantly exceed skywave components, DNS receivers must operate close to their transmitters; nominal coverage extends only 440 km from the master station. Consequently, DNS chains have much shorter baselines than Loran-C chains - typically 150 km compared with 1000 km. A single Loran-C chain will serve the same area as many DNS chains. However, since DNS baselines are short, and receiver bandwidths narrow, DNS transmitters need only radiate tens of watts of power in contrast with the hundreds of kilowatts transmitted by Loran-C stations.

It is from these differences between the systems, rather than from the more obvious differences in their transmission characteristics, that the distinctions between their accuracy and coverage result.

3 Random errors and repeatability

3.1 Loran-C

Random errors in the positions displayed by Loran-C receivers are generally ascribed to transmitter timing errors, to receiver errors and to the uncertainties in timing measurements due to limited signal-to-noise ratios (SNRs). The first two factors used to lead to substantial uncertainties of position. However, improvements in receivers and in chain control techniques have reduced the resulting timing uncertainties to as little as 36 ns (1σ) [3], which is negligible in comparison with the SNR effects experienced over most of the coverage area of a chain.

Traditionally, the noise to which a Loran-C receiver is subject has been assumed to be random in nature and atmospheric in origin. This assumption is true throughout most of the World for well-designed receivers which employ notch filters that are correctly adjusted to reduce any carrier-wave interference to a negligible level. But in North-West Europe it is untrue. There it has been clearly demonstrated [4] that the dominant source of noise is carrier-wave interference received from the many stations with which Loran-C is obliged to share its frequency band. And although many of these interferers give rise to position errors which are effectively random in nature, others do not. Interfering transmissions which are synchronous, or nearly synchronous, with spectral lines of the Loran-C signal being received can cause apparently-permanent or slowly-varying errors in the positions measured. Nevertheless, because these position errors are random in space, if not in time, they are generally treated in the same way as the other random errors.

In estimating the Loran-C random errors due to noise, it is customary to make certain simplifying assumptions. For example, the US Coast Guard (USCG) deem the limit of coverage to be reached when the signal-to-noise ratio falls to -10 dB. The resulting uncertainty in the measurement of the times of arrival of signals with this SNR is assumed to be 100 ns ($1\text{-}\sigma$). A second coverage limit is then applied: the worst-case geometry of any position fix is assumed to be such as to limit the $2d_{rms}$ position error to 0.25 nautical miles (463 m) when all signals are received with the limiting SNR. Thus, since the errors are presumed to be randomly distributed, it may be claimed that, throughout the published coverage of a Loran-C chain, the random uncertainty of position is less than 463 m at 95% confidence.

It is less common to predict contours of random position errors within the coverage area. To do so accurately, it is necessary to estimate point-by-point the SNR of each of the signals which contributes to the position fix. The uncertainties in the individual time-of-arrival measurements and in the time-differences are then calculated. Finally, taking the geometrical factors into account, the resulting random errors in the positions are determined. The results are generally expressed in the form of contours of $2d_{rms}$ repeatabilities of position, as in Fig. 3.

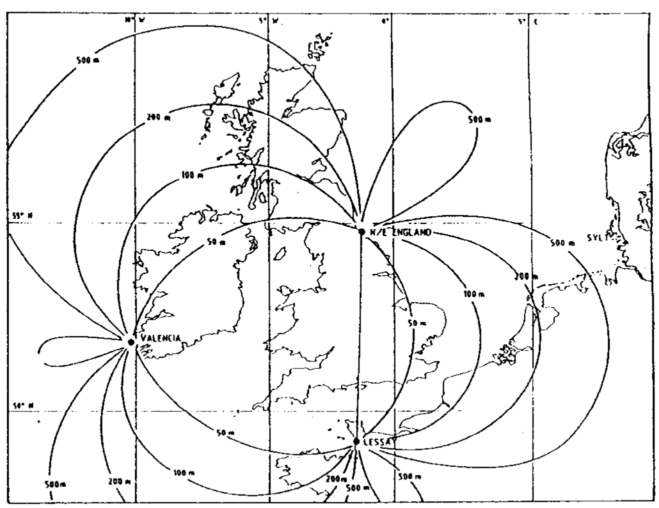


Fig. 3 Contours of repeatable accuracy (95% confidence) for a Loran-C triad consisting of a master station in N.E. England and secondary stations at Lessay, France and Valencia, Ireland (after Megapulse [3]).

In Europe, the effects of the lower SNR values due to carrier-wave interference have either been ignored so far or taken into account in relatively simple ways. USCG coverage charts appear to be based upon consideration of atmospheric noise alone and are widely regarded as over-optimistic. The policy of the international North-West European Technical Working Group, which is planning the new Loran-C chains, has been to assume that the effects of all interference sources can be equated to an atmospheric noise level of 61 dB/μV/m. The justification for this value is discussed in another paper in this Convention [5]; suffice it to say here that it is a conservative figure based upon operational experience of the use of the existing Loran-C chains in the region. The advantage of this approach is that, by employing this value of equivalent atmospheric noise, standard prediction techniques can be used to estimate the coverage areas of the proposed chains. Within those areas the repeatability will again be 463 m at the 95% confidence level (Fig. 4). In the same way, other repeatability contours can be determined.

3.2 <u>The Decca Navigator System</u>

Let us now identify the sources of random error in the Decca Navigator System and compare its performance with that of Loran-C. In making these comparisons, DNS errors will be expressed as $2d_{rms}$, or 95% confidence, values for consistency with Loran-C, rather than as $1d_{rms}$, or 68% confidence, as is customary for the DNS.

The sources of random errors in the Decca Navigator System, as with Loran-C, include transmitter and receiver timing inaccuracies, interference and noise. Chain timing control is excellent and receiver errors are negligible. In consequence, the DNS can provide a 95% repeatability ($2d_{rms}$ error) in its areas of prime coverage of better than 50m. DNS receivers have bandwidths of only a few Hertz, much less than the 20-40 kHz of Loran receivers. As a result, errors due to carrier-wave interference are normally negligible, especially since the DNS enjoys exclusive frequency allocations. These narrow bandwidths also mean that the DNS is relatively immune to atmospheric

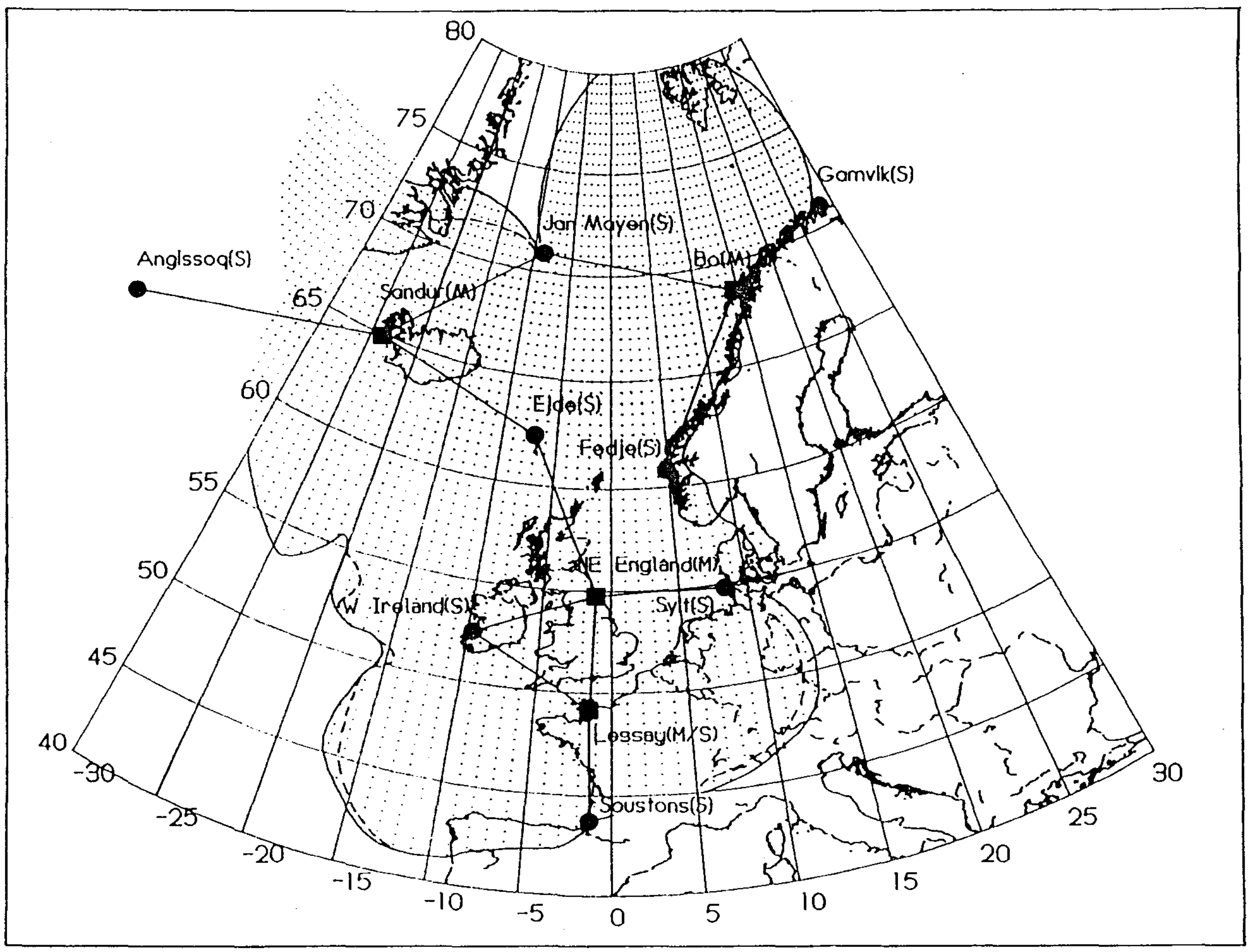
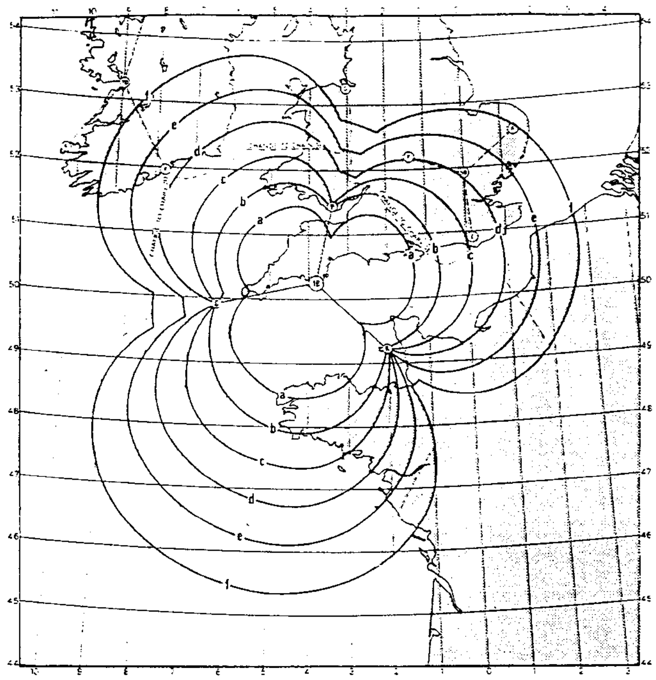
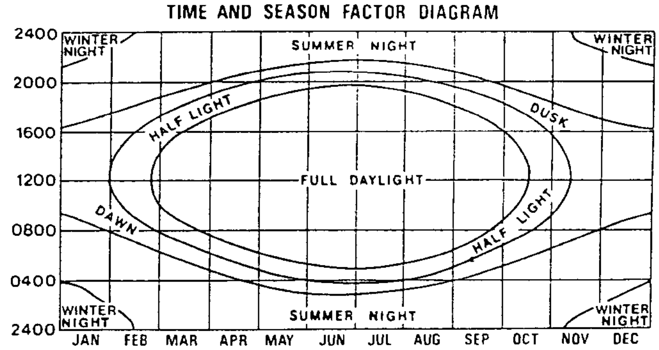


Fig. 4 Coverage of proposed North-West European Loran-C system [12]. Within the solid contour the absolute accuracy is predicted to be 463m (95% confidence).



DECCA PERIOD (See Time and Season Factor Diagram below)	CONTOUR a	b	c	d	e	f
HALF LIGHT	<0·10	<0·10	<0·10	0·13	0·25	0·50
DAWN/DUSK	<0·10	<0·10	0·13	0·25	0·50	1·00
SUMMER NIGHT	<0·10	0·13	0·25	0·50	1·00	2·00
WINTER NIGHT	0·10	0·18	0·37	0·75	1·50	3·00

TIME AND SEASON FACTOR DIAGRAM



(a) (b)

Fig. 5 Random errors of the Decca Navigator System. (a) Contours of predicted repeatability at the 68% confidence level. (b) Corresponding repeatability values (in nautical miles) for various times and seasons [13].

noise; only in tropical regions, at the worst seasons of the year and times of the day, is atmospheric noise the limiting factor in DNS coverage.

In all other circumstances it is skywave propagation which determines the maximum range of DNS operation. Receivers are unable to distinguish between the wanted groundwave signals and the unwanted skywaves. The only relief from skywave interference is that afforded by the fact that the skywave errors in the four frequency components which contribute to the Multipulse system (see Section 2 above) are substantially uncorrelated. The pulses, consequently, suffer smaller skywave errors than do the individual single-frequency transmissions. Certain types of DNS receiver take advantage of this fact by employing the Multipulse system alone as the source of time difference information under the worst conditions of skywave interference.

The skywave errors of the DNS vary profoundly with location, time of day and season of the year. Their short-term temporal distribution is approximately Gaussian, although slightly leptokurtic. Under optimal conditions, skywaves contribute only a small part of the total error of 50m, $2d_{rms}$, cited above. At night, however, and especially in winter, ionospheric propagation increases greatly and skywaves become the dominant source of random errors. In the outer regions of coverage, 5% of all fixes lie more than 11 km (6 nautical miles) from the mean measured position. Figs. 5a and 5b illustrate the complex way in which the random errors of a typical DNS chain vary with time and season. At higher latitudes the proportion of each winter's day during which the worst conditions obtain is, of course, greater than is shown here.

3.3 Comparison between the systems

The lowest values of random error generally claimed for both systems are of the order of 50m (95% confidence). The worst-case random errors of Loran-C are restricted to 463m (95%). Those of the DNS can reach 11 km. Fig. 6 shows a comparison between the areas within which the existing DNS chains and the proposed North-West European Loran-C chains claim to provide a 95% confidence repeatability of better than 400m at all times and seasons.

4 Propagation over land paths

In order to be able to calculate the difference of distance of the receiver from each pair of transmitters, one needs to know the velocity of propagation of the signals. This velocity is a function of the conductivity, and to a lesser extent the permittivity, of the ground over which the signals have travelled. It is conventional to consider the propagation time of a signal travelling from a transmitter to a receiver as being the sum of two parts: the time the signal would have taken if the path had lain entirely over sea-water, plus an 'additional secondary factor', or ASF, which is due to the effect of the land.

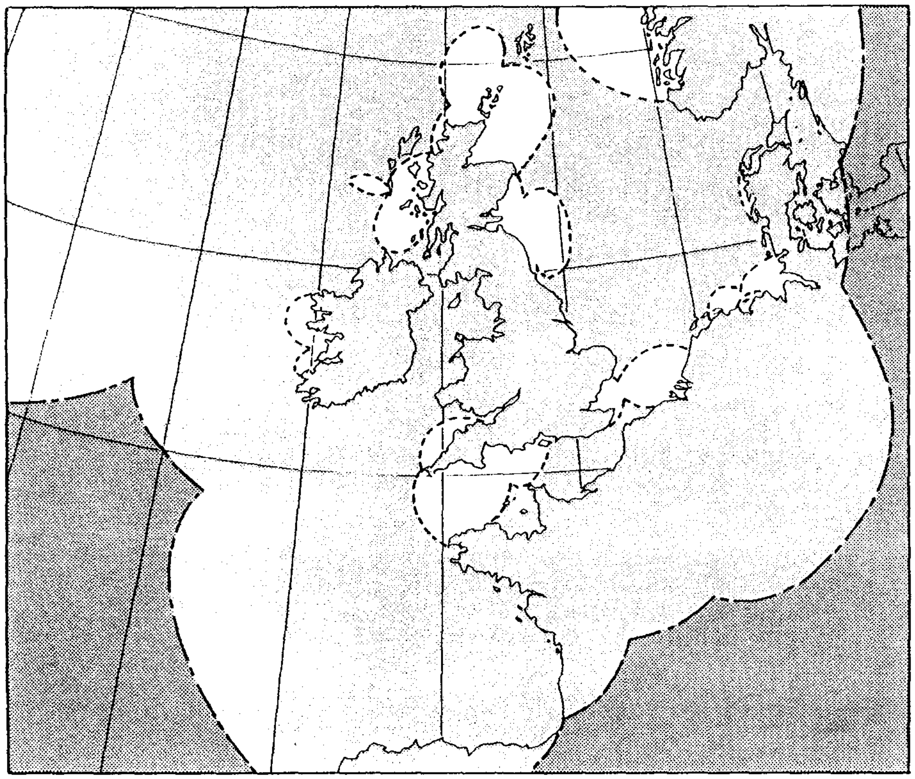


Fig. 6 Areas within which the Loran-C (- —— -) and the Decca Navigator System (- - -) repeatabilities are better than 400m (95% confidence) at all times and seasons (DNS land coverage omitted) (after [2]).

The relationships between ASF values and the lengths and conductivities of land paths are well understood [6]. Fig. 7, for instance, illustrates the growth of ASF with distance for various types of terrain. It is drawn for a frequency of 100 kHz and is applicable to both Loran-C and the DNS. Where paths are of

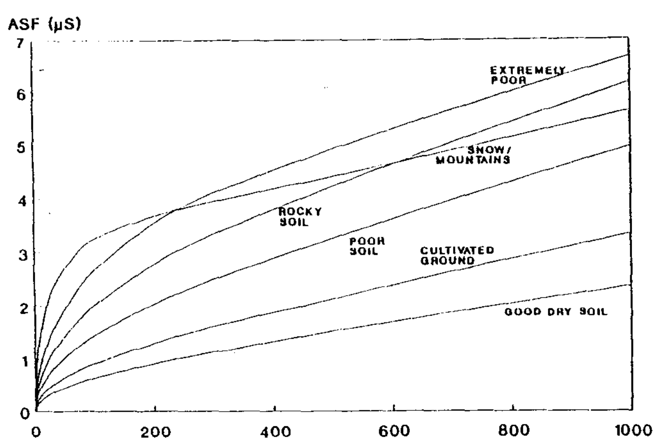


Fig. 7 Growth of additional secondary factor (due to propagation over land) with distance for various types of terrain (after Brunavs [14]).

inhomogeneous conductivity, the Millington-Pressey method [7,8] allows the ASF values to be calculated. Thus, in principle at least, we can draw hyperbolic lines of time difference, or calculate positions from time-difference readings, in a receiver. To do so precisely requires a detailed map of ground conductivity values. A receiver which stores such a map can easily determine the Great Circle paths from the transmitters to itself and hence calculate the ASF delays in the signals that it is receiving.

There are, of course, practical limitations to the application of this technique. Published ground conductivity maps are frequently inadequate and the Millington-Pressey method cannot model perfectly the transient effects which occur when signals cross coastlines. There are also profound differences between the ways in which Loran-C and DNS receivers of various kinds implement these techniques. In consequence, the systematic errors in position measurements vary greatly, as will now be seen.

4.1 Loran-C

Recent developments in Loran-C practice have resulted in very low residual effects due to land paths. Enge and McCullough [9] have shown that imperfectly-mapped conductivity variations and modelling errors result in small systematic discrepancies in the ASF values calculated. These discrepancies can generally be

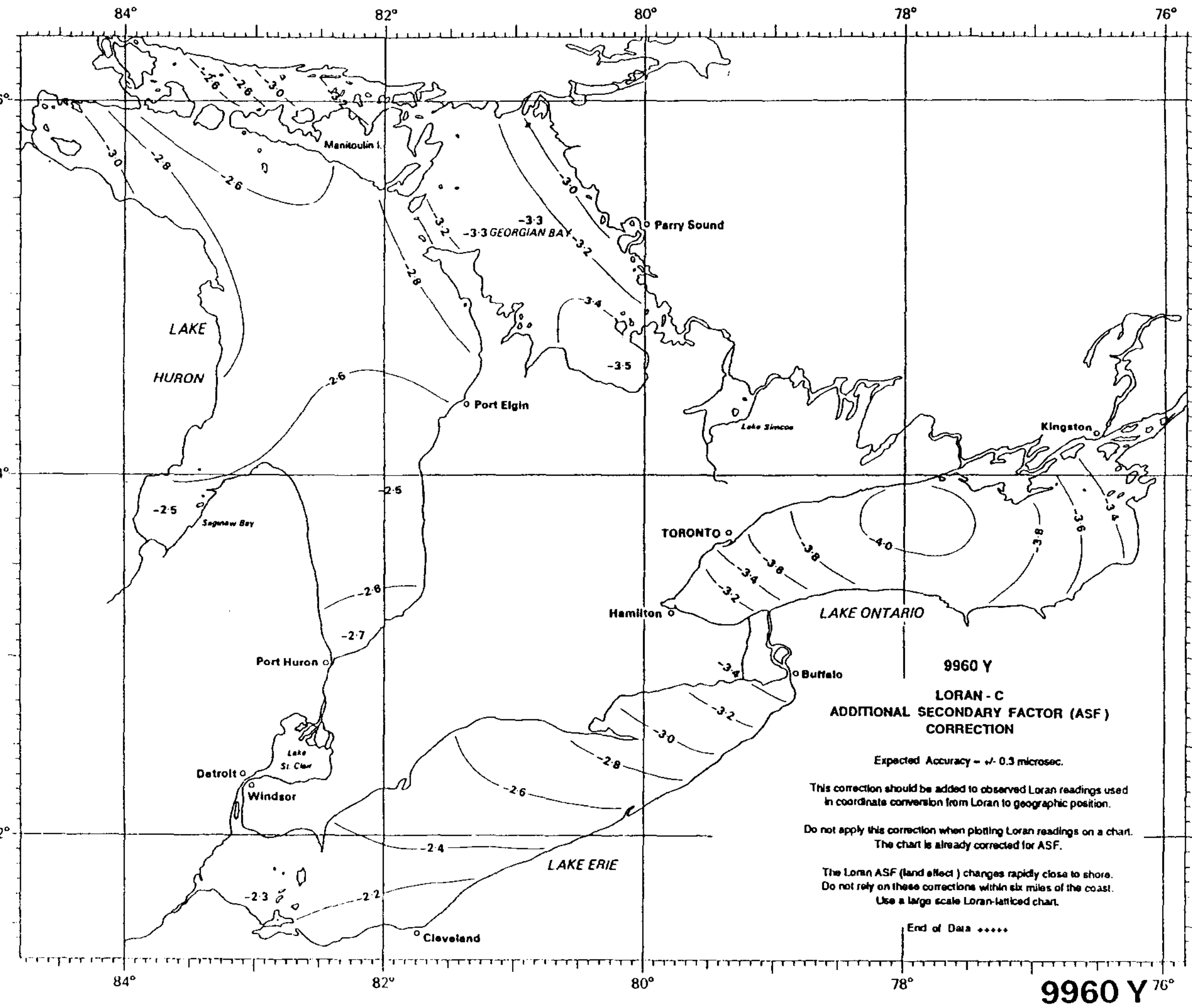


Fig. 8 Plots of additional secondary factors of time differences determined by the Canadian Hydrographic Service by computer modelling and survey [15].

substantially eliminated, and certainly reduced to the order of the minimum random errors of the system, by adjusting the results of the conductivity model to give an optimum fit with a sparse set of survey measurements. Using this technique the Canadian Hydrographic Service (Fig. 8) claim a time-difference accuracy of 0.3 μs, which is equivalent to 45m position error on a baseline.

The best Loran-C practice currently is to map ASF values in this way and publish the results. Although, at one time, users were required to look up corrections in tables and enter values manually into receivers, the information can now be stored in read-only memories (ROMs). The receivers take the corrections into account automatically when calculating positions. This technique is now being widely used in airborne receivers to permit non-precision instrument approaches to runways, the ASF corrections for large numbers of airports being stored in the ROMs. By adopting this practice, the effects of land paths are reduced to the residual inaccuracies of ASF mapping and to the effects of seasonal variations in the velocities of propagation.

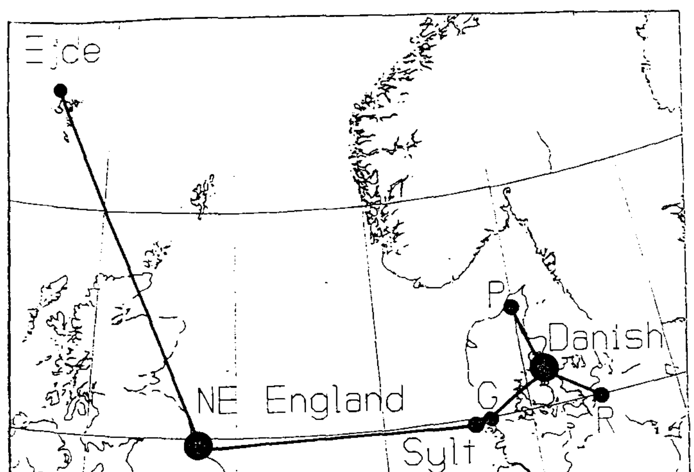


Fig. 10 Off the Danish west coast Loran-C ASFs are negligible since, though paths are long, they lie almost entirely over sea-water. Decca Navigator ASFs are substantial because the master signal must cross the land-mass of Jutland.

It is now also possible to correct substantially for these seasonal effects. Many airborne receivers employ plug-in ROMs which are replaced regularly. This practice ensures that the ASF corrections are kept up-to-date together with the large volume of other aeronautical data which is now customarily stored in such receivers. Other types of receiver automatically apply corrections for seasonal variations of velocities of propagation. In many temperate areas of the World, however, seasonal effects are small and many users choose to ignore them. For example, Enge [10] has estimated that, in the region of the British Isles, uncorrected seasonal ASF variations to the planned service would contribute a position uncertainty of only 40-70m ($2d_{rms}$).

4.2 The Decca Navigator System

The DNS approach to ASF effects contrasts sharply with that of Loran-C. In preparing DNS charts, a single, average velocity of propagation is assumed for the each master-secondary pair. In certain areas the resulting discrepancies have been surveyed and values published either at sample points or in the form of contours. Elsewhere no values are available. The ASF effects can be substantial: values between 500 and 1000m are shown in Fig. 9 which illustrates the corrections to be applied to a single hyperbolic coordinate in an area of the Bristol Channel. Much greater values are shown at points close to the Norwegian coastline. A significant additional disadvantage of this approach is the inconvenient form of the error chartlet which has been shown to be widely ignored by users [11]. This is because it must be read by an operator and values entered manually into the receiver in the form of corrections to hyperbolic lines of position. However, this is an unfamiliar practice for most users who are accustomed to receivers which display position data in latitude and longitude form or as bearings and distances to waypoints.

4.3 Comparison between the systems

In the course of the debate in the United Kingdom concerning the relative merits of the two systems it was claimed that, because Loran-C chains cover much larger areas and have much longer baselines than those of the DNS, the 'fixed errors' of Loran-C are much greater than DNS ones. This is, at first sight, an attractive and reasonable argument. On closer examination it turns out to be a far from universal truth.

It is true that the baselines of Loran-C chains are invariably longer than those of the DNS and that, in general, Loran receivers are further from their transmitting stations. But ASFs are not due to all paths but only to land paths, and land paths are not necessarily longer when Loran-C is used. Take, by way of example, the sea area west of Denmark (Fig. 10). The DNS covers this area by means of stations on the adjacent land. The signals from the master station travel over land paths, across Jutland, which contribute significant ASFs to the time differences. The paths from the Loran-C stations, in contrast, although much longer, lie almost entirely over sea water, and the resulting ASFs are negligible.

Even if it were true, however, that Loran-C land paths were longer than those of the DNS, this would not necessarily result in significantly different

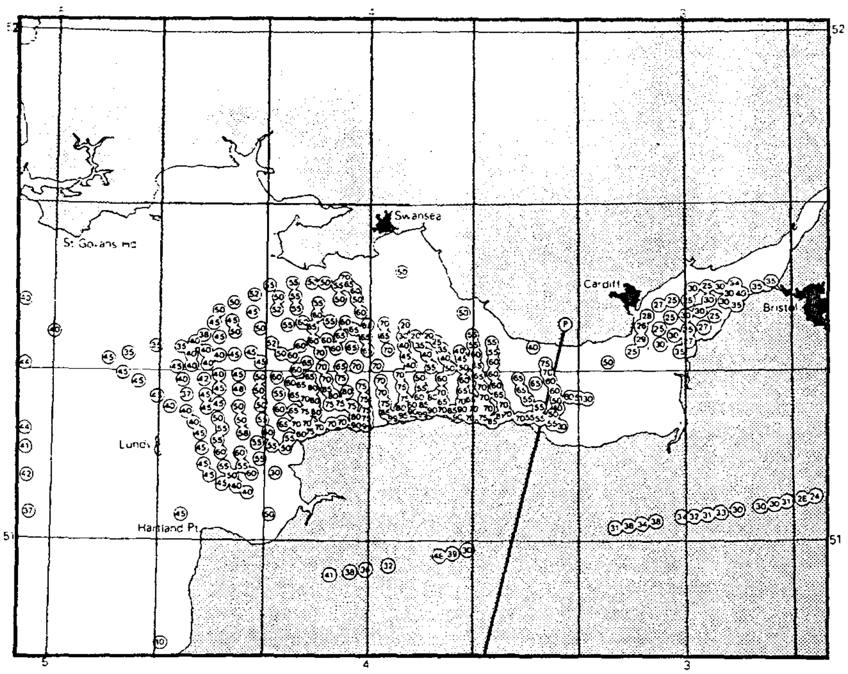


Fig. 9 'Fixed errors' of one pattern of the Decca Navigator System in the Bristol Channel. The figures represent corrections expressed in hyperbolic coordinates [13].

values of ASFs. Fig. 7 shows clearly that the rate of increase of ASF with distance is grossly non-linear. Consider the curve for 'rocky soil', for example: an ASF of approximately 1.5 μs builds up over the first 50 km of land path; a further 200 km is required to double this ASF. In fact, the build-up of ASFs occurs most rapidly close to the transmitting stations.

This fact has a further important implication: it should be clear from the earlier discussion that ASFs themselves do not cause position errors, only our imperfect ability to model and correct for them. This is made clear by imagining a chain, one transmitter of which has a large but constant ASF at all points; it would be a trivial task to subtract this ASF value from all time differences. Rather it is uncorrected small-area changes in ASFs, such as those due to coastal effects, headlands and so on which can cause position errors. In this respect the DNS suffers the disadvantage that, since most receivers are closer to the transmitting stations than is the case with Loran-C, the ASF variations contributed by such geographical features to DNS positions will, in fact, be larger.

We thus conclude that there is no case for arguing that Loran-C suffers greater errors due to ASF effects than does the Decca Navigator System. But overshadowing all of these relatively subtle points is the fundamental difference in operational practice between the two systems: Loran-C receivers can carry out automatic correction for the bulk of ASF effects by reference to read-only memories containing ASF values. Users of such receivers are essentially immune to ASF effects. No such technique is known to be available for DNS users who, in most cases, experience ASF errors in full.

4.4 Terminology

This difference in practice is reflected in an interesting difference of semantics. Whilst it is normal Loran-C terminology to refer to 'ASF values', the equivalent term in DNS language is 'fixed errors'. This reflects a misleading viewpoint: that propagation over all-sea paths is somehow the norm and that land paths are an aberration which causes 'errors'. There is, however, nothing erroneous about propagation over land; the error is in ignoring it and assuming a single, uniform velocity of propagation. This over-simplification, at one time justifiable by limited computer power, is now unnecessary. We can, and should, calculate the effects of land paths just as we calculate those of sea paths. Shakespeare summed up the situation thus: 'The fault, dear Brutus, is not in our stars, but in ourselves'! He meant, no doubt, that, if we are prepared to model the propagation of radio waves with sufficient precision, we can reduce the discrepancies between predicted and observed positions to small values. The residual effects of propagation over land should then be comparable with the minimum random errors of both systems, and negligible compared with the maximum random errors.

4.5 Fishermen's databases

Fishermen in North-West Europe have built up records, sometimes over many years, which show fishing grounds and the locations of wrecks and other hazards. Commonly, these have been recorded using the Decca Navigator System. Changing to Loran-C means that fishermen must amend their databases and it is important to consider how this task can best be effected.

Fishermen do not generally appear to apply the published DNS 'fixed error' corrections, even where these are available. In consequence, the positions marked in their records are subject to the systematic errors of the DNS. Thus, even were the Loran-C positions error-free, it would still be necessary to amend their databases so as to eliminate the DNS systematic errors.

The most straightforward solution will be for fishermen to do this during the substantial overlap period when both systems are in simultaneous operation. Having used the DNS to return to a recorded point, the record will be marked with the position indicated by a Loran-C receiver.

Alternatively, the possibility of producing conversion tables has been considered. An ASF database is to be compiled for Loran-C using the process of modelling and survey described above. The same procedure can be carried simultaneously for the existing DNS chains. A conversion table from DNS to Loran-C can then be generated which will allow a vessel equipped with a Loran-C receiver to return to a position recorded using the DNS. It should be clear from the discussion in Section 3 above, however, that whichever technique is employed to amend a database, the ability of the fisherman to return to the original DNS positions (whether he uses the DNS or Loran-C) will be limited by the random errors which obtained at the times and seasons when they were recorded.

5 Absolute errors

When navigation systems are being specified it is common for a certain absolute accuracy to be demanded. This was the case in the United Kingdom: the Consultative Document [2] required an absolute accuracy of 0.25 nm (463m) at the 95% confidence level. To meet such a requirement we must be able to sum the random and systematic errors in a meaningful way.

Loran-C practice is frequently unclear in this respect. Some sources imply that the 0.25 nm, 95%, published coverage shows the repeatability limit, others absolute accuracy. In fact, this confusion is not as serious as might at first sight appear provided that it is assumed that a user will be applying published ASF corrections. In this case the systematic error component need only reflect the residual terms due to any inadequacies of the ASF corrections.

Recent practice in Europe [12] has been to set this figure at a conservatively-high value of 0.125 nm or

232m (95%) (which is assumed to be random in distribution since, if it were systematic, it would have been corrected!). If the total, absolute, error is to be 463m (95%), and errors are combined by means of a root of sum of squares, the allowable random errors are 400m. The difference in coverage between a random error limit of 400m and one of 463m is small, probably well within the tolerance of the prediction process. Furthermore, the greatest random errors do not generally coincide with the greatest residual systematic errors; random errors are largest at the extremes of coverage which, for marine users of the proposed European chains, are in the Atlantic Ocean. Systematic errors, in contrast, are largest in inshore waters where, generally, random errors are small. Thus the published coverage can, in practice, be taken to represent either the repeatability, or the absolute accuracy when ASF corrections are applied, at approximately the 0.25 nm, 95% confidence, level.

DNS practice does not provide any straightforward means of mapping absolute accuracy.

6 Conclusions

The random errors of the Decca Navigator System are dominated by skywave effects and they range from below 50m (95%) to more than 11 km. Loran-C random errors can also be as low as 50m but should never exceed 463m. The effects of propagation over land paths are handled quite differently in the two systems. Loran-C techniques, which model and correct ASFs for publication on ROM, result in much lower systematic errors than the DNS practice of adopting a single velocity of propagation for each baseline.

7 Acknowledgements

The author thanks his colleagues Richard Farnworth, Dr. Mark Searle and David Williams of the University of Wales, Bangor, and also Dr. Nick Ward of Trinity House, Dr. Stuart Ruttle of the Irish Lighthouse Service and Professor Per Enge of Worcester Polytechnic, MA, for the stimulating discussions on which this paper is based. The opinions expressed, however, are his alone.

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DESIGNING TO HARMONIC INTERFERENCE

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ABSTRACT

This paper presents an elementary unified approach to the treatment of harmonic interference as it is sampled and decoded by the Loran-C receiver. The approach features an approximation process which applies to large amplitude interference and binary detectors. Results of this approach have led to a basis for specifying the performance of binary receivers as a function of continuous wave interference (CWI) frequencies and for identifying problem areas. Additionally, solutions are described that are advocated as practical alternatives to multiple notch filtering for CWI rejection.

1. EFFECTS OF CWI ON LORAN-C RECEPTION

1.1 LORAN-C DECODER FREQUENCY CHARACTERISTICS

The response of the Loran-C receiver to harmonic signals hinges on the frequency characteristic of the decoder/sampler. (See Fig. 1) It is a complex function of pulse coding and pulse spacing. Sampling at the GRI rate actuates a comb filter with "line" spacings of 1/GRI. Sampling at the intra-group pulse rate superimposes a second filter with line spacings of 1/.001 = 1000 hz. Additionally, binary pulse coding produces an interleaved set of lines depending upon whether successive pulses are alternated in sign from pulse to pulse or from group to group. The result is a composite dual spectrum of lines spaced at 1/2GRI hz and modulated by a pulse group line spectrum of 500hz spacing. The impact of pulse spacing is less pronounced since phase coding is more or less scrambled within the pulse group. However it is possible to arrive at an overall apectrum defined by an envelope of lines peaking at 500 hz intervals. A salient feature of the Loran code is that although 8 samples are taken on the CWI per pulse group, the output will never be more than 2 samples of CWI, i.e., the decoder automatically attenuates any and all harmonics by 12 db. This compares with a noise attenuation of 9 db = 10 log (8).

1.2 BEAT FREQUENCY

CWI frequencies are demodulated to a beat frequency range of about 5 to 10 Hz at the output of the Loran-C sampler. Only the beat frequency is significant in the subsequent analysis. This beat frequency is determined by multiplying the CWI frequency and group repetition interval (GRI) to determine the number of beat frequency (BF) cycles during the group repetition interval. It is important to note that only the fractional cycle is significant, since it is indicative of the time required to slew through 360 degrees or to achieve one cycle of beat. To show how this works, consider the west coast chain GRI of .0994 seconds and a CWI frequency of 94.5 Khz.

> Number of BF cycles = .0994 x 94500 = 9393.3 where 0.3 cycles is the slew rate of the interference per GRI

At a slew rate of 0.3 cycles per .0994 seconds the beat frequency is

$$\frac{1}{1/.3 \times .0994} = \frac{.3}{.0994} = 3.018 \text{ Hz}$$

Note, this applies only if there is no alternating phase coding for the odd pulses of the loran pulse group. For even pulses for which the phase reverses each GRI, the offset is 0.5 - 0.3 = 0.2 cycles and

$$BF = \frac{1}{1/0.2 \times .0994} = 2.012 \text{ Hz}$$

Hence, two beat frequency components result, one associated with even pulses and one associated with odd pulses. In this case, the greater concern is with the lower beat frequency of 2.012 Hz or the even-pulse response.

1.3 DESIGN ANALYSIS

Assuming large amplitude CWI, the effects of frequency are bounded by 1) harmonic oscillation of readout while monitoring Loran phase lock and 2) loss of Loran phase lock due to capture by the interference. These two bounds are definable. Within these bounds a rather indeterminate gray area of partial capture or cycle slip exists.

1.3.1 CAPTURE - The phase lock loop (PLL) tracker is treated as a first order loop with an input gain of 0.02 microseconds per sample. Using an effective pulse rate of 1/4 x 80 = 20 pulses per second, the PLL has a slew capacity of 20 x .02 = 0.4 usecs per second. The maximum beat frequency (BF) within this slew rate is

$$BF = \frac{0.4 \text{ usecs/sec}}{10 \text{ usecs/cycle}} = .04 \text{ cycles/sec}$$

where 10 microseconds relates to 1 cycle of 100 Khz. Therefore, BF = .04 Hz is the maximal threshold.

1.3.2 HARMONIC OSCILLATION - For beat frequencies substantially greater than the capture threshold, the detector output will oscillate about the true value in the same period as the beat frequency. For large amplitude CWI and hard limiting, simply relate the peak to peak excursions due to CWI to the 1/2 period of the beat. If the beat frequency is 0.5 Hz then the peak to peak response will be:

$$\frac{1}{2} \times \frac{1}{0.5} \text{ seconds} \times \frac{1}{4} R \frac{\text{counts}}{\text{second}} = 20 \text{ counts} \quad (R = 80)$$

For the above example of 0.02 microseconds per count, the peak to peak oscillation is:

$$20 \text{ counts} \times .02 \text{ usecs/count} = 0.4 \text{ usecs}$$

1.3.3 PARTIAL CAPTURE - This is the "gray" area where the tracking detector cycle slips in attempting to lock-on to the interference. The response will be saw-toothed and may impair the maintenance of lock-on to the desired signal. No attempt is made here to determine the scope of this "grey" area. In the case of capture at 0.04 Hz, for example, this gray area might very well extend to 0.1 Hz.

The above equations have been applied to determine the CWI response specifications for a standard airborne Loran-C hard-limiting receiver. The results are listed in Table 1 below.

TABLE 1

CWI PERFORMANCE FOR TYPICAL AIRBORNE BINARY LORAN-C RECEIVER DESIGNED FOR AIRBORNE APPLICATIONS

FUNCTION	BEAT FREQ (MIN)	PROBABILITY
Initial Search	Indeterminate	-
Phase Acquisition	.15 hz	6%
Phaselock Maintenance	.10 hz	4%
0.3 usecs Phaselock Jitter	1.00 hz	40%
SETTLE snr Measurement	Indeterminate	-
TRACK snr Measurement	.50 hz	20%
GUARD snr Measurement	.17 hz	7%
Cycle Identification	.20 hz	8%
Phase Lock Capture Threshold	.05 hz	.2%

Notes:

1. Probability refers to the chance that a randomly varying frequency might fall within the beat frequency window and therefore create a problem.
2. For 160 pulses per second, for example, the minimum beat frequency values will be doubled. The probability factors however will be the same.
3. These results apply to all CWI of amplitudes substantially larger than signal to noise ratio (snr).

As an example of how the above data applies, phase acquisition is feasible given an interfering frequency of within 0.15 hz synchronism. There is a 6% probability that a random frequency interference would exceed this tolerance and impair phase acquisition. Alternatively, there is a 40% probability that large CWI will cause 0.3 microseconds of phase oscillation. For a GRI of 50,000 microseconds there is still a 40% probability of a 0.3 microsecond oscillation in the output.

2. PROBLEM AREAS

2.1 AMPLITUDE EFFECTS IN THE BINARY DETECTOR

Exposure to large amplitude CWI produces two effects, (1) desensitization proportional to relative CWI amplitude and (2) possible total loss of sensitivity due to stationary phase effects. For the purpose of this discussion, large CWI amplitudes are assumed that exceed the noise specifications. Amplitude suppression then occurs in the binary detection when the instantaneous CWI exceeds the signal or signal + noise process in amplitude and singly controls the output of the binary detector. This response will be intermittent and proportional to the ratio of CWI to S+N.

The problem is best illustrated by an example, i.e., assume 30 db of relative CWI and 15 db of noise, attribute an additional 4 db to CWI due to it's sinusoidal shape, resulting in a net 19 db of proportional amplitude suppression relative to the S+N process. This translates into a reduction in sampling rate by a factor of about 1/9. Theoretically, this reduction also applies to the search and position fixing functions which are possible in 30 db of CWI but require more time, i.e., 9 times as long for the above postulated case.

2.2 PHASE QUANTIZATION

This problem was first described by R. Frank (Reference 5). It is a frequency-derived problem that is illustrated in the example of Fig. 2. Assume GRI = .0994 sec and let the CW frequency be 94 Khz. This yields:

$$\text{cycles per GRI} = 94000 \times .0994 = 9343.6$$

Since the cyclic offset is exactly 0.6 cycles it can be readily seen that over time (5 cycles) will be sampled coincident to only 5 phases of CW spaced 72 degrees or about 2 usecs in time. Unless the Loran signal is of sufficient amplitude to break through 20% of the time there is a possibility that the signal will be totally obscured and the detector "dead zoned".

This problem will be alleviated for frequencies that are not multiples of 500 hz by virtue of phase changes across the 1000 microsecond pulse interval as well. For example an offset of 250 hz will double the number of phases at which the CW can be sampled for signal.

The phase quantization problem can be readily assessed for any known frequency by concurrently observing fractional phase change across both the GRI and pulse intervals.

3. REMEDIES/SOLUTIONS

3.1 ADAPTIVE INTERFERENCE CANCELLATION BY SELECTIVE SAMPLING

The objective of this CWI rejection remedy is to provide an EVEN-ODD SELECTOR that monitors the interference in two interleaved pulse groups (even/odd), applies Loran-C coding, and checks the response for balance (See Fig. 3). As indicated in Section 1.1, the loran code is such that two sets of line spectra exist, one coincident to the odd pulses and the other to the even pulses. In the event that a CW interference spectral line coincides with an even-pulse line, sampling the odd pulses will desensitize the receiver to that interference. All that is required is a sensor to detect synchronism in either the even or odd pulse sequences and enables sampling only on the pulse set that is asynchronous to the interference.

3.2 MULTIPLE STROBES

The problem of single strobes for Loran-C detectors such as the phase tracker is that most of the time the Loran-C signal to the binary detector will be obscured by a large amplitude interference. In Figure 4 the case is illustrated when an interference frequency that produces a fractional 0.6 cycle phase shifts across the GRI span. Zero crossings are seen to alternate among five distinct phases of the baseband cycle. A window centered on these crossings is defined where the signal + noise (S+N) may be greater than the CWI such that the binary detector will see only S+N. What is required is a practical means of strobing in each of these windows for signal rather than waiting for a window to be coincident with a single strobe locked to a Loran phase.

A simple and sure way to achieve sampling within the window is to generate a train of strobes of sufficient number such that at least one strobe will coincide with a window and yield a signal sample. Ideally, by virtue of pulse selection, if necessary, those samples seeing only harmonic interference should cancel out and the net outcome would consist only of S+N samples.

Instead of repeatedly sampling the signal in the vicinity of a zero crossing for tracking purposes, the strobes will be symetrically distributed over a range of plus and minus 90 degrees. In this case, the multiple strobe group will tend to center on the signal crossing, the same as for a single tracking strobe, even though a window may never occur coincident to the zero crossing being tracked.

Three penalties apply to multiple strobing. (1) There is a direct loss of db in signal sensitivity coincident to random phase sampling of the Loran-C signal over the span of plus and minus 90 degrees. (2) In the event of near synchronous frequencies there is an additional sacrifice of 3 db due to sampling only half the pulses. (3) The output of the phase tracker will be biased by the slope of the leading edge of the Loran pulse; i.e., there will be signal imbalance across the 5 microsecond band of the multiple strobe group. Unless compensated, this could produce a time difference error of as much as 0.3 microseconds. This error is predictable and can be substantially offset by self-adaptive software measures alone.

4. COMMENTS/TECHNICAL OBSERVATIONS

A) If the interfering frequencies are at or near synchronism, coarse and non-random sampling of the signal may result. Therefore, frequencies that are both synchronous or near synchronous to the GRI and the 1000 microsecond pulse interval should be considered prime targets for notching.

B) A composite of many harmonics might well be treated as noise. However the dispersive effects should be less than those for the equivalent rms noise. Therefore consideration should be given to increasing the gain of the detector to the extent allowable by the noise specifications. This gain adjustment could be implemented as a self-adaptive feature since the condition is readily detectable by binary means.

C) No attempt has been made to evaluate other Loran-C receiver functions such as SEARCH and ACQUISITION Presumably pulse selection should protect against false detection. In the worst case it is expected that the time factor could be extended in proportion to interference amplitude. The potential benefits of multiple strobes are yet to be fully explored as a partial solution to the search time problem and PLL performance.

D) This study pertains to worst case unmodulated CWI. CWI negative effects should be mitigated by modulation of the CWI carrier.

5. SUMMARY & CONCLUSIONS

CWI rejection capabilities can be added to a binary Loran-C receiver with relatively simple modifications. Such modifications do not involve analog filtering, complicated signal processing or presets. Two specific modifications that have been discussed are:

1) Selective Pulse Sampling - This is a known approach, having been revealed in 1965 by Messers. Frank, Meranda & Phillips. However, it is not believed to be in widespread use.

2). Multiple Strobes - Application may be new to Loran. The concept of applying selective pulse sampling and multiple strobing as complementary CWI rejection devices is believed to be novel.

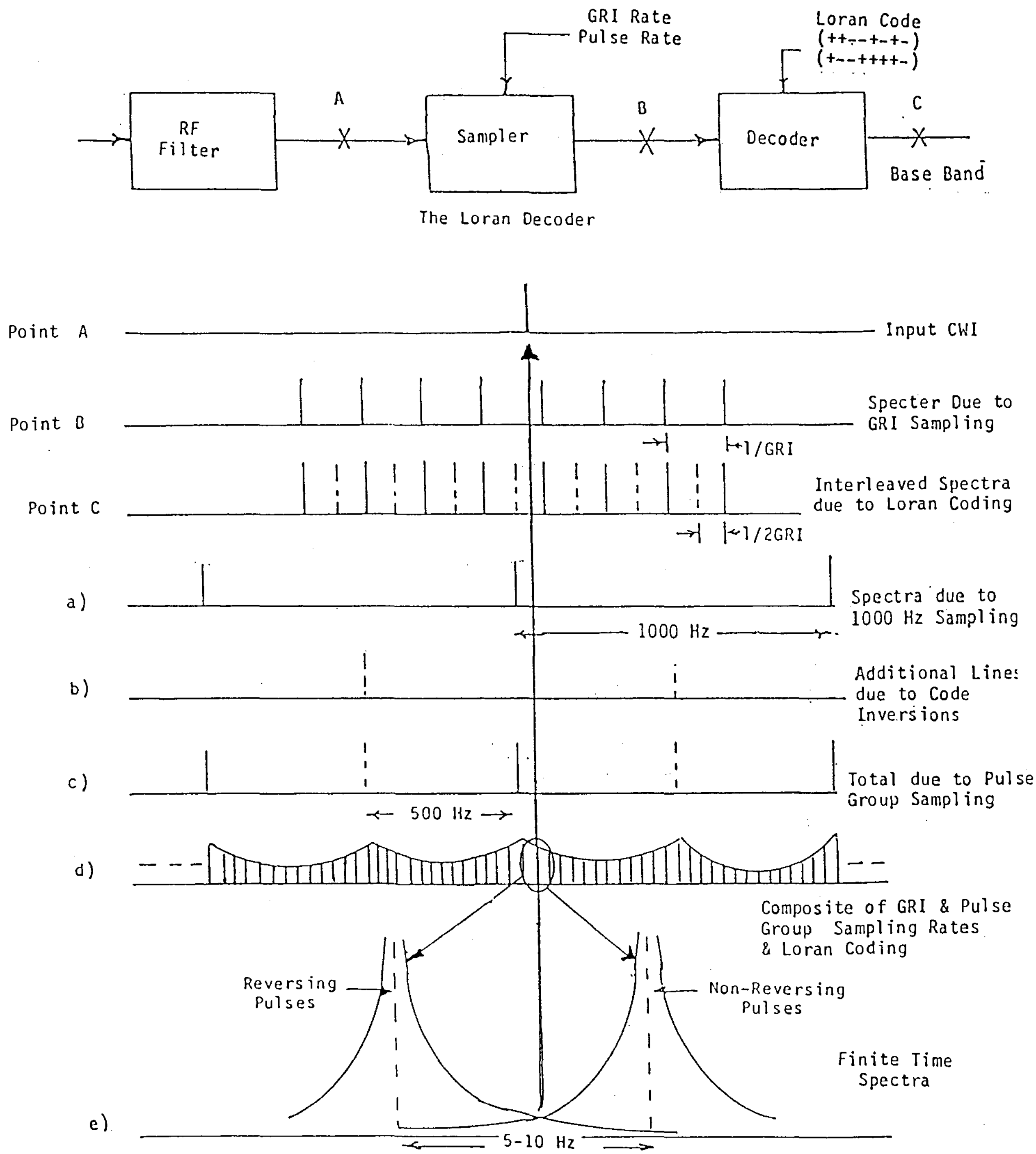

FIGURE 1 DEVELOPMENT OF FREQUENCY SPECTRA AS SEEN BY THE LORAN -C DETECTOR

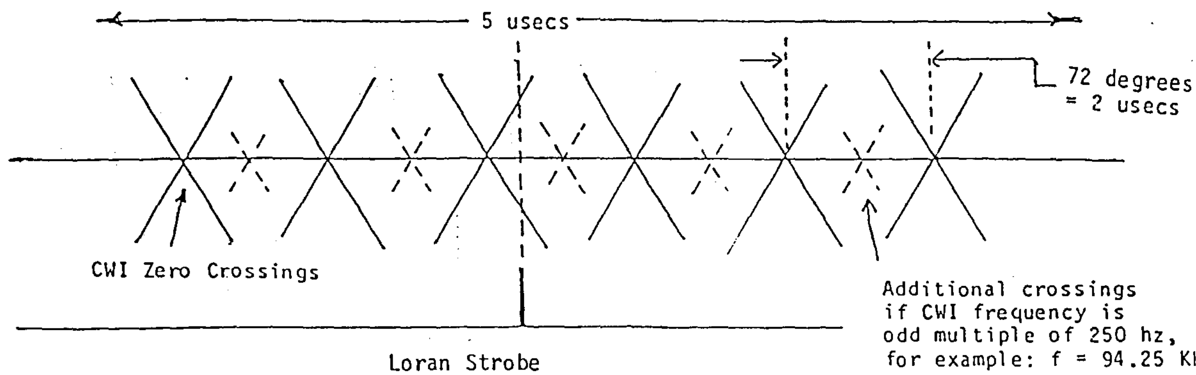

FIGURE 2 PHASE QUANTIZATION DUE TO SUBSYNCHRONOUS CWI OF 94.5 Khz FOR LORAN RATE 9940

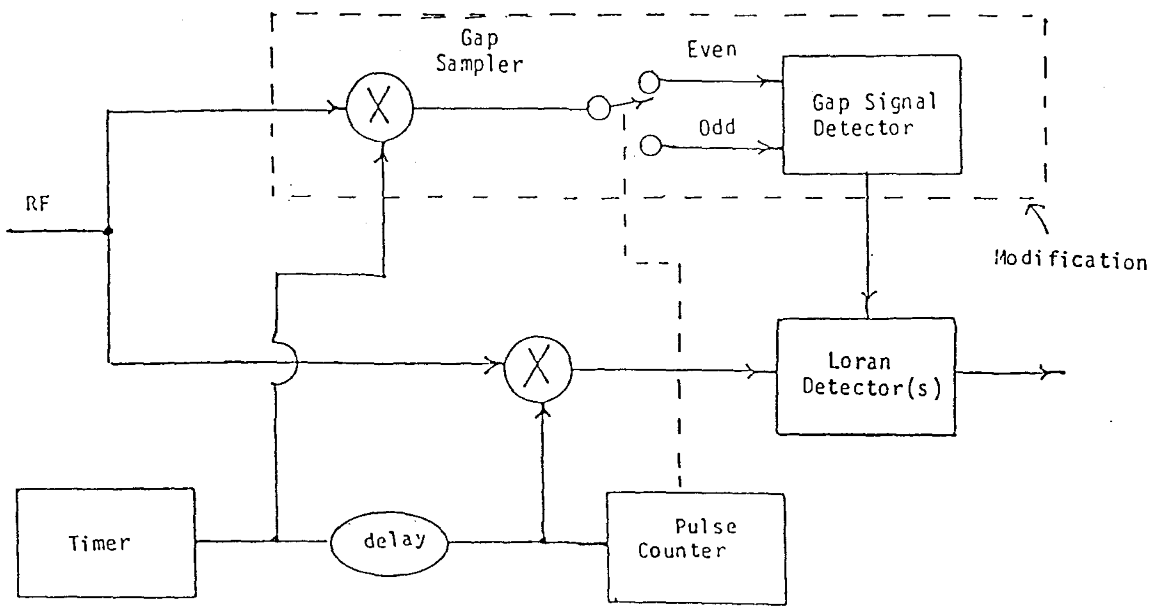

FIGURE 3 EVEN-ODD SELECTOR