THE WILD GOOSE ASSOCIATION

PROCEEDINGS OF THE
SEVENTEENTH ANNUAL TECHNICAL SYMPOSIUM
25-27 OCTOBER 1988
PORTLAND, OREGON

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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 organized in 1972 and its membership now includes hundreds of professional engineers, program managers, scientists and operational personnel from all segments of government, industry, and the user community throughout the world, working for the advancement of LORAN.

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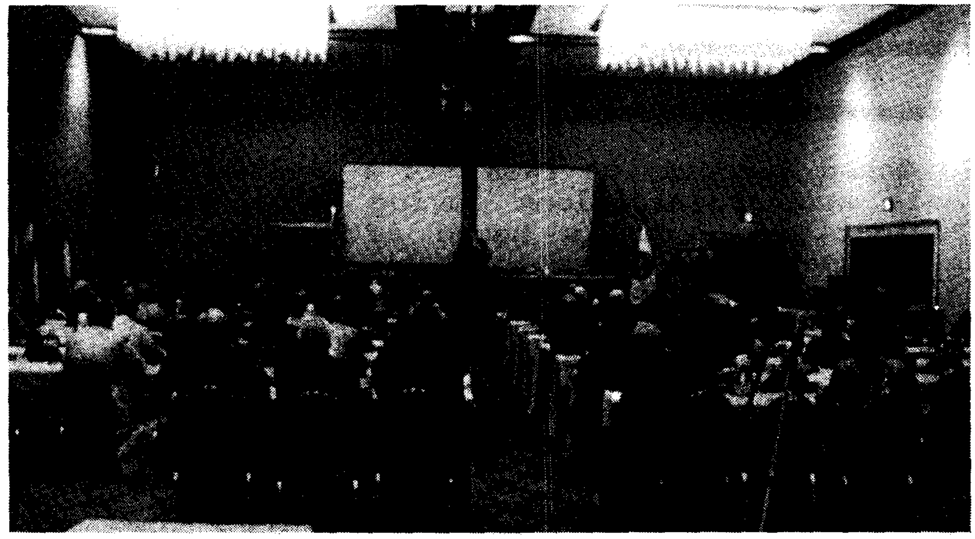


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U.S. House of Representatives
Fifth District, Oregon

BANQUET SPEAKER
Mr. Jon Michael Smith
National Air and Space Administration
Deputy Assistant Administrator for Commercial Programs

LUNCHEON SPEAKER (10/25)
Vice Admiral Clyde E. Robbins
U.S. Coast Guard
Commander, Pacific Area

LUNCHEON SPEAKER (10/26)
Mr. John Kern
Federal Aviation Administration
Acting Deputy Associate Administrator for
Registration and Certification

LUNCHEON SPEAKER (10/27)
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U.S. Department of Transportation
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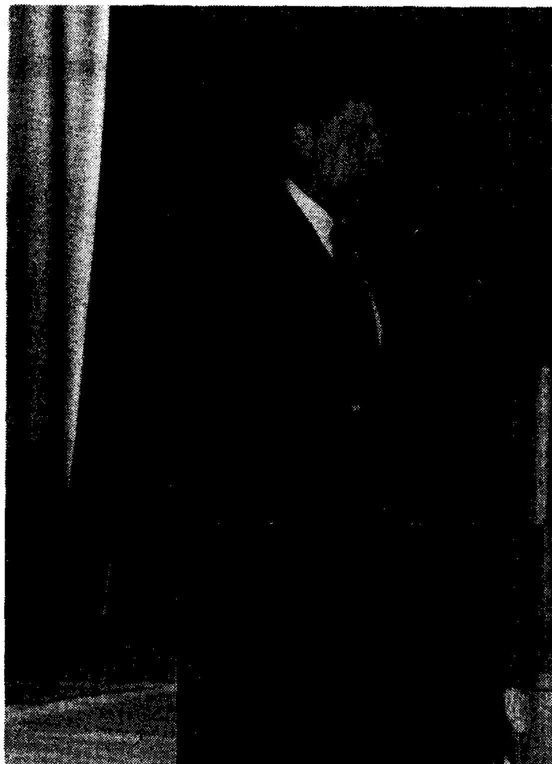


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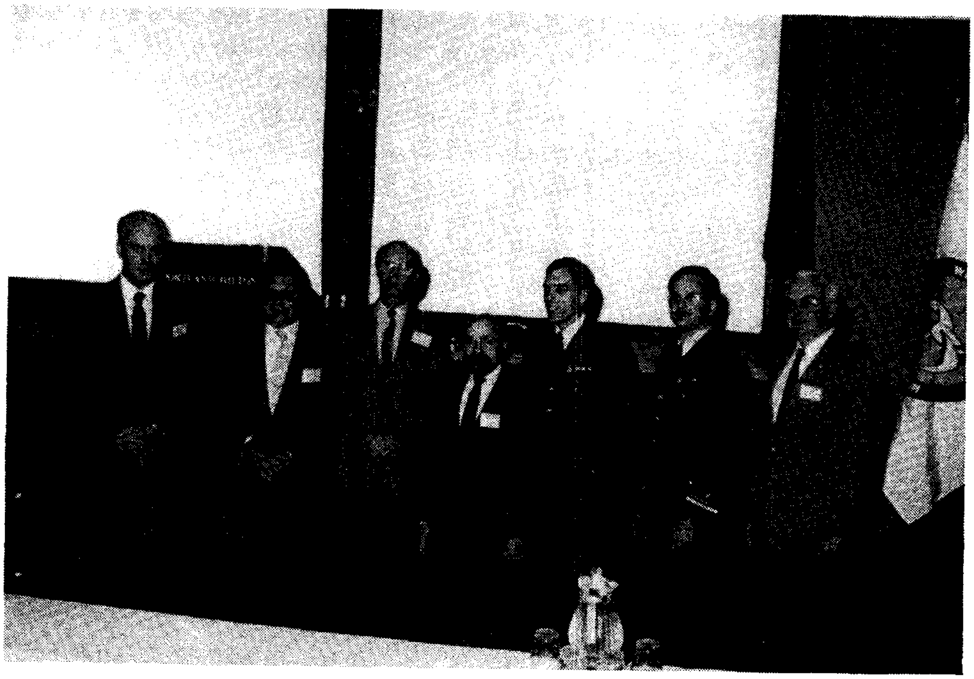
SESSION 1

DOMESTIC AND INTERNATIONAL PLANS

JAMES F. CULBERTSON
COASTWATCH INC.



A STATUS REPORT
LORAN-C AND INTERFERENCE FROM POWER LINE CARRIER SYSTEMS

RONALD J. GRANDMAISON

U. S. COAST GUARD HEADQUARTERS
MARINE RADIO POLICY BRANCH
WASHINGTON, D.C.

ABSTRACT

Loran-C was developed in the 1950's for use as a maritime radionavigation aid. In addition to maritime radionavigation, it is now being used for en route navigation and non-precision instrument approaches to airports by small commercial and private aircraft, for terrestrial radio navigation, as a source for precise timing information, and by some providers of radiodetermination satellite systems. One possible source of interference to Loran-C is from Power Line Carrier (PLC) systems. There are over 10,000 PLC transmitters in use in this country, approximately 3300 of which operate in the Loran-C band (90-110 kHz).

On October 2, 1987, the Federal Communications Commission (FCC) released a Notice of Proposed Rule Making (NPRM) to amend Part 15 of its rules regarding the non-licensed operation of radio frequency devices, including PLC systems. While the FCC proposed no specific changes for PLC systems, which operate on a non-interference basis to authorized services under Part 15 and are exempt from field strength limits, the U. S. Coast Guard took this opportunity to respond to the NPRM and suggested the adoption of field strength limits for all existing and future PLC systems operating in the 75-125 kHz band in order to reduce the potential of interference to Loran-C radionavigation receivers. We also asked the FCC to make available to the Loran-C user certain PLC technical and operational information essential in resolving actual cases of interference.

This paper discusses the status of Loran-C and PLC systems as related to the NPRM, and the support required from the Loran-C community to fully convince the FCC that unless restrictions are imposed on PLC systems interference from these devices will adversely affect safety of navigation.

INTRODUCTION

In 1986 a Memorandum of Agreement was executed between the Federal Aviation Administration (FAA) and the USCG for the establishment of working arrangements for providing Loran-C radionavigation service for civil airborne users. In fact, the FAA has already begun the process of approving Loran-C for non-precision approaches into some airports. The addition of two Loran-C chains in the mid-continental U. S. is scheduled to be completed in 1990. When continental U. S. Loran-C coverage is completed, the FAA intends to fully implement Loran-C in the National Airspace System.

PLC systems are presently the predominant Part 15 equipment operating in the Loran-C band and are exempt from field strength limits under present and proposed FCC rules. With the anticipated growth in the number of small commercial and private aircraft that will be using Loran-C for en route navigation and non-precision instrument approaches, there is widespread concern that the potential for interference attributed to the non-existence of field strength limits for PLC systems operating in the Loran-C band will adversely affect safety of navigation.

On March 4, 1988, USCG filed formal comments in General Docket No. 87-389 asking the FCC to impose emission limits on all PLC devices and that if this would not be practical to restrict these devices from the band 75-125 kHz.

PLC USE IN THE LORAN-C BAND

Data on PLC use in the 90-110 kHz band has been obtained from the North American Electric Reliability Council (NERC) and are shown below:

Number of Transmitters	Function	Maximum Power
2857	Relaying	100 watts
156	Voice	100 watts
110	Control/Supervision	10 watts
72	Telemetry	100 watts
52	Speech +	100 watts
28	Miscellaneous	100 watts

As may be seen, 87 percent of the PLC transmitters operating in the Loran-C band are used for protective relaying. For this function, the carrier is normally turned off and only transmits when an action is needed. The keyed signal results in switching within the power system to change the flow of electric power. In a memorandum from IRAC to the National Telecommunication and Information Administration (NTIA) Office of Spectrum Management, concerning a report written by Karl Nebbia of NTIA (see References 5 and 7), IRAC recommended that "The Department of Transportation conduct tests to determine the impact of short-term and short-term periodic relaying PLC transmissions (duration on the order of 300 milliseconds) on LORAN-C receivers. (If higher field strengths of short-term and short-term periodic "relaying" PLC signals can be tolerated by LORAN-C receivers, some sharing of PLCs and LORAN-C may be possible)." We solicit comments from the Wild Goose Association on this NTIA recommendation.

EMISSION LIMITS PROPOSED BY USCG

The USCG based its proposed emission limits for PLC systems on current Coast Guard Coverage Diagrams, CCIR Reports 322-2 and 915-1, RCTA Publication DO-194 and CCIR Recommendation 589-1. Using a worst-case 95 percentile noise level of 53 dB/uV/m, a minimum signal-to-noise ratio of -10 dB and appropriate unwanted-to-wanted signal ratios set forth in CCIR documents 589-1 and 915-1, we predicted that the magnitude of the PLC interfering signal at the Loran-C receiver should be limited to the following levels:

100 kHz	23 dB/uV/m
+/-5 kHz	25 dB/uV/m
+/-10 kHz	30 dB/uV/m
+/-15 kHz	38 dB/uV/m
+/-20 kHz	48 dB/uV/m
+/-25 kHz	60 dB/uV/m

Because Instrument Flight Rules for non-precision approaches to airports require that the Minimum Descent Altitude be at least 250 feet above ground level without obstructions, we asked the FCC to impose the above emission levels at a distance of 75 meters from power lines containing PLC transmissions.

USCG REQUEST FOR PLC TECHNICAL AND OPERATIONAL INFORMATION

Part 15 and U. S. Footnote 294 provide a reference to Part 90 with regard to a notification procedure for PLC systems. NERC is required under Part 90 to inform the FCC and NTIA of PLC technical and operational information. This information is necessary to help the Loran-C user track down and resolve cases of PLC interference. However, NERC has yet to make the database available because for reasons of national security it does not want FCC or NTIA to release the data to Loran-C users without its prior approval. USCG has consistently opposed this NERC position. We have asked the FCC to take action to resolve this matter. We have also asked NTIA to help us with this problem. NTIA wrote to the FCC in May asking that they ensure NERC release PLC data to Loran-C users; the FCC has not yet responded to the NTIA request.

STATUS OF THE NPRM

Several entities, including some Loran-C receiver manufacturers, Geostar, Radio Technical Commission for Maritime Services (RTCM), FAA, NTIA, and the National Business Aircraft Association filed comments in support of the USCG FCC filing. However, the Utilities Telecommunications Council (UTC) representing over 2000 electric, gas, water and steam utilities, filed reply comments asking the FCC to reject the Coast Guard's proposal to restrict PLC operations because of a lack of evidence of interference to Loran-C receivers from PLC systems. UTC also asked the FCC to reject the PLC database request because it felt that such wide distribution of information on PLC operations would expose electric utilities to tremendous security risks for no apparent reason, since no cases of PLC interference have been demonstrated by USCG.

Since the comment and reply comment phase of the NPRM is now complete, we are not permitted to respond to the UTC pleading. It is not known whether the FCC will defer the PLC interference issue to a separate proceeding or continue addressing the problem in another phase of the current proceeding, but it is certain that we will have at least one more opportunity to present our arguments, perhaps in a petition for reconsideration of FCC action on the NPRM should the FCC be swayed by the UTC filing. We expect to know more about the FCC position on the PLC problem within the next few months.

DOCUMENTATION OF CASES OF PLC INTERFERENCE TO LORAN-C

There have been numerous reports published addressing the problem of potential interference from PLC systems to Loran-C radionavigation receivers, but none of these reports has focused on actual reported cases of interference. The primary reason for my being here today is to solicit information on cases of probable interference from PLC to Loran-C receivers. Lack of documented cases is our weakest argument before the FCC. Without documented cases of interference, we may not be able to resolve what we consider to be a problem to the Loran community. In order to convince the FCC that there exists a real problem with PLC in that it is a threat to safety of navigation, and to counter the arguments of UTC, we need the help of the Loran-C user community in providing USCG with documented cases of interference and the amount of cooperation, if any, the user has received from the electric utilities involved in such cases.

All information on documented cases of interference should be sent to:

Ronald J. Grandmaison
U. S. Coast Guard Headquarters
G-TTS-3, Room 6302
2100 Second Street, S.W.
Washington, D.C. 20593-0001

(202) 267-1389

REFERENCES

1. Arnstein, Paul H., "Loran-C and PLC, Partners or Adversaries," NMEA News, Nov/Dec 1987.

2. CCIR, Report 322-2, "Characteristics and Applications of Atmospheric Radio Noise Data," ISBN 92-61-01741-X, Geneva 1983.

3. CCIR, Rec. 589-1, Rep. 915-1, "Interference Between Fixed, Maritime Mobile and Radionavigation Services in the Bands Between 70 kHz and 130 kHz," ISBN 92-61-02781-4, Geneva 1986.

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5. Memorandum from J. Hersey (USCG) to Executive Director IRAC, Reliability of PLC Data, IRAC Document 25849/1, March 15, 1988.

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8. NTIA, Manual of Regulations and Procedures for Federal Radio Frequency Management, Chapter 7, September 1987.

9. RTCA, DO-194, "Minimum Operational Performance Standards for Airborne Area Navigation Equipment Using Loran-C Inputs," November 1986.

10. Title 47, U. S. Code of Federal Regulations, Part 15, October 1987.

11. Title 47, U. S. Code of Federal Regulations, Part 90, October 1987.

12. Utilities Telecommunications Council, "Reply Comments of the Utilities Telecommunications Council in FCC Docket 87-389," June 8, 1988.

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14. U. S. Coast Guard, "Loran-C User Handbook," Department of Transportation, May 1980.

15. U. S. Departments of Defense and Transportation, DOD-4650.4, DOT-TSC-RSPA-87-3, "1986 Federal Radionavigation Plan," 1987.

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THE LORAN-C MIDCONTINENT EXPANSION PROJECT
A STATUS REPORT

Douglas D. Heyes

U.S. Coast Guard
Office of Command, Control, and Communications

ABSTRACT

The Loran-C Midcontinent Expansion Project (MEP) is a joint U.S. Coast Guard (USCG) and Federal Aviation Administration (FAA) project designed to provide coverage to the area of the mid-U.S. not currently serviced by Loran-C. Under an agreement with the FAA, the USCG has determined that two new Loran-C chains are required to complete coverage of the "midcontinent gap". The USCG and FAA are proceeding with the chain and monitor configurations, land acquisition, station design, equipment procurement, and existing station upgrades necessary to complete the new chains by the end of 1990. This paper will discuss the current status and future plans of the project.

BACKGROUND

In 1986, the Administrator of the Federal Aviation Administration and The Commandant of the U.S. Coast Guard signed a Memorandum of Agreement "for the establishment of working arrangements for providing Loran-C radionavigation service for civil airborne users" (1). A subsequent USCG/FAA Interagency Agreement was signed, under which the Coast Guard was to "identify and procure all equipment necessary to establish Loran-C signal coverage in the midcontinental area of the United States" (2).

SYSTEM DESIGN

The completed MEP project will require construction of two new Loran-C chains. The new chains are designated as the South Central U.S. Chain (SOCUS) and the North Central U.S. Chain (NOCUS). These new chains consist of four new transmitting stations, five existing transmitting stations which will be dual-rated, and five new monitor sites. Engineers at USCG Headquarters designed the two new chains to take advantage of existing Loran-C transmitting stations (LORSTAs) and to keep new construction to a minimum. Operational control of the new chains is to be accomplished from existing USCG control sites. Predicted Loran-C groundwave coverage for the two new chains is depicted in Figures 1 and 2.

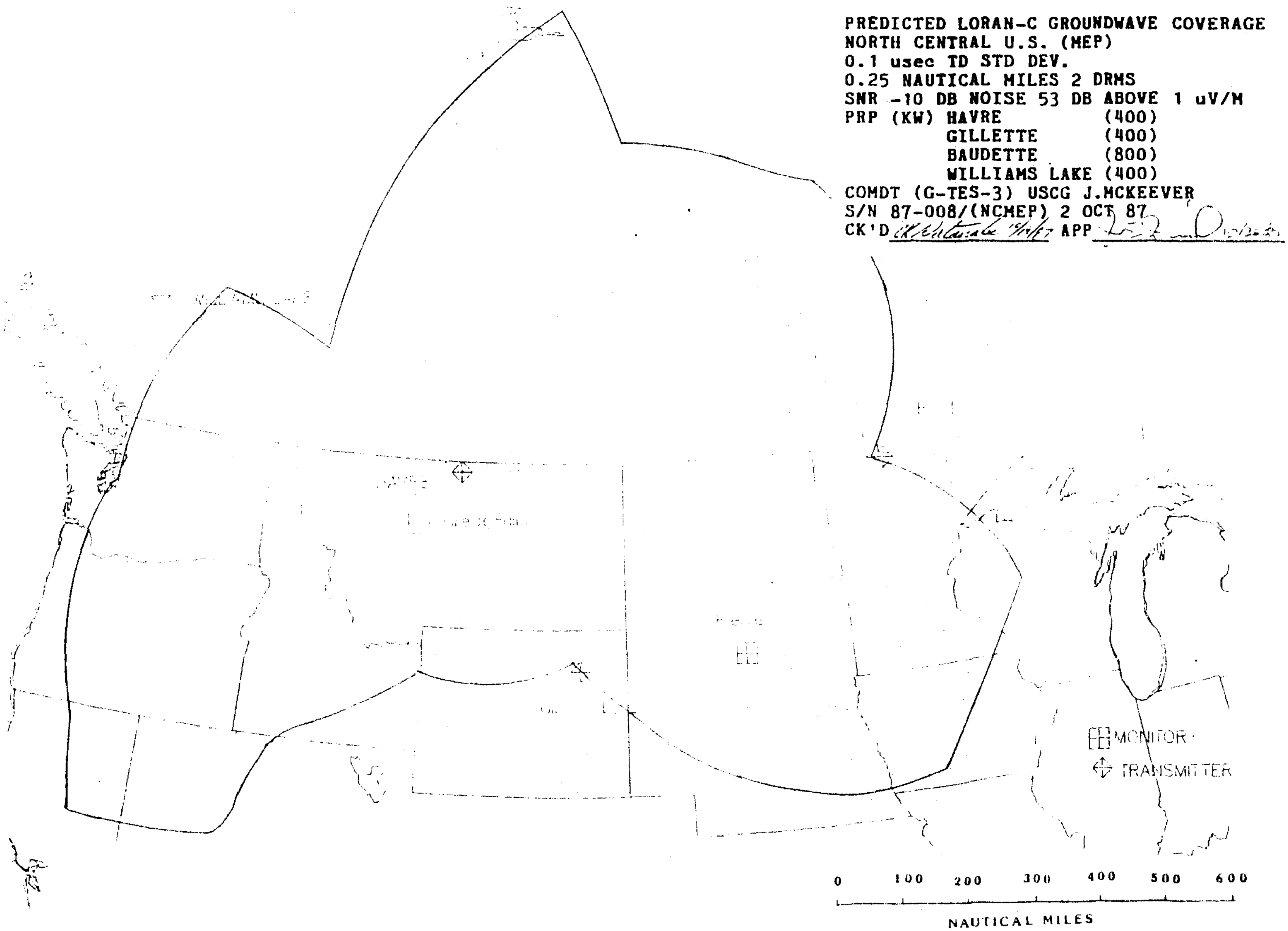

FIGURE 1. NOCUS LORAN-C CHAIN COVERAGE

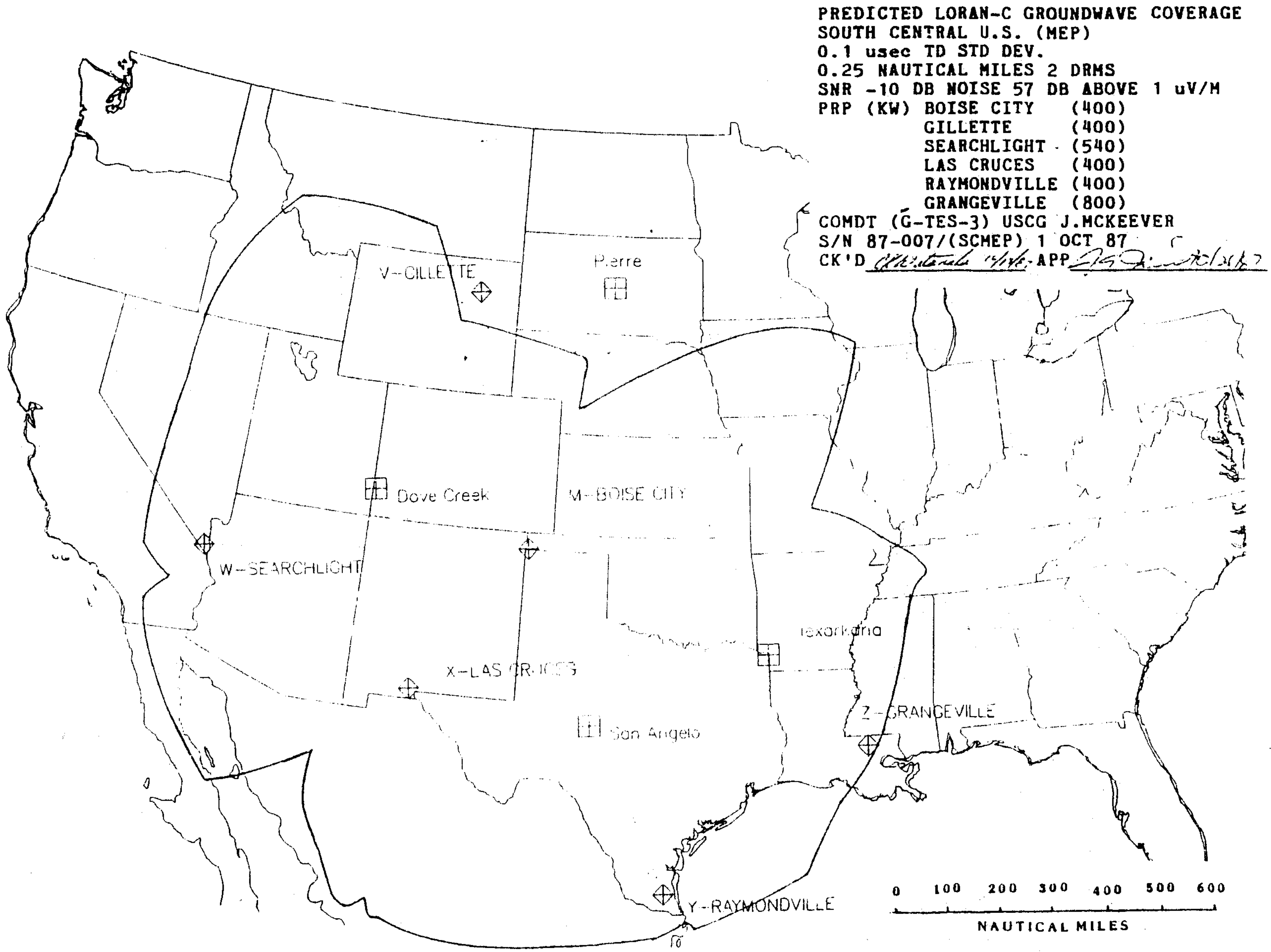

FIGURE 2. SOCUS LORAN-C CHAIN COVERAGE

TRANSMITTING STATIONS

Station Description

All four new LORSTAs will be essentially identical with respect to buildings, physical plants, transmitters, antennas, personnel allotments, and maintenance philosophy. To reduce design costs, all the stations were designed with sufficient space to hold a 56 Half Cycle Generator (HCG) transmitter and equipment for dual-rating if required in the future. Each station will be located on one quarter section of land (a 160 acre square). Station transmitters at all except LORSTA Boise City will be the AN/FPN-64(V)1 Solid State Loran-C Transmitter (32 HCGs) manufactured by Megapulse, Inc. of Bedford, Massachusetts. LORSTA Boise City will be equipped with a more powerful AN/FPN-64(V)4 transmitter with 56 HCGs. Each LORSTA will have a 700 foot top-loaded monopole guyed antenna manufactured by Tower Engineering and Construction Company of South Dakota. These transmitter and antenna combinations will produce a nominal peak radiated power of about 400 kilowatts. Timing and control equipment will be standard USCG suites installed at each LORSTA. Backup electrical power will be provided by two automatic start diesel prime movers driving two 300 kilowatt generators.

Site Selection

After the general areas for the four new LORSTAs were identified, surveys of the candidate sites were completed by the FAA regional offices involved and their contractors, Freese and Nichols, Inc. of Fort Worth, Texas, and the U.S. Army Corps of Engineers, Walla Walla, Washington, District. From the candidates, final site choices for the four new LORSTAs were made and arrangements for leases are underway. Specific information for all of the stations involved is contained in Table 1.

Construction

Construction of the new LORSTAs is scheduled to begin in mid-1989 and continue through early 1990. Transmitter and electronics installations will begin immediately upon station completion.

Personnel

The LORSTA crews, all USCG Petty Officers, will consist of one Electronics Technician Chief Petty Officer (E-7) as Officer-in-Charge, two Electronics Technicians (one E-6 and one E-5), and one Machinery Technician (E-6).

Maintenance

Routine maintenance and station business are conducted during a normal workday, while equipment casualties and corrective maintenance outside normal work hours are handled by one of the station technicians who remains on call within 30 minutes travel time of the station. This is the system currently in use at most of the LORSTAs in the continental U.S. and Canada.

TABLE 1. SOCUS AND NOCUS TRANSMITTING STATIONS

Loran-C Station	Antenna Location (Note 1)		Range (Note 2)	Designations (Note 3)
New Stations:				
Boise City, OK	36°30'20"N,	102°53'59"W	600 NM	SOCUS(M), GL(Z)
Las Cruces, NM	32°04'18"N,	106°52'04"W	530 NM	SOCUS(X)
Gillette, WY	44°00'11"N,	105°37'23"W	800 NM	SOCUS(V), NOCUS(X)
Havre, MT	48°44'38"N,	109°58'53"W	700 NM	NOCUS(M)
Existing Stations:				
Searchlight, NV	35°19'18.18"N	114°48'17.43"W		SOCUS(W), USWC(Y)
Raymondville, TX	26°31'55.01"N	97°50'00.09"W		SOCUS(Y), SEUS(X)
Grangeville, LA	30°43'33.02"N	90°49'43.60"W		SOCUS(Z), SEUS(W)
Baudette, MN	48°36'49.84"N	94°33'18.47"W		NOCUS(W), GL(Y)
Williams Lake, BC	51°57'58.78"N	122°22'02.24"W		NOCUS(Y), CWC(M)

Notes:

(1) The antenna locations given for the new stations are based on planning information and data available now. During the course of station design, the antenna may be located at a position other than that listed. However, it is expected that the actual antenna locations will not vary by more than two seconds.

(2) The range limits were determined using the method described in enclosure (2) of reference (3). Due to the different conditions existing at each transmitting station, the ranges of the four new stations are different despite having the same nominal peak radiated power. The range limits are irregular circles with the estimated radii provided.

(3) GL = Great Lakes Chain; USWC = U.S. West Coast Chain; SEUS = Southeast U.S. Chain; CWC = Candian West Coast Chain.

Existing Stations

A team from the USCG Electronics Engineering Center (EECEN) in Wildwood, New Jersey has completed the installation and testing of dual-rating equipment at LORSTAs Searchlight, Nevada and Raymondville, Texas. LORSTA Grangeville, Louisiana, will follow in February 1989. The dual-rate installation at LORSTA Baudette, Minnesota should be accomplished in May 1989. Negotiations between the U.S. and Canadian governments are in progress concerning the dual-rating of LORSTA Williams Lake, British Columbia, and should be finished in time for that installation to be complete by about September 1989.

MONITOR SITES

Five new Loran-C Monitor Sites (LORMONSITEs) will be installed during 1989. The exact locations of these LORMONSITEs has not been decided but engineers from USCG EECEN have visually inspected all of the potential sites and have completed engineering investigations and electromagnetic interference studies at the four candidate sites for the two southern-most LORMONSITEs. Plans are for all of the new LORMONSITEs to be co-located with FAA facilities or on nearby airport property. LORMONSITE equipment will include the USCG standard Austron 5000A Monitor receiver and will be maintained by FAA technicians or contractors. Some of the details of baseline control are contained in Table 2.

CONTROL SITES

Control of the new chains will be accomplished from two existing control sites located at LORSTAs Malone, Florida, and Middletown, California. LORSTA Malone will be responsible for control of the five secondary SOCUS chain and LORSTA Middletown will control the three secondary NOCUS chain. The chain control site at LORSTA Seneca, New York, will control the new M-Z baseline of the Great Lakes chain created when LORSTA Boise City, Oklahoma, is added to that chain. All four of the new LORSTAs will be equipped with, and controlled by, the Coast Guard's Loran-C Remote Operating System. Under this system, operational control and data transfer are accomplished remotely from the control site. The control sites are also able to monitor station security, environmental conditions, and effect the recall of duty personnel when required.

CERTIFICATION

All baselines of the new chains and all new LORMONSITEs must be certified as operational by the USCG before they can be used safely for navigation purposes. Because all of the new LORSTAs and LORMONSITEs will not be completed concurrently, certification of each chain as operational will probably be accomplished immediately following a short on-air test period. The work being done now, dual-rating of existing stations and LORMONSITE installations, prior to construction of the new LORSTAs, should expedite certification of the new chains.

TABLE 2. LORMONSITE BASELINE CONTROL INFORMATION

Loran-C Monitor Site	Signals Monitored	Control Site
Great Falls, MT	NOCUS M (A2)	Middletown, CA
	NOCUS W (A2)	Middletown, CA
	NOCUS X (A2)	Middletown, CA
	NOCUS Y (A2)	Middletown, CA
Pierre, SD	NOCUS M (A1)	Middletown, CA
or	NOCUS W (A1)	Middletown, CA
Bismarck, SD	NOCUS X (A1)	Middletown, CA
	GL Z (A2)	Seneca, NY
	SOCUS V (A2)	Malone, FL
Little Rock, AR	GL W (A1) (Note 1)	Seneca, NY
or	GL Z (A1)	Seneca, NY
Pine Bluff, AR	SOCUS Z (A1)	Malone, FL
	SOCUS Y (A2)	Malone, FL
Midland, TX	SOCUS X (A1)	Malone, FL
or	SOCUS Y (A1)	Malone, FL
Big Springs, TX	SOCUS M (A2)	Malone, FL
	SOCUS W (A2)	Malone, FL
	SOCUS Z (A2)	Malone, FL
Cortez, CO	SOCUS M (A1)	Malone, FL
or	SOCUS V (A1)	Malone, FL
Durango, CO	SOCUS W (A1)	Malone, FL
	SOCUS X (A2)	Malone, FL
Whidbey Island, W (existing site)	NOCUS Y (A1)	Middletown, CA

Notes:

(1) This signal is currently monitored at LORMONSITE New Orleans, LA.

AVIATION USERS

The MEP provides the opportunity to examine special features for aviation use, such as a rapid malfunction alarm, facilitation of cross-chain and master independent operation, etc. Some of the features are under study by the USCG, the FAA, and Special Committees of the Radio Technical Commission for Aeronautics (RTCA). The Coast Guard has recently contracted for the development of a software coverage diagram generator. In addition to standard Loran-C marine hyperbolic navigation coverage diagrams the new software will generate coverage diagrams for aviation coverage as defined by the FAA Advisory Circular AC90-45A and TERPS. Some other optional features will be generation of diagrams showing coverage in the event of a transmitting station outage; single/multi-chain, master dependent/independent receiver coverage; and multi-chain, direct-ranging receiver (DLR) coverage.

SUMMARY

At the inception of the MEP project it was agreed that the chains would be on-air and certified as operational by the end of 1990. Now, with most of the planning done and some of the equipment procured and actually installed and tested, there seems to be a good possibilty that the 1990 date may be met. A problem involving the transmitting antenna procurement, which might have delayed the project, appears to have been solved, while the discovery of Native American artifacts on the site selected for LORSTA Las Cruces may delay construction of that station or require selection of an alternate site. A complete archeological survey of the site began in October 1988. The USCG and FAA are well on their way to completing coverage of the continental United States with one of the most convenient and dependable navigation systems in existence, Loran-C.

REFERENCES

1. Memorandum of Agreement between the Federal Aviation Administration (FAA) and the United States Coast Guard (USCG) for the establishment of working arrangements for providing Loran-C radionavigation service for civil aviation users, USCG/FAA, 1985, Held at USCG Headquarters, Washington, DC.

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INTERFERENCE AND LORAN-C: A EUROPEAN PROBLEM

Len P. Remmerswaal and *Durk van Willigen*

ABSTRACT

The expansion of Loran-C in Europe with it's already heavily loaded LF frequency spectrum is a challenge to the receiver designer. The number of CW interferences often exceeds the number of notch filters available in Loran-C receivers. So, decisions have to be made about which interfering signals are to be suppressed. However, the complex nature of the disturbance of phase and envelope of Loran-C signals by CW interference makes understanding of the process difficult. Therefore, a practical vector-analysis method is outlined which helps to explain the effects of asynchronous and various types of synchronous interferences and noise. The net result on the phase and envelope tracking process is demonstrated with the LOran Simulation Program LOSP which runs on a personal computer. Finally, some general ideas on interference-reduction technics are discussed.

1 - INTRODUCTION

It is becoming a more and more realistic thought that in the near future Loran-C will be a major radio navigation system in the north-western part of Europe [1]. Together with Navstar/GPS in the SPS (C/A) mode, it will provide accurate fixing facilities with adequate redundancy to the mariner and also to the land user.
However, already existing radio navigation systems like the intensively used Decca Navigator, introduce frequency-spectrum sharing problems on the European continent. Due to the narrow bandwidth of the Decca Navigator signals, Decca receivers are hardly hampered by the high-power broad-band Loran-C signals. Unfortunately, the opposite cannot be said for the basically large-bandwidth Loran-C receivers. And, to make things even worse, a number of high-powered FSK and time-standard transmitters do also a firm attack on the proper functioning of Loran-C receivers.

It is known that Loran-C receivers are highly susceptible to near-band and in-band continuous-wave interferences. Therefore, receiver manufacturers have implemented many ingenious hardware and software solutions to minimize interference effects. The way in which phase and envelope of the Loran-C signal is disturbed by interference is complex. It highly depends on how the field strength and the frequency of the disturber are related to the Loran-C signal. And the number of interferences also plays an important role. A glimpse to the frequency spectrum from 60 - 140 kHz as experienced in the Netherlands (Fig. 1) may easily panic the receiver designer. However.

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understanding the mechanisms of distortion may help him to take the appropriate countermeasures. Therefore, in the following paragraphs a practical analysis method will be outlined and the most common types of interferences will be explained. The effects of them on the tracking process are demonstrated by means of software simulation technics. Finally, some general aspects of interference-reduction technics will be discussed.

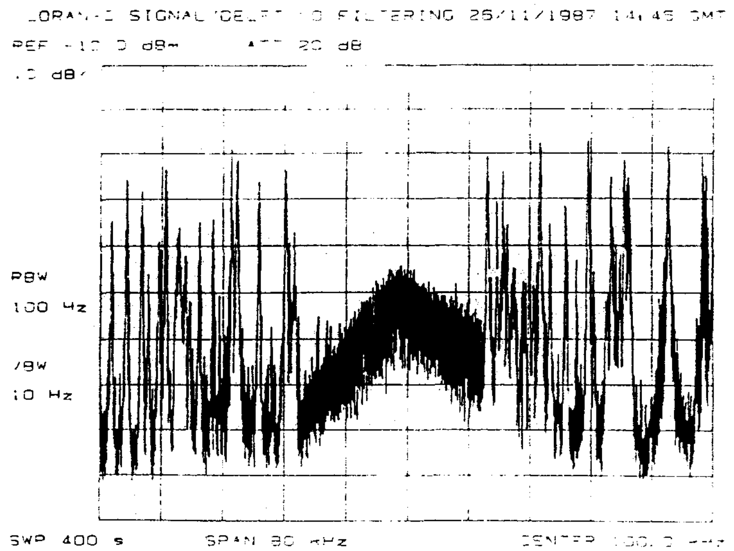

Fig. 1. *Typical frequency spectrum of 60 - 140 kHz as received at the Delft University of Technology in The Netherlands.*

2 - ANALYSIS METHOD

The effects of CWI on phase-tracking performance are readily analyzed by using phasor diagrams.

In the usual operation with phasor diagrams a reference frequency is chosen. A sinusoidal signal with that frequency causes a stationary phasor in the diagram. The phasor's length represents the signal's amplitude, its angle to the positive Y-axis represents the signal's phase and the projection on the X-axis represents the actually measured value. A signal of any other frequency shows up as a rotating phasor. The rotation frequency is the difference between of the reference frequency and the considered signal frequency.

In a sampling system it is convenient if the phasor represents the signal at the sampling moment. Any signal whose frequency is an integer multiple of the sampling rate is represented by a stationary phasor. If there is a phase tracker in the system, its aim is to change the sampling moment such that the phasor coincides with the Y-axis. This means that the system is sampling when the signal's phase is zero.

In the Loran-C environment, where a sampling scheme with more than one sampling interval is used, things are a bit more complicated. The phasors of Loran-C and interferences are positioned such that the phasors reflect amplitude and phase at the moment of sampling, as with sinusoidal signals. The tracker's aim is again to align the Loran-C phasor with the Y-axis. With which halve of this axis alignment takes place is decided on by the desired slope of the zero-crossing.

Phasors represent signals after multiplication with the receiver's phase code.

If the phase-tracker does not change its sampling moments and the geodetic position of the receiver does not change, then all phase-decoded Loran-C phasors are stationary in the diagram, instead of continuously phase-shifting π rad. Interferences, which are received uncoded, are encoded by the multiplication and appear as such in the diagram.

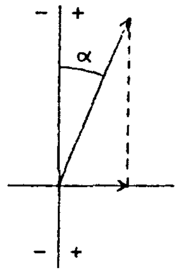

Fig. 2. *Phasor diagram with Loran-C signal. The + and - symbols denote the hard limiter's response. The Y-axis is the decision axis. The image of the phasor on the X-axis is the actually measured value of the signal.*

A phase-tracking error is represented by the angle between the Loran-C phasor and the vertical axis (α in fig. 2). The receiver must reduce this angle to zero. In hard-limiter receivers all received signals (i.e. Loran-C plus interferences plus noise) with its phasors on the right side of this axis are evaluated as positive, while all signals on the left are called negative. The vertical axis is therefore named the decision axis. In the absence of interference the phase-tracking device tries to align the Loran-C phasors with this decision axis. The phase tracker will be stable on one half of the axis, while there will be meta-stability on the other half. Which half is stable and which meta-stable is decided on by the slope of the zero-crossing to be tracked.

The Minimum Performance Standards (MPS) [2] define three types of Continuous Wave Interference:

Asynchronous Interference: $$|f_{int} - \frac{N}{2GRI}| > f_b \qquad (1)$$

Synchronous Interference: $$|f_{int} - \frac{N}{2GRI}| = 0 \qquad (2)$$

Near-synchronous Interference: $$|f_{int} - \frac{N}{2GRI}| < f_b \qquad (3)$$

where N = 1,2,3....,
f_{int} = the interference frequency,
f_b = the tracking bandwidth of the receiver.

It is convenient to write these formulas as:

$$f_{int} = \frac{N + q}{2\ GRI} \qquad (4)$$

where $N = 1,2,3...$ and $-0.5 < q <= 0.5$.

Then, for asynchronous interference $|q| > f_b \cdot 2GRI$,
for synchronous interference $|q| = 0$,
for near-synchronous interference $|q| < f_b \cdot 2GRI$.

When describing these interferences in a phasor diagram, two timing frames

should be observed.
The first one lasts a 2-GRI period, and is used to study effects that occur within this interval. In this timing frame 16 samples are taken. 8 Samples are taken 1 ms from each other, and 1 GRI later another 8 samples are taken. These samples produce 16 phasors for each interference in the phasor diagram. Only if the interference frequency is a multiple of 1 kHz, its phasors form 2 groups of 8 coinciding phasors. If the interference is also synchronous with 1 GRI (that is: its frequency is also an exact multiple of 1 / GRI) there is one set of 16 coinciding phasors.

We shall call this timing frame the small frame. Its 16 interference phasors will be the small frame's phasors. The vectorial addition of these 16 phasors will be named the small frame's resultant. Note the difference from the resultant that is obtained by adding a Loran-C phasor and an interference phasor from the same sample.

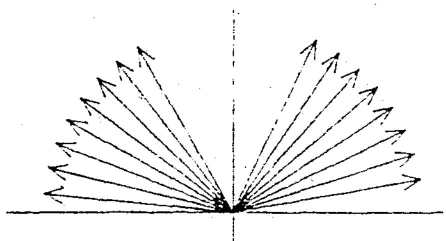

Fig. 3. *Sixteen phasors, representing sixteen consecutive samples of an interference signal.*

The second timing frame is called the large frame. It is used to study the effects that result from the 2GRI repetition rate. In this larger frame the behavior of the small frame's resultant is observed every 2 GRI. Alternatively, one phasor may be selected from the set of 16 small frame's phasors, and its behavior observed. Such phasor will be called a large frame's phasor. Note that a small frame's resultant and a large frame's phasor can denote the same thing.

During each period of 2GRI, the phase of a synchronous interference shifts exactly $2N\pi$ rad, where N is from equ (4). This means that each large frame's phasor coincides with its predecessor: the consecutive phasors have a phase shift of 0 rad.

A nonsynchronous interference causes phasors with a phase shift of $2q\pi$ rad, and these phasors rotate with a frequency of $q\pi$/GRI rad/s.

In 1969 Frank [3] has already pointed out that for nonlinear phase detectors, such as in the hard-limiter receiver, an additional type of interference should be defined:

$$\text{Subsynchronous Interference:} \qquad \left| f_{int} - \frac{N+m/n}{2\,GRI} \right| = 0 \qquad (5)$$

where n is the order of synchronism and m is any number such that $0 < m < n$.

Referring to equ (4): $|q| = m / n$.

An interference with such a frequency is said to be subsynchronous of order n, or shortly n-synchronous. An n-synchronous interference yields n large-frame's phasors before alignment occurs again.

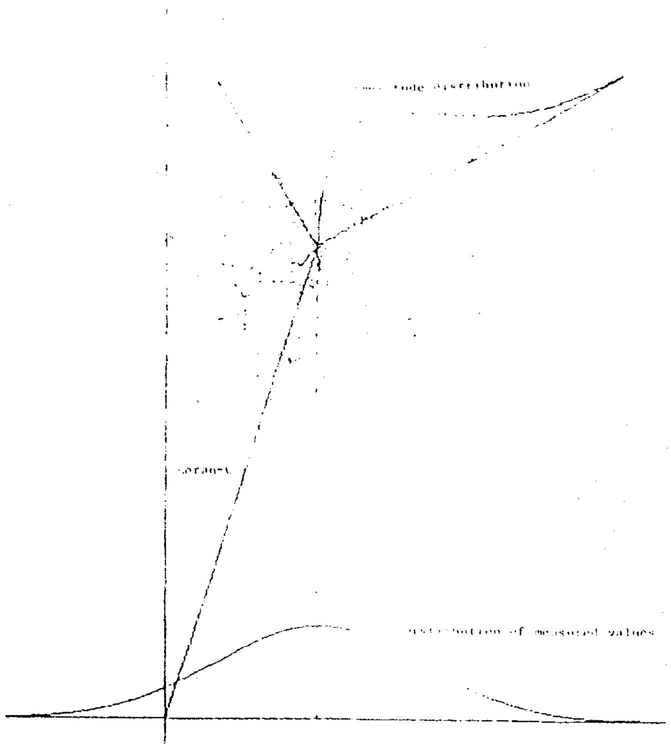

Fig. 4. *Loran-C signal in a noisy environment. Every dot is the end of a noise vector, added to the Loran-C vector. The noise has a Rayleigh amplitude distribution and a uniform phase distribution. Its projection on the X-axis has the Gaussian distribution.*

Noise can also be depicted in the phasor diagram. White or band-limited noise has a Gaussian distribution. The projection of the end points of noise phasors on the X-axis show this distribution. The noise's phase distribution is uniform. The noise's amplitude distribution has a Rayleigh distribution. A plot of a phasor diagram with many samples of a Loran-C signal with noise appears as in fig. 4.

In order to verify any theory that is derived from phasor analysis, simulations have been performed of a hard limiting receiver using a sequential-detection filter algorithm [5].

3.1 - SYNCHRONOUS INTERFERENCE

Synchronous interference is characterized by the variable q in equ (4) being equal to 0. The large frame's phasors are then all aligned and the phase tracker chooses its sampling moment such that the receiver's integrator will have a zero result after 2GRI.

For a linear receiver this is the position where the sum of the small frame's resultant and the Loran-C phasor yield a phasor which is aligned with the decision axis. Generally this is not the position in which the Loran-C phasor is aligned with the decision axis. The size of the phase error which thus occurs arises from relative signal-amplitudes, phase coding, interference frequency, GRI, receiver implementation and phase difference between interference and Loran-C signal.

3.2 - NEAR-SYNCHRONOUS INTERFERENCE

Near-synchronous interference is characterized by the variable q in equ (4) being very small, but not equal to 0. The large frame's phasors are each positioned $2q\pi$ rad from their predecessor. The phase tracker tries to keep the resultant of the Loran-C phasor and the small frame's resultant on the decision axis by adjusting its position. If it succeeds in doing so we have:

$$L \cdot \sin(\alpha) = S \cdot \sin(\beta) \qquad (6)$$

where
- L = the amplitude of the Loran-C signal
- S = the amplitude of the small frame's resultant
- α = the receiver's phase error
- β = the interference's phase at the sampling moment

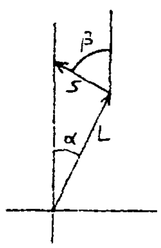

Fig. 5. *Loran-C and a small frame's resultant. The phase tracker tries to keep the resultant of these on the decision axis. The phase tracking error is α, while β is the interference's phase offset at the sampling moment.*

With non-synchronous interference the phase difference between Loran-C signal and interference changes uniformly with time:

$$\beta - \alpha = 2\pi \, \ell_{near} \qquad (7)$$

where $\ell_{near} = \dfrac{q \ \pi}{GRI}$

This ℓ_{near} can be identified as the difference between the interference frequency and the nearest synchronous frequency.

From equ (6) and equ (7) we get the receiver's phase error as a function of time for the linear receiver:

$$\alpha(t) = \tan^{-1}\left(\frac{\sin(2\pi\ell_{near} t)}{\frac{L}{S} + \cos(2\pi\ell_{near} t)}\right) \qquad (8)$$

This equation only holds for S < L and in the case where the phase tracker is able to comply with equ (6), that is, if $\alpha(t)$ does not change too quickly. Parameters involved here are:

- the L-to-S ratio
- ℓ_{near}
- the receiver's tracking bandwidth

The L-to-S ratio is determined by Signal to Interference Ratio (SIR) and the phase coding.

For the hard-limiter receiver things are more complicated. A small frame's resultant cannot be derived and so an equation like equ (6) has no meaning. However, something can be said if all the small frame phasors coincide. This applies if the interference is 1-GRI synchronous or near-synchronous and is also a multiple of 1 kHz.

For a linear receiver the length of the small frame's resultant would be a quarter of the length of one small frame's phasor, when using the standard phase coding scheme. In the hard-limiter receiver 12 of every 16 samples compensate each other. The remaining 4 positively decoded samples will each yield a resultant, that is, the sum of a Loran-C phasor and an interference phasor, which jitters around the decision axis in a fashion as shown in fig. 5. Hence the apparent small frame's resultant is exactly equal to a single interference phasor, which is 4 times the small frame's resultant in the linear case. The expected waveform for $\alpha(t)$ is found, but the maximum phase error is larger, provided that still $S < L$.

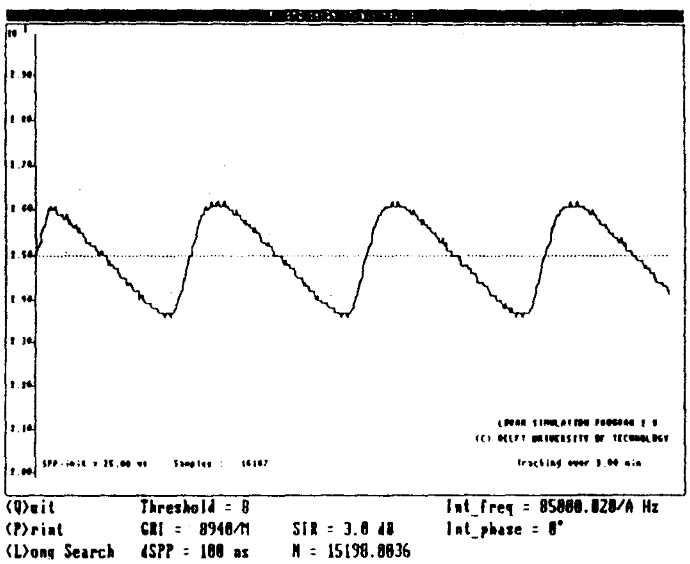

Fig. 6. *Simulation of a hard- limiter receiver with near synchronous interference. The interference is 1-kHz synchronous.*

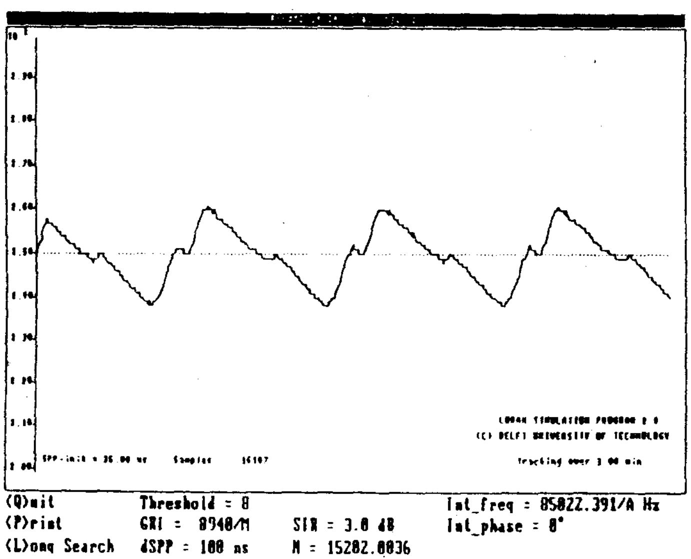

Fig. 7. *Simulation of a hard- limiter receiver with near synchronous interference. The interference is not 1-kHz synchronous.*

If the interference is slightly less 1-kHz synchronous, the phasors composing a small frame's resultant spread out in the phasor diagram. The phase tracker's behavior changes very little if all interference phasors are still on the same side of the decision axis. The same maximum phase error is obtained. However, when interference phasors start crossing the decision axis, sample-compensation schemes change and therefore the apparent small frame's resultant changes. At this moment the phase error is close to zero (both interference phasors and Loran-C phasors coincide with the decision axis). Differences with the original waveform are therefore located at its zero crossings. Simulations confirm this result (figs. 6 and 7).

3.3 - SUBSYNCHRONOUS INTERFERENCE

As Frank [3] pointed out long ago, subsynchronous frequencies are found between the synchronous frequencies. Distinction should be made between even-order (n in equ (5) is even), and odd-order (n in equ (5) is odd) interference. Figures 8a and 8b show typical phasor diagrams for 2- and 3-synchronous interferences.

(a) (b)

Fig. 8. (a) *Two large frame's interference vectors of 2nd order sub-synchronous interference.* (b) *the same, now for 3rd order sub-synchronous interference.*

The large frame's phasors are not aligned, as with synchronous interference, nor are they scattered along the phasor diagram, as with asynchronouos interference. The large frame's phasors coincide after a few periods of 2GRI: after n periods for n-synchronous interference. In the mean time n consecutive phasors form n evenly distributed vectors in the phasor diagram.

If n is large this situation degrades to either near-synchronous interference (if m is small relative to n), or to asynchronous interference (if m is of the order of n). Frequencies that obey equ (5) should only be called sub-synchronous if coincidence is reached in a short time, relative to the receivers tracking bandwidth.

A linear receiver is immune to sub-synchronous interference. The adjacent large frame's phasors which form a sub-synchronous set are linearly added in the integrator and thus cancel themselves within the relatively short time of n·2GRI.

With a hard-limiter receiver the phasors are not linearly added: only positive and negative unity contributions are added. In the situation of figure 8a this yields a zero result for Loran-C and interference together. The phase tracker stays immobile. In effect, the starting value of the phase error may vary over a large region in this immobile situation: we have a dead zone [3]. As long as

$$| L \sin \alpha | < | S \sin \beta | \qquad (9)$$

this situation exists.

If this condition is not met, the phase tracker takes action to diminish α. This is in situations as in fig. 9. As the phase difference between interference and Loran-C signal does not change, the phase tracker moves in such manner that equ (9) is met again. It maintains a phase error

$$\alpha = \arcsin(S/L \cdot |\sin \beta|) \qquad (10)$$

where the symbols have the same meaning as in equ (6).

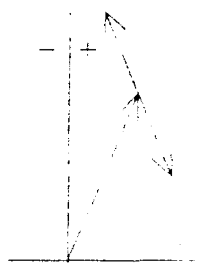

Fig. 9. *Loran-C and a 2-synchronous interference in a position that causes phase-tracker action.*

This behavior is typical for all even-order synchronous interferences. Higher even-order interferences will present more self canceling phasor pairs. Only if all pairs meet equ (9) there is a dead zone.

The influence of odd-order sub-synchronous interference (fig. 8b) very much resembles the influence of 1-synchronous interference. Phasors compensate each other in pairs, while the phase tracker performs its action on the remaining one that is closest to the decision axis. This results in a continuous phase error, as with 1-synchronous operation.

Near sub-synchronous interference

As an interference's frequency might deviate sightly from a synchronous frequency (yielding a small value for variable q in equ (4)) it might deviate from a sub-synchronous frequency, and yields a small value for variable q in equ (11):

$$f_{near} = \frac{N + m / n + q}{2 \; GRI} \qquad (11)$$

where N, n, and m are as in equ (5), while q/2GRI is the offset from the exactly sub-synchronous frequency.
With a stationary phase tracker, the interference phasors go round in 2GRI/q seconds. However, n phasors will have gone round, and therefore an oscillation of n·q/2GRI Hz is found in the phase tracker's behavior.

With near 2-synchronous interference we might start observations in a dead zone. This means that the Loran-C phasor does not move in the phasor diagram, while the interference phasors rotate with $2q\pi/2GRI$ rad/s. This eventually brings the resultant phasors into a region where there is tracking action. In fig. 8a this would be possible if the interference phasors were smaller than the Loran-C phasor: the interference phasors would turn round until both end points were on the same side of the decision axis, which initiates phase-tracker action. This action causes all phasors to rotate in such a direction that the phase tracking error diminishes. This extra rotation of all phasors is either in the same or in the opposite direction of the interference phasor's original rotation: this phasor is either accelerated or decelerated.

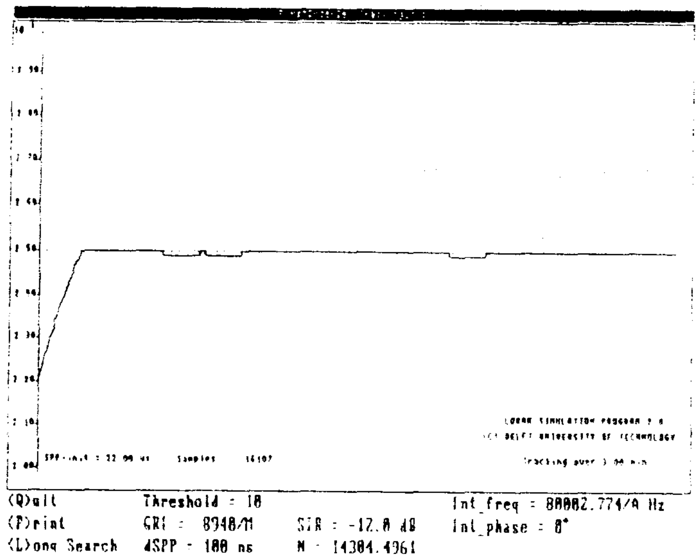

Fig. 10. *A 2nd order near-subsynchronous interference. Movement of the interference and of the phase tracker in the phasor diagram are in opposite directions.*

In the latter case the resultant phasors take a lot of time to cross the region of tracking action before entering the dead zone again. Depending on ℓ_{near} and the speed of the receiver, the phase error might be reduced to zero in this time. The phase tracker is then left in a dead zone, but with no or very little phase error. Fig 10 shows this possibility.

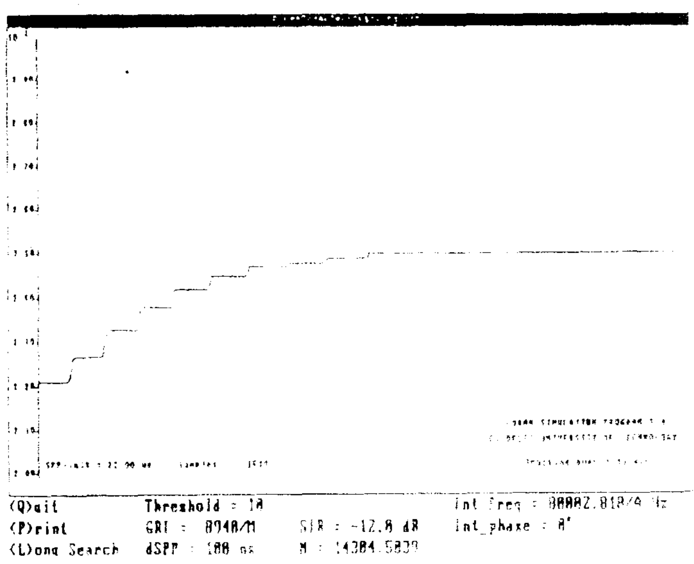

Fig. 11. *A 2nd order near-subsynchronous interference. Movement of the interference and of the phase tracker in the phasor diagram are in the same direction.*

If the interference's phasors are accelerated it is more likely that dead zone is entered again before the phase error is back to zero. The receiver then holds its new phase error, until the dead zone is crossed again. The receiver's phase error diminishes in step wise fashion. This is shown in fig. 11.

For odd-order sub-synchronous interference the effects are as for 1-synchronous interference. The observed frequency is n·q/2GRI Hz. This multiplication of the observed frequency occurs because the interference phasor, whose resultant with the Loran-C phasor is kept on the decision axis, changes n times per period. Figure 12 shows an example for n = 3.

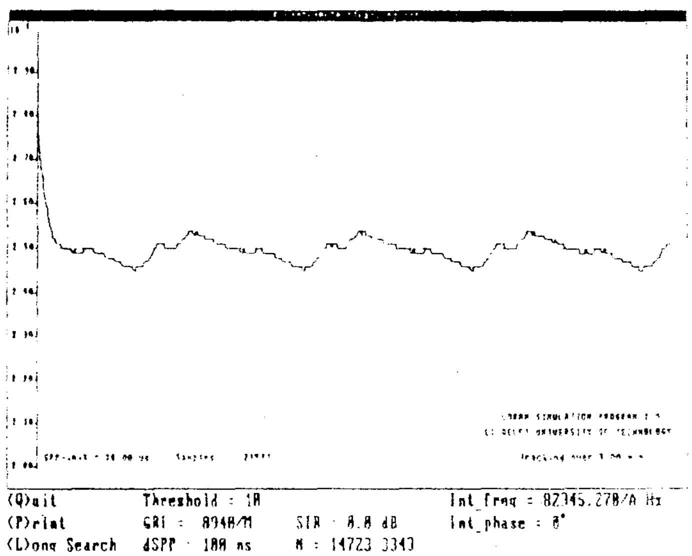

Fig. 12. *A 3d order near subsynchronous interference.*

Subsynchronous effects due to phase coding

Some receivers use phase coding techniques in order to eliminate synchronous interference. Virtually all receivers use such techniques to eliminate long-delayed sky waves. This works fine in linear receivers. In hard limiter receivers, effects such as in fig. 8a are created: sky wave phasors are received either positive or with a 180° phase shift. Subsynchronous pairs that are created in this manner do not consist of phasors that are sampled 2GRI apart, but of phasors that are sampled within a 2GRI period. Experience, however, shows that no dead zone phenomena are present. This is caused by the always-present noise, as will be seen later. The effects of phase coding a strong interference however, might not be canceled by noise, in which case sub-synchronous effects occur.

3.4 - ASYNCHRONOUS INTERFERENCE

Asynchronous interference is all CWI that can not be placed in one of the other classes.

If the tracker's phase error is large, the effects of asynchronous interference are much like those of noise. The observation probability p_{obs}, i.e. the probability of judging the polarity of the Loran-C signal correctly, is degraded. This causes the tracking process to slow down. In [4] it is indicated how SNR and asynchronous SIR should be compared for equal p_{obs}.

Asynchronous interference has a mean value approaching zero when measuring during a period of a few GRI. It does not keep the phase tracker from finding the Loran-C signal's zero crossing.

When this zero crossing is found, the polarity indicated by the hard-limiter is primarily determined by the noise or by the interference. With noise this means that the polarity might be equal for a large number of consecutive samples. This causes the phase tracker to make incidental large excursions. With asynchronous interference this is not the case: detected polarity changes rather rapidly (or it would not be asynchronous interference). The integrator absorbs most samples, and the phase tracker shows a regular, small amplitude behavior.

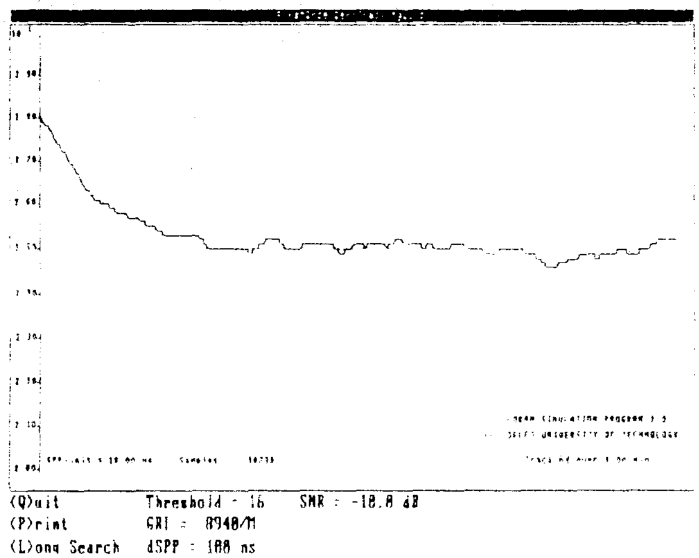

Fig. 13. Step response and phase tracker's excursion in the presence of noise.

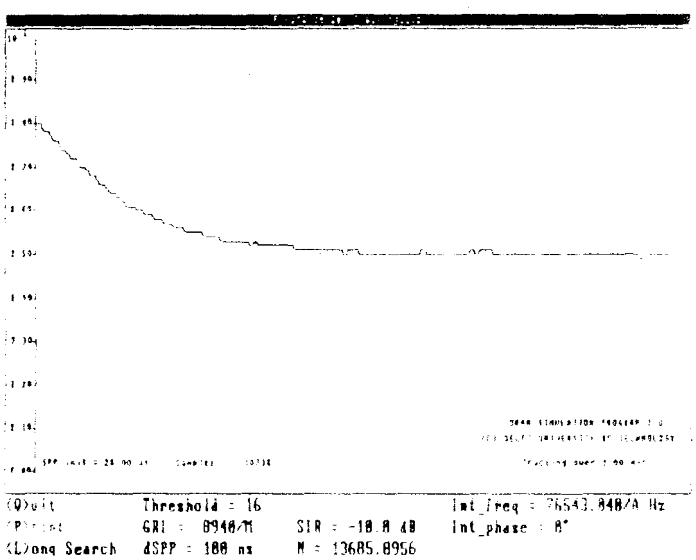

Fig. 14. Step response and phase tracker's excursion in the presence of asynchronous interference.

Figures 13 and 14 show simulations for signals with comparable p_{obs} caused by respectively noise and asynchronous interference. Although the step responses are more or less equal for both instances, behavior is quite different, once the zero crossing is reached.

4 - NOISE INFLUENCES

In a hard-limiter receiver, p_{obs} is the probability of the hard-limiter making a right decision on the polarity of an incoming signal that is contaminated with noise or interference. As indicated in [4], noise makes p_{obs} linearly dependent on the signal's amplitude relative to the noise level for SNR's up to 0 dB. Figure 15 shows the normalized output of an integrator, which is placed after the hard-limiter, against the SNR (output is 1 if all samples are considered positive) for Gaussian noise. The output is shown after a fixed number of samples. The hard limiter's response to the signal is changed by the noise: it is linearized. This linearization holds for signal levels up to 0 dB, where the amplitude is equal to σ, where σ^2 is the noise's output level. Signal levels above 10 dB (amplitudes up to about 3 σ) cause p_{obs}, and thus the output, to be equal to 1: the input signal is clipped. Between 0 dB and 10 dB there is a gradual transition between the linear operation and the clipping operation ('soft' clipping).

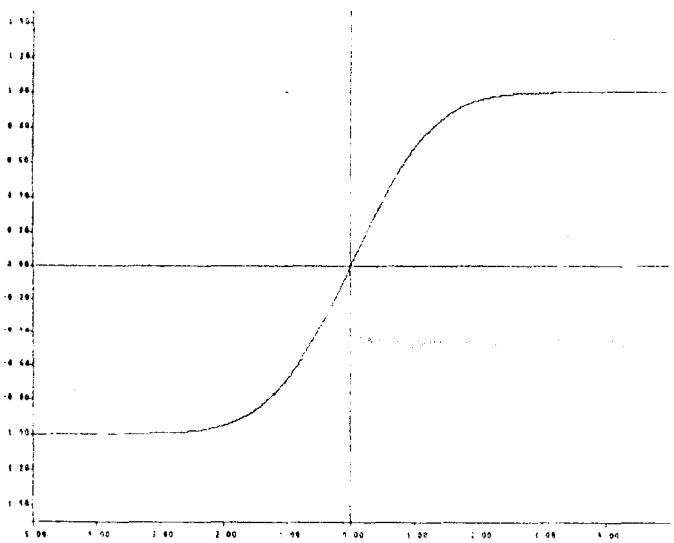

Fig. 15. *Characteristic of a hard limiter in combination with an integrator and noise. The noise's power level is σ^2.*

This phenomenon has two major effects:
One is the reduction of speed of the phase tracker: for low SNR the phase tracker receives a small error signal. This is very clearly demonstrated by having the phase tracker start with a significant phase error. As the phase error is reduced and the zero crossing of the Loran-C signal reached, the SNR diminishes, and so does the adjustment speed. Figure 12 shows a simulation of such an experiment.

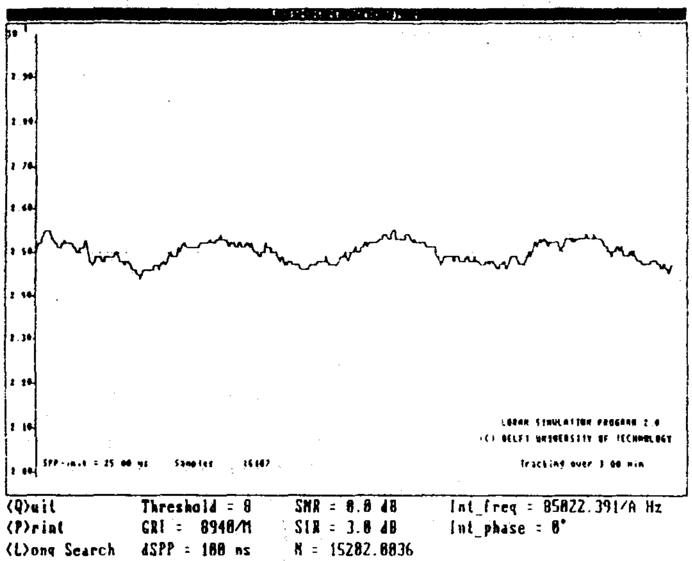

Fig. 16. *Near synchronous interference in the presence of noise.*

The receiver's response to near-synchronous interference is directly affected by this sensitivity for noise, because equ (6) only holds if the phase tracker is fast enough to keep the resultant of the Loran-C signal and the interference on the decision axis. If it is not fast enough, for example because of low SNR, the oscillation of the phase error (as it is shown in fig. 6 and 7) loses it's amplitude. Alternatively phrased: the receiver's bandwidth is directly affected by the SNR. Figure 16 shows a simulation with near-synchronous interference at a still fairly low noise level. Compare this with fig. 7, which demonstrates the same simulation, except for the noise level, that is higher in fig. 16.

The second important effect is with sub-synchronous interference. As we have seen, in linear receivers the sub-synchronous sets of interference phasors cancel themselves out. In a hard-limiter receiver, if the noise level is sufficiently low, both samples might be larger than the clipping boundary (3 σ in fig. 15). Then they are interpreted as being equal, and the previously described dead-zone phenomena occur. If the smaller resultant is within the soft clipping zone, the two samples are not interpreted as equal. The phase tracker receives an error signal and phase tracking, though possibly very sluggishly, occurs. Figure 17 shows an experiment where interference and noise levels are selected such that the phase tracker crosses the dead region very slowly. Observe the relatively high SNR and Interference to Noise Ratio (INR) at which this dead zone canceling occurs. Only very strong interferences are able to cause dead zones.

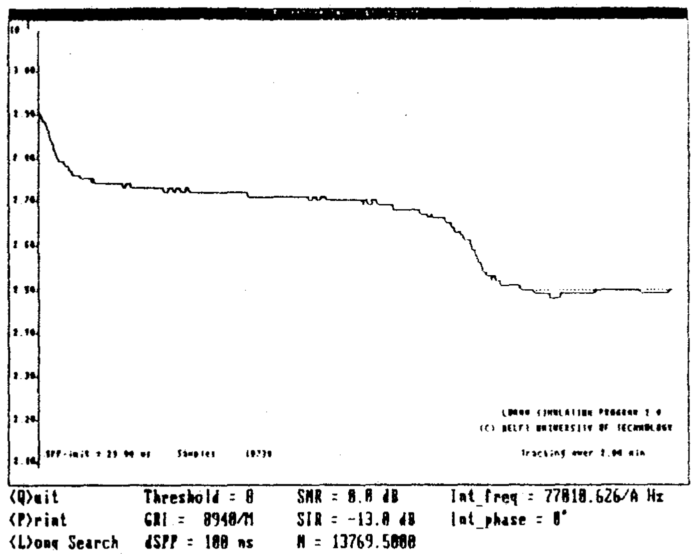

Fig. 17. *A 2nd-order (m/n=1/2) subsynchronous interference in the presence of noise. The dead zone is (slowly) crossed.*

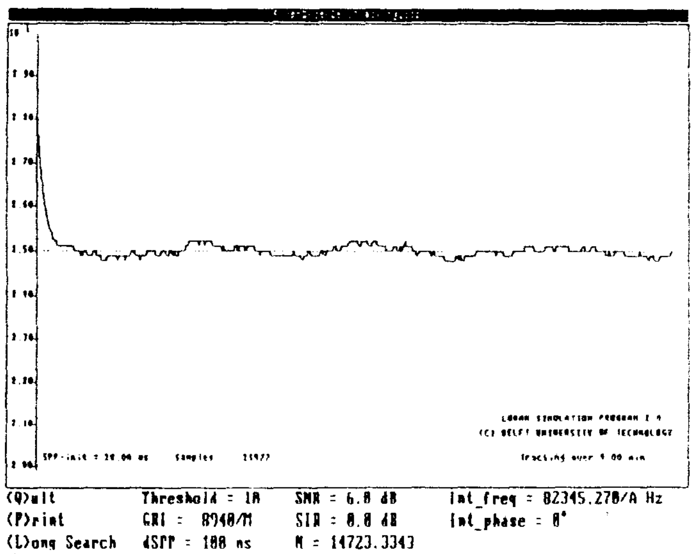

Fig. 18. *A 3rd-order near sub- synchronous interference in the presence of noise.*

Odd-order synchronous interference shows a reduced phase-tracker's offset. The phasor pairs that cancel themselves out in the absence of noise, thereby allowing the remaining phasor to cause a tracking error, don't do so if noise is present. The resultant from each pair has a corrective influence on the phase-tracker's behavior. With much noise complete cancellation occurs, as with linear receivers. Figure 18 shows an example of third-order near-synchronous interference in the presence of noise. All other parameters are as in fig. 12.

5 - INTERFERENCE REDUCTION TECHNIQUES

Until now, all analyses and simulations are related to phase disturbances of the signal carrier. Unfortunately, the envelope of the burst is also affected by CWI. This envelope contains the only information from which the receiver can derive which cycle is actually being tracked. So, any error in this envelope-tracking process means a range error of at least 3 km.

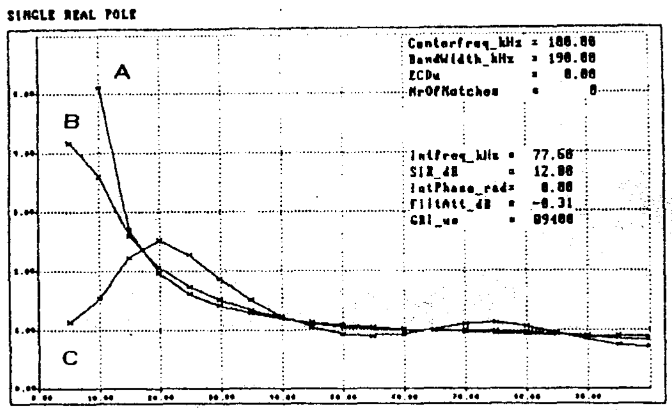

Fig. 19. *Distortion in the envelope tracking due to synchronous interference. GRI = 8940, f_{int} = 77,500 Hz. Curve a gives the undistorted envelope- ratio information while curve b and c shows the influence of the interference for SIR = 12 dB and SIR = 0 dB respectively.*

Curve a in Fig. 19 gives the ratio of two successive sine wave peaks, at -7.5 us and +2.5 us respectively, as function of the tracked zero-crossing of the burst. Analog receivers measure the amplitudes of two neighboring sine wave peaks and calculate the ratio in order to determine the tracked cycle. Hard limiter-type receivers apply special envelope-deriver circuits to convert the envelope-ratio information into polarity information. Curve c shows the drastic change of the ratio curve when synchronous interference - 77.5 kHz/GRI=8940-M/SIR=0 dB - is added to the Loran-C signal. At a SIR equal to +12 dB, the disturbance is acceptably low (curve b in Fig. 19). The given example is very realistic for European areas. DCF77 is a German synchronous high-power time-signal transmitter at 77.5 kHz which is synchronous to the French 8940 Loran-C chain.
Simulations show that correct phase and envelope tracking is possible when the signal-to-synchronous-interference ratio is better than +12 dB. This is the post-band pass filter value; the SIR at the antenna input of the receiver is mostly quite different from this value.

Although the simulations of the phase and envelope tracking errors as demonstrated in Fig. 6 and 19 are realistic for many places in Europe, the situation is not yet hopeless. Band pass and notch filters are very effective requisites for improving the SIR to acceptable levels.
Band pass filters, centered at 100 kHz, must have a large bandwidth in order to preserve the steep leading edge of the Loran-C envelope. Feldman [6] has performed analysis on phase and envelope distortion as function of bandwidth and type of the selected filter. Small bandwidths and steep filter slopes reduce the robustness in discriminating ground wave from sky wave signals. However, they do help to attenuate interferences outside the Loran-C band, i.e. 60-90 kHz and 110-140 kHz. Fig. 20 shows the interference reduction when the original spectrum of Fig. 1 is filtered by an industry-type bandpass filter, e.g. Seiko SH-C35-2.

The Seiko filter attenuates signals at 77.5 kHz about 30 dB more than the Loran-C signal. The field strength at Delft of the 8940 Master (Lessay) is 3.0

mV/m and of DCF77 (77.5 kHz) equal to 1.4 mV/m. After the band pass filter we then obtain a comfortable SIR-value of 36 dB.

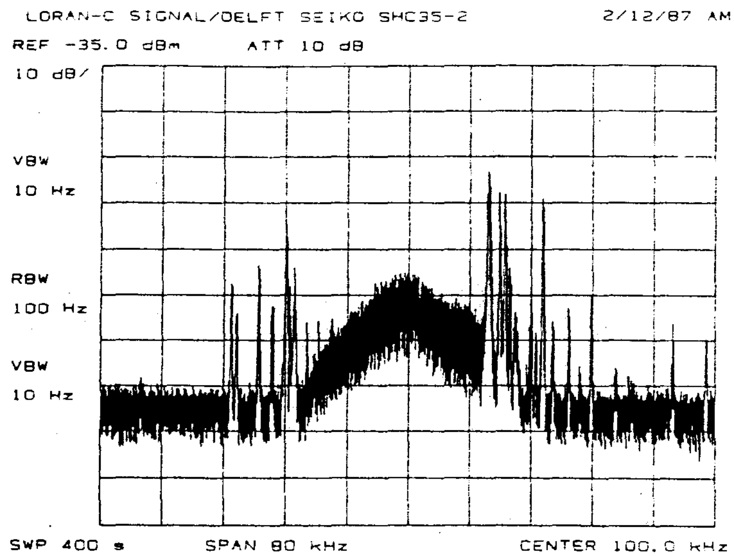

Fig. 20. *Bandpass-filtered spectrum as received at the Delft University of Technology in The Netherlands.*

However, the expected expansion to land navigation may bring users much nearer to interfering transmitters than in the just given example. This will reduce the SIR significantly. Knowing the effective radiated powers of the Loran-C and the interference transmitters, and also knowing the ground wave field strength attenuation with distance, we can determine the area where the SIR sinks below +12 dB. Considering again the French 8940 master and the German DCF77 transmitter we find a circular area around the DCF 77 station with a 32 km radius. Although this result seems acceptable, it should be realized that the non-serviceable area exceeds 3000 km^2. And, there is more than just one synchronous interfering station in Europe operating!
Bandpass filters cannot further improve the SIR value significantly without reducing sky wave rejection capabilities. However, additional attenuation of CW interference without seriously altering the leading edge of the burst can be achieved with narrow-band notch filters. Fig. 21 gives the overall frequency response of the Seiko band pass filter cascaded with a 2 kHz wide notch filter tuned to 77.5 kHz. The notch depth is 30 dB. It is estimated that the interfering station can now be approached to about 1 km, reducing the non-serviceable area to 3 km^2.

However, reconsidering Fig. 20, we see that many notch filters are needed to clean up the spectrum significantly. Fortunately, the proper functioning of a Loran-C receiver is much less susceptible to the majority of asynchronous signals than to the minority of synchronous signals. An asynchronous SIR down to 12 dB hardly affects the tracking.

As navigation receivers move around, the signal strength of all these interferences will change continuously. This means that a set of fixed-tuned notch filters is only optimally set for a specific area. Therefore, many receivers are equipped with automatically tuning filters. The tuning commands are generally derived from the signal strength of the disturbers. This process may easily select rather harmless asynchronous signals for notching instead of a far more dangerous synchronous interference. Therefore, some well-known synchronous signals can better be handled by fixed-tuned notch filters.

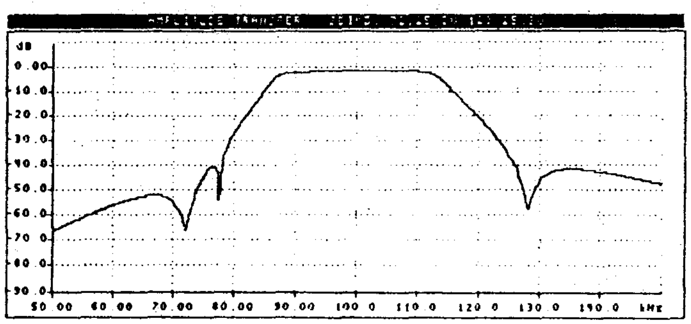

Fig. 21. *Frequency response of Seiko band pass filter cascaded with a 2 kHz wide notch filter at 77.5 kHz. The zeros at 72 and 128 kHz are from the Seiko filter.*

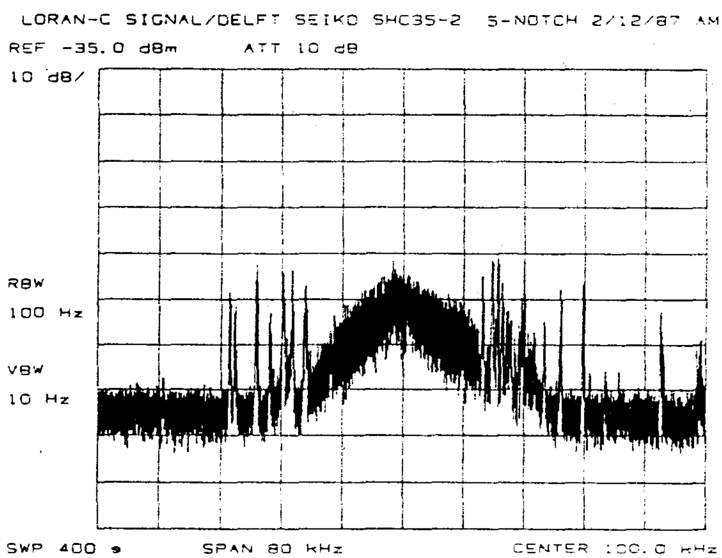

Fig. 22. *Received frequency spectrum filtered by Seiko band pass filter cascaded with five automatically tuning notch filters.*

Fig. 22 depicts the quality improvement of the received frequency spectrum by cascading the Seiko filter with five automatically tuning notch filters. Analyzing the plot once more reveals that still many additional notch filters are required for a further significant reduction of the interference power level.

6 - CONCLUSION

Loran-C receivers in Europe must operate under rather hostile spectral conditions. In many areas interferences form a greater threat than atmospheric noise.

Vector analysis may give a detailed picture of the phase-tracking process disturbed by different types of interference. However, software simulation of the received signals and the phase-tracking process - LOSP - is required to visualize the performance of various receiver configurations under interference conditions.

Dangerous synchronous interference is best eliminated by a careful selection of the GRI of the chain or by shutting down some "synchronous" transmitters. Because of historical rights, the latter option will be hard to effectuate. If incompatibility sustains, fixed-tuned notch filters are a good solution. Our remaining asynchronous friends are to be made ineffective with automatically tuning notch filters on basis of hardware or software technology.

7 - ACKNOWLEDGEMENT

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We would like to thank Ad Duym for his help with using LOSP. Ad is the initial designer of this simulation program.

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Len P. Remmerswaal has done his master's thesis work on this project at the Delft University of Technology. He is now with Philips Telecommunications and Data Systems Netherlands PTDSN.

Dr. Durk van Willigen heads as professor a group of students and staff working on the design of signal processors and electronic circuits for Loran-C, Navstar/GPS, Omega end MLS receivers. He is also the president of the consultancy REELEKTRONIKA bv.

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FEDERAL RADIONAVIGATION PLAN UPDATE

BRIEF HISTORY

1986 FRP

CURRENT AND FUTURE STATUS OF RADIONAVIGATION SYSTEMS

CURRENT AND FUTURE RADIONAVIGATION PLANNING

HISTORY OF THE FRP

NATIONAL PLAN FOR NAVIGATION

- 1970 EDITION
- 1972 EDITION
- 1974 ANNEX
- 1977 EDITION

GAO REPORTS

- 1974
- 1978

INTERNATIONAL MARITIME SATELLITE TELECOMMUNICATIONS ACT, NOV 1978

THE FRP

1984 EDITION

PRELIMINARY POLICY ON AN OPTIMUM SYSTEM MIX

- o DOD PHASE OUT MILITARY AIR USE OF OMEGA AND OVERSEAS LORAN-C BY 1992, VOR/DME AND LAND-BASED TACAN BY 1997 AND CEASE TRANSIT OPERATION IN 1994
- o CIVIL USER PHASE OUT OF LORAN-C AND OMEGA AFTER CERTAIN PROBLEMS WITH GPS WERE RESOLVED
- o A 15 YEAR TRANSITION PERIOD FOR PHASE OUT OF LORAN-C AND OMEGA AS GPS BECAME OPERATIONAL
- o RESOLUTION OF INTERNATIONAL COMMITMENTS.

1986 EDITION
CURRENT POLICY GOALS

- o DOD PHASE OUT MILITARY AIR USE OF OMEGA AND OVERSEAS LORAN-C BY 1994, VOR/DME AND LAND-BASED TACAN BY 1997, AND CEASE TRANSIT OPERATION IN 1996. ADDITIONALLY, DOD WILL PHASE OUT MILITARY USE OF ILS

- o CIVIL USER PHASE OUT OF VOR/DME, LORAN-C AND OMEGA CONTINUES TO DEPEND ON RESOLUTION OF CERTAIN GPS RELATED ISSUES

- o ESTABLISHMENT OF A 15 YEAR TRANSITION PERIOD

- o RESOLUTION OF INTERNATIONAL COMMITMENTS.

FACTORS AFFECTING SELECTION OF THE SYSTEM MIX

- GPS IS NOT OPERATIONAL
- CHANGES IN USER PROFILES
- DYNAMIC RADIONAVIGATION TECHNOLOGY
- USER INPUT FROM RADIONAVIGATION CONFERENCE

GPS

BLOCK II SATELLITE LAUNCHES BEGINS IN EARLY 1989

GROUND SYSTEM IS OPERATIONAL

21—SATELLITE CONSTELLATION IN PLACE BY 1992

24—SATELLITE CONSTELLATION BEING CONSIDERED

DOT OPERATION OF A CGS SERVICE

- CGIC
- PPS

CURRENT AND FUTURE STATUS OF NAVIGATION SYSTEMS

Loran—C

DOMESTIC SYSTEM EXPANSION ON SCHEDULE FOR 1990 OPERATION

OVERSEAS SYSTEM OPERATION TURNED OVER TO HOST NATIONS OR SHUT DOWN AFTER 1994

HAWAIIAN CHAIN SHUT DOWN AFTER 1994

SUBSTANTIAL INCREASE IN POPULATION

REMAIN IN OPERATION UNTIL WELL INTO 20TH CENTURY

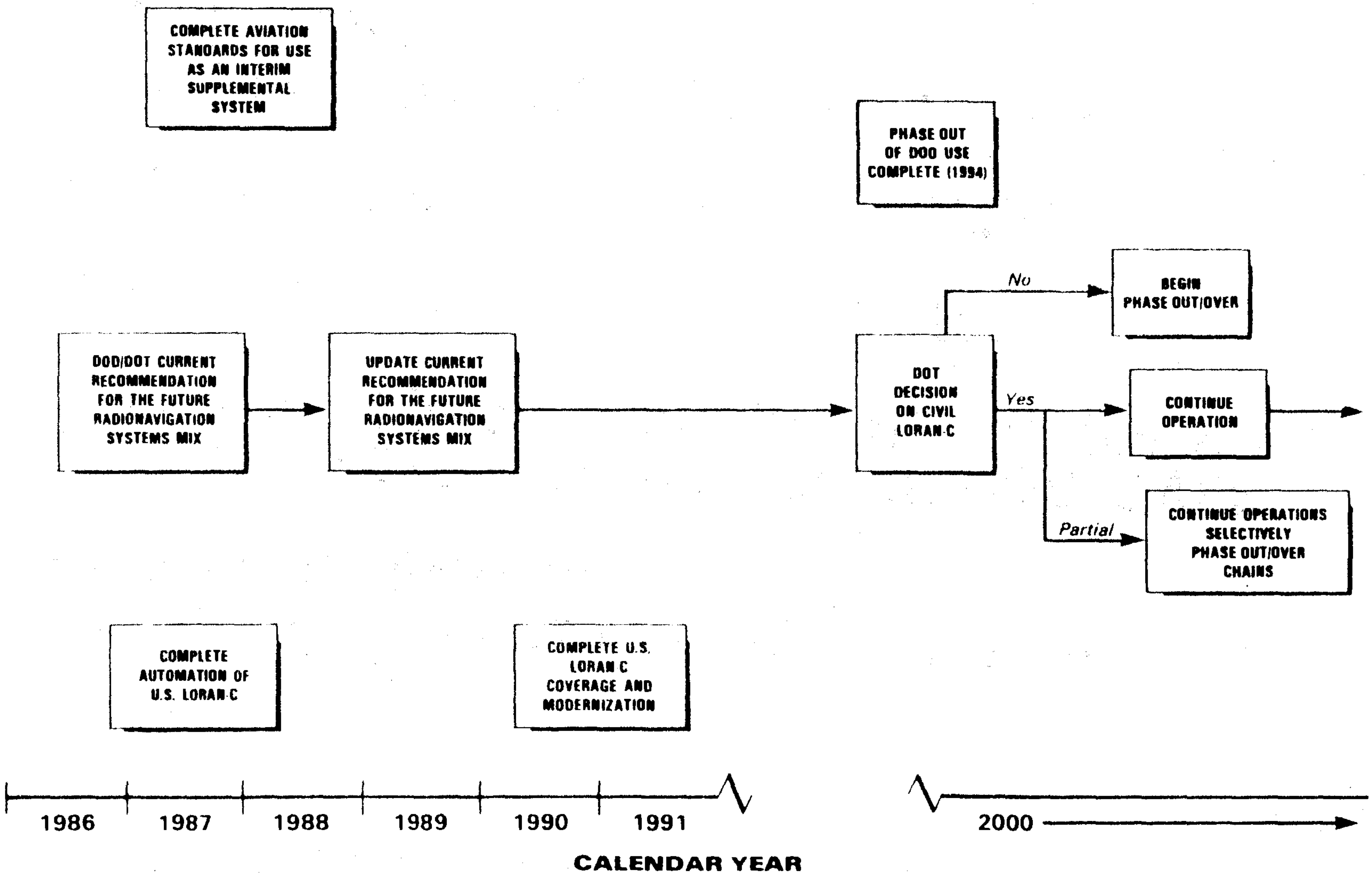

FIGURE 3-1. OPERATING PLAN FOR THE LORAN-C SYSTEM

CURRENT AND FUTURE RADIONAVIGATION PLANNING

GPS OPERATIONAL IN 1992

NOT ECONOMICAL FOR MOST USERS INITIALLY

DISCONTINUANCE OF OMEGA OR LORAN—C IN LIEU OF GPS SERVICE NOT LIKELY TO OCCUR UNTIL THE FOLLOWING ISSUES ARE RESOLVED:

- o RESOLUTION OF GPS ACCURACY, INTEGRITY AND FINANCIAL ISSUES
- o GPS MEETING THE NEEDS OF CIVIL AIR, MARINE, AND LAND USERS CURRENTLY MET BY EXISTING SYSTEMS
- o ECONOMICAL GPS RECEIVERS BECOMING AVAILABLE
- o RESOLUTION OF INTERNATIONAL COMMITMENTS
- o DESIGNATION OF AN APPROPRIATE TRANSITION PERIOD FOR ANY PHASED OUT SYSTEM (CURRENTLY 15 YEARS).

JOINT SOVIET/AMERICAN LORAN OPERATIONS, THE BERING SEA CHAIN

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Washington, D.C.

Abstract

On 28 April 1988, the U.S. Coast Guard negotiated a proposal with the Soviet Union for the implementation of a mixed Loran-C/Chayka chain in the North Pacific. This agreement was signed at the May, 1988, Summit. This paper will discuss the similarities and differences of The US Loran-C and USSR Chayka systems, and present the agreed upon design for a Bering Sea Chain. This proposed chain would provide marine and aviation coverage over the five-hundred-mile-wide coverage gap that exists in the North Pacific between the North Pacific Chain, and the Northwest Pacific and Soviet Eastern USSR chains.

I. INTRODUCTION

The U.S. Coast Guard and agencies of the Soviet Union have carried on a dialogue concerning radionavigation since 1980. Most of the effort up to 1987 focused on standardization of signal characteristics and the avoidance of mutual interference, both from each other's Loran-C/Chayka, as well as third party radio sources. In August, 1987, in Washington D.C., the Soviets proposed that both countries join in actual operations. They suggested the United States and the Soviet Union effect joint Loran-C/Chayka chains by dual-rating existing stations. The Coast Guard agreed to consider joint operations with Loran stations in Alaska.

Both parties met again in April, 1988, in Leningrad, and presented their chain configuration options. After much enthusiastic discussion, a chain configuration was agreed upon made up of the Chayka stations at Petropavlovsk (Kamchatka peninsula) as master and Kurilsk (Kuril Islands) as secondary, with the Loran station at Attu (Alaska) as the other secondary. The inclusion of the Chayka station at Aleksandrov was agreed on as a test station and secondary until upgrades at the low power Chayka station at Kurilsk boost that station's power to provide adequate range.

This agreement was signed at the May, 1988, Moscow summit. Considerable details remain to be worked out; a monitor scheme needs to be fully developed, command and control, and operational doctrines must be defined, and receiver testing must be carried out. The Coast Guard foresees that the initial equipment installation to dual-rate Attu will be completed in 1990.

II. TECHNICAL DIFFERENCES BETWEEN CHAYKA AND LORAN-C

Standardization of the two systems has resulted in essentially identical signal format with respect to phase code, group format, and Group Repetition Interval (GRI). Historical differences in Chayka and Loran-C transmitter development, however, have resulted in differences in pulse shape between the two systems.

Chayka transmitters are of two types, tube and Thyratron. The envelope of the signals formed by tube transmitters are approximated by the second-order exponential power function(2):

$$U_{(t)} = U_m \, (t/tm * e^{1-t/tm})^2$$

where U_m is pulse amplitude, and t_m is the time to peak of pulse.

Thyratron transmitters generate a signal by impact excitation of a two or three-pole output circuit. The envelope is approximated by an exponential-sinusoidal function(2):

$$U_{(t)} = U_m \, (\, (\sin bt)/b * e^{-at})^n$$

where a and b are chosen to determine steepness of growth and speed of attenuation of the generated pulses, and n=1 for two-pole output networks, and n=2 for three-pole networks(2).

Loran-C pulse envelopes are approximated by:

$$U_{(t)} = U_m \, t^2 * e^{-2t/tm} \, .$$

The issue of pulse shape is critical for reliable signal acquisition. The receiver chooses the correct carrier cycle zero-crossing for tracking by determination of a well-defined slope on the pulse envelope. Error or distortion in pulse shape from that defined, or expected by the receiver, can cause the receiver to lock onto the wrong cycle zero-crossing. This cycle selection error causes errors in increments of 10 microseconds. The shape of the leading edge of pulses transmitted from an individual station must be stable, and also must be identical to within a few per cent of RMS distortion, to the pulses from sufficiently synchronous to universal time (UTC) to provide for tractable control. In fact, Petropavlovsk drifted not much worse with respect to the NORPAC master at St. Paul (-540 ns/week) than Attu did with respect to St. Paul (+440 ns/week). This degree of synchronization is noteworthy in that Petropavlovsk was observed as the BMl secondary of the Eastern USSR Chain. As a master station in the Bering Sea Chain, its synchronism with Soviet universal time, and thence to UTC, should become even closer.

A curious phenomenon occurred for the first fifteen days of the test (23 February-08 March 1988) and disappeared for the last twenty days for which data were available (09 March-28 March). The Petropavlovsk signal would shift every six hours by about 1 microsecond relative to the Attu time base. The shifts appeared as fairly smooth unimodal humps in the traces, positive or negative, before returning to center. Coast Guard experts reviewing the curves could not identify the cause of the phenomenon. Soviet experts were queried at the Leningrad meeting. They could not explain the shifts but took copies of the relevant plots and agreed to investigate. Since the effect did finally disappear, indications are the baseline can be controlled reliably, but knowing the cause would inspire more confidence.

V. CONCLUSIONS

The implementation of a useable Loran-C/Chayka radionavigation chain is technically feasible. The diplomatic overtures to implement such a chain have been carried out but many details remain. Technical differences appear slight and easily dealt with compared to operational considerations. Differing command and control doctrine and user interface philosophies, communications difficulties, and considerations of state add to the technical challenge of implementing a joint US/USSR Bering Sea Chain.

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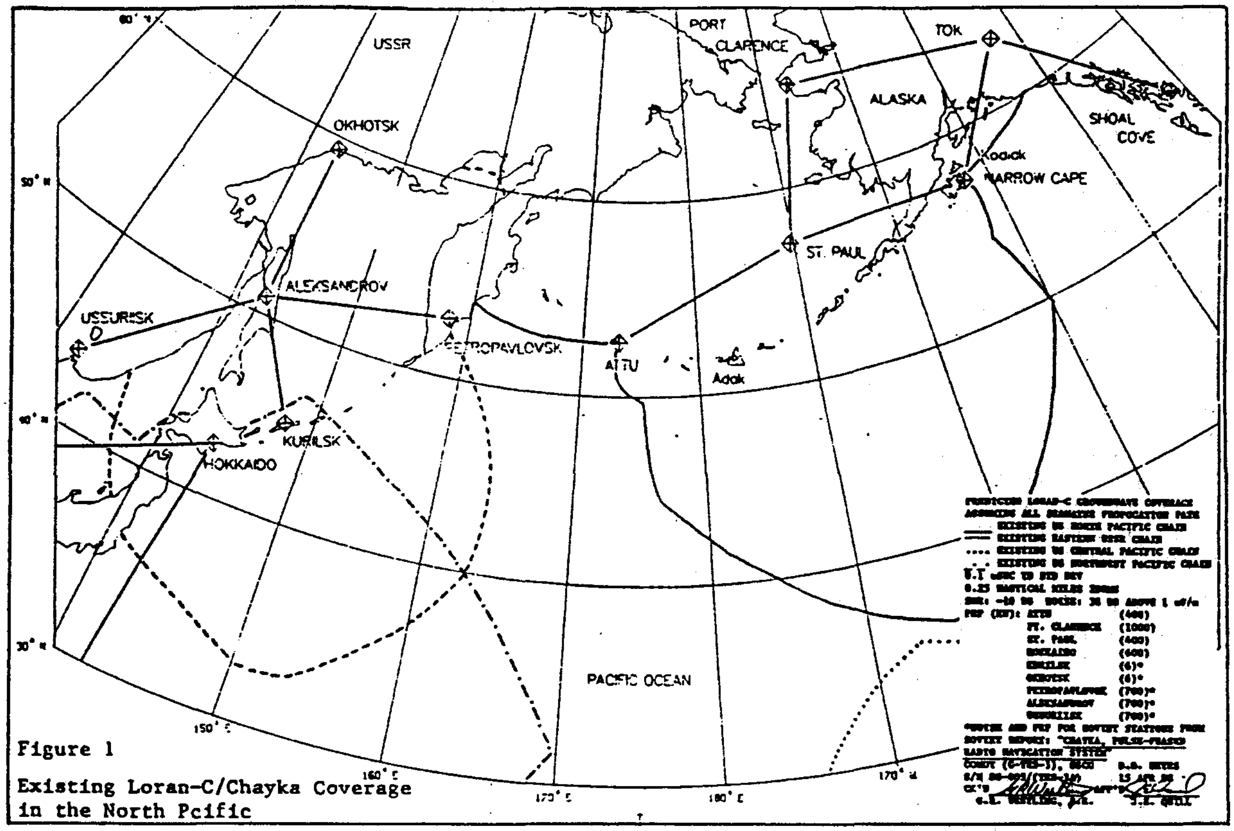


Figure 1

Existing Loran-C/Chayka Coverage in the North Pcific

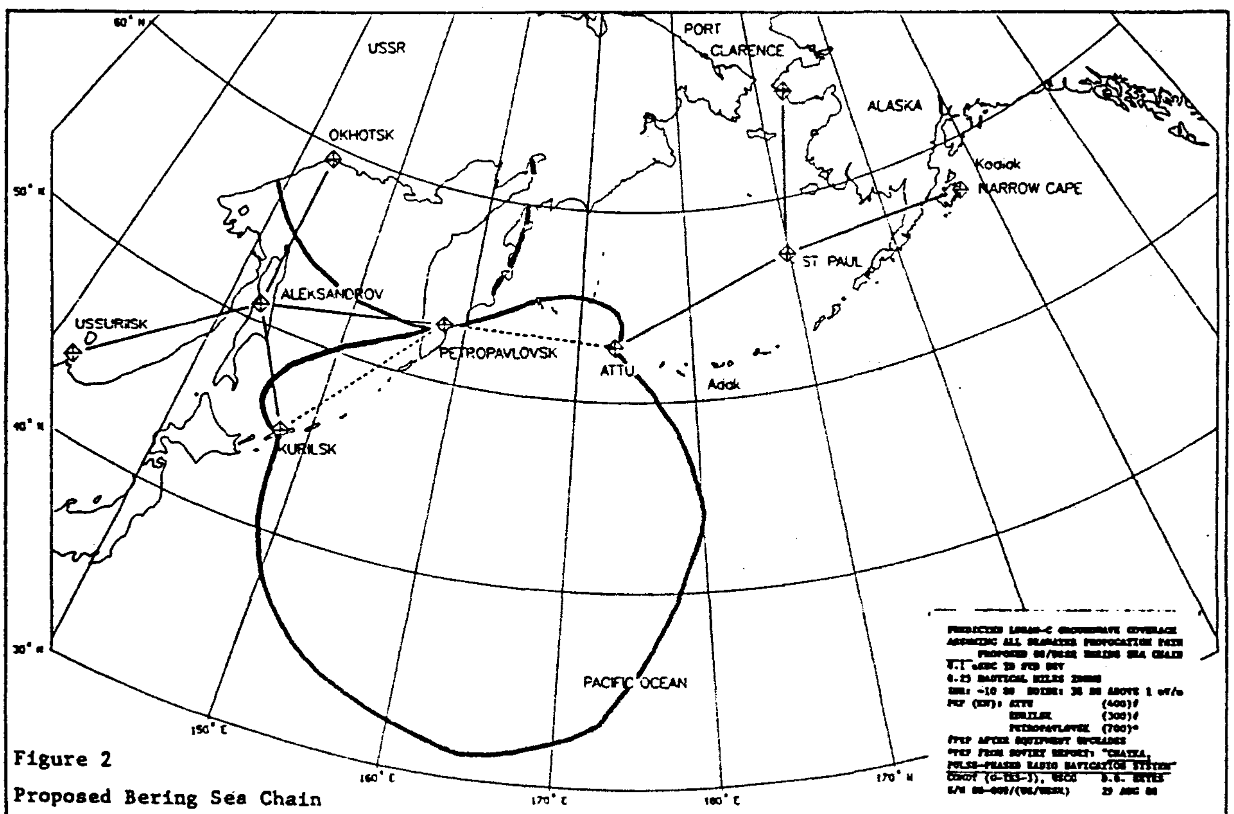


Figure 2

Proposed Bering Sea Chain

Table 1
Bering Sea Chain proposed configuration

FUNCTION	LOCATION[1,4]	POWER(KW)	DUAL RATE
Master	Petropavlovsk 53°04'42.8"N, 142°42'04.9"E	700[1]	7950(BM1)[1]
Xray/BM1	Kurilsk 45°12'45.7"N, 147°51'37.1"E	300[2]	7950(BM3)[1]
Yankee/BM2	LORSTA Attu 52°49'44.0"N, 173°10'49.0"E	400[3]	9990(X)[4]

1. See reference 2
2. Assumes agreed upon equipment upgrades, present PRP is 6kW(2).
3. Assumes transmitters are replaced with 400 kW AN/FPN-44A's, present PRP is 325 kW(4).
4. See reference 4

Figures 1 and 2 are coverage limit diagrams. For ease of computation, and considering that the paths to the international marine and aviation user areas are over water, coverage computations for figure 1 is on all seawater paths. Figure 2 takes into account the land path over the Kamchatka Peninsula. Noise values for range computations were taken from recently published information (3).

The coverage shown for the existing Chayka Eastern USSR Chain (7950, master at Aleksandrov) is transcribed from reference 2. The coverage for the existing Loran-C chains and proposed joint chain is based on new computations using noise values recently available(3). Information on location, and present function (i.e. secondary designation) of existing stations is from reference 4 for Coast Guard stations and reference 2 for Soviet Chayka stations.

IV. MONITOR AND CONTROL

Soviet and Coast Guard monitor and control philosophies differ. The Coast Guard controls time-difference (TD) in the service area from a system area monitor (SAM); in the Chayka method, time differences are measured at each end of a baseline and communicated to the secondary station. These time differences are combined algebraically to extract coding delay (CD) and emission delay (ED). Control action is provided to keep emission delay constant (6). Desired emission delay is recomputed periodically, based on monitor data from the user area, to remove seasonal propagation effects.

In configuring a joint Loran-C/Chayka chain, the question arises of how to control the individual baselines of such a chain. In principle, the most acceptable solution is to control baselines of two Chayka stations (or two Loran-C stations) by the means of their respective systems, and control baselines of a Chayka master and a Loran-C secondary in the Coast Guard manner. In the Attu/Kamchatka case, especially considering the difficulties of communicating across the international date line, it seems easiest for both parties if the Coast Guard simply controls the time difference of the proposed secondary by tracking the Chayka master.

Where should a SAM receiver be placed for control of the Attu/Kamchatka baseline? An ideal geographic location for a primary monitor for the BERSEA Master-Yankee (MY) baseline is on the Komandorskie Ostrova (Commander Islands). These Islands are about twelve nautical miles north of the MY baseline on the baseline-perpendicular. However, communications and physical access problems appear to be considerable. These difficulties, plus the installation cost of a new monitor site at Komandorskie Ostrova, suggest the use of the existing NORPAC monitors at Adak and the addition of a near-field monitor on Attu Island itself.

Adak would be on the BERSEA (MY) baseline extension. Placement of a monitor on the baseline extension results, effectively, in control of coding delay rather than control of service area time difference. The Coast Guard generally tries to avoid this type of control from a primary monitor because changes in propagation in the path from the transmitting station to the monitor can cause translational shifts over the entire hyperbolic time difference grid with the greater distortion <u>in</u> the service area. In contrast, a monitor in the service area close to the baseline-perpendicular would be expected not to translate the grid but only to stretch it a minimal amount with the least amount of distortion in the service area. Fortunately, the environmental effects that cause these changes are such phenomena as sudden ionospheric depressions (SID), and freezing or snow cover of a land path. SIDs are confined to lower latitudes, and there is little land from Petropavlovsk to Attu or Adak, where the waters are also ice-free.

Attu-Kamchatka Signal Study

To observe Chayka signal stability, an additional back-up control receiver was installed at the Loran Station at Attu to receive the signal transmitted from Petropavlovsk and track it relative to the Loran-C time base at Attu. To do this, a local trigger signal at the Chayka Eastern Chain (7950) rate was provided by a rate generator tied to Attu's cesium frequency standard suite. This test configuration simulated the tracking of Petropavlovsk, as a master, by Attu, as a secondary. The receiver used, the Austron 2000C, is a manual lock-on, linear, time-of-arrival receiver.

The study showed that the Soviet signal from Petropavlovsk can be easily locked onto and tracked by the Coast Guard's standard back-up control receiver at the secondary end of the baseline. The study also showed that the Chayka signal timing is other transmitters. A stable pulse shape that provides for consistent acquisition of a particular cycle zero-crossing is required, to this end, modern receiver design can customize signal acquisition firmware to allow for differences in stable Chayka and Loran-C pulse shapes. A receiver test performed and reported on by Soviet engineers sheds light on the ability of Loran-C receivers to use Chayka signals.

Receiver Testing by the Soviet Union

In Leningrad, V. Bikov, of the Soviet Ministry of Marine Fleet, reported on tests he conducted on the ability of commercial Loran-C receivers to receive Chayka signals. Summarized from his informal report:

> Several tests were carried out on the operation of Loran-C receivers with Chayka signals using the LR-770 receiver (produced by Furuno, Japan) and LC-70, LC-80, LC-90, and LC-1000 receivers (produced by Furuno, Japan).
>
> The receivers were designed for operation with Loran-C signals. Geographic locations for the Chayka stations of chains 8000 and 7950 were entered into the LC-90 and LP-1000 receivers by Furuno at the request of the Soviet engineers to provide coordinate conversion.
>
> The purpose of the tests was to estimate Loran-C receivers' characteristics operating with Chayka signals, and to compare the results with those from the reception of Loran-C signals.
>
> The most comprehensive tests were carried out with the LC-90 and LP-1000 receivers during 20 March-20 April 1988, using the 7950 Eastern USSR Chayka Chain.
>
> Tests were carried out to determine:
>
> - the probabilities of correct cycle selection,
>
> - groundwave receiving range, and
>
> - autoacquisition time under various reception conditions.
>
> The tests demonstrated:
>
> - The probability of correct cycle selection was up to 97% at a range of 900 nautical miles in the main coverage area.
>
> - Groundwave signals from Chayka stations were received by the LC-90 and LP-1000 receivers at ranges up to 1000-1170 nmi with a probability of 95%.
>
> - At ranges of 1000-1170 nmi, average autoacquisition time for stations in the tests was 3.5 minutes, probability of correct cycle selection was 83%.

Engineer Bikov concludes:

> "These tests of Loran-C receivers demonstrated that the Chayka system signals are received and processed by Loran-C receivers without degradation of specifications determined by Loran-C characteristics, namely, the operation of LC-90 and LP-1000 receivers by Chayka signals was similar to their operation with Loran-C signals."

From these analyses and Soviet testing, it appears that modern Loran-C receivers' ability to reliably lock onto signals of the proposed Chayka/Loran-C chain can be ensured by proper receiver design and prudent operational procedures.

Other, less critical but still noteworthy, technical differences exist between Chayka and Loran-C systems. Some Chayka chains periodically insert separate timing pulses. The ninth pulse in a Chayka master pulse train is positioned differently than in Loran-C. Standard phase sampling point and phase modulation tolerances need standardization.

Operational differences between the two systems are considerable. Out-of-tolerance situations are dealt with differently, and Chayka lacks an equivalent "blink" indication. A structure to provide notices to users/mariners/aviators as well as planned off-air notification and solicitation procedures must be developed and agreed upon. The joint command, control and communications structure, including a civil user interface, may be a considerable hurdle.

III. PROPOSED CONFIGURATION, BERING SEA (BERSEA) CHAIN

The published coverage of the Chayka Eastern Chain and the computed coverage for the Loran-C North Pacific chain (NORPAC, 9990) shows a gap in coverage about five hundred nautical miles wide to the south of the line between Petropavlovsk and Attu (figure 1). Without the Eastern USSR chain, there is a gap between the Coast Guard's Northwest Pacific Chain (NORWESPAC, 9970) and NORPAC about 750 nautical miles wide. According to the computed coverage limits, NORPAC provides satisfactory marine coverage over essentially all the Bering Sea.

Table 1 lists the stations in the proposed Bering Sea Chain with station designations. The proposed functions were chosen to avoid confusion with the dual-rate designations. Since the baseline distances for the three baselines are about equal, minimum GRI should not be materially affected by the ordering of the secondaries. Power is peak-radiated-power (PRP).

LORAN-C IN NORTH-WEST EUROPE - A STATUS REPORT

A Stenseth
NODECA
Oslo mil/Akershus
Norway

At the Sixteenth Annual Technical Symposium in October last year, Dir Gen Kjell Raasok and myself presented an overwiev of plans for LORAN-C in North-West Europe and status of actvities associated with these plans. I do not intend to repeat in detail what was said then, but for the benefit of those not attending, recall a few main points before bringing you up to date on present developments.

The US decision to cease funding support of the present US Coast Guard North European LORAN-C system in 1994, led to cooperation between interested nations on the question of whether or not accept an offer to take over the stations constituting this system. The LORAN-C working group presented its report in July 1985. It was recognized that the consequence of a take over would be further development of the system to meet civilian European requirements and that a multinational approach would give the most cost effective solution.
Eventually this led to the establishment of "Policy Group LORAN-C" in May 1987 to investigate the feasability of such an apporach. The Group consists today of representatives from 8 European countries (Denmark, the Federal Republic of Germany, France, Iceland, Ireland, the Netherlands, Norway and the United Kingdom). Canada is associate member to protect her interest in continued operation of the LORAN-C station at Angissoq, Greenland and US Coast Guard is offering advice on technical and other matters as required.

So much for the review. The Policy Group has met 3 times since October last year. At the meeting in Paris in November 1988 it was concluded that the French requirements were not fully met by the configuration presented. A Technical Working Group was therefore tasked to recommend a modified configuration meeting these requirements. The Group was further to recommend a method for timing control of the future system and organize field trials to confirm the validity of the recommended configuration.

At this point in time it was also realized that the proposed LORAN-C coverage in Danish waters and the Baltic would be less than required, and the concept for an additional mini LORAN-C system covering these areas, was adopted. The original main configuration became then Phase I of the system whereas the additional mini system was referred to as Phase II. The new configuration for Phase I proposed by the Technical Working Group is depicted in this viewgraph - as you will see a new station in South-West Ireland is introduced primarely to meet French and Irish requirements and the originally proposed Bushmill station in Northern Ireland is moved over to the North-East coast of England. This configuration is based on Edje as Master and the proposed new North-East english station as Secondary. A proposal to move the Master function from Edje to the new North-East english station is under consideration to enhance the coverage in this area. A possible Phase II configuration is indicated in this viewgraph. Phase II is so far expected to be realized 4 to 5 years later than Phase I.

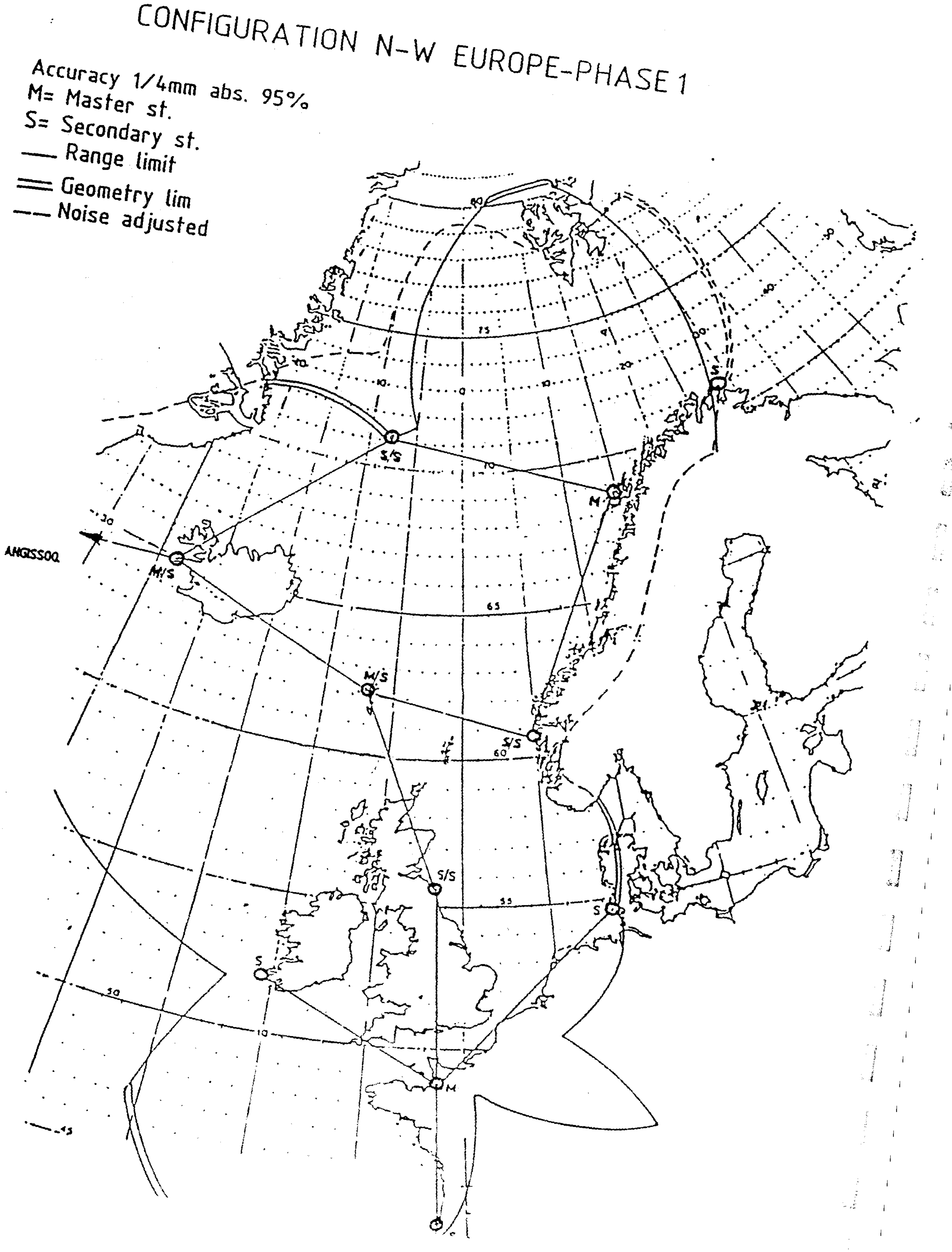
The Technical Working Group also looked at the problem of timing control based on a study by MEGAPULSE sponsored by UK. The Group recommendation is for a full Time of Transmission (TOT) control concept. At present USCG use System Area Monitors for timing control of LORAN-C chains in North-West Europe, so a possible transition to TOT prior to 1994, would have to be in concert with USCG.

In May this year a set of field trials was organized to compare the results of the theoretical propagation calculations with values measured between existing LORAN-C stations and sites in South-West Ireland and the UK. This area was chosen because here the capability of the system is stretched to its maximum because of the distance to Sandur, Iceland and significant man-made interference. The results observed broadly confirm that the method of coverage prediction used is appropriate. However, certain aspects require further study and refinement. It was finally concluded that a Cross Chain Capability would - not only in this case, but generally - provide increased opportunities of finding more suiteable pairs of stations for comfortable signal reception. This again led to a recommendation that Cross Chain Capability be a desirable option in the design of receivers for Europe.

However, no matter how good the technical solutions are, it is the availability of resources that decide the final course of action. This question was therefore the main issue at the Policy Group meeting in Reykjavik in June this year. At this meeting a Cost Sharing Formula for investments to be recommended to the authorities in the participating countries, was agreed and I regard this as a major step forward. A Cost Sharing Formula for Operations and Maintenance Costs is still an outstanding and difficult item to be discussed. Hopefully a recommendation on this topic will be one result from the next Policy Group meeting in Copenhagen in November. Another outstanding item to be discussed in Copenhagen is the text of a Memorandum of Understanding formalizing the rights and obligations to be undertaken by the participating nations. A draft MOU has already been circulated and a 2nd draft is expected shortly. If agreement on O&M cost sharing is obtained in Copenhagen, I believe there is a fair chance that we might also reach an agreement on the MOU text.

The final step would be for the responsible authorities in the participating countries to consider the recommended solution for approval and allocate the necessary recources so that contracts can be signed and works in the fields started.

For Norway it is of prime importance to have the project off the ground a soon as possible primarily because we have a number of pressing requirements that would have to be met by other less cost effective systems if a LORAN-C solution is not in sight. An interesting new development in this respect is the rediscovery of LORAN-C as a very cost effective navigation aid by the off/shore industry earlier this year. In a rig move, a high precision LORAN-C receiver was calibrated by a differential GPS package. This combination gave an absolute accuracy of less than 20 meters at the anchoring position. This accuracy was achieved in spite of failure in one GPS satellite resulting in more than 12 hours since last calibration of the LORAN-C information, when the anchors were dropped.


CONFIGURATION N-W EUROPE-PHASE 1
Accuracy 1/4mm abs. 95%
M= Master st.
S= Secondary st.
Range limit
Geometry lim
Noise adjusted
ANGISSOQ
M/S
S/S
M
S
75
65
60
55
50
45
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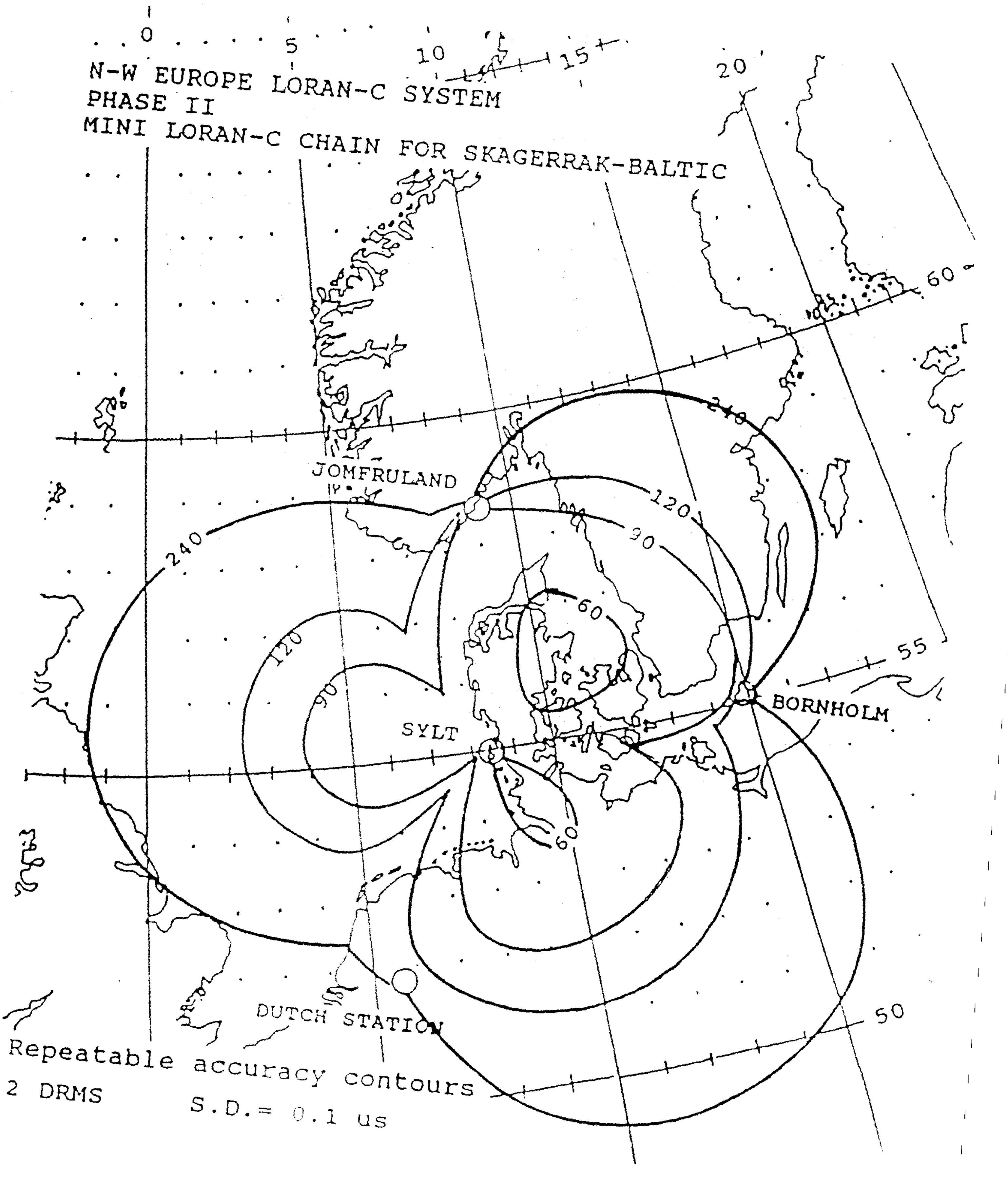

0
5
10
15
20
N-W EUROPE LORAN-C SYSTEM
PHASE II
MINI LORAN-C CHAIN FOR SKAGERRAK-BALTIC
60
240
JOMFRULAND
120
90
240
60
120
90
55
BORNHOLM
SYLT
60
DUTCH STATION
50
Repeatable accuracy contours
2 DRMS
S.D.= 0.1 us

THE DEVELOPMENT OF LORAN IN CHINA

GAN GUOQIANG
Xian Research Institute of Navigation Technology

ABSTRACT

Loran is a mature radio navigation system. It has got and will get extensive application in China. In this paper, from Loran A as beginning, the history of Loran development in China was briefly described. In 1988, we finished the system test of China south sea Loran C chain. The paper looked ahead the developing prospects of Loran C in China, and think there is extensive future of Loran C navigation system in China.

As a mature radio navigation system, Loran has acquired extensive application in the world. After more than 40 years, from Loran A to Loran C, more and more countries in the world have been building and using Loran system. Presently, with such superiority: the repeated positioning precision of high accuracy, capability of continuance navigating and positioning and using simple and low cost user equipment, Loran C not only exists with NAVSTAR, GPS, and etc., but is developing as well. Besides in marine navigation, in other applications of navigation such as in the air or inland area, Loran C also has its extensive future.

The Loran development in China begins from Loran A. In March 1965, China government committed Xian Research Institute of Navigation Technology (hereafter: Xian RINT) to research Loran A system. At the end of 1966, China completed her first Loran A chain in the Yellow Sea area. It uses tube transmitters of 160KW. The range of ground wave on the sea 550-700 NM, and the precision of positioning is better than 2 NM. During the trial period for a few years users were satisfied with the performance of the Yellow Sea Loran A chain. In 1969, the government decided to enlarge Loran A system, till 1975, seven new Loran A stations had been completed on the coast of China. Adding original three stations of the Yellow Sea, there are ten stations constituting nine Loran A chains, and basically covering the whole China coastal area, from Liaoning (north) to Guangdong (south). (figure 1)

The completion of Loran A system Improved the radio navigation situation on China coastal area, but its performance was far from away to satisfy the better and better requirement of precision and range from different kinds of user. During this time, China navigation personnel noticed the development of international radio navigation, and studied various navigation systems including Omega, Loran C, NAVSTAR, and GPS, etc., trying to find out the best suitable system as China main coastal navigation system. The results of studying showed that Loran C navigation system was the one to fit this requirement of China. On the high precision area of Loran C, the precision of repeated positioning will be better than 100 M, which will satisfy most of high precision positioning users on the sea. The range of ground waves, that is 1000 to 1300 NM will also satisfy the positioning requirement from middle range or far away on the sea. Specially, the capabilities of user's equipment such as continuous positioning, easy operation and low cost, are very suitable for the requirements of a great number of fishing boat and transportation ships on the sea. In March, 1979, the China government formally approved to build China Loran C navigation system. In the plan, six navigation stations will be built, which constitute China south sea, east sea and north sea, three chains, to cover the whole area of 1000 NM out of China coast line.

Since the limitation of budget, as first step, the south sea chain was to be built. This chain consists of three transmitter stations and one monitor station. The transmitter stations are located at Chongzuo, Guangxi (west secondary station), Hexian, also Guangxi (master station), and RaoPing, Guangdong (east secondary station), the monitor station is located on an island near Taishan, Guangdong. Since the convex shape of south sea coast line and limitation of mountains at west Guangxi, the base lines of south sea chain are quite short, about 500 KM, and Xian RINT has been responsible for system design and adjustment, equipment researching and introducing.

In October 1984, Xian RINT signed a contract with Megapulse, Inc. of U.S.A., in which, Xian RINT bought three sets of 64 HCG Solid-State Transmitters, and also, Xian RINT bought cesium frequency standard form FTS, Inc. of U.S.A. The antenna for transmitting is a top-load umbrella antenna with 247 M (810 ') height, which is designed and manufactured by China. The equipments of time-frequency group and synchronizing monitoring are designed and manufactured by Xian RINT . With the cooperation between Xian RINT and Megapulse, Inc., in October 1987, the installation of the transmitters and antennas of three stations were completed, adjusting and testing of the equipments for each station were successfully proceeded. In the summer of 1988, the system testing of south sea chain were proceeded. The content of system test included synchronizing of the system chain, TD testing of fixed points on the land and positioning of the working area on the sea and etc., of the user was satisfied very well with the results of practical testing. Additionally, the range and positioning precision reached expected specifications.

The establishment of China south sea chain attracts the extensive attention and interesting from different kinds of users in China. The departments of transportation, communication, geology and mining, fishing and exploitation of sea and ocean, all of them, are eagerly looking forward to the fast development of China Loran C. As the second step of China Loran C development, the north, east sea chains will be built. They will connect with the south sea chain, making the Loran C working area to cover the whole China coastal waters.

Presently, preparation for building north, east sea Loran C chains has begun. The new building chains consist of three stations, located at the provinces of Jilin, Shadon, and Anhui. These three stations with the east secondary station of south sea together will construct two chains, the ranges of base lines will be about 800 KM. (figure 2)

At the same time of developing China coastal Loran C navigation, the application of Loran C in aviation and expanding and exploiting towards inland are also being researched. Besides, such as building some small power stations to satisfy precision requirement in some special area, applying Loran C differential technology, and timing technology, all of these will have good futures in China.

In general, along with the construction and application of coastal Loran C navigation system, the extensive application in aviation and inland certainly will be developed. Loran C has a broad prospect on China.

Fig. 1: Loran A chain in China
Fig. 2: Loran C chain in China

As a result, approval of the GPS NAVSTAR as a "sole means" of navigation system is a long way off, if it ever does happen. Therefore, combining the use of its signals with Omega or Loran C is most appropriate. By integrating the three sensors, the size and weight of the resultant package can be reduced. By further developing the interoperability of these systems, a more reliable and accurate system can be derived, even though the full acceptability of the GPS NAVSTAR system (or its alternates) may be in question.

Side Issues

Following are four side issues that may also be of interest.

- Omega Station Saving

  GPS will save money through use of the GPS timing signals via receivers at each station,. The Coast Guard up to now had to transport a special calibrated atomic clock time standard across the world to recalibrates each station on a regular basis. At a rate of one station per month: very expensive!

- GPS ACCURACY

  No doubt GPS NAVSTAR is potentially a great navaid. C.M.C. experience shows 2D accuracy of 3 to 4 meters in a P-Code 5 channel receiver and 20-30 meters in a C/A code signal. The C/A code signal receiver is to be degraded to allow only 100 meters when the full constellation is up - still very good!

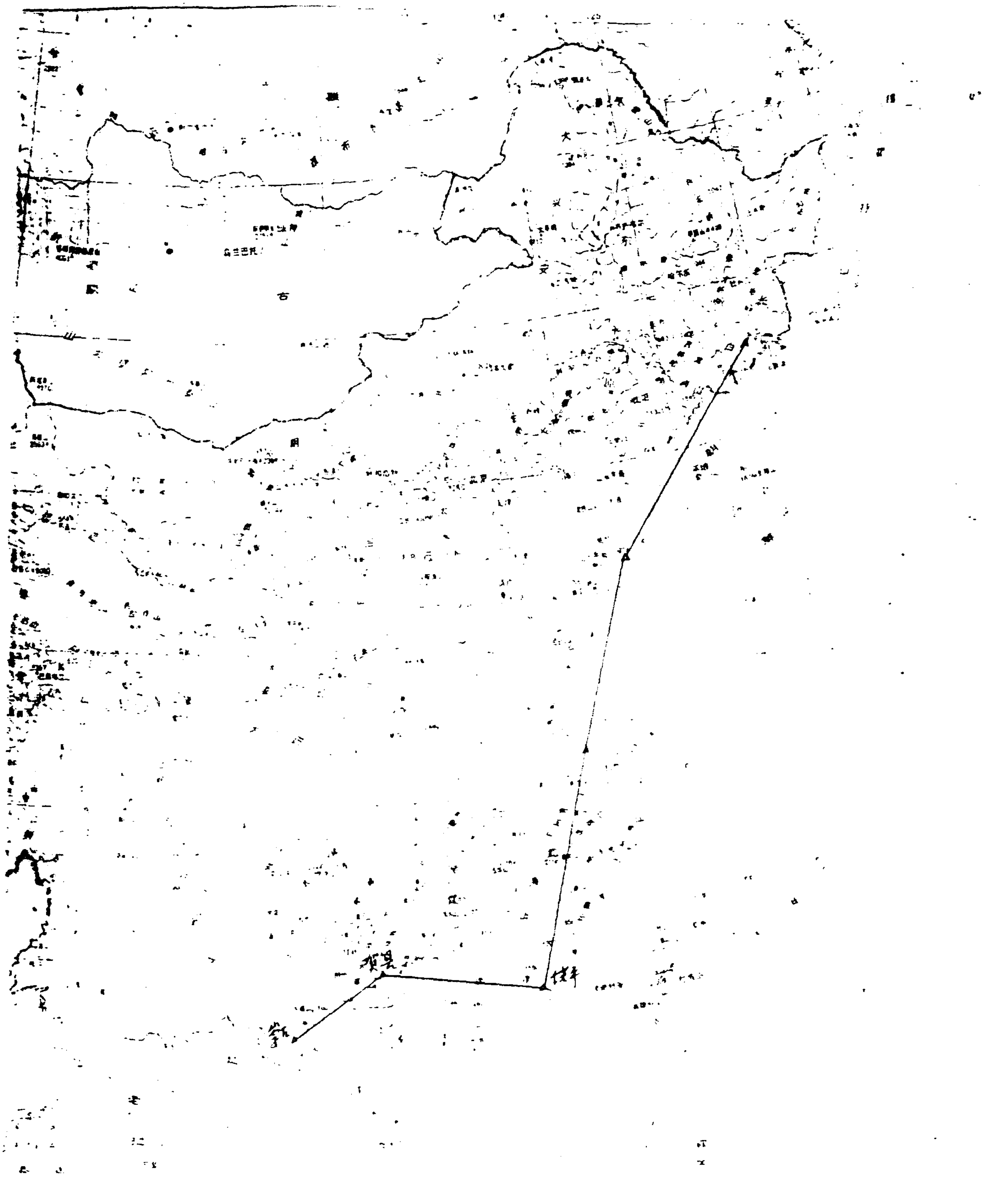
- Omega accuracy improvement

  With GPS timing signals to improve Omega Rx clock accuracy, navigation accuracy should be improved to 0.75 to 1.0 N. Miles instead of the present 1.5 to 2.0 N. Miles.

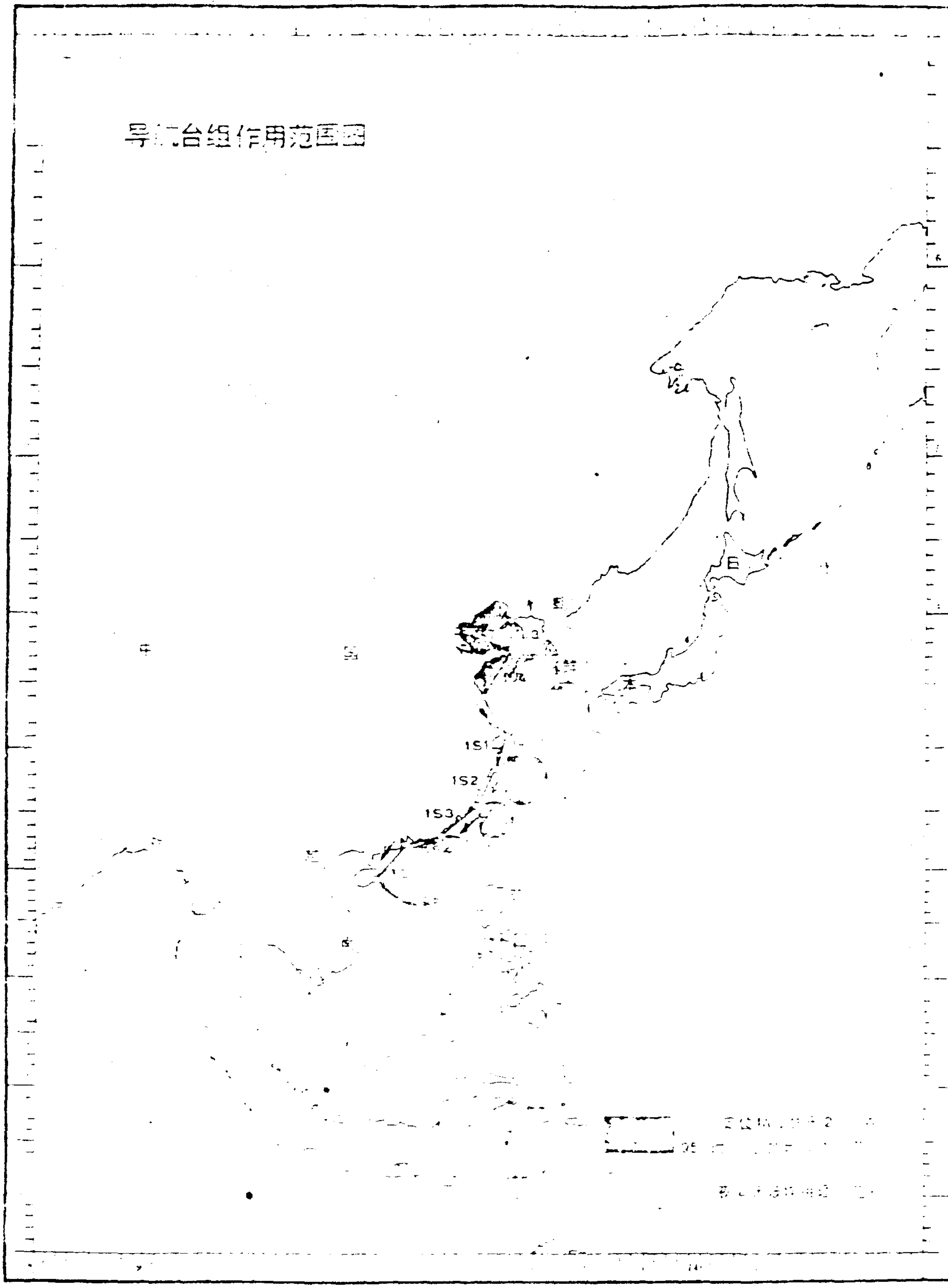
- GPS Military

  GPS signals are easy to block in times of conflict by relatively low power above user aircraft altitude levels. Omega is almost impossible to jam. (Ref. J. Saganowich, G. Litchford, Fort Monmouth).

Editors Note: This paper was received by telecopy from China during the convention and was read by Ed McGann of Megapulse. To preserve the international flavor of the WGA 17th Convention, it is published in its original form.



图二 中国罗兰C台链

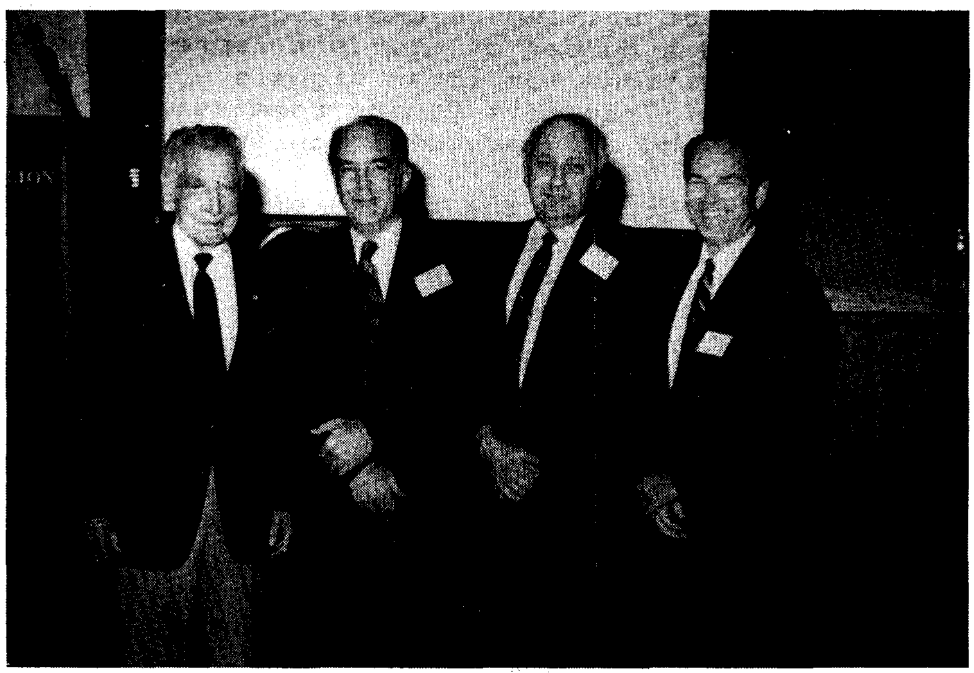


图一 中国罗兰A台链

SESSION 2

AIRBORNE DEVELOPMENTS AND APPLICATIONS

DR. ROBERT LILLEY
OHIO UNIVERSITY



LORAN-C PROPAGATION IN BRITISH COLUMBIA

WALTER N. DEAN

ABSTRACT

British Columbia is provided with loran navigational signals by the West Canadian Chain, 5990. Although the chain was originally designed as an aid to marine navigation, there has been increased interest in use of loran by aviation and terrestrial navigators

The terrain of British Columbia contains some extremely rugged areas and a number of glaciers representing very poor propagation conditions for loran signals. The Pacific Region Aviation Group of Transport Canada commissioned an evaluation of the coverage and accuracy of loran in the British Columbia.

This paper describes the series of airborne measurements made throughout the province. The results of data analysis are a ground conductivity map of British Columbia and a loran coverage map which is the result of field observations.

INTRODUCTION

The history of the West Canadian Loran-C chain (5990) reflects the consequences of misunderstanding the radio propagation characteristics of the region. Figure 1 shows the province of British Columbia and the stations of the loran chain. It was originally designed as a three-station chain, the Master at Williams Lake, the X secondary at Shoal Cove dual rated to the Gulf of Alaska chain (7960) and the Y secondary at George, dual rated with the Western U.S. chain (9940). To the surprise and embarrassment of some, when the 5990 chain went on the air, it was virtually impossible to receive Shoal Cove in the Straits of Juan de Fuca, although the distance is only 525 nautical miles. The reason, it was quickly realized, was that the conductivity of the rugged mountains along the coast was much poorer than anticipated. In a flurry of activity, the station at Port Hardy was constructed and put on the air as the Z secondary, and the coastal confluence was finally fully served by Loran-C.

This chain configuration has proved satisfactory for marine navigation for a number of years, but the increasing use of loran by aircraft, especially general aviation, led aviation authorities in British Columbia to seek an evaluation of the 5990 chain for air navigation in that province. There had been considerable discrepancy between theoretical predictions and reported observations of loran performance. A number of estimates of ground conductivity were avaliable, from a variety of sources, which lack detail and differ appreciably in the values assigned to different areas in British Columbia.

FIELD DATA COLLECTION PROGRAM

In order to make direct measurements to evaluate the ground conductivity in British Columbia, and to map the availability and accuracy of loran signals in the province, it was decided to make a series of flight tests. To evaluate ground conductivity, it would be necessary to measure loran signal strength over a series of paths representing the areas critical to the coverage over British Columbia. Measuring the accuracy of the loran grid would be accomplished by checking loran readings against known positions around the province. The two objectives would be achieved by a series of flights carrying loran receiving and measuring equipment around the province. Transport Canada provided the vehicle for the test program, a Beech King Air 100, identified as Transport 967. The aircraft is normally used for test and calibration of air navigation systems.

TEST INSTRUMENTATION

The principal test instrument was a loran receiver, the ARNAV model R-40, selected primarily because it provides a digital output which includes a measure of the loran signal amplitude. An additional receiver, an ARNAV model R-30, was also carried along as backup, and to provide a comparison of receiver performance. The data from the R-40 are output on an RS-232 standard interface in ASCII format. The data were fed to a Tandy model 102 portable computer, which selected and formatted the required data. The reformatted data were then output from the computer to a printer and to a tape recorder.

Figure 2 is a copy of a typical data printout. The first line, obviously, is date, time, latitude and longitude to precision of .01 minutes. The second line gives the waypoint name, distance and bearing to waypoint, track, groundspeed, estimated position error and GRI. On the third line are master oscillator error (TDV) master signal strength, ECD, SNR and status (T=track), X TD, S, E, SN and STA. On the fourth line are the same for Y and Z secondaries.

The series of waypoint names is entered and stored in the waypoint memory. The exact locations were not known beforehand, as they were selected by the pilot as identifiable ground locations. The waypoints were all positioned at lat/lon 0/0, which accounts for the unusual distance and bearing at each point. Because the Tandy 102 is slow, the data transfer was at a 300 baud rate, which was perfectly satisfactory for data logged approximately every five minutes. The data output is triggered by pressing the "hold" button on the keyboard of the R-40.

DATA COLLECTION

The data collection program was designed to meet the two objectives, measurement of ground conductivity and evaluation of system accuracy, with efficient use of aircraft flight time. Figure 3 shows the paths of the seven test flights. The first flight included a semicircle around the Master station at Williams Lake at a distance of 20 miles. The data taken close to the Master provided a field strength calibration benchmark for calculation of ground conductivity. At each location, the values of signal strength measured provide the basis for construction of the conductivity map, which will be discussed later. Similar calibration flights past Shoal Cove and Port Hardy served to refine and confirm the calibration.

A GPS receiver had been scheduled for use as a position calibration source, but it turned out not to be available in time for the scheduled tests, so it was decided to select ground points by reference to topographic charts, visually sighted by the pilots.

Figure 3 shows the seven flight routes taken over five days. Most of the routes were selected as specific routes frequently used by aircraft in traveling around British Columbia, of particular interest to Transport Canada. Measurements of positional accuracy were taken along all the routes, with some additional data points used for field strength calculation. The first run, A, started at Vancouver and went north to Williams Lake, where a series of readings were taken 20 miles from the Master transmitter for calibration purposes. The route went then by way of Prince George and Fort St. John to Fort Nelson. The next morning Run B went northwest from Fort Nelson to the head of the Mackenzie Trench, then down the trench to Prince George. Run C, that afternoon, went from Prince George to Smithers, then north toward Whitehorse. Run D, the next morning, went south from Whitehorse, past the Shoal Cove, Alaska, station, to Terrace. From there Run E went southeast across the mountains to Vancouver.

Run F covered the southeast portion of the province, going from Vancouver east to Cranbrook, then northwest up the trench to Kinbasket Lake. From there the run went southwest down the VFR route to Kamloops, then down the canyon to Hope, and returning to Vancouver. The final run, G, went up the coast from Vancouver, past the Z station at Port Hardy, to Sandspit.

DATA ANALYSIS

As stated above, the procedure used for fixing the position of the aircraft was to visually fly over points identifiable on aeronautical charts. An estimate of the accuracy of this approach can be obtained from the following series of estimates of the probable errors in Table 1.

TABLE 1 ESTIMATED MEASUREMENT ERRORS

Chart inaccuracy	0.1 n.m.
Chart reading error	0.2 n.m.
Aircraft positioning error	0.2 n.m.
Probable position error (RSS)	0.3 n.m.

The remaining error components affecting the positioning results consist of the errors in the loran receiver. These are the Time Difference errors, which consist of random errors, caused by noise and interference, and bias errors, caused by propagation variations. The noise and interference produce random fluctuations whose amplitudes vary with time and location. The propagation variations are a function of the varying characteristics of the terrain over which the signals pass.

The geometric accuracy to be obtained from the 5990 loran chain calculated for the area of British Columbia is shown in figure 4. The general outline of the province, the location of the stations of the 5990 chain, and the survey routes are shown. The numbers represent thousands of feet position error per microsecond of time difference error It can be seen that the geometric accuracy is generally good, except in the northern parts of the province. The loran coverage in the northwest corner of the province is actually provided by the Gulf of Alaska chain, and is not shown on this diagram. In the east central portion of the province, east of Williams Lake, the accuracy deteriorates if Shoal Cove cannot be received.

A total of 218 good data points were taken in measurement of loran system accuracy on the 5990 chain. Three points were discarded which were found to contain an error in identification of the waypoint. For each point, the latitude and longitude as read by the loran was compared with the position determined from the chart. The error distance in nautical miles was recorded. An estimate of the overall accuracy of the system and its relation to the positioning of the receiver can be obtained from Table 2.

TABLE 2 AVERAGE DISTANCE ERRORS

GDOP	NO. POINTS	AVG ERROR
1	55	0.49 nm
2	45	0.48
3	17	0.46
4-5	32	0.49
6-7	20	0.54
8-10	15	0.83
11-15	13	1.96
>15	21	1.68

It should be noted that there was a bias in the latitude errors, an average of 0.21 nautical miles, caused in part by uncompensated propagation errors. If these were calibrated out, the above results would be notably improved.

Interpretation of the signal strength data to determine earth conductivity was more complex. It was not possible to make a direct signal strength calibration of the loran receiver prior to the tests. Calibration was accomplished by flying close enough to the transmitter at Williams Lake that the loran signal field strength would be very little affected by the conductivity in that area. That gave one point of calibration which allowed use of the amplitude calibration of the R-40 loran receiver as a field strength measurement throughout the tests.

To relate field strength variations to ground conductivity over the ranges of distance and conductivity found in this study, it was necessary to pull data from some of Jim Wait and Ralph Johler's classic works (Ref. 1&2) and generate some new graphs. Figures 5 and 6 plot the additional attenuation, above inverse distance, at 100 kHz, as a function of effective ground conductivity, for a distances of from 10 to 500 statute miles. The first use of the graphs was to estimate the attenuation close to Williams Lake. On the assumption that the conductivity in that area, a rather level plain, had a value of 2 or higher, reference to figure 5 indicated the attenuation at 20 miles to be less than 1 dB. This made the calibration of field strength quite simple.

The radiated power for each loran transmitter published by the Coast Guard was used in each case for calculation of attenuation along the paths to each data point, and the curves from figures 5 and 6 then applied to determine the effective conductivity of each path. Analysis of the many paths then produced the final estimate of soil conductivity for British Columbia. Figure 7 is an overall propagation chart which includes the poorest values of conductivity. This plots expected loran signal field strength versus distance over uniform paths of different conductivities.

Figure 8 shows the results of the conductivity analysis. The conductivity value of 0.1 millmhos per meter is lower than shown on any other conductivity maps, but this is the value which fits the observed data. The worst conductivity previously considered for mountainous regions was sigma of 1.0. On figure 7, the 40 dB level is reached at about 650 nautical miles. If the sigma is really 0.1, as in B. C., this level is reached at 325 miles, half the distance. No wonder the range of the chain is less than had been expected.

The actual coverage area, the area within which satisfactory loran navigation can be achieved, depends on, among the other variables, the atmospheric noise level. The standard reference for atmospheric noise is CCIR Report 322, WORLD DISTRIBUTION AND CHARACTERISTICS OF ATMOSPHERIC RADIO NOISE. From the charts and formulae in that report it was calculated that the atmpspheric noise level in the loran band 90-110 kHz, the noise level not exceeded 95% of the time at night is 39 dB above one microvolt per meter. The corresponding daytime value is 32 dB. Using the criterion of -10 dB signal-to-noise ratio to determine the maximum range, two sets of limits, shown in figure 9, sestablish the areas for full time and for daytime only operation. The signal field strengths used for the curves were the measured values, supplemented by calculations based on the conductivity chart.

CONCLUSIONS

The major conclusion relative to the ground conductivity is that the large area of very poor conductivity, designated as 0.1 on figure 8, is the dominant feature affecting the performance of loran in British Columbia. The measured area of good loran coverage conforms quite closely to the calculated area based on noise levels and signal strength. The system error can be seen to be quite small if the northerly bias (0.21nm) and the experimental error (0.3nm) are deducted from the measured position errors. One area of poor operation is east of Williams Lake, the baseline extension of the Z secondary, where the signal from Shoal Cove, the X secondary, is weak. The reason for this is seen in the conductivity map. Over half the propagation path of signals from Shoal Cove has conductivity of 0.1, resulting in very low signal strength.

In the north, signals from George (Y) are severely attenuated, so that only skywaves are received. The signals from Port Hardy (Z) are also attenuated to the result that operation north of the 58th parallel is marginal.

ACKNOWLEDGEMENTS

Special thanks for support of the test program are extended to the personnel of Transport Canada's Pacific Region Aviation Group, the pilots of Transport 967, and especially Dick Logie, who acted as project coordinator.

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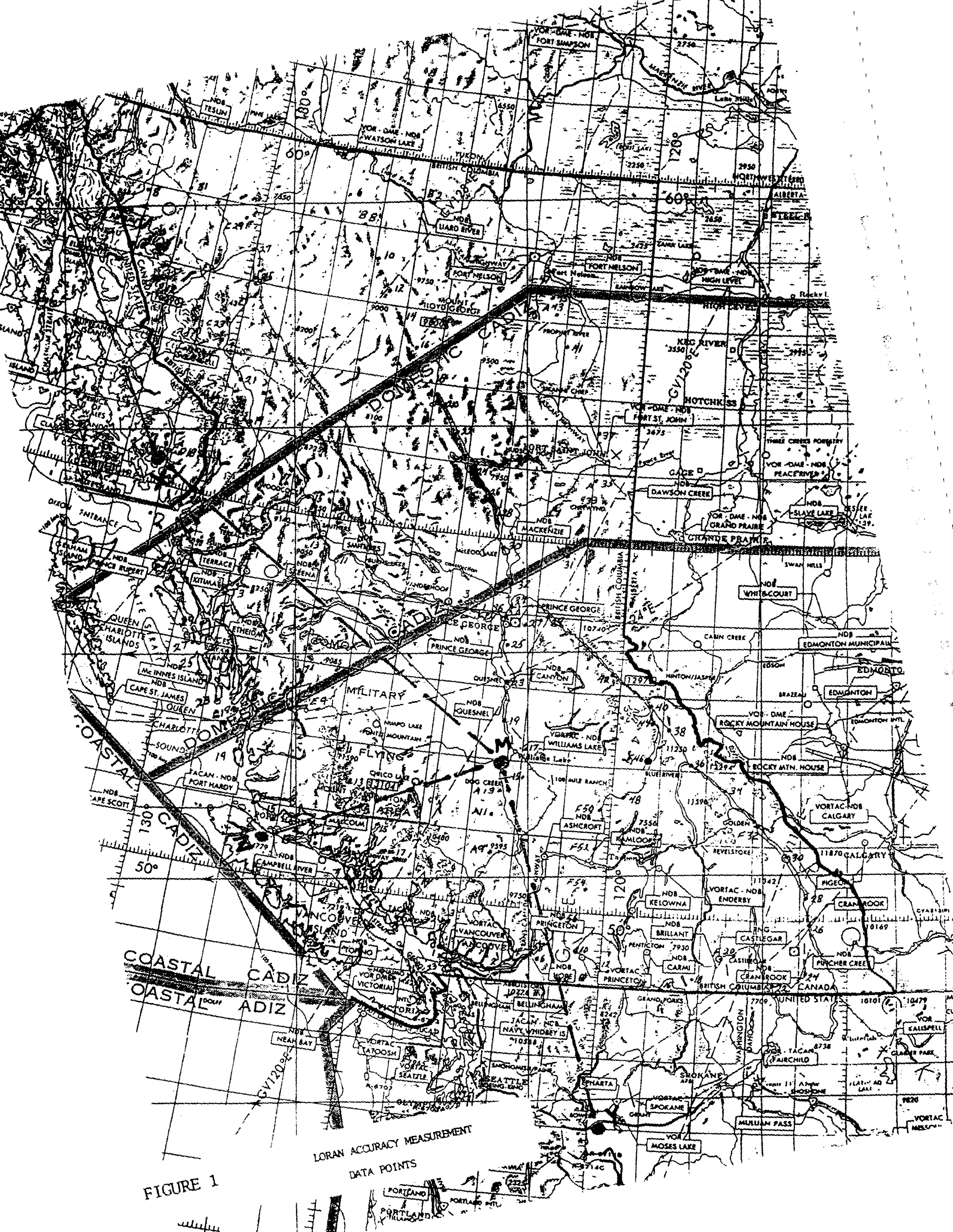

LORAN ACCURACY MEASUREMENT

DATA POINTS

FIGURE 1

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WP G16    DIS 99999 BRG 0035 TK 280 GS 204 EPE 01 GRI 5990
TDV -009    S 28 E -17 SN 94 STA T TD 1399685 S 13 E -31 SN 88 STA T
TD 3004949 S 40 E -14 SN 90 STA T TD 4114587 S 74 E +05 SN 99 STA T

12/07/88 10:45:03 PST   LAT N 50 5952 LON W 127 3217
WP G17    DIS 99999 BRG 0035 TK 294 GS 213 EPE 01 GRI 5990
TDV -014    S 19 E -17 SN 92 STA T TD 1394039 S 30 E -26 SN 87 STA T
TD 3007224 S 33 E -13 SN 92 STA T TD 4116217 S 74 E +07 SN 99 STA T

12/07/88 10:55:22 PST   LAT N 51 2928 LON W 128 0674
WP G18    DIS 99999 BRG 0034 TK 297 GS 222 EPE 01 GRI 5990
TDV -013    S 30 E -18 SN 94 STA T TD 1363187 S 52 E -07 SN 87 STA T
TD 3020373 S 01 E -17 SN 83 STA T TD 4130045 S 70 E -02 SN 99 STA T

12/07/88 10:58:07 PST   LAT N 51 3921 LON W 128 0979
WP G19    DIS 99999 BRG 0034 TK 334 GS 229 EPE 01 GRI 5990
TDV -025    S 31 E -15 SN 93 STA T TD 1356855 S 49 E -11 SN 88 STA T
TD 3024749 S 01 E -31 SN 71 STA T TD 4135800 S 69 E -02 SN 99 STA T

12/07/88 11:01:20 PST   LAT N 51 5023 LON W 128 1678
WP G20    DIS 99999 BRG 0034 TK 307 GS 218 EPE 01 GRI 5990
TDV -017    S 36 E -17 SN 94 STA T TD 1347533 S 48 E -15 SN 88 STA T
TD 3028991 S 01 E -31 SN 74 STA T TD 4141129 S 67 E -04 SN 99 STA T

12/07/88 11:04:02 PST   LAT N 51 5923 LON W 128 2480
WP G21    DIS 99999 BRG 0033 TK 306 GS 229 EPE 01 GRI 5990
TDV -016    S 32 E -17 SN 95 STA T TD 1338428 S 44 E -17 SN 87 STA T
TD 3032077 S 01 E -29 SN 66 STA T TD 4144738 S 68 E -04 SN 99 STA T

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WP G22    DIS 99999 BRG 0033 TK 307 GS 227 EPE 01 GRI 5990
TDV -012    S 32 E -15 SN 92 STA T TD 1328809 S 46 E -15 SN 88 STA T
TD 3035193 S 01 E -30 SN 61 STA T TD 4148478 S 67 E -06 SN 99 STA T

12/07/88 11:09:31 PST   LAT N 52 1554 LON W 128 4309
WP G23    DIS 99999 BRG 0033 TK 286 GS 215 EPE 02 GRI 5990
TDV -008    S 40 E -14 SN 92 STA T TD 1319382 S 54 E -13 SN 88 STA T
TD 3036870 S 01 E -33 SN 61 STA T TD 4149957 S 67 E -03 SN 98 STA T
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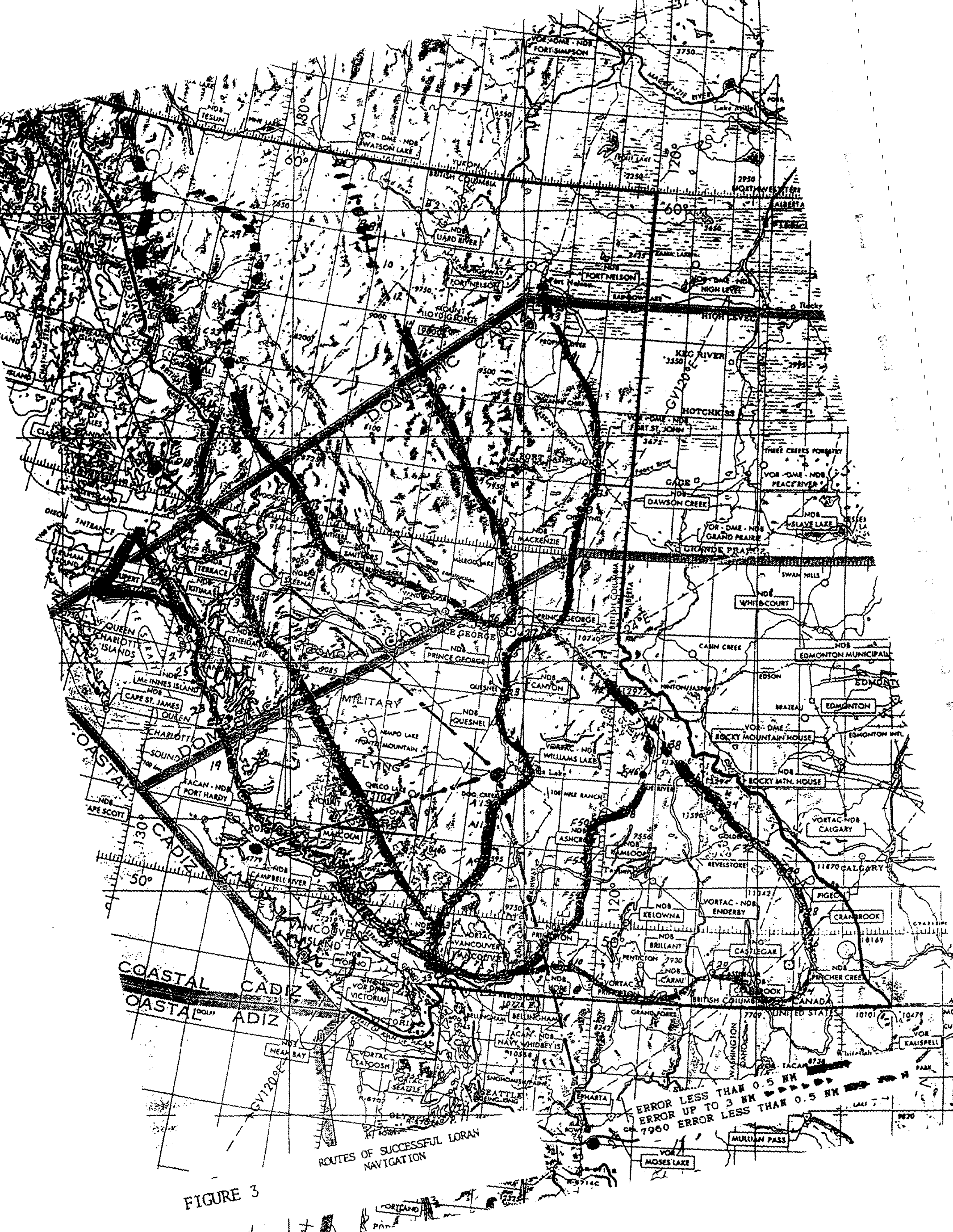
FIGURE 2



ROUTES OF SUCCESSFUL LORAN NAVIGATION

FIGURE 3

ACCURACY ESTIMATES FOR LORAN IN BRITISH COLUMBIA

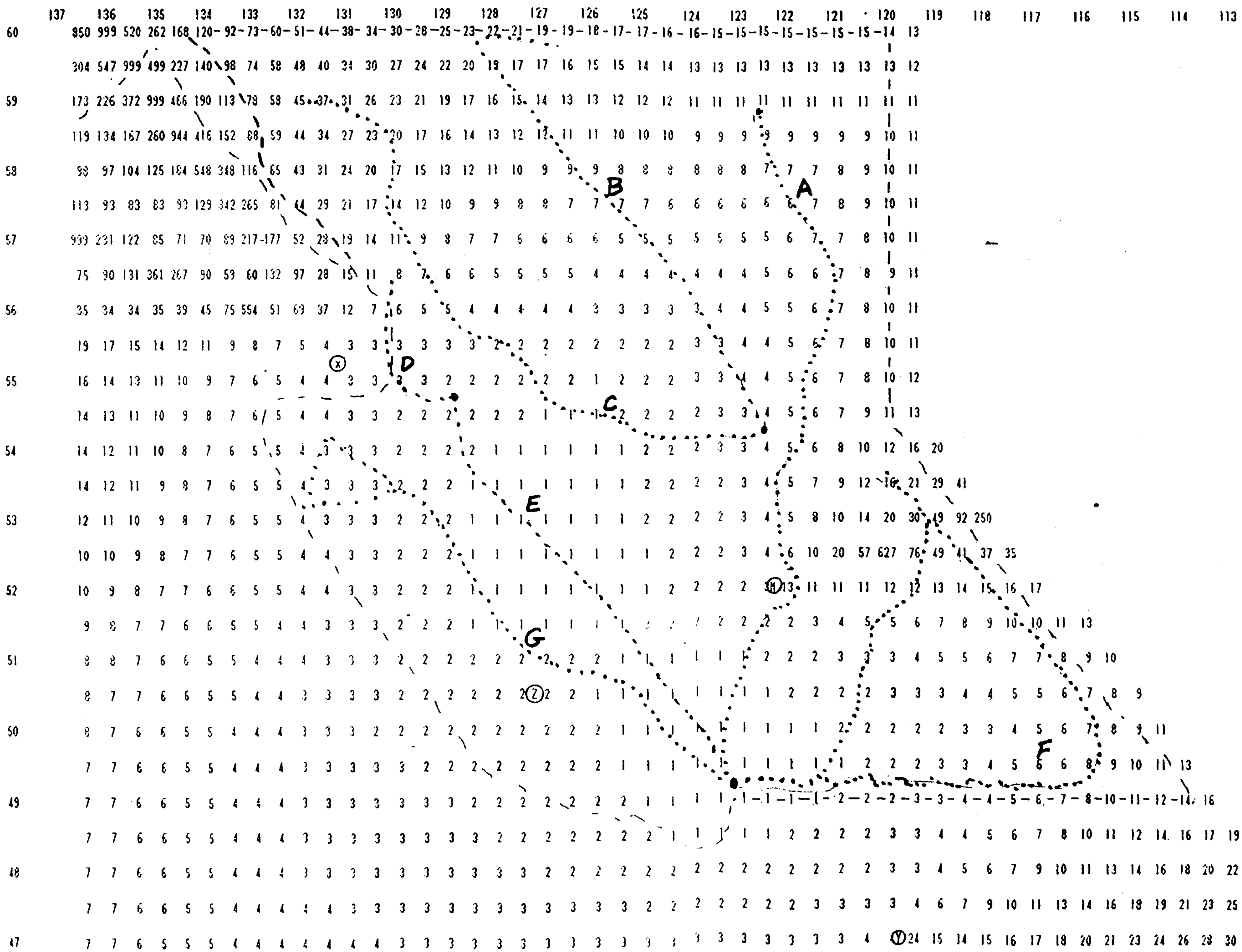
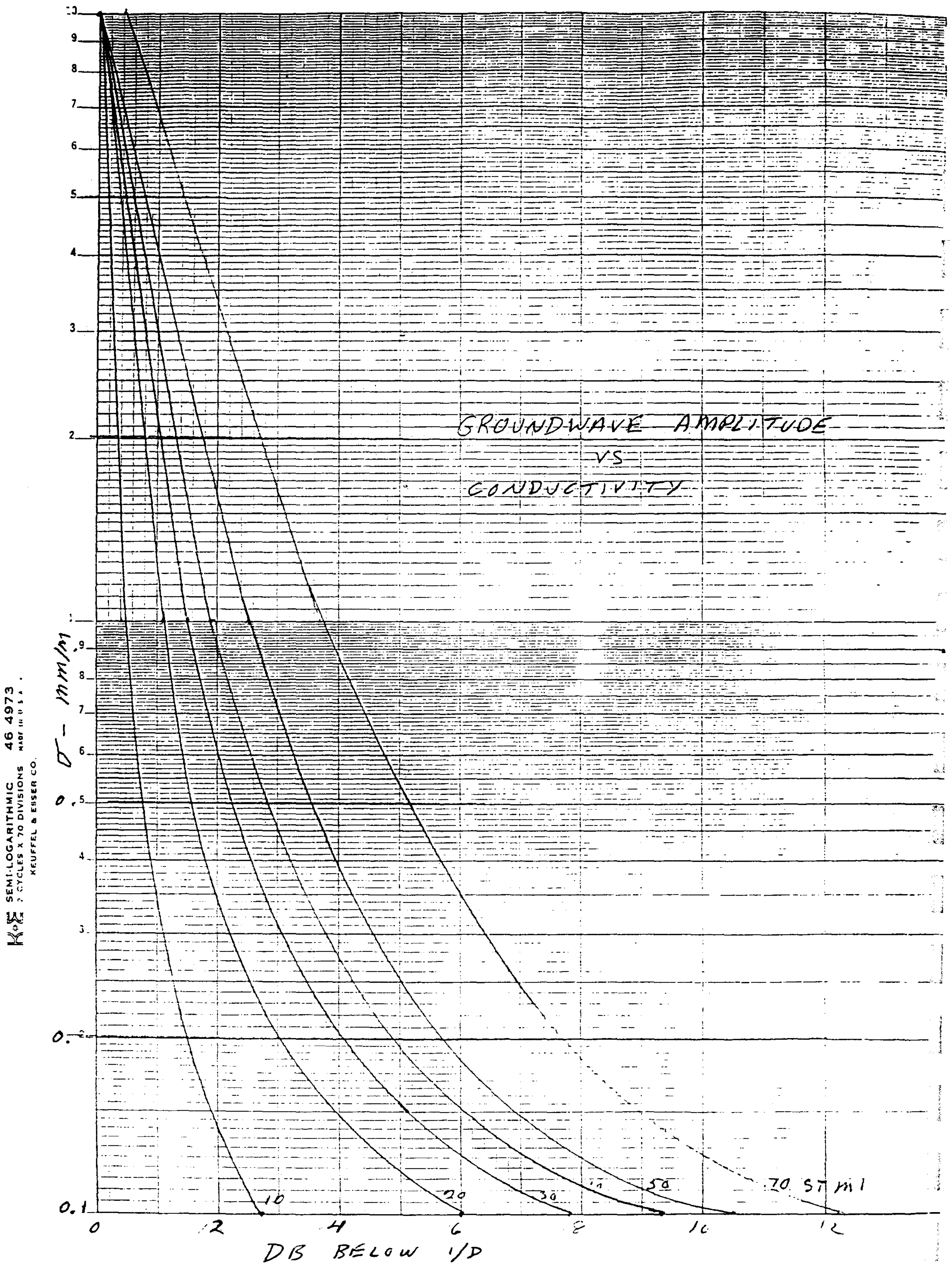


FIGURE 4


GROUNDWAVE AMPLITUDE
VS
CONDUCTIVITY
σ - mm/m
DB BELOW 1/D
10
20
30
50
70 ST mi
0
2
4
6
8
10
12
0.1
0.2
0.5
SEMI-LOGARITHMIC 46 4973
2 CYCLES X 70 DIVISIONS
KEUFFEL & ESSER CO.

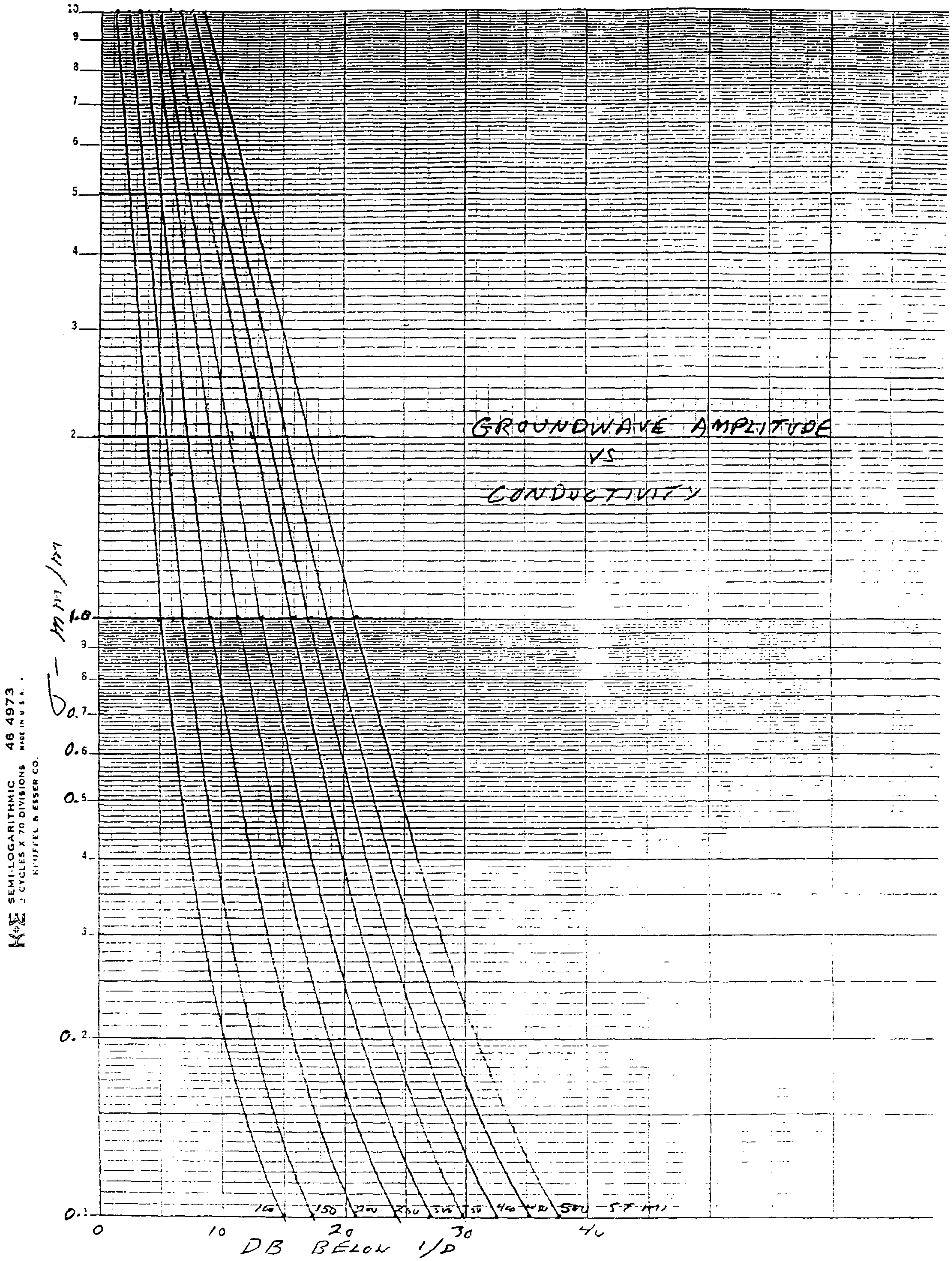

GROUNDWAVE AMPLITUDE
VS
CONDUCTIVITY
σ - mm/m
DB BELOW 1/D
100
150
200
250
300
350
400
450
500
5.F MI
0
10
20
30
40
KE SEMI-LOGARITHMIC 46 4973
2 CYCLES X 70 DIVISIONS MADE IN U.S.A.
KEUFFEL & ESSER CO.

FIGURE 6

GROUNDWAVE FIELD STRENGTH

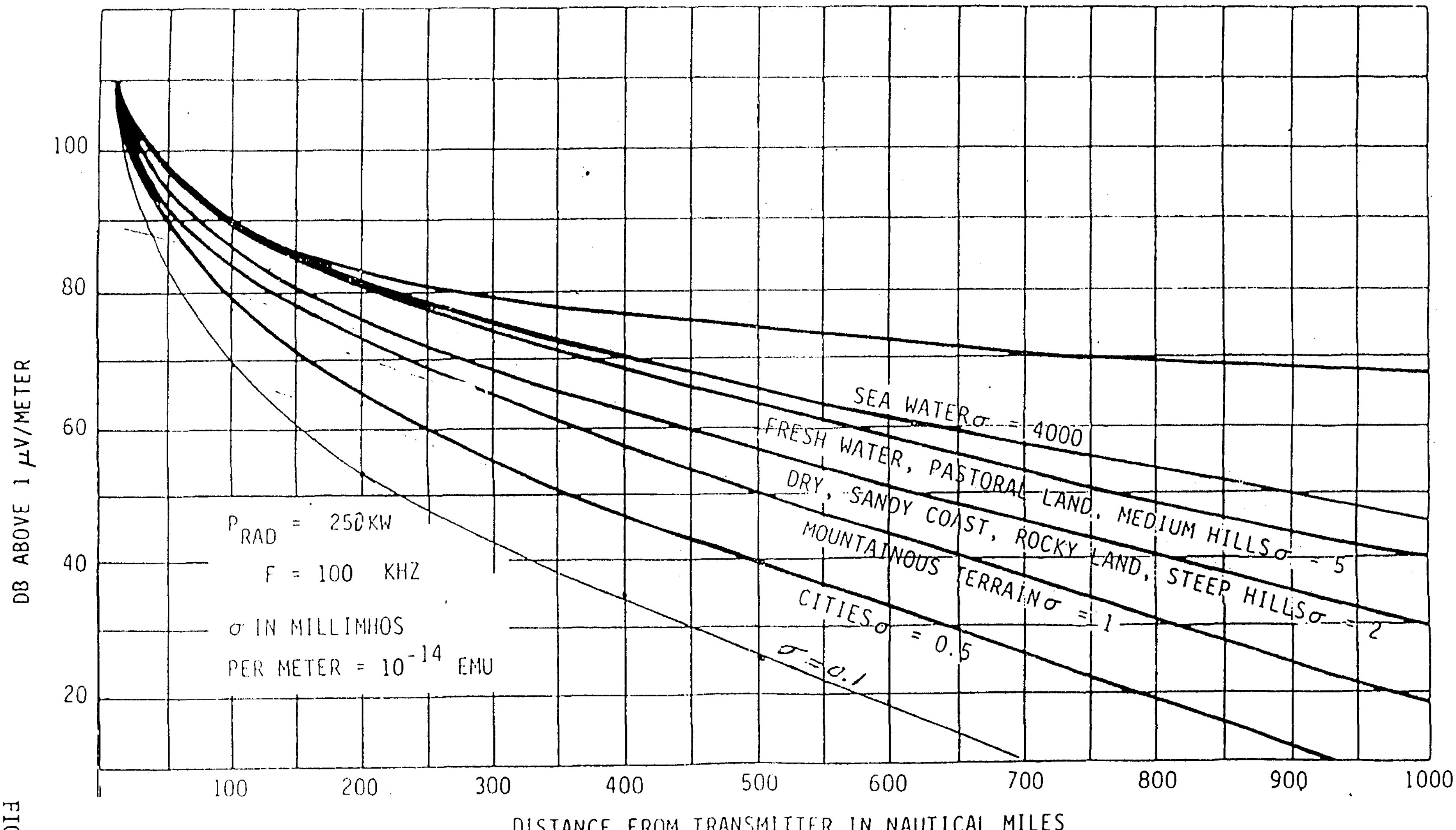


FIGURE 7

FIGURE 8

GROUND CONDUCTIVITY IN BRITISH COLUMBIA

IN MILLIMHOS PER METER

AREA OF NORMAL LORAN OPERATION

WEST CANADIAN CHAIN 5990

FIGURE 9

"A REALTIME LORAN NAVIGATION SYSTEM FOR AERIAL PHOTOGRAPHY"

J. Fred Welter, President
North West Geomatics Ltd.
Edmonton, Alberta, Canada

Aerial photography requires precise positioning over the project area to various degrees of accuracy depending upon the scale of the photography being acquired. The procedure or practice to date has been to plot the proposed flight line layout on the best topographic maps available. The task is to then position the aircraft as accurately over this location as is possible by an optical navigation sight. This can become increasingly complex; requiring considerable skill on the part of the navigator and pilot where sufficiently detailed maps are not available. In extreme cases it may be necessary to acquire small scale reconnaissance photography on which to plot the desired lines and then refly the required scale. Post recovery is the reverse, after the photography is processed and printed a comparison is made to the map to determine the actual position of the photo center. Only at this time is one assured of the area as having been adequately covered.

North West Geomatics had, in addition to the aerial photography capacity, expertise in hydrographic and geodetic surveys. This association encouraged the aerial photography section to assess electronic positioning aids. Loran was initially assessed in 1985 as a possible navigation aid augmenting visual navigation. The initial results out of our Edmonton base were rather discouraging. A project with good Loran coverage in California convinced us of the potential benefits. Since 1985 we have modified existing Loran receivers to operate as range/range units on multiple chains. Extensive software was developed permitting real time electronic navigation to an accuracy of 150 meters. The system is still being improved but has been a most cost effective and time saving addition. There are considerable applications in other sea or air navigation that could utilize this technology.

The paper will provide an overview of the technology and procedures used with problems encountered and their solutions.

1 INTRODUCTION

Loran-C (an acronym for LOng RAnge Navigation; the 'C' refers to the third version of the system) is a hyperbolic radio positioning system developed by the US Navy for defense purposes. The system was initially designed for marine use but in recent years has seen considerable hardware developed for aircraft. The system works on the time difference between receiving a pulse from the master and a secondary transmitter. The pulses are phase coded to distinguish between master and secondary, and also to resolve the skywave interference between successive pulses in the pulse group transmitted by each transmitter. The pulses are transmitted at nominally 100 kHz with decreasing signal strengths out to 85 kHz and 115 kHz. The high resolution of this low frequency system is made possible by the receiver identifying and tracking the beginning of a specific cycle within each pulse. Designed as a pulsed system to avoid skywave interference, the transmitters can produce high power during a short duration of each pulse; thereby ranges of up to 4000 kms have been achieved. The system was originally designed for marine use where the low frequency wave propogates very well over the water surface. The recent use inland creates some unique and difficult problems due to signal attenuation over the various land paths. Additionally, designed originally for optimum marine coverage, the geometry inland is often lacking. Coverage is again confined to the east and west coastlines of Canada and the US, the Great Lakes, Hawaii, the north Atlantic, Europe, Middle East and parts of Asia.

2 INITIAL EVALUATION OF LORAN

Development of a Loran based navigation system for aerial photography applications has not been a simple or easy task. Our firm first evaluated Loran with a standard Arnav R40 receiver with mapping software in 1985. The unit was installed in a Cessna Conquest propjet operating throughout Western Canada; from Saskatchewan to British Columbia and into the North West Territories. Initially the R40 was connected to a Hewlett Packard Model 85 computer logging raw data to disc over the serial line. The results were most discouraging. This was single chain, hyperbolic on the Canadian West Chain (5990) with the default secondaries being Shoal Cove, Alaska and George, Washington. In retrospect; but of considerable consternation at the time, the problems were geometry aggravated by peculiar transmission problems with Shoal Cove. Numerous missions were conducted with the system passively logging data. After each mission the results were reviewed. Our assessment after the 1985 Canadian evaluation was that the system was unreliable and of insufficient accuracy to be of use in our aerial photography applications. We were convinced that we would have to wait until the Global Positioning System was fully operational or for more difficult areas install a local VHF or UHF system.

In the fall of 1986 our firm was engaged to perform an aerial photography contract in southern California. We decided to evaluate the Loran in this operations area, again with the R40 and HP85 computer. Some additional software was developed to permit simple tracking along a predefined line. Again all of the data output by the R40 was written to disc, as well as the raw time differences at the instant of exposure. The initial results as provided by the R40 were inconclusive. The actual photo centers were plotted on topographic maps and geographic coordinates digitized for over 2000 points. Software was developed to compute geographical inverses and theoretical time differences at each camera exposure. The theoretical time differences as compared to the recorded values had a definite correlation. Up to this time geographic coordinates as provided by the R40 had been used in all our evaluations. Apparently the algorithm only computes a single triad, initially selected by default but can be set manually. Software was developed to permit reprocessing the data utilizing all the triads, iterating from the computed R40 position. This was subsequently improved by rigorous least squares hyperbolic processing. The improvement to the results was spectacular, we were now able to see some real potential to Loran. Additional research and evaluation was warranted. The technical problems that we isolated as having to solve were:

1) dynamic filter system
2) geometry related to hyperbolic positioning
3) system calibration

Prior to the start of the 1987 season the Arnav R40 unit with its mapping software had been utilized to assist in navigation with the data stored to disc. In early 1987 we commenced development of our present real time navigation software and hardware.

3. AERIAL PHOTOGRAPHY FLIGHT MANAGEMENT SYSTEM

A team comprised of aerial photography personnel, software and hardware experts were assembled. Upon identifying our requirements they were not dissimilar to the standard hydrographic procedures using either hyperbolic or range/range positioning systems. The software started with a hydrographic package as developed by Challenger Surveys and Services Ltd, Edmonton. This package contained the standard menus, hyperbolic algorithms and least squares adjustment routines. As previous test data was reprocessed two problems became obvious:

1) the acquisition and processing speed were unique to aircraft and the hydrographic routines were completely inappropriate.
2) hyperbolic positioning alone on a single chain was geometry dependent causing considerable degradation in results in our operations area.

The ramifications of the aircraft speeds were not fully realized until this point and continue to cause inaccuracies to the present. We had selected a HP series 200 computer system. This system had more than adequate processing speed and capacity for hydrographic applications. The HP series 200 has a MC 68000 processor with 16/32 bit internal architecture and was one of the most powerful portables available. The operating system was HP Basic 4.0. Every effort was made to minimize cycle speed in that we realized the timing would be critical. The cycle time for a single chain including all of the mathematics and refreshing the monitors was 3 seconds, of which + 1 second was spent getting Loran data over the serial line. With aircraft speeds of 150 m/sec this was deemed unacceptable.

Arnav was most helpful when approached with our problems. The R40 puts out a standard data string with the usual navigation data for incorporation into other navigation instrumentation. A test string is also available which in addition to the standard information includes all of the time differences and signal characteristics. The strings are very long (+/- 150 characters and +/- 500 characters) for the standard and test string respectively, transmitted at 4800 baud maximum. Special EPROMS were provided by Arnav to transmit only the required information. Essentially we are interested in the chain and time differences only; as well as the operational status of each station (ie. signal strength, signal to noise and envelope cycle discrepancy). In addition the request interval was divided by 10, essentially permitting continuous output. With the data acquisition improved the cycle time was reduced to less than 2 seconds.

Software solutions were reviewed for a speedier throughput; ie. non-iterative routines and an attempt to map and use a local rectangular grid system instead of geographic coordinates. Rectangular coordinates quickly proved unsatisfactory as did spherical coordinates. The accuracies sought versus distances and speeds dictated a true ellipsoidal earth model (WGS 72) with rigorous computation of all parameters.

A sophisticated filter algorithm similar to a Kahlmann filter was developed to permit any degree of dead reckoning from nil to absolute from previous heading and velocity. To date heading and velocity has been determined solely by geographic inverse between previous positions. The filter is adjustable through operator input with default being 1.0 g or 9 meters/sec. The maximum filter setting is 0.1 g, essentially holding the aircraft to nil acceleration. The default and value generally used is 1.0 g. This compares to the acceleration allowed in hydrographic work of 0.01 to 0.02 g; a factor of 1000 times.

For the start of the 1987 season we were operational with single chain, hyperbolic realtime navigation in our 3 aircraft. [Figure 1] The standard procedure for each project was to digitize the flight lines on the flight maps provided. This was performed on a digitizing table by transformation of defined geographic or UTM values. The beginning and end of each flight line was digitized and written to disc as geographic coordinates. The navigator could load a particular flight line, ie. beginning and end of line into the system. By adding the position of the aircraft solved from the Loran system he was able to electronically relate the aircraft to the line. Considerable effort was put into simple, yet effective menus and displays. The operator can view any of the following :

1) filter operation
2) survey parameters
3) Loran operation
4) base stations being used
5) miscellaneous printouts etc.

The pilot has a small (10 cm square) secondary monitor showing only the essential line and aircraft relationship, ie. distance from start, lateral distance off the line, etc. This was mounted directly in front of the pilot on the sunscreen. [Figure 2]

Figure 1

Figure 2

Using the system in production in 1987 assisted the crew immeasurably in positioning the aircraft. Previously a skilled crew were able to break off one line and commence another line in 6 minutes, all done visually while the aircraft banked and turned in the opposite direction to within 500 meters. Mistakes were often made, particularly in difficult areas, necessitating another two turns taking up to an additional 10 minutes. The Flight Management System (FMS) permitted end turns averaging 4 minutes with a very high success rate.

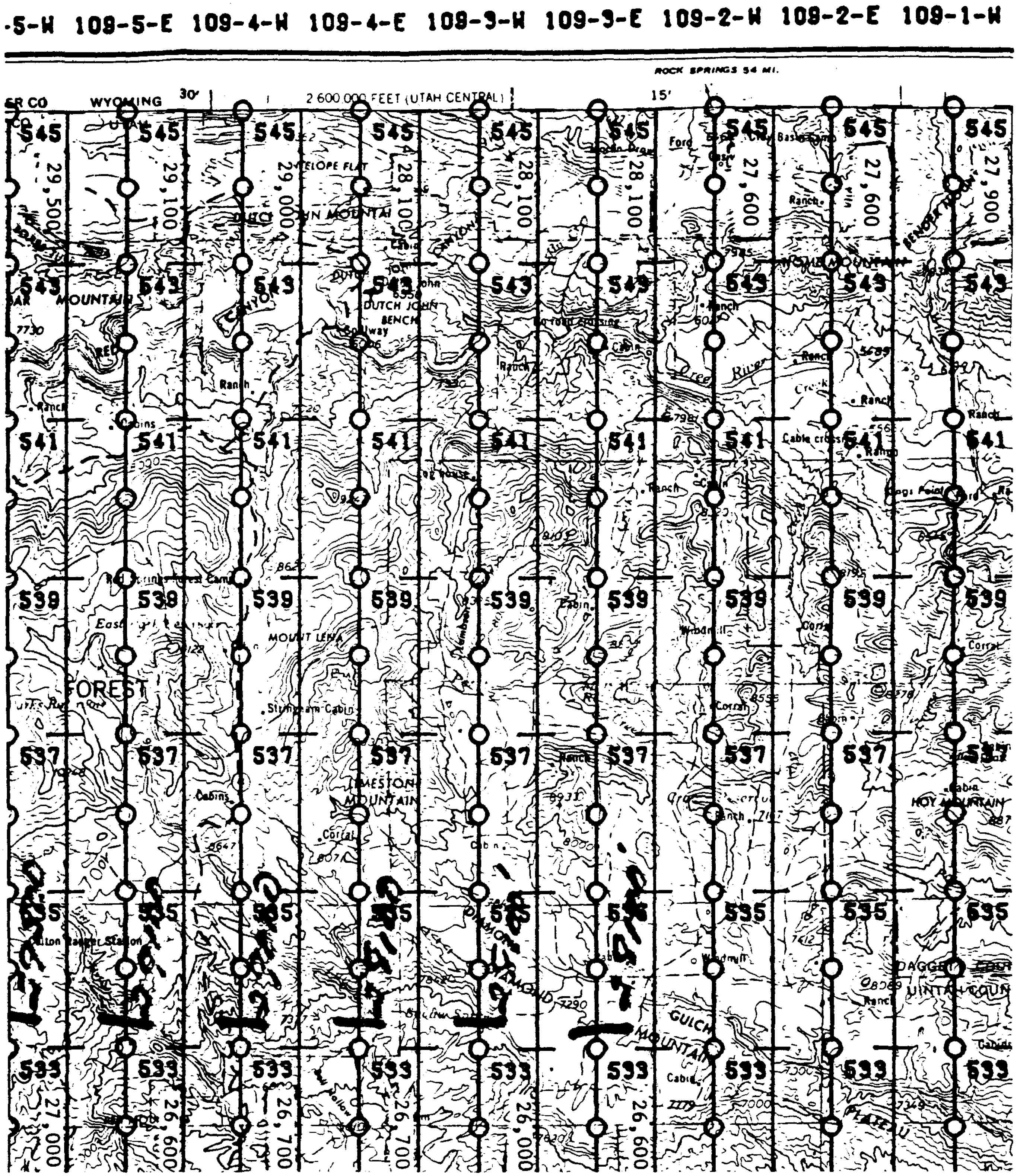
The initial 1987 prototype system was not completely satisfactory in that we were still experiencing occasional accuracy problems due to aircraft speed, cycle time and hyperbolic geometry. The accuracies we were experiencing were approximately 500 meters over a two hour mission in Western Canada.

In the summer of 1987 the US Geological Survey (USGS) tendered the first phase of the National Aerial Photography Program (NAPP). This was 1:40000 scale flown at 6000 meters above the ground. The photo centers were designed to fall on predetermined geographic coordinates within a 300 meter error circle. The expected execution would be by visual navigation off 1:100,000 USGS maps, the 1:250,000 series would not provide sufficient accuracy. The fallback would be the 1:24,000 series which because of the small area covered would necessitate several filing cabinets in the aircraft. We were sufficiently confident in our FMS to tender on this work assuming to do same electronically with some improvements to our system. Simulations dictated we could never expect the required accuracy with hyperbolic methods operating off a single chain. Simulations were performed with two chains and using range/range or true times rather than the time differences. The simulations indicated the required accuracies could be achieved. The R40 was modified to accept an external 10 mHz input replacing the internal oscillator. This was provided by a portable rubidium frequency standard complete with battery backup. Again Arnav were most helpful in providing the modification procedure and range/range software internal to the R40. The initial results were most encouraging. Unfortunately range/range positioning over the large areas we proposed to cover exposed unique problems not encountered in hyperbolic mode. Primary and secondary phase corrections must be applied due to changes in the atmosphere and due to the degradation of the wave travelling over land. This is by no means an exact science. After some considerable effort to model the corrections we decided it was not predictable and could only be eliminated by calibration prior to takeoff and then in the operations area. The calibration process solves for primary and secondary phase corrections on all time differences as well as any cycle slips and then maintains and uses this information on all future time differences. This was quite straightforward for a static calibration but was incredibly complex for dynamic calibrations; fixing and adjusting up to 5 ranges while moving over 250 meters. After considerable airborne testing this was finally resolved. We are now able to calibrate on the ground prior to takeoff or during flight over known geographic coordinates and adjust/correct all ranges simultaneously. Accuracies were now at 150 meters.

The range/range software was developed in time for the USGS NAPP contract we were contracted to perform in Utah/Idaho. Over 12000 kms (5000 photos) were successfully completed, all electronically positioned. Algorithms were developed to permit the operator to input the line and station number which automatically computed the geographic coordinates of the line. The pilot electronically positioned the aircraft and the computer fired the camera at the instant the required coordinates were passed. The system was extremely productive and cost effective. Our production was increased by up to twice that expected by being able to accurately and consistently navigate to the required location. Again end turns were consistently and accurately made within 4 minutes versus 8 minutes estimated with conventional visual navigation. Figure 3, 4 and 5 show a sample area on a 1:250,000 map, the same area on a 1:100,000 map and the electronic printout respectively.

Minor improvements have been made to the software and hardware since the 1987 season. Early in 1988 a second R40 with range/range was added to the FMS to provide a crosschaining capability. The cycle time was degraded necessitating fabrication of a buffer box concatenating and being continuously and automatically refreshed with data at 0.2 second intervals from the two R40's. The cycle time now varies from 2.5 to 3 seconds when operating two chains comprised of 6 to 8 stations.

Work has been conducted throughout northern and western Canada with the dual chain range/range FMS in all our company aircraft with considerable success. We have worked along the Arctic Coast and as far east as the Saskatchewan/Manitoba border. A long wire antenna is used to improve the low signal strengths found in some areas. The R40 has the ability to operate on extended range or with sky waves at some considerable distance from the chain. This is appropriately weighted in the algorithms and corrected for during calibration, again with considerable success.



-5-W 109-5-E 109-4-W 109-4-E 109-3-W 109-3-E 109-2-W 109-2-E 109-1-W
ROCK SPRINGS 54 MI.
WYOMING
2 600 000 FEET (UTAH CENTRAL)
545
543
541
539
537
535
533
29,500
29,100
29,000
28,100
27,600
27,900
27,000
26,600
26,700
26,000
DUTCH JOHN BENCH
MOUNT LENA
FOREST
Cabins
Corral
Ranch
Windmill
HOY MOUNTAIN
GULCH
MOUNTAIN
DAGGETT
UINTAH

Figure 3

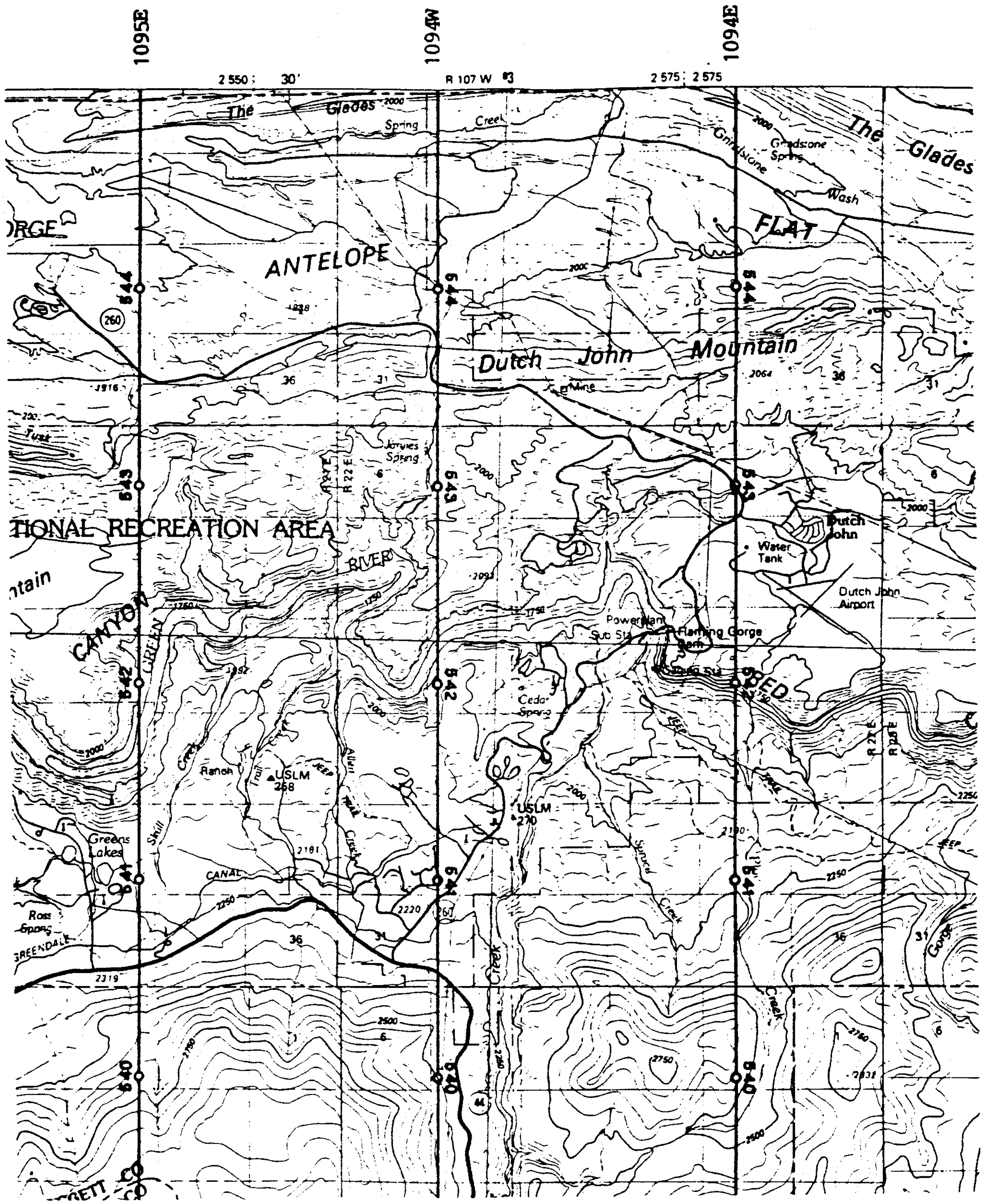

1095E
1094W
1094E
2 550
30'
R 107 W
2 575
The Glades
Spring Creek
Gridstone Spring
Gridstone Wash
FLAT
ANTELOPE
Dutch John Mountain
Mine
Jarvies Spring
R 22 E
TIONAL RECREATION AREA
RIVER
CANYON
GREEN
Dutch John
Water Tank
Dutch John Airport
Power Plant
Sub Sta
Flaming Gorge Dam
Cedar Spring
Ranch
USLM 258
USLM 270
Greens Lakes
Ross Spring
GREENDALE
CANAL
JEEP TRAIL
Spring Creek
544
543
542
541
540

Figure 4

DATA FROM FILE: A6107
DATE OF CALIBRATION: 23 AUG 1988 TIME OF CALIBRATION: 16:07:00

CHAINS: 5990: CANADIAN WEST COAST CHAIN 9940: U.S. WEST COAST CHAIN

STATIONS	LATITUDE	LONGITUDE (W)	DELAY	SHIFTS(usecs)
WILLIAMS LAKE, B.C.	51-57-58.8	122-22-02.2	.00000000	-4925.27
SHOAL COVE, ALASKA	55-26-20.9	131-15-19.7	.01334360	+0.00
GEORGE, WASHINGTON	47-03-48.0	119-44-39.5	.02892736	-4940.92
PORT HARDY, B.C.	50-36-29.7	127-21-29.0	.04226661	-4914.89
FALLON, NEVADA	39-33-06.6	118-49-56.4	.00000000	-2008.78
GEORGE, WASHINGTON	47-03-48.0	119-44-39.5	.01379690	-2008.78
MIDDLETOWN, CALIF.	38-46-57.0	122-29-44.5	.02809450	-2008.45
SEARCHLIGHT, NEVADA	35-19-18.2	114-48-17.4	.04196730	-2008.36
CALIBRATION POINT:	40-46-33.0	111-57-33.0		

REC#	PHOTO	LINE#	DATE	TIME-GMT	LATITUDE	LONGITUDE	D_LAT(ft)	D_LONG(ft)
001	0545	1094E	23 Aug	16:53:24	40-59-56	109-24-24	-440	+148
002	0544	1094E	23 Aug	16:53:49	40-58-06	109-24-23	-102	+70
003	0543	1094E	23 Aug	16:54:14	40-56-16	109-24-24	+144	+109
004	0542	1094E	23 Aug	16:54:40	40-54-23	109-24-26	+69	+285
005	0541	1094E	23 Aug	16:55:05	40-52-29	109-24-22	-83	-16
006	0540	1094E	23 Aug	16:55:30	40-50-36	109-24-26	-185	+242
007	0539	1094E	23 Aug	16:55:55	40-48-44	109-24-31	-85	+623
008	0538	1094E	23 Aug	16:56:20	40-46-55	109-24-30	+276	+543
009	0537	1094E	23 Aug	16:56:45	40-45-00	109-24-29	+15	+485
010	0536	1094E	23 Aug	16:57:10	40-43-09	109-24-26	+191	+233
011	0535	1094E	23 Aug	16:57:36	40-41-16	109-24-24	+85	+96
012	0534	1094E	23 Aug	16:58:01	40-39-22	109-24-24	-23	+106
013	0533	1094E	23 Aug	16:58:26	40-37-30	109-24-24	-10	+145
014	0532	1094E	23 Aug	16:58:51	40-35-39	109-24-26	+185	+284
015	0531	1094E	23 Aug	16:59:16	40-33-48	109-24-26	+288	+305
016	0529	1094W	23 Aug	17:05:17	40-29-59	109-28-06	-80	-88
017	0530	1094W	23 Aug	17:05:45	40-31-54	109-28-10	+169	+197
018	0531	1094W	23 Aug	17:06:12	40-33-43	109-28-09	-214	+132
019	0532	1094W	23 Aug	17:06:41	40-35-40	109-28-04	+216	-236
020	0533	1094W	23 Aug	17:07:09	40-37-30	109-28-08	-36	+28
021	0534	1094W	23 Aug	17:07:37	40-39-21	109-28-09	-164	+95
022	0535	1094W	23 Aug	17:08:05	40-41-18	109-28-09	+263	+99
023	0536	1094W	23 Aug	17:08:32	40-43-06	109-28-08	-138	+61
024	0537	1094W	23 Aug	17:09:00	40-45-01	109-28-07	+70	-72
025	0538	1094W	23 Aug	17:09:27	40-46-52	109-28-10	-49	+228
026	0539	1094W	23 Aug	17:09:56	40-48-47	109-28-07	+159	-39
027	0540	1094W	23 Aug	17:10:24	40-50-39	109-28-01	+146	-530
028	0541	1094W	23 Aug	17:10:52	40-52-31	109-28-04	+62	-250
029	0542	1094W	23 Aug	17:11:18	40-54-21	109-28-08	-140	+48
030	0543	1094W	23 Aug	17:11:46	40-56-12	109-28-07	-302	-62
031	0544	1094W	23 Aug	17:12:15	40-58-07	109-28-05	-19	-175
032	0545	1094W	23 Aug	17:12:43	41-00-00	109-28-07	+34	-6

Figure 5

4 FUTURE DEVELOPMENTS

The FMS has proved itself and we will be properly packaging the system, probably with a IBM compatible laptop with the new 386 processor. Early tests indicate that the cycle time will be reduced to less than 1 second because of the multitasking capabilities. This will improve the accuracies by an as yet unknown amount. We have also investigated incorporating heading and speed inputs into the algorithm. Heading input could be achieved from directional gyros,etc or an auxiliary digital fluxgate compass.

North West Geomatics Ltd. expects to be able to market the FMS by mid 1989 for those airborne applications requiring realtime navigation accuracies of better than 250 meters.

5 ACKNOWLEDGEMENTS

The author and North West Geomatics Ltd. express their appreciation and acknowledgement to Arnav and in particular Walt Dean of that firm. On numerous occasions we were at a loss as to some unexplained phenomenon experienced in our testing. Mr. Dean's 30 plus years experience in the business invariably had a practical and effective solution to our questions.

Additional discussions with David H. Gray of the Canadian Hydrographic Service and Steve Grant of the Bedford Institute of Oceanography also proved most helpful.

LORAN FOR AVIATION

...AN UPDATE

- PROGRESS TO DATE
- RECENT ACCOMPLISHMENTS
- TRANSMITTER STATUS
- NFOLDS
- OPERATIONAL MONITORS

TSC

DTS-52

LORAN-C AIRBORNE RECEIVER MANUFACTURERS

1978 - TELEDYNE

1981 - TEXAS INSTRUMENTS

1982 - MICROLOGIC
ARNAV, INC.
INTERNATIONAL AVIONICS, INC.
ANI/ONI

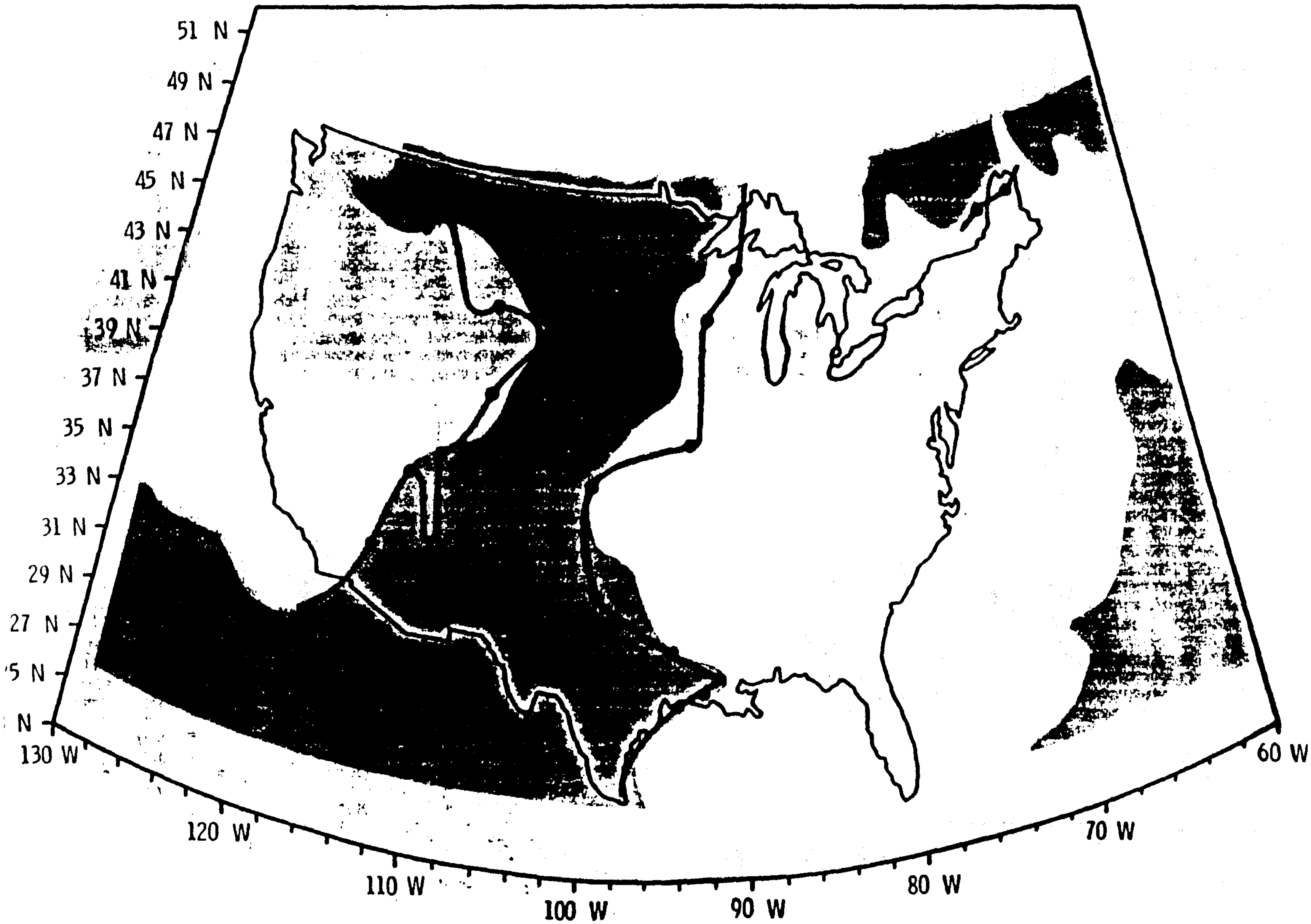
1983 - FOSTER AIRDATA
NAUTICAL ELECTRONICS CO.
RACAL AVIONICS, INC.
SRD LABS
II MORROW
SITEX/KODEN

* Approximately 5000 units in field to date. II Morrow produces 500/month.

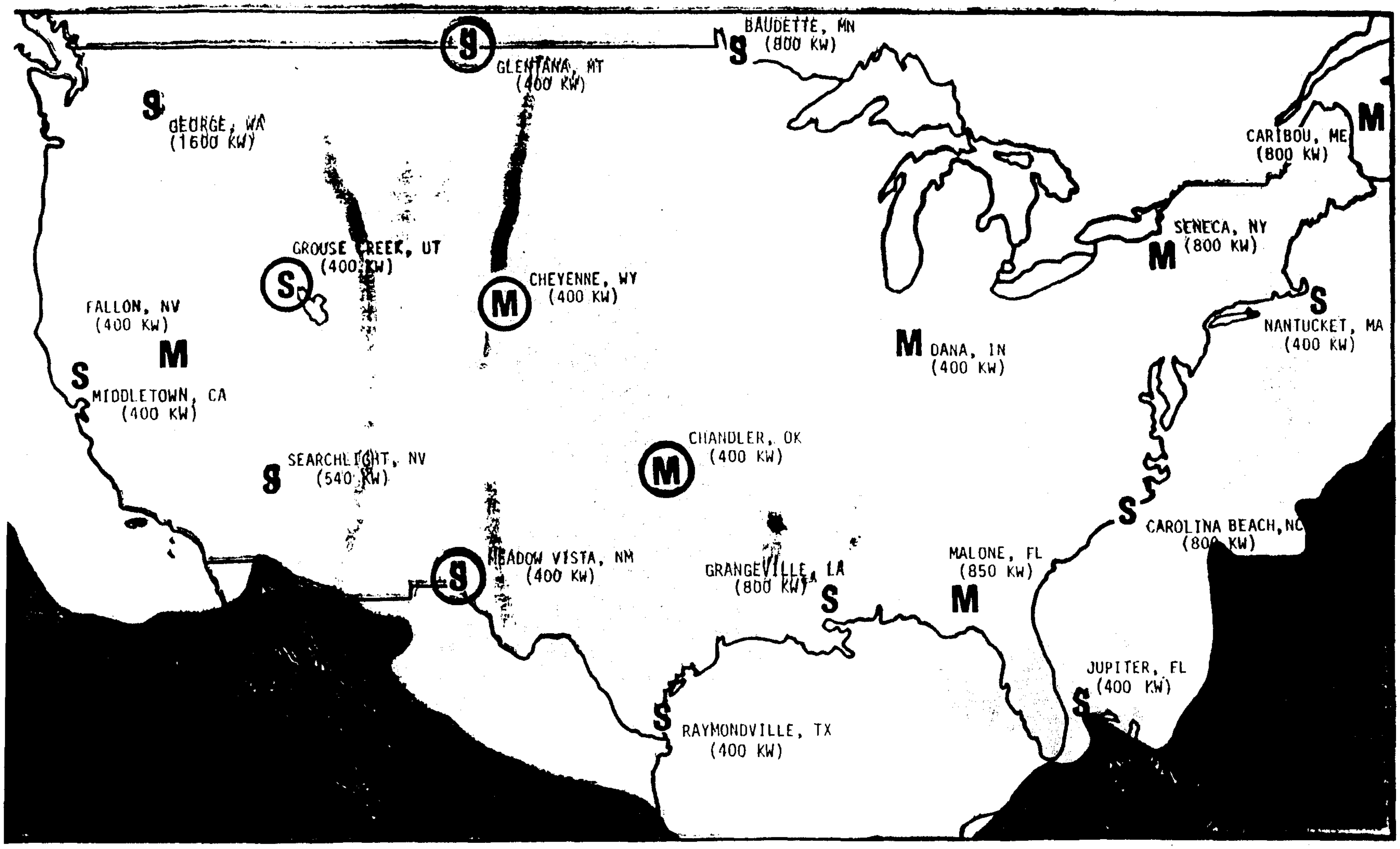
Sept. 30, 1983

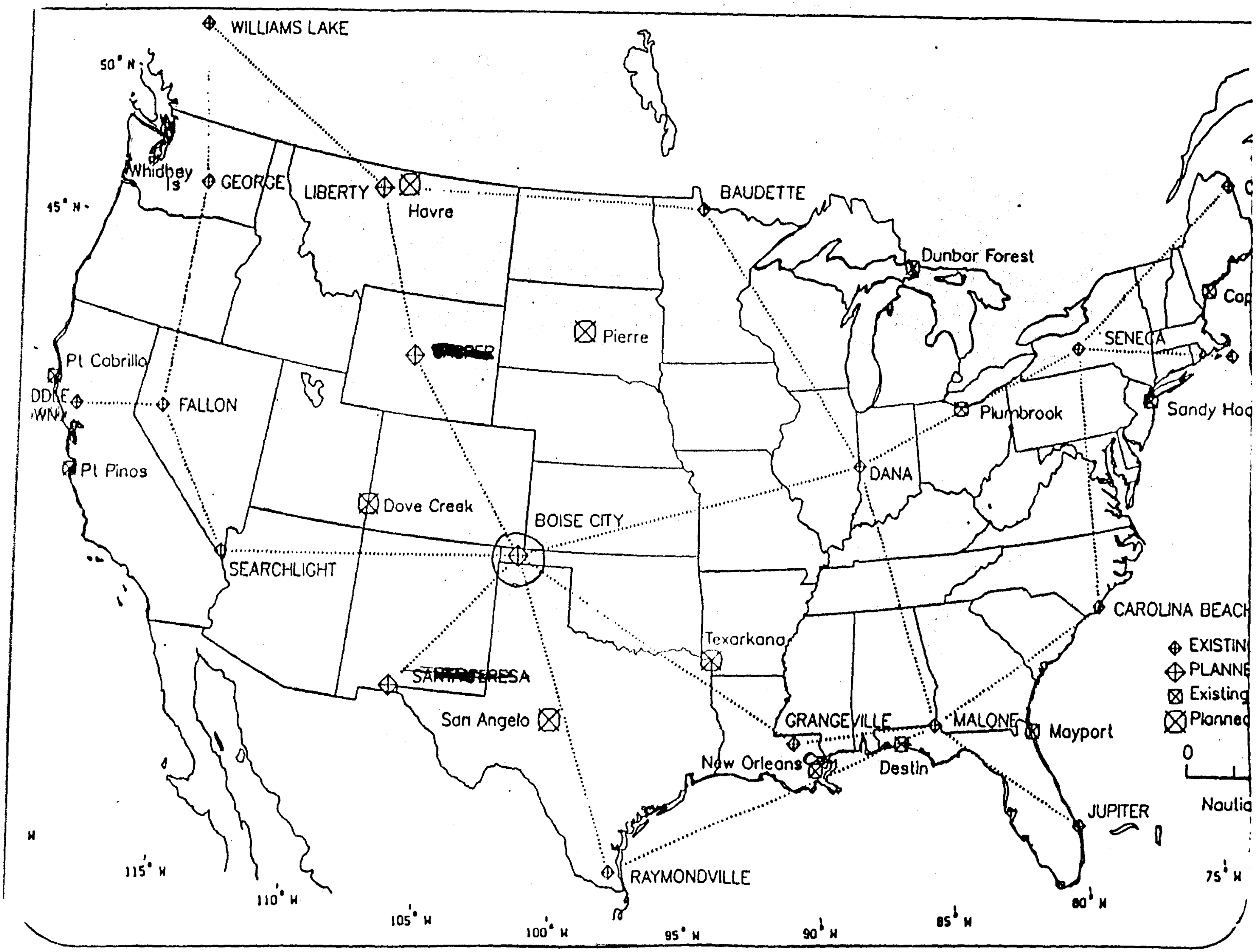
LORAN-C COVERAGE SUMMARY

GRADIENT - 7000 FEET/MICROSECOND, NOISE BANDWIDTH 30KHZ



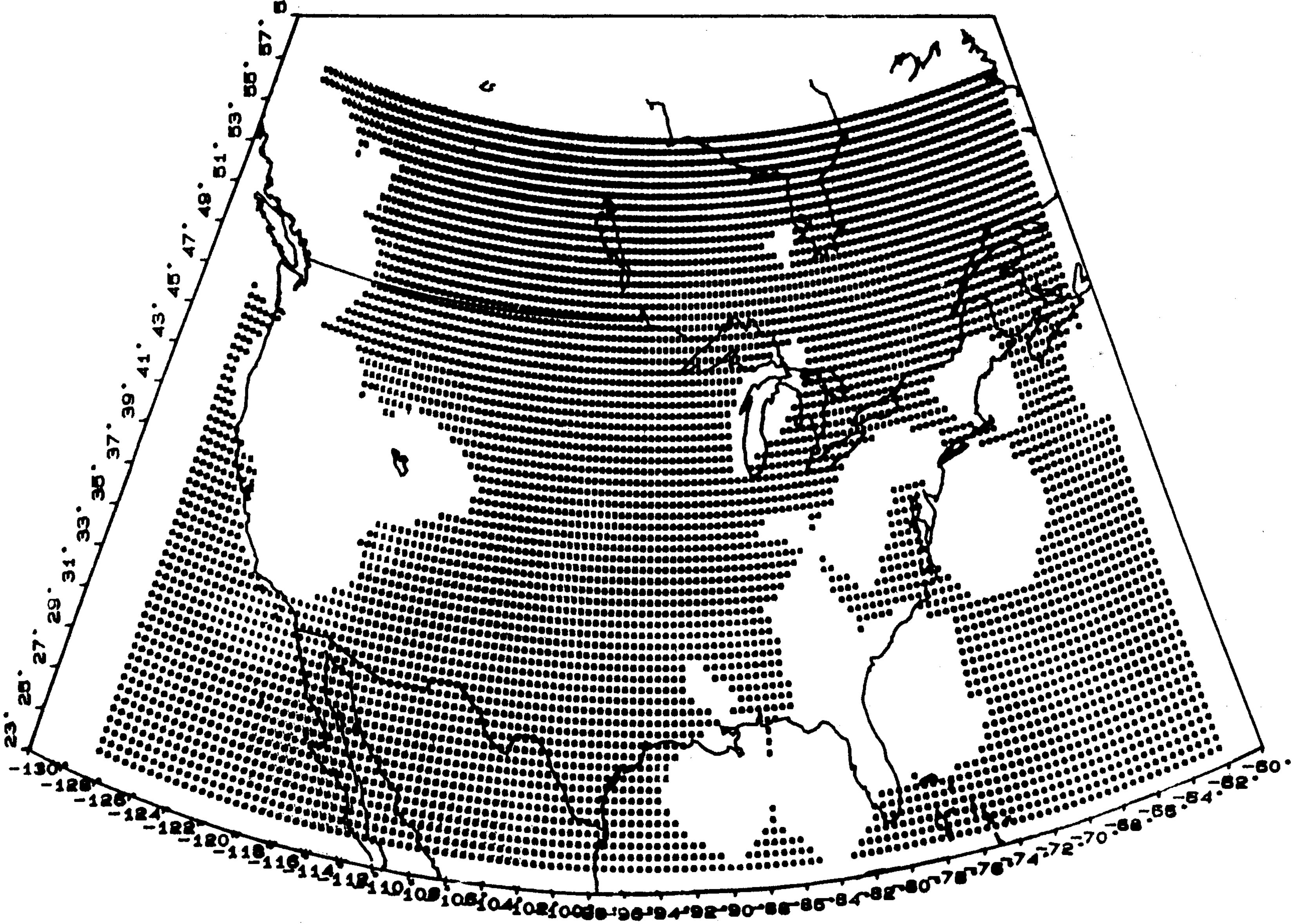
COVERAGE WITH 5 NEW 400KW STATIONS



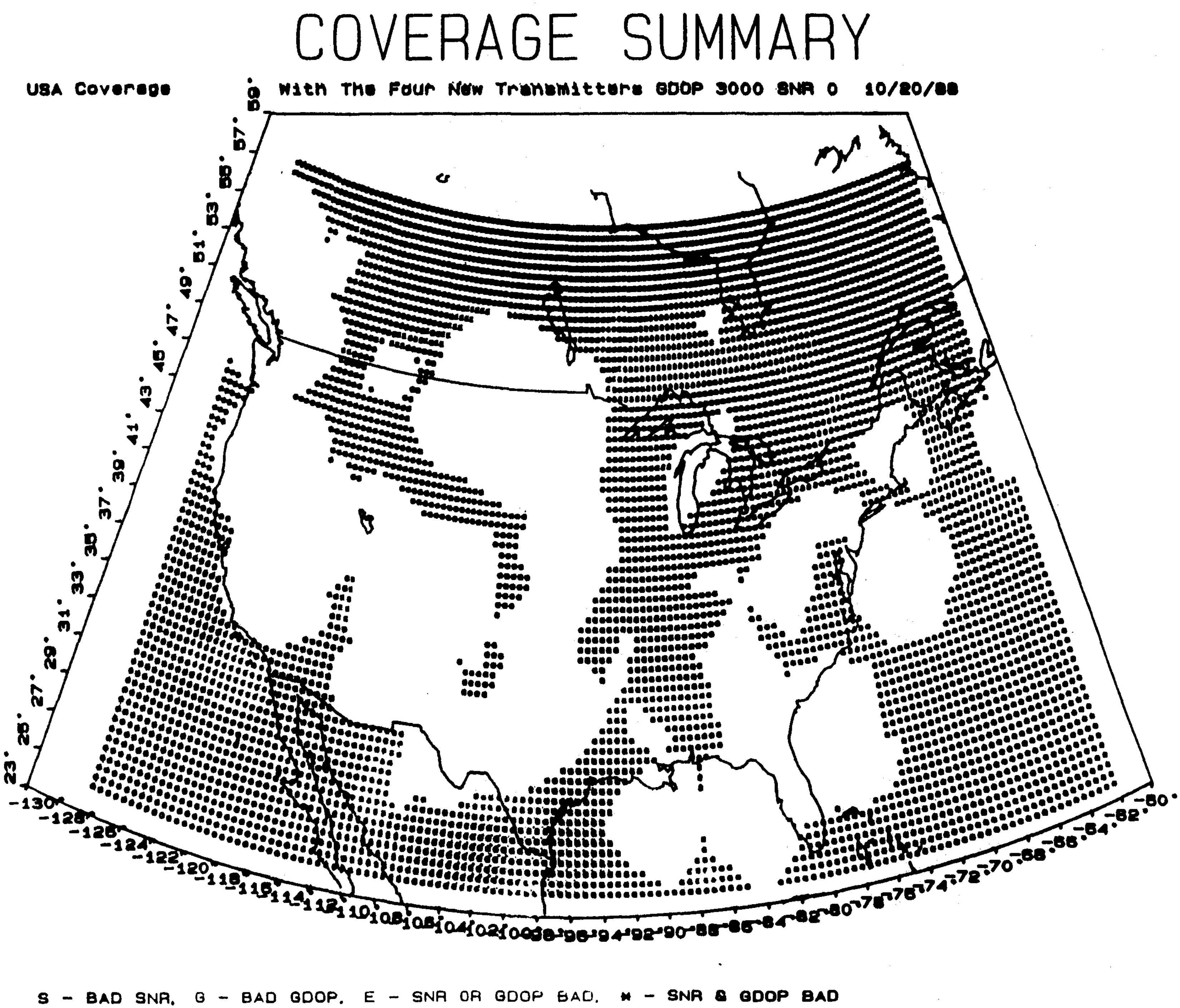

WILLIAMS LAKE
50° N
45° N
Whidbey Is
GEORGE
LIBERTY
Havre
BAUDETTE
Dunbar Forest
Pierre
SENECA
Pt Cabrillo
FALLON
Plumbrook
Sandy Hoo
Pt Pinos
DANA
Dove Creek
BOISE CITY
SEARCHLIGHT
CAROLINA BEACH
Texarkana
EXISTIN
PLANNE
Existing
Planned
San Angelo
GRANGEVILLE
MALONE
Mayport
New Orleans
Destin
0
JUPITER
Nautic
RAYMONDVILLE
115° W
110° W
105° W
100° W
95° W
90° W
85° W
80° W
75° W

COVERAGE SUMMARY

USA Coverage — Without Four New Transmitters GDOP 3000 SNR 0 10/19/88

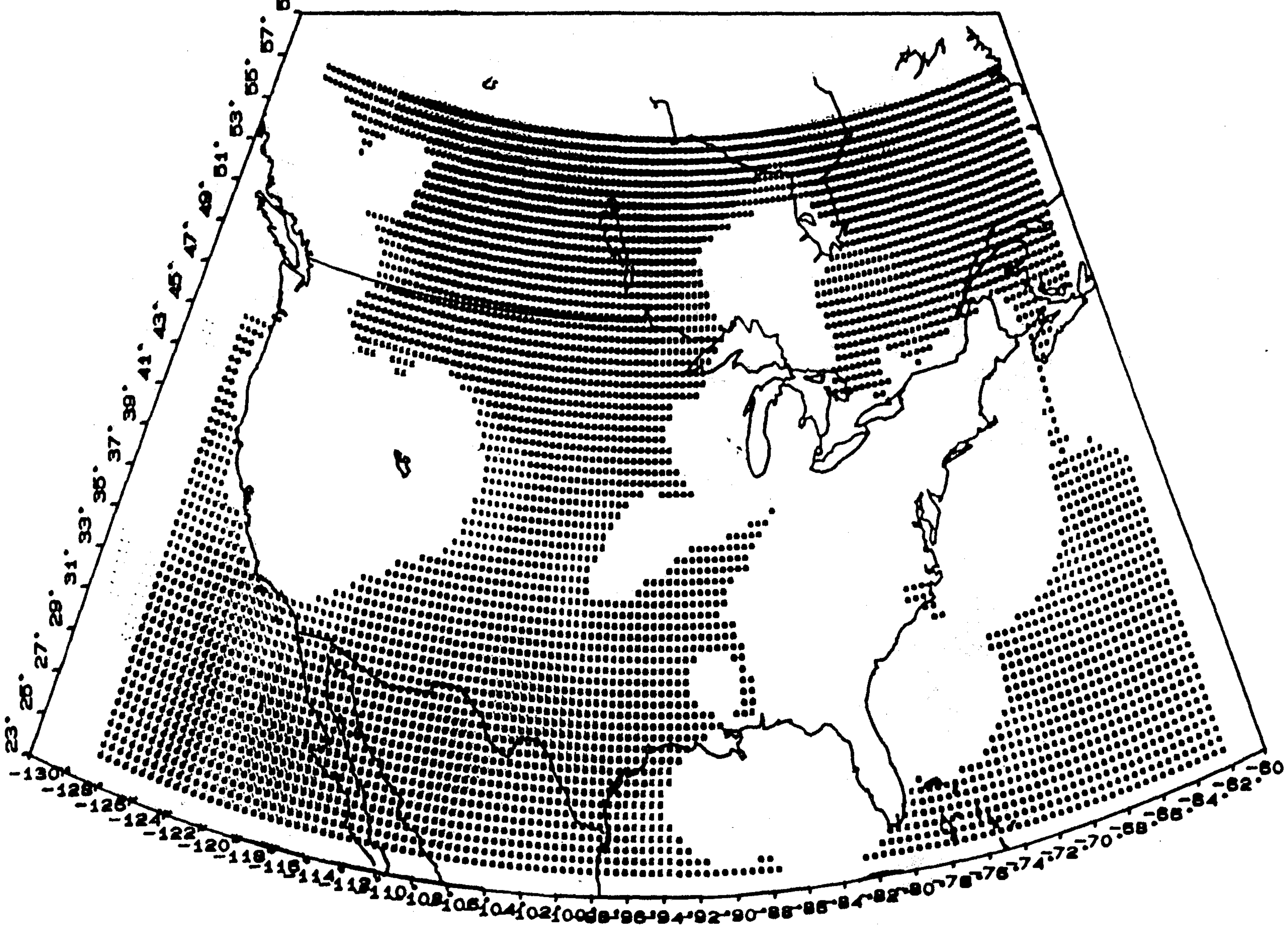


S - BAD SNR, G - BAD GDOP, E - SNR OR GDOP BAD, * - SNR & GDOP BAD


COVERAGE SUMMARY
USA Coverage
With The Four New Transmitters GDOP 3000 SNR 0 10/20/88
S - BAD SNR, G - BAD GDOP, E - SNR OR GDOP BAD, * - SNR & GDOP BAD

COVERAGE SUMMARY

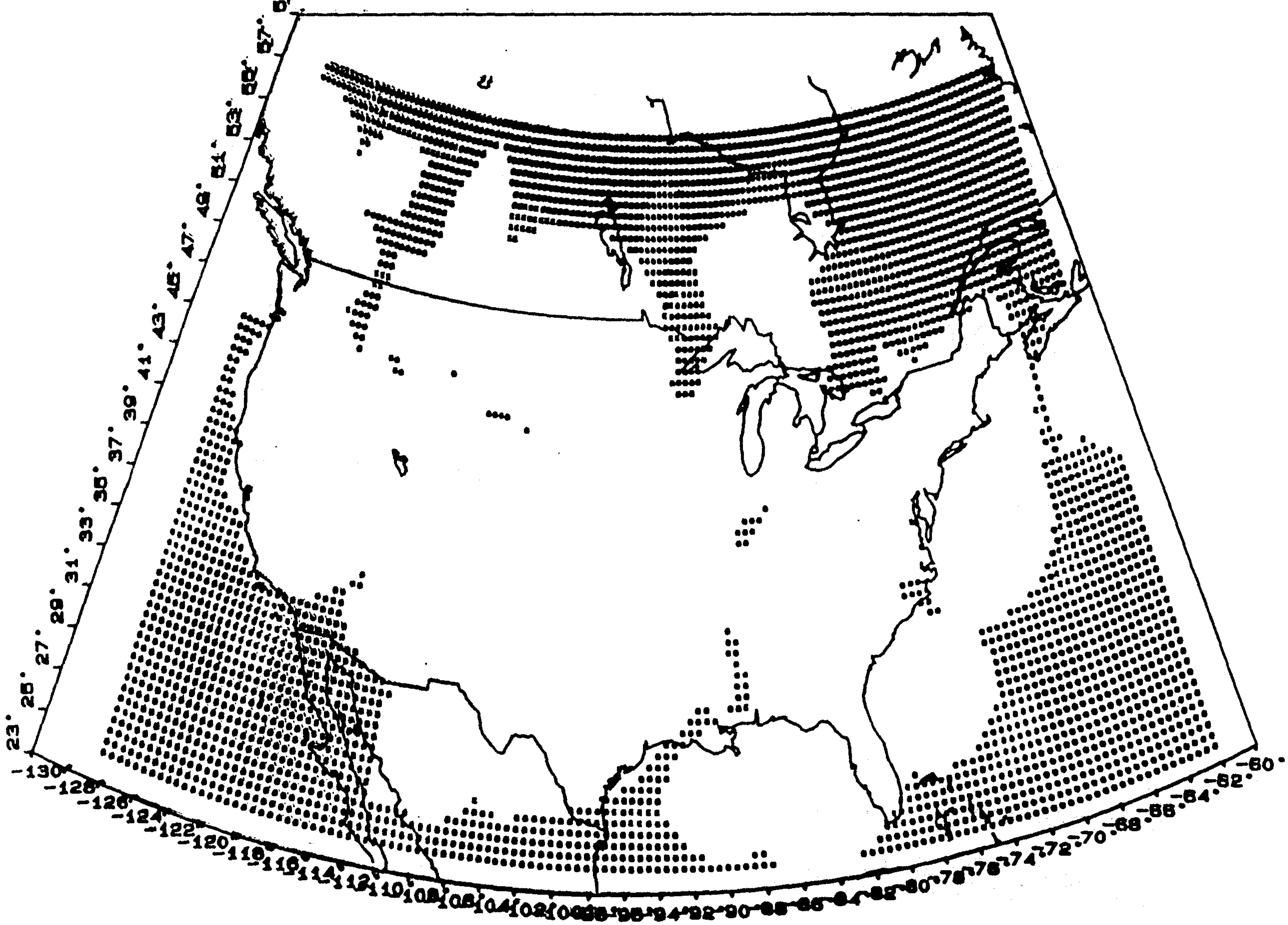
USA Coverage Without Four New Transmitters GDOP 3000 SNR -6 10/19/88



S - BAD SNR, G - BAD GDOP, E - SNR OR GDOP BAD, * - SNR & GDOP BAD

COVERAGE SUMMARY

USA Coverage   With the Four New Transmitters GDOP 3000 SNR -6 10/20/88

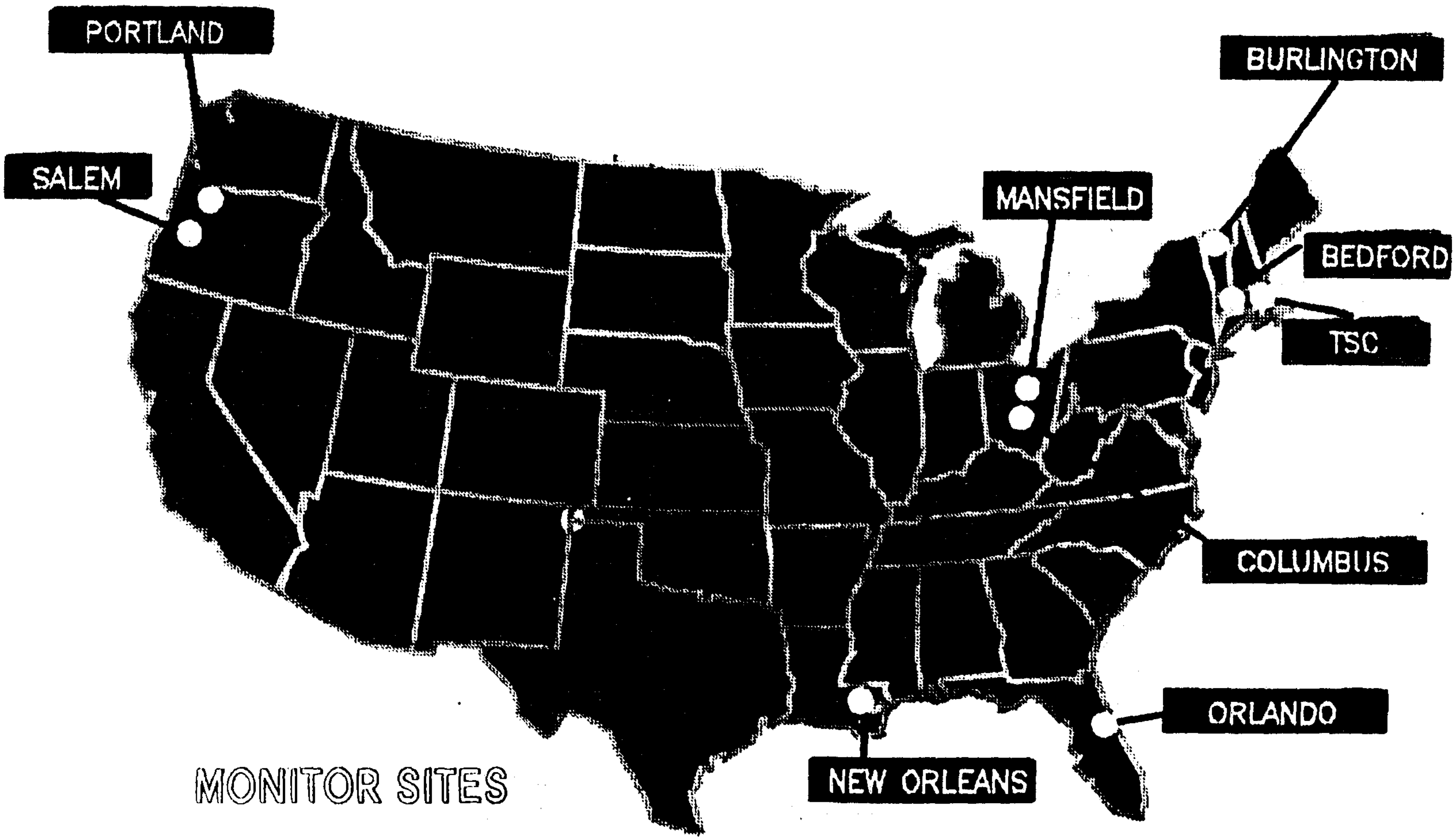


S - BAD SNR, G - BAD GDOP, E - SNR OR GDOP BAD, * - SNR & GDOP BAD

FAA EARLY IMPLEMENTATION PROJECT

- OBJECTIVE: INTRODUCE LORAN INTO THE NAS
  ON A LIMITED BASIS TO
  - ACQUAINT FAA ORGANIZATIONS TO A NEW NAVAID
  - DEVELOP USER FAMILIARITY
  - CHECK OUT AND REFINE NEW SUPPORT SYSTEMS
  - DEVELOP PROCEDURES AND OPERATIONS
  - PREPARE FOR FULL OPERATIONAL CAPABILITY

EARLY IMPLEMENTATION PROJECT MONITOR SITES



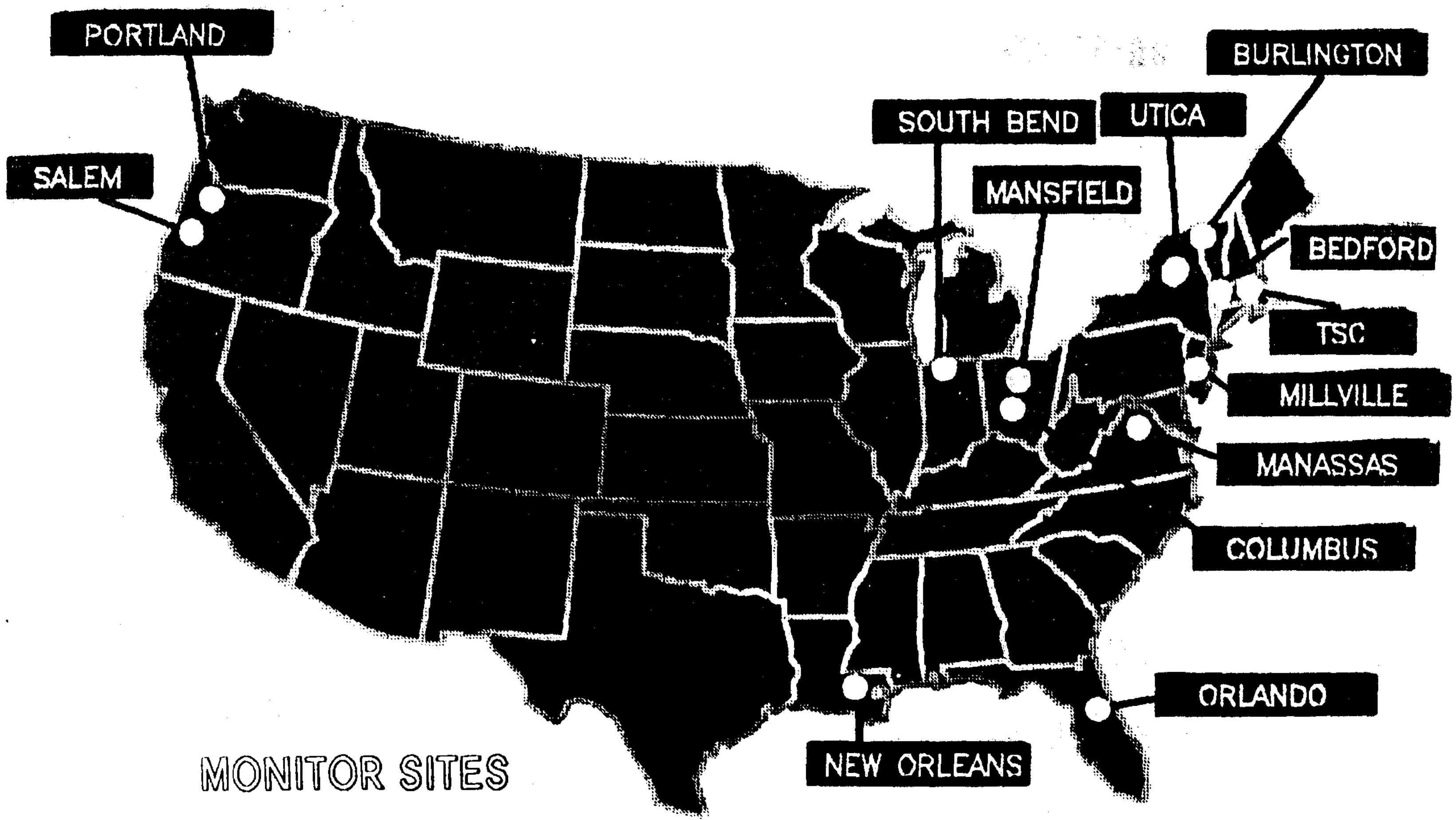
NOV. 4, 1985

FIRST NON - PRECISION APPROACH

AT L.G. HANSCOM FIELD

CO-PILOT: ADMIRAL DONALD G. ENGEN

EARLY IMPLEMENTATION PROJECT
MONITOR SITES PHASE II



INAUGURAL LORAN NON-PRECISION APPROACHES

BEDFORD,MA	11-04-85
BURLINGTON,VT	02-11-86
COLUMBUS,OH	10-06-86
PORTLAND,OR	05-30-86
SALEM,OR	05-30-86
LAKEFRONT,LA	10-21-86
ORLANDO,FL	05-22-87
VENICE,LA	04-15-88
KALAMAZOO,MI	07-29-88
NORWICH,NY	08-30-88

VENICE , LA: April 28 - May 2 1987

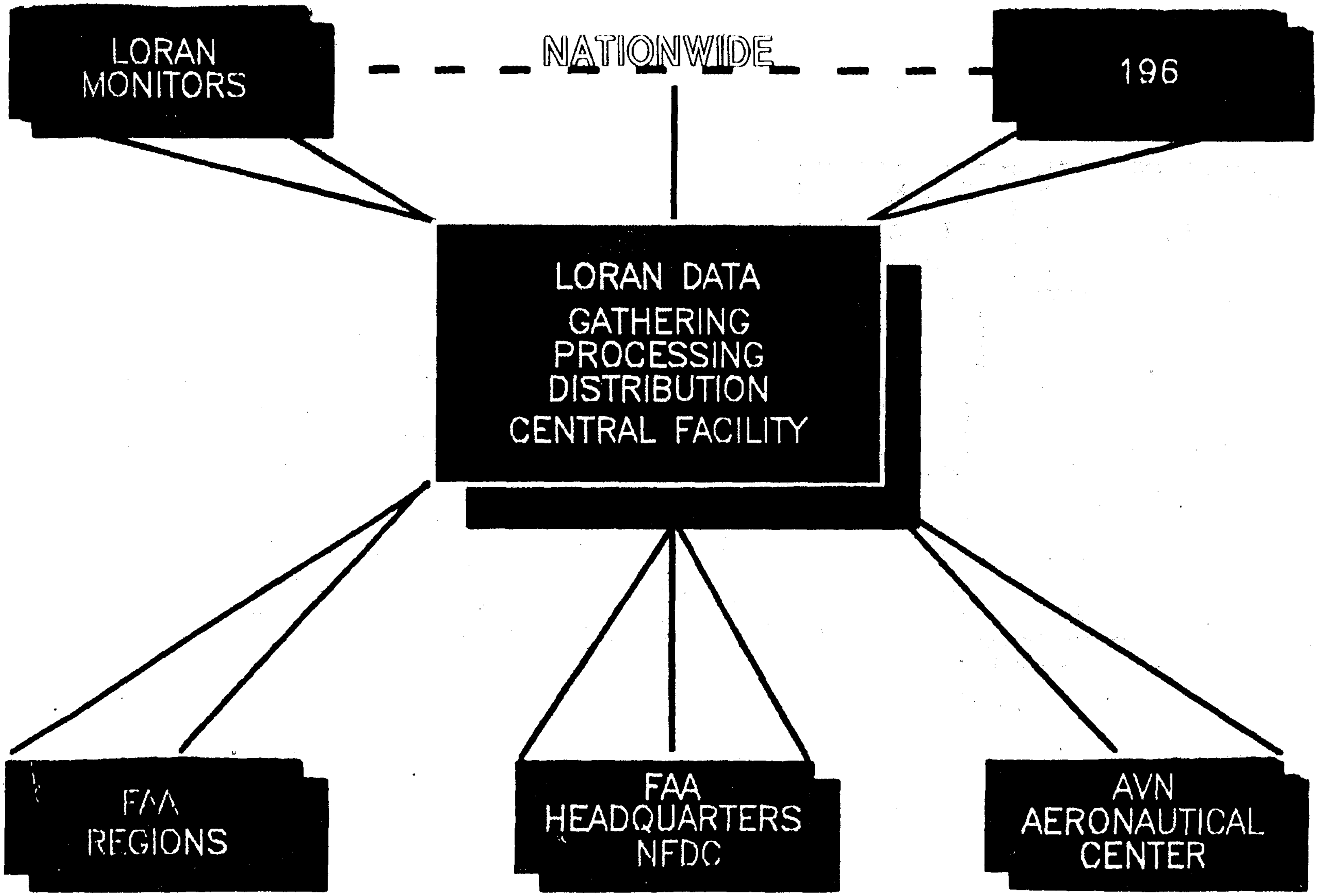
- FIRST LOCATION WHERE A LORAN NONPRECISION APPROACH IS ESTABLISHED THAT DOES NOT OVERLAY AN EXISTING CONVENTIONAL AID (ILS, VOR, NDB) APPROACH.

- FIRST FACILITY WHERE A NON-PRECISION APPROACH IS USED WITHOUT THE MONITOR AND AIRPORT BEING COLLOCATED.

NFOLDS FUNCTION

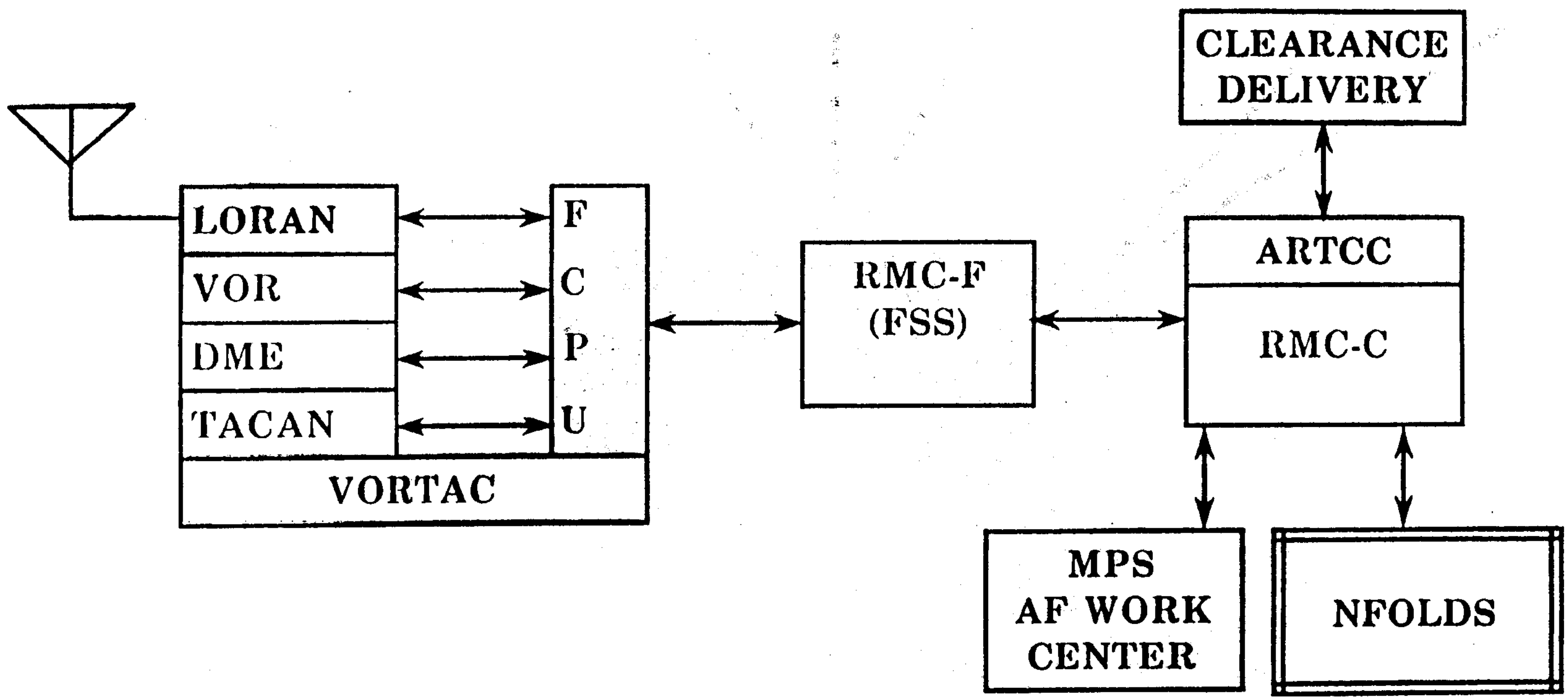
THE NFOLDS PROGRAM ESTABLISHES A FACILITY TO GATHER THE MONITOR DATA FROM EACH OF THE INSTALLATION SITES, PROCESS THE DATA AND DISTRIBUTE DATA PRODUCTS.

LORAN MONITOR DATA



LORAN MONITOR IN THE U.S. NATIONAL AIRSPACE SYSTEM

OPERATIONAL CONFIGURATION



FAA - LORAN LONG TERM PLANS

- INTEROPERABILITY WITH GPS
- COMPATIBILITY
- AIRPORT CAPACITY RELIEF
  - o STATE PARTICIPATION
  - APPROACH PROCEDURES
- DEPENDENT SURVEILLANCE

SOLE - MEANS NAV - SYSTEM KEY FACTORS

- ACCURACY
- INTEGRITY
- AVAILABILITY
- COVERAGE
- RELIABILITY

SESSION 3

LORAN TECHNOLOGIES

JOHN BEUKERS
BEUKERS PROMOTIONS INC.

LORAN–FIX DISPLACEMENTS DUE TO A MODEL CHANGE IN PULSE PROPAGATION VELOCITY

E. A. Lewis and D. E. Meyers
Megapulse, Inc., Bedford, MA 01730

ABSTRACT

Conventional Loran fixes are found by measuring Time Differences (TD's) between groundwave pulses from three transmitting stations. Slight changes in pulse propagation velocity cause changes in the TD's and result in a small displacement of the plotted fix. This paper considers the displacements caused by the passage across the coverage area of weak frontal velocity step. Analysis is given for both absolutely synchronized transmissions, and for SAM-synchronized transmission. Computer results are presented for selected illustrative scenarios.

PART I: ANALYSIS

1.0 PULSE-VELOCITY MODEL

Part I of this paper discusses theoretically the displacement of the hyperbolic fix position caused by a simple-model change in groundwave pulse velocity. In this flat-earth model, the velocity is uniformly* v_o on the leading side of a straight-line "front"; while on the trailing side, the velocity is uniformly $v_o(1-f)$ where f is a small fraction, perhaps in the order of 10^{-4}. Initially, the front lies well outside the coverage area and the effective velocity is v_o, but as the front advances, remaining parallel to its original line, the pulse travel-times tend to increase. After the front has passed beyond the coverage area, the velocity is again uniform but slightly lower than it was initially. The variation of travel times and TD's during the passage cause displacements of the fix which are difficult to visualize intuitively**, and must be calculated by a detailed analysis. Part I of this paper gives formulae for computing the directional components of the displacements and their magnitude in meters. Part II gives numerical results in the form of displacement-contours for a number of arbitrarily selected cases.

2.0 TD CHANGES IN TERMS OF PATH TRAVEL-TIME CHANGES

Let points A, B, and C represent the geographical locations of the Loran stations, Station B being the master. The following notations are used:

$(TOT)_A$:	Instant the Loran pulse leaves the antenna of Station A.
T_{AP}:	Travel time of the pulse from A to point P in the coverage area.
$(TOA)_{AP} = (TOT)_A + T_{AP}$:	Time of Arrival at P of pulse from A.

*A more complicated model might allow the velocity to vary with propagation distance.

**With absolute synchronization it is intuitive that the passage of the model front leaves no permanent fix-displacement at the special point which is equi-distant from all three stations. Also, it is clear that with ideal SAM-synchronization discussed in Section 2, there is never any appreciable fix-displacement at the SAM itself.

Similar quantities with subscript A replaced by B and by C apply to stations B and C. Ignoring coding delays, which play no role in the following considerations, additional notations are:

$$(TD)_{ABP} = (TOA)_{AP} - (TOA)_{BP} = (TOT)_A + T_{AP} - (TOT)_B - T_{BP}:$$

= Time Difference in arrival at P of pulses from A and B.

$$(TD)_{BCP} = (TOA)_{BP} - (TOA)_{CP} = (TOT)_B + T_{BP} - (TOT)_C - T_{CP}:$$

= Time Difference in arrival at P of pulses from Stations B and C.

Unprimed quantities are used to designate pre-frontal conditions with pulse velocity v_o, and double primes indicate quantities which may have been modified by the passage of the front. The changes in TD's at P due to the front are then written formally:

$$\Delta(TD)_{ABP} = (TD)''_{ABP} - (TD)_{ABP} = [(TOT)''_A + T''_{AP} - (TOT)''_B - T''_{BP}] - [(TOT)_A + T_{AP} - (TOT)_B - T_{BP}] \quad (2.1)$$

$$\Delta(TD)_{BCP} = (TD)''_{BCP} - (TD)_{BCP} = [(TOT)''_B + T''_{BP} - (TOT)''_C - T''_{CP}] - [(TOT)_B + T_{BP} - (TOT)_C - T_{CP}] \quad (2.2)$$

Two cases must now be considered. In the simpler case, the transmissions are all synchronized to some absolute time base (sometimes called TOE or TOT synchronization). Then

$$\left.\begin{aligned} (TOT)''_A &= (TOT)_A \\ (TOT)''_B &= (TOT)_B \\ (TOT)''_C &= (TOT)_C \end{aligned}\right\} \quad (2.3)$$

and Equations (2.1) and (2.2) become

$$\Delta(TD)_{ABP} = (T''_{AP} - T_{AP}) - (T''_{BP} - T_{BP}) \quad (2.4)$$

$$\Delta(TD)_{BCP} = (T''_{BP} - T_{BP}) - (T''_{CP} - T_{CP}) \quad (2.5)$$

In the second synchronization scheme (sometimes called SAM synchronization), a Systems Area Monitor (SAM), located at a chosen point S in the coverage area, receives the Loran signals, and via communication links, adjusts the transmission times of Stations A and C so as to prevent the AB and BC TD's at S from changing. The formal changes in TD's at S, written in analogy with Equations (2.1) and (2.2), are then to be set equal to zero:

$$\Delta(TD)_{ABS} = [(TOT)''_A + T''_{AS} - (TOT)''_B - T''_{BS}] - [(TOT)_A + T_{AS} - (TOT)_B - T_{BS}] = 0 \quad (2.6)$$

$$\Delta(TD)_{BCS} = [(TOT)''_B + T''_{BS} - (TOT)''_C - T''_{CS}] - [(TOT)_B + T_{BS} - (TOT)_C - T_{CS}] = 0 \quad (2.7)$$

It is assumed that the SAM does not control Master Station B, so that as before

$$(TOT)''_B = (TOT)_B \quad . \tag{2.8}$$

It follows from the last three equations that

$$(TOT)''_A = (TOT)_A - (T''_{AS} - T_{AS}) + (T''_{BS} - T_{BS}) \tag{2.9}$$

$$(TOT)''_C = (TOT)_C + (T''_{BS} - T_{BS}) - (T''_{CS} - T_{CS}) \tag{2.10}$$

Substituting Equations (2.8), (2.9), (2.10) in Equations (2.1) and (2.2) gives

$$\Delta(TD)_{ABP} = \{(T''_{AP} - T_{AP}) - (T''_{BP} - T_{BP})\} - \{(T''_{AS} - T_{AS}) - (T''_{BS} - T_{BS})\} \tag{2.11}$$

$$\Delta(TD)_{BCP} = \{(T''_{BP} - T_{BP}) - (T''_{CP} - T_{CP})\} - \{(T''_{BS} - T_{BS}) - (T''_{CS} - T_{CS})\} \tag{2.12}$$

These equations for the SAM-synched case are similar to Equations (2.4) and (2.5) for absolute synchronization, except that each contains an extra term of similar type.

3.0 CALCULATION OF TD CHANGES

In an XY rectangular coordinate system let the equation of the frontal line be

$$y = y_o + mx \tag{3.1}$$

where m is the slope of the line and y_o its intercept on the y-axis. For brevity the special case $m = \infty$, which leads to even simpler expressions, is excluded from the following discussion. The passage of the line is simulated by choosing a succession of increasing values for y_o. If point P has coordinates (x_P, y_P), the perpendicular distance D_P from P to the line is given by

$$D_P = \frac{y_P - mx_P - y_o}{\overset{+}{}\sqrt{1 + m^2}} \tag{3.2}$$

This formula gives a positive distance if P is above the line, and a negative distance if it is below the line. Similarly the distance of transmitter A (coordinates x_A, y_A) from the line is

$$D_A = \frac{y_A - mx_A - y_o}{\overset{+}{}\sqrt{1 + m^2}} \tag{3.3}$$

The reader may show by making rough sketches, that the fraction F_{AP} of the path AP having velocity v_o must have one of the four possible values listed in the chart, Table 3.1, depending on the values obtained for D_A and D_P. In the case $D_A \rightarrow 0$ <u>AND</u> $D_P \rightarrow 0$, the propagation path grazes the interface between the two velocities and wave refraction phenomena including total reflection may be significant. Since those topics are beyond the scope of this paper, the grazing case is simply regarded as being indeterminate.

Table 3.1. Possible Values of the Fraction F_{AP}

D_P \ D_A:	>0	=0	<0
>0	0	0	$\left\lvert \frac{D_A}{D_A - D_P} \right\rvert$
=0	0	*	1
<0	$\left\lvert \frac{D_P}{D_A - D_P} \right\rvert$	1	1

The travel time on the path AP is evidently

$$T''_{AP} = F_{AP} \frac{\widehat{AP}}{V_o(1 - f)} + (1 - F_{AP}) \frac{\widehat{AP}}{V_o} \quad . \tag{3.4}$$

Since f << 1, to a sufficient approximation

$$\frac{1}{1 - f} = 1 + f \tag{3.5}$$

and since the initial travel time was

$$T_{AP} = \frac{\widehat{AP}}{V_o} \tag{3.6}$$

it follows that

$$T''_{AP} - T_{AP} = \frac{f\ F_{AP}}{V_o} \cdot \widehat{AP} = \frac{f\ F_{AP}}{V_o} \cdot \sqrt{(x_P - x_A)^2 + (y_P - y_A)^2} \tag{3.7}$$

Similarly for Stations $B(x_B,y_B)$ and $C(x_C,y_C)$,

$$T''_{BP} - T_{BP} = \frac{f}{V_o} F_{BP} \cdot \sqrt{(x_P - x_B)^2 + (y_P - y_B)^2} \tag{3.8}$$

$$T''_{CP} - T_{CP} = \frac{f}{V_o} F_{CP} \cdot \sqrt{(x_P - x_C)^2 + (y_P - y_C)^2} \tag{3.9}$$

Similarly with a SAM at $S(x_S,y_S)$,

$$T''_{AS} - T_{AS} = \frac{f}{V_o} F_{AS} \cdot \sqrt{(x_S - x_A)^2 + (y_S - y_A)^2} \tag{3.10}$$

$$T''_{BS} - T_{BS} = \frac{f}{V_o} F_{BS} \cdot \sqrt{(x_S - x_B)^2 + (y_S - y_B)^2} \tag{3.11}$$

$$T''_{CP} - T_{CS} = \frac{f}{V_o} F_{CS} \cdot \sqrt{(x_S - x_C)^2 + (y_S - y_C)^2} \tag{3.12}$$

For each path the fraction F_{BP}, etc., is to be found by reference to a table similar to Table 3.1, using equations similar to Equations (3.2) and (3.3) obtained by the appropriate changes of subscripts. The changes in TD's are then given by Equations (2.4) and (2.5) for absolute station synchronization or by Equations (2.11) and (2.12) for the SAM-synched case.

4.0 FIX-DISPLACEMENT

It remains to find the fix-displacement in terms of the two TD changes. For this purpose it suffices to assume that the propagation velocity is uniformly v_o over the coverage area. Then the TD at field point P for Station-pair AB, depends on the distances $\widehat{AP}$ and $\widehat{BP}$:

$$(TD)_{ABP} = \frac{1}{v_o} (\widehat{AP} - \widehat{BP}) \tag{4.1}$$

Small displacement dx and dy move the field point from P to P′, and cause a change in TD given by the total differential:

$$d(TP)_{ABP} = \frac{\partial(TD)_{ABP}}{\partial x} dx + \frac{\partial(TD)_{ABP}}{\partial y} dy \tag{4.2}$$

$$= \frac{1}{v_o}\left(\frac{\partial\widehat{AP}}{\partial x_P} - \frac{\partial\widehat{BP}}{\partial x_P}\right)dx + \frac{1}{v_o}\left(\frac{\partial\widehat{AP}}{\partial y_P} - \frac{\partial\widehat{BP}}{\partial y_P}\right)dy \tag{4.3}$$

now

$$\frac{\partial\widehat{AP}}{\partial x_P} = \frac{\partial}{\partial x_P} \sqrt{(x_P - x_A)^2 + (y_P - y_A)^2} = \frac{x_P - x_A}{\widehat{AP}} \tag{4.4}$$

and similarly for the other partial derivatives. Then on replacing differentials by finite differences indicated by the Δ-symbol.

$$v_o\Delta(TD)_{ABP} \approx \alpha_1\Delta x + \beta_1\Delta y \tag{4.5}$$

where

$$\alpha_1 = \frac{x_P - x_A}{\widehat{AP}} - \frac{x_P - x_B}{\widehat{BP}} \tag{4.6}$$

$$\beta_1 = \frac{y_P - y_A}{\widehat{AP}} - \frac{y_P - y_B}{\widehat{BP}} \tag{4.7}$$

Similarly the move from P to P′ causes a change in the TD for Station-pair BC:

$$v_o\Delta(TD)_{BCP} \approx \alpha_2\Delta x + \beta_2\Delta y \tag{4.8}$$

where

$$\alpha_2 = \frac{x_P - x_B}{\widehat{BP}} - \frac{x_P - x_C}{\widehat{CP}} \tag{4.9}$$

$$\beta_2 = \frac{y_P - y_B}{\widehat{BP}} - \frac{y_P - y_C}{\widehat{CP}} \tag{4.10}$$

Solving Equations (4.5) and (4.8) simultaneously,

$$\Delta x \approx \frac{v_o}{\mathcal{D}} \{\beta_2\Delta(TD)_{ABP} - \beta_1\Delta(TD)_{BCP}\} \tag{4.11}$$

$$\Delta y \approx \frac{v_o}{\mathcal{D}} \{\alpha_1\Delta(TD)_{BCP} - \alpha_2\Delta(TD)_{ABP}\} \tag{4.12}$$

where

$$\mathcal{D} = \alpha_1\beta_2 - \beta_1\alpha_2 \tag{4.13}$$

Since the Δ(TD)'s were found in Sections 2 and 3, the x-, y-displacements can now be found. The magnitude of the displacement

$$\widehat{PP'} \approx \sqrt{(\Delta x)^2 + (\Delta y)^2} \tag{4.14}$$

(It is noted that if changes in TD's are calculated in nanoseconds, taking v_o = 0.3 meters/ns gives the displacement magnitude in meters.

PART II

The numerical calculations were originally programmed on an HP-41CX pocket calculator. This program was checked by laboriously working through a few examples by hand. The program was then transferred in modified form to a PC-type computer.

The algorithm developed by Dr. Lewis was implemented on PC clone computer with an 8087 math chip installed. The programming was done in a high level language called "FORTH." The operating system was from "Harvard Software."

The program was set up to allow versatile implementation by the user. The parameters under user control are:

a) Station location. Master and two Secondaries.

b) SAM location.

c) Location of the field points. (Depending on outputs required, either five (5) points may be specified or a range of field points may be specified.)

d) The angle of the front may be from 1 to 179 degrees in increments of 1 or more degrees.

e) The distance of front with respect to the Master may be specified. The range is from -10,000 to +10,000 in increments of 1 or more.

There are two types of control used in the Loran-C. These are Time of Transmission (TOT) and Surface Area Monitor (SAM). In the former case, the time differences of the Secondaries from the Master station are fixed. In the latter, the emission time of the Secondaries from the Master are adjusted to keep the error zero at the SAM site. In the presence of a front, each of the control systems will have displacement. This model allows an examination of the displacement under varying conditions.

The conditions which we have chosen to present are for the three stations to be in a symmetric configuration. In recti-linear coordinates, the Master station "B" is 0,0, the Secondaries are "A" -866,500, and "C" at 866,500. The propagation front is represented as a straight line inclined at an angle of 45 degrees to the vertical. The propagation velocity is considered to be lower below the front line. The front is shown in three positions in the coverage area. These are just entering, in the middle, and just leaving. The displacements are represented by curves drawn to enclose the 50 meter and under displacements and the 100 meter and under displacements.

Twelve figures are shown. These represent the fronts in three positions: 1) just entering the coverage, 2) in the middle, and 3) leaving the coverage. There is one representation of TOT control and three representations of SAM control. The three SAM are for three differing SAM locations.

In the TOT control, under conditions of uniform propagation, the zero will be at the perpendicular bi-sector of the two baselines. For this configuration, the zero is 0,1000. In Figures 1 and 5 the zero error is at that point. Note along the front the 50 and 100 meter contours are distorted. In Figure 3, the front is in the middle of the coverage area. There are major distortions in the 50 and 100 meter displacements.

Figures 2, and 4 through 6 represent SAM control. The SAM is located at the 0,1000 location. By definition, under SAM control, a zero error will be at the SAM location. Again note the distortion of the contours along the front line.

Figures 7, 9, and 11 are again SAM control with the SAM control at location 0,500. Figures 8, 10, and 12 are SAM control with the SAM near one of the Secondary -500, 500.

The distortion of the displacement contours when the anomaly is in the middle of the coverage area was a surprise. Several checks were done to confirm the distortion.

SUMMARY

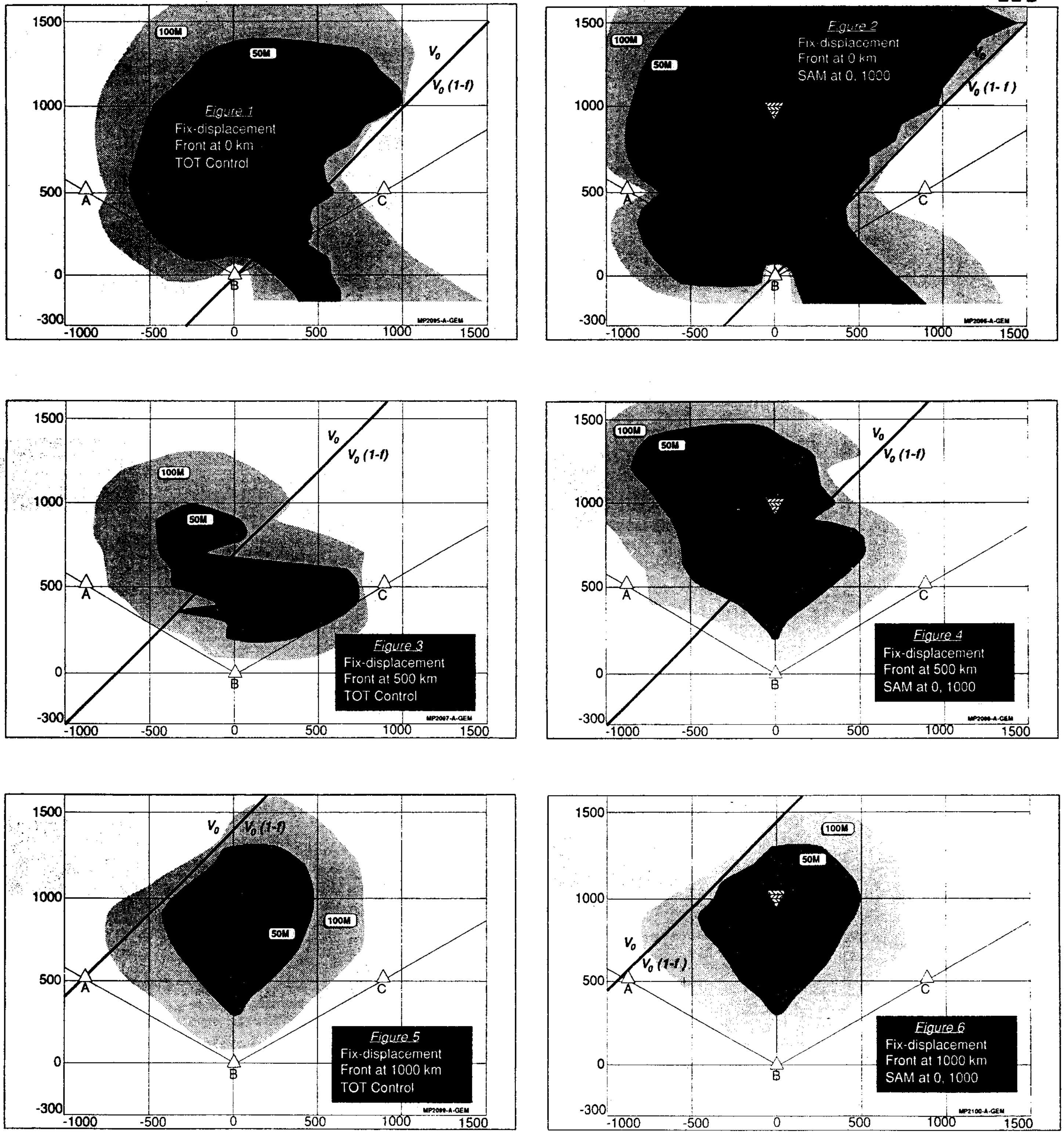
We have developed a program which will be of aid in the analysis and evaluation of past and future Loran-C installations.

The algorithms can be expanded to account for spherical earth. Efforts are being made to improve the presentation of the data generated.

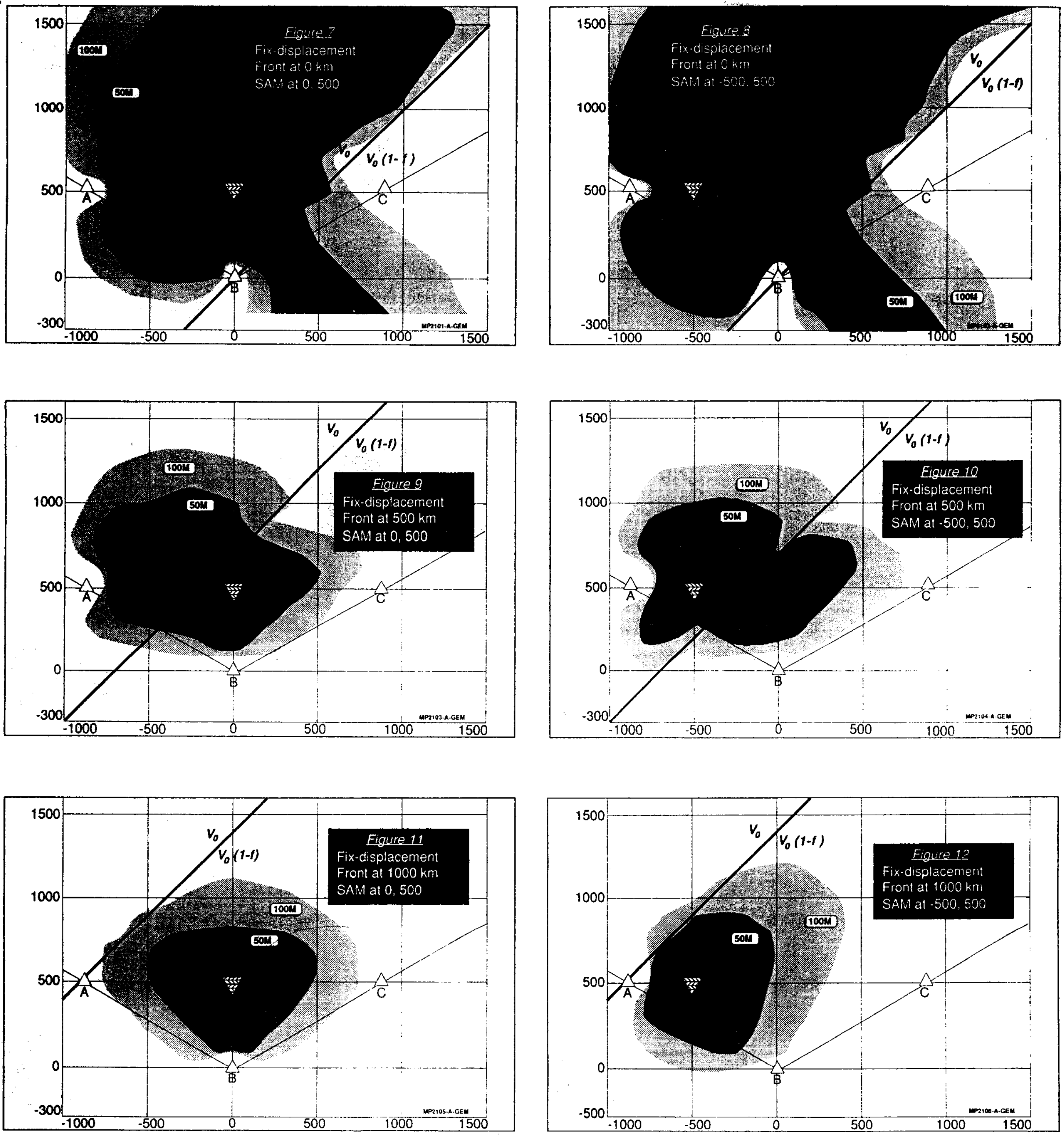
BIOGRAPHIES

Edward A. Lewis, born in 1918; graduated from Dalhousie University with B.Sc. and M.Sc. degrees. Following World War II service in the Canadian Navy, he received the degree of Ph.D. from Massachusetts Institute of Technology in 1949. He became a civilian scientist with the USAF, retiring from the position of Chief of the Radio Wave Propagation Branch of Rome Air Development Center in 1980. In 1988 He retired from the position of Senior Scientist at Megapulse, Inc., and is currently on consultant status. Dr. Lewis is the author of a number of theoretical and experimental scientific papers and technical reports.

Donald E. Meyers, born in 1929. Entered Air Force in 1948. Following the service, he graduated from the University of Connecticut with a B.S. in Electrical Engineering. In 1957 he joined the Applied Research Laboratory of GTE. In 1972 he joined Megapulse, Inc. During this time he worked on the development of the Solid-State Transmitter. He is currently employed by Megapulse as a Senior Systems Engineer.



Figures 1-6. **Loran fix displacement (50 and 100 meter) due to propagation velocity change. The front is represented by the heavy 45° line and is located at 0, 500, or 1000 km from the Master transmitter (B) as shown. Secondaries are under Time of Transmission (TOT) control in figures 1, 3, and 5, and under System Area Monitor (SAM) control in figures 2, 4, and 6, with the SAM at 0, 1000.**



Figures 7 - 12. **Loran fix displacement (50 and 100 meter) due to propagation velocity change. The front is represented by the heavy 45° line and is located at 0, 500, or 1000 km from the Master transmitter (B) as shown. Secondary transmitters are controlled by a Surface Area Monitor located variously as indicated in each figure.**

ABSTRACT.

Hereunder described has the intention to demonstrate a method for hardlimit-recievers that has two main targets:

- define a Loran-C-burst-start and subsequentely point out the selected zero-crossing of the burst valid for time-measurement

- identify whether incoming signal has a high probability of beeng a Loran-C-signal

Above targets shall be reached with:

- simple analogue signal-processing; delays and additions

- only one-bit A/D-conversions

- digital signal-processing

REFERENSES, MOTIVES.

The author worked earlier with navigation but not with Loran-C.

During the last few years a lot of conferences etc. have taken place regarding navigation in a general as well as more special sense.

The references that follow have, during the last decade, stimulated the authors reflections regarding Loran-C:

- 1977-79: cooperation with the Danish group behind the AP-navigator, a Decca type pleasure-boat-navigator.
- the thesis 1980 of Dr Lars Olsson, the Lund Institute of Technology, Sweden.
- the thesis 1985 of Dr Durk van Willigen, the Delft University of Technology, The Netherlands..
- papers from a couple of conferences arranged by Royal Institute of Navigation, Gt Britain.
- papers from NORNA 88 a conference arranged by some scandinavian navigational institutions.

Living with these referenses in the back of the head it can be concluded that - in spite of the GPS-system's fine performance - the Loran-C-system will not only survive in Europe but that it will also grow there. Even if there no doubt are additional problems for Loran-C in Europe.

Furthermore: in the part of Europe where I live - east coast of Sweden by the (the authors view: not unimportant) Baltic Sea - we have even more Loran-problems: only marginal coverage from the North Atlantic chain; Swedish Decca chains are run at low cost by the Swedish National Administration of Shipping & Navigation. They are planned to last for a long while.

This means that the investment climate for Loran-C in the Baltic area could be better.

But evidentely Sovjet's Chaika (Loran-C-similar system) has a coverage over the better part of the Baltic Sea. Future will tell if the US Coast Guard and their Russian counterparts can get things tuned together so that Loran-C and Chaika can form a true navigational system together.

Maybe the Loran-C-system one day can be a strong system in my "home market".

Waiting for this let us look at burst-sensing in Loran-C--recievers of hardlimit-type.

A Burst-Sensor.

Hardlimiting the Loran-C-signal

- is good when it comes to determine the time of the zero-crossings.

- gives no help to determine which zero-crossing that is to be read.

- gives no help to indicate if the probability is high that the a zero-crossing comes from a Loran-C-signal and not from an interference.

It is well-known how the waveform of a Loran-C-burst looks. The useful part lies in the beginning of the burst. But in the early beginning the zero-crossings are of low amplitude, to much overridden by noice. A few zero-crossings later sky-waves are polluting the navigational information content.

The part of the burst with useful information (typically 10-40 µsec after burst-start) gives rise to a number of zero-crossings that as well could have been generated from a CW-signal.

No good; could envelope-manipulation help us to select the specified zero-crossing with hard-limiting; without direct analogue comparisons?

Let us for a moment think of the envelope of the Loran-C signal and the first resp. second time-differential of same envelope (E, E'resp. E" of fig. 1).

It can be noted from fig. 1. that the second time-differential of the envelope is the only of these functions that changes sign during the first part of the burst - which is the only part we are interested in. Can we use this peculiarity?

If the second time-differential of the envelope - in some mysterious way - was produced in the reciever, modulated on the same carrier then we could - using an algorism - combine it (hardlimited) with the real Loran-C-signal (also hardlimited) and obtain a switch message saying: "We are now ≈ 19 µsec's after burst-start."

But the second time-differentiation of the envelope modulated on the same carrier as the recieved Loran-C-signal is not so easyly produced in a Loran-C-reciever. We can therefore use the words William Shakespere put in prince Hamlet's mouth: " 'tis a consummation devoutely to be wished."

But are there other ways to use the change of sign of the envelope's second derivate that comes decently close to burst start?

Maybe there is.

Let us do non-stringent first and second time-differentiations of the incoming signal as described hereunder. We call it:

Falsification 1.

A) Start with the real recieved Loran-C-signal L(t) where

$$L(t) = t^2*e^{-2*t/65}*\sin(2*\pi*f*t).$$

and where t = time after burst-start in µsec;
f = carrier frequency. (100 kHz.).

B) Apply on L(t) the time-differentiating formula

$$dL(t)/dt = \text{limes}((L(t+\delta t)-L(t))/\delta t) \text{ when } \delta t \to 0.$$

but let δt (instead of -> 0) be the time of one period of the carrier wavelenght, namely 10 µsec.

C) This is done by delaying the Loran-C-signal one period and then subtract the original signal from the delayed one.

D) The difference from C) above can we now call a false, on the same carrier modulated, first time-differential of the envelope.

E) Do similar falsifications to obtain a false, modulated second time-differential of the envelope.

The Loran-C-signal (L in fig. 2) and the falsified two differentials (L'_{F1} and L''_{F1} in fig.2) are demonstrated in fig. 2. If one now applies hard-limiting to the obtained waveforms and thereafter gives a digital command that a signal reports "no" if Loran-C and false second derivate are both poitive or both negative whereas the report is"yes" for other conditions. The "yes" report (L_{SW} in fig. 2) comes here almost 30 µsec. after burst-start.

This is no doubt one way to report burst-start (after a known delay) using a hardlimiting process and without making amplitude comparisons using analog methods or multi-bit A/D-conversions.

But the report comes a bit late: ≈ 30 µsec. after burst-start. Let us see if we can do something smarter:

Falsification 2.

A) Do the same operations as in the first falsification with the following two changes:

B) Set δt = 5 µsec. instead of 10 µsec.

C) Use addition of the original signal to the delayed one instead of subtraction. (Adding every second halfperiod of modulated carriers gives results of the same type as subtracting every second period of the modulated carrier frequency.)

Let us have a look at L, L'_{F2}, L''_{F2} resp. L_{SW} in fig. 3; similar waveforms as fig.2 but resulting from the operations specified under "Falsification 2." above. Same type of operations gives us report of start ≈ 24 µsec. after burst-start. Cood enough; let

Analogue processing is [illegible] now applied [illegible] following the rules of "falsification 2". Only delays and adding of signals are used.

Realization of the analogue part is shown in fig. 4. with the output signals here called A, B and C.

Signal A: The recieved Loran-C-signal,
Signal B: The first time-differentiation of the envelope modulated with the same carrier as signal A.
Signal C: The second time-differentiation of the envelope modulated with the same carrier as signal A.

Signal B as well as signal C are now obtained via non-stringent derivations as defined in falsification 2 above.

We can now go over to one-bit A/D-conversion of signal A, B and C; thereby obtaining the hardlimited signals A_H, B_H and C_H respectively Dirac-pulses A_D, B_D and C_D.

Therefore let us have a look at fig 5. showing these signals.

If we now wants to use these puls-trains to

a) find the selected zero-crossing (25 µsec after burst-start) and
b) at the same time find out (with decent probability) that the chosen zero-crossing comes from a Loran-C-transmitter burst

then let us for instance use a set of conditions as described hereunder to create the needed algorism:

- make a shift register (size: two registrations/enough bits) for time-reading
- make another shift register (four registrations/one bit) for polarity observations
- if A_D, B_D and C_D are simultaneous (within specified value) with A_D and B_D of same polarity then let A_D initiate a clock reading to be sent to the shift register for time
- if C_D has the same polarity as A_D and B_D then send '+' to the shift register for polarity
- if C_D has the opposite polarity as A_D and B_D then send '-' to the shift register for polarity
- if the four registrations in the polarity register are '-', '-', '+' and '+' respectively then accept the time-readout that was done before last readout as '<u>probably Loran-C-burst; time-reading 25 µsec. after burst-start</u>'.

This algorism gives a "yes" for time reading only if A_D and B_D are simultaneous and have the same sign. This means that we have repeated zero-crossings 5 µsec apart and the thus obtained indications are carried on 100 kHz and that the last halfperiod of the carrier has a bigger absolute value than its predecessor but is of opposite sign.

When the algorism's last reading of the polarity register is: ('+','+','-' and '-') time is 30 µsec after burst-start. Reading time-register before latest input gives then the redout value is 25 µsec after burst-start.

It seems obvious that an interfering signal will meet difficulties if it wants to outmaneuver this algorism. The need

Comments:

- a built-out system using the principles above produces probably fewer but more reliable time-readouts; the consequenses for the sequential tracking system that follows has not been dealt with in this paper

- possible enlargements of the algorism to make (for instance) sky-wave-adaptability possible has neither been dealt with

- because of the historical (and geographical) background of the author as indicated above there might be a risk that some of what is said above is not new. A number of claims are therefore given to the Swedish Patent authorities to get these questions sorted out.

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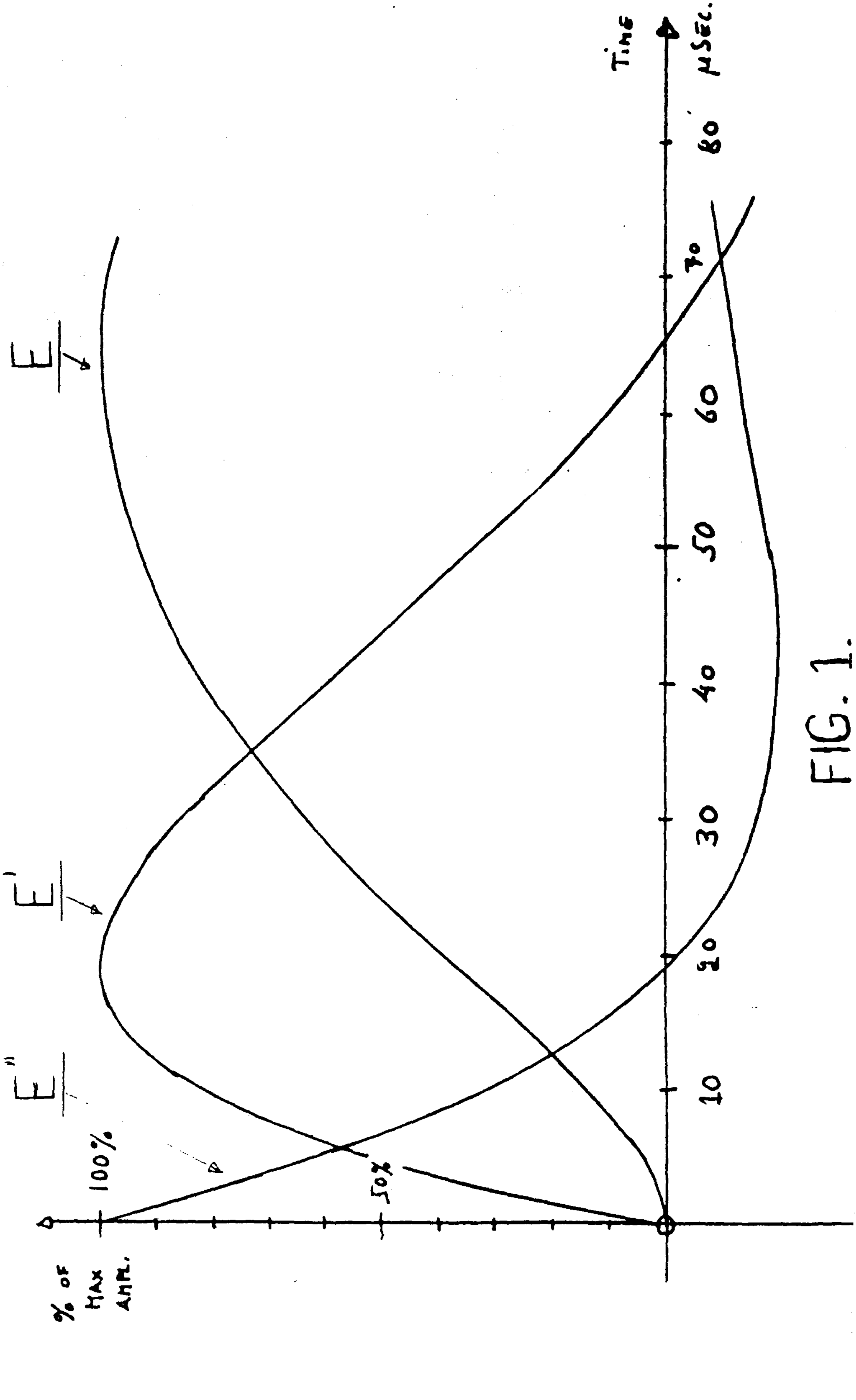


FIG. 1.

FALSIFICATION 1.

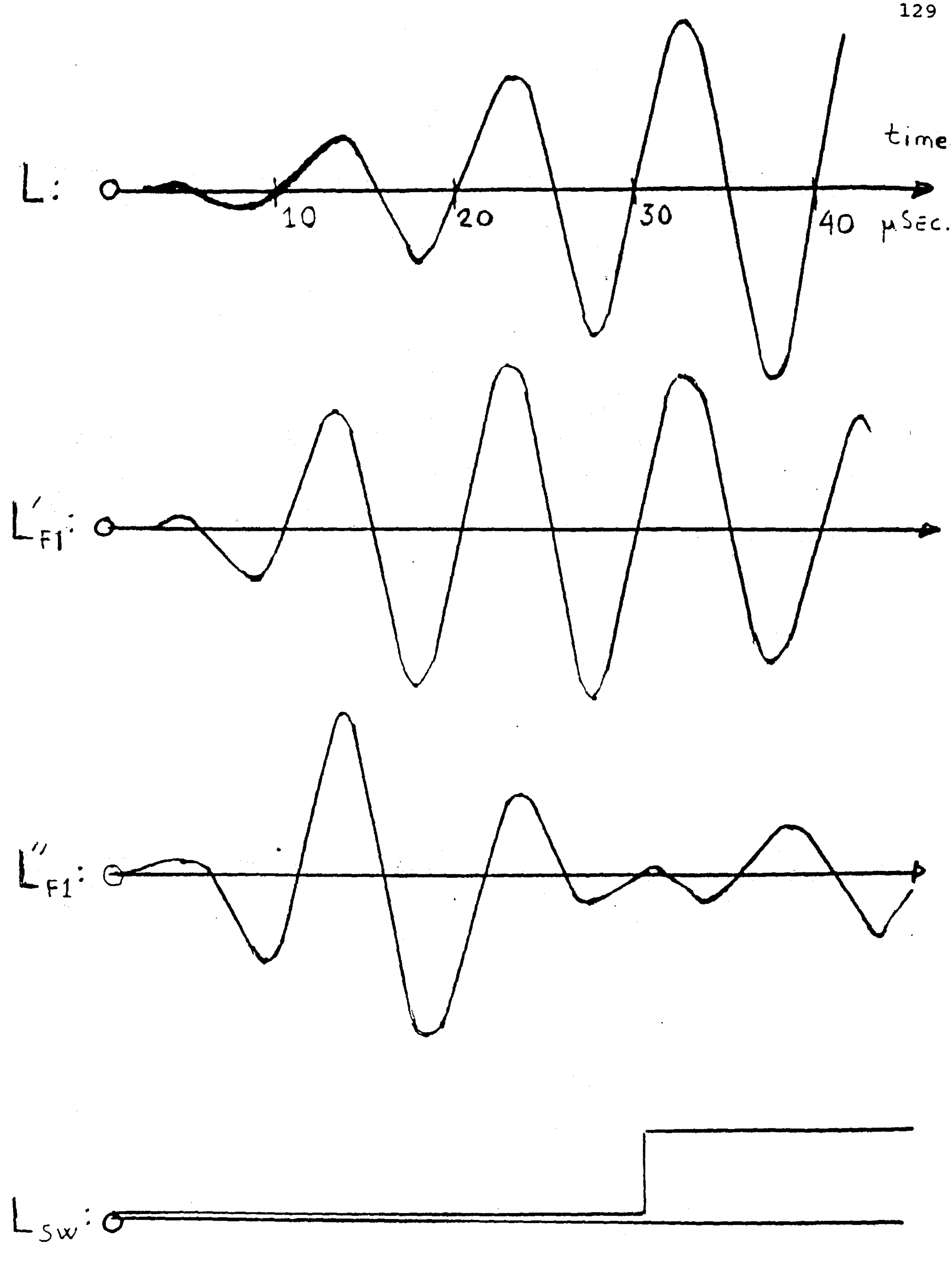


FIG. 2.

FALSIFICATION 2.

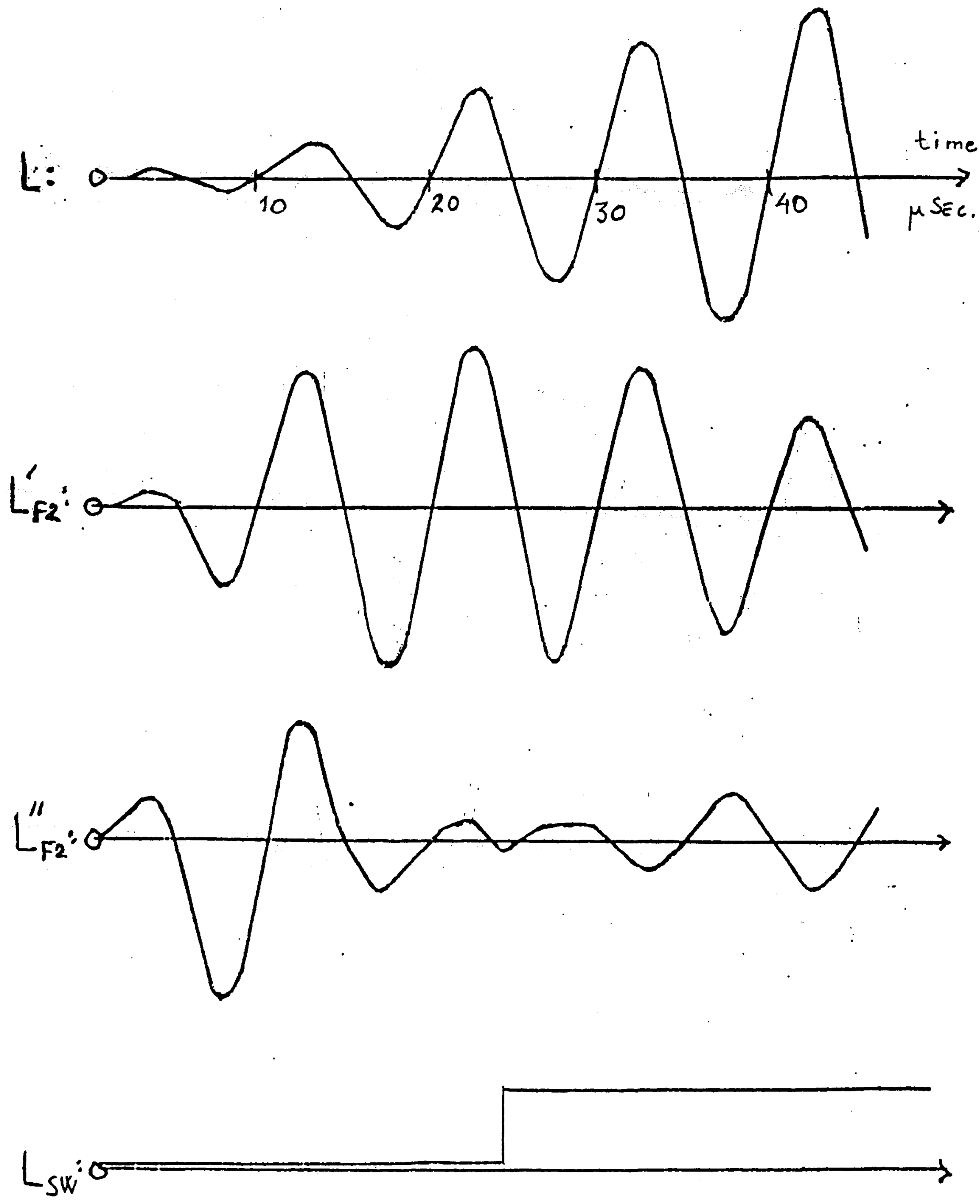


FIG. 3.

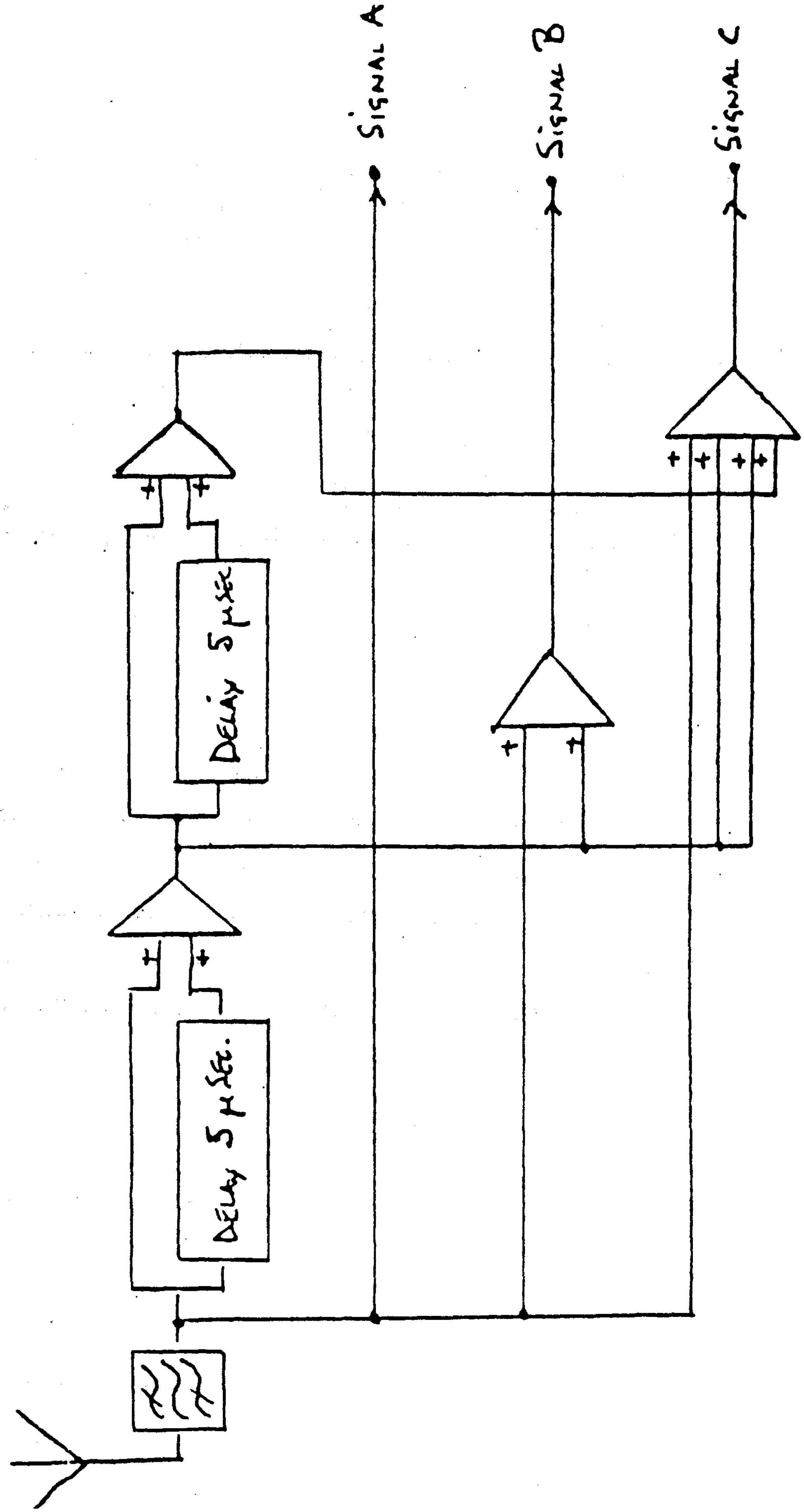
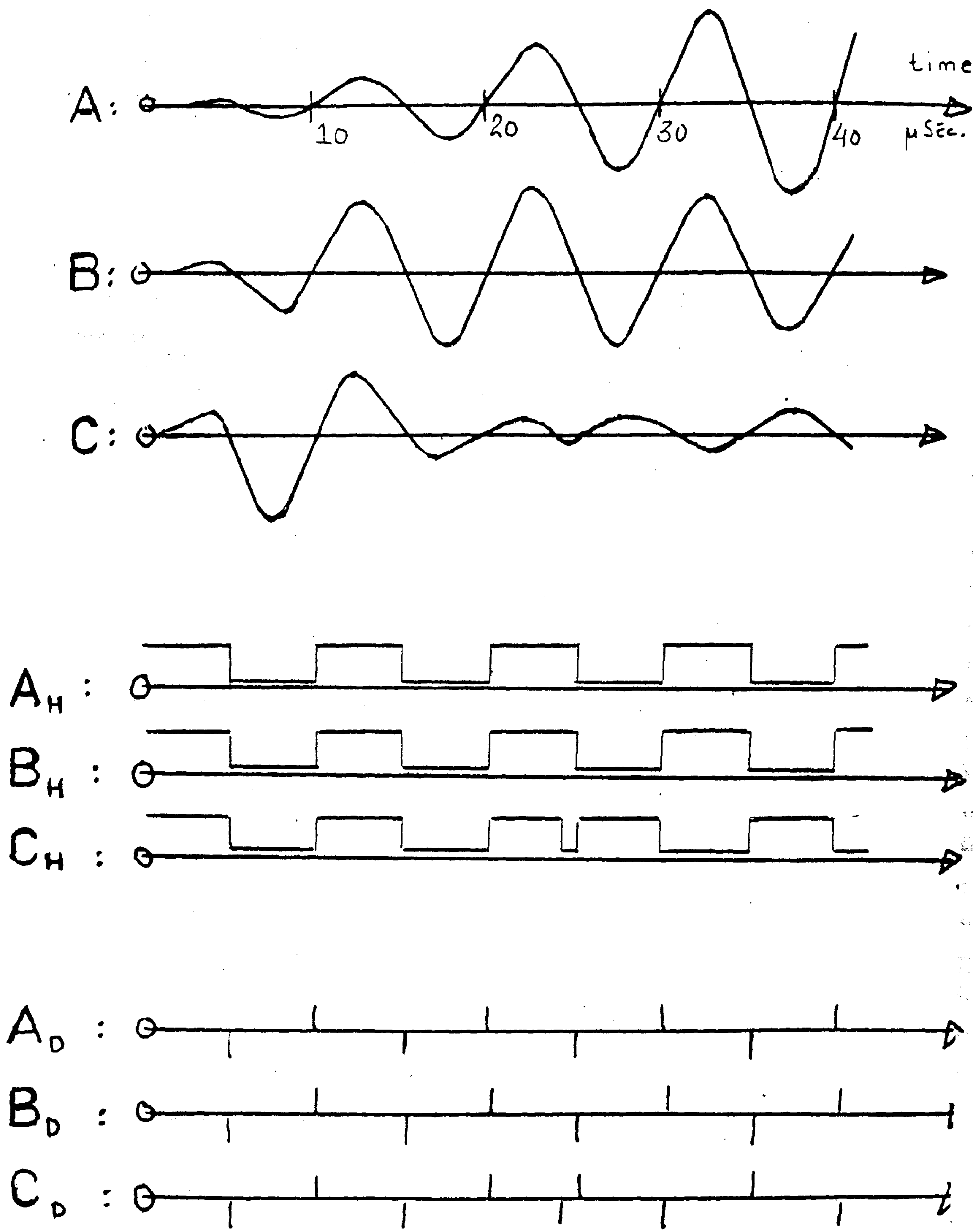


FIG. 4.

FIG. 5.



PERSONAL NAVIGATION

by

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ABSTRACT

The combination of the latest techniques in Digital Signal Processing along with the current technologies relating to multiple High Integration microprocessors, VLSI circuit use and HCMOS processes has yielded a new generation of LORAN receiver characterized by high performance, low power consumption and true handheld portability. This new type of design described herein as a Linear Averaging Digital Receiver will establish new standards of performance for LORAN navigation and will result in the application of LORAN to new market concepts, i.e. the "Personal Navigator".

HARD LIMITED versus LINEAR AVERAGING DIGITAL Receivers

The majority of LORAN receiver designs today have evolved to the standard Hard Limited approach mainly because it offers a reasonable level of performance with low cost and simplicity of design. With high integration microprocessors, a minimum of electronic support circuits are needed; single and dual circuit board LORANs are the state-of-the-art for the industry.

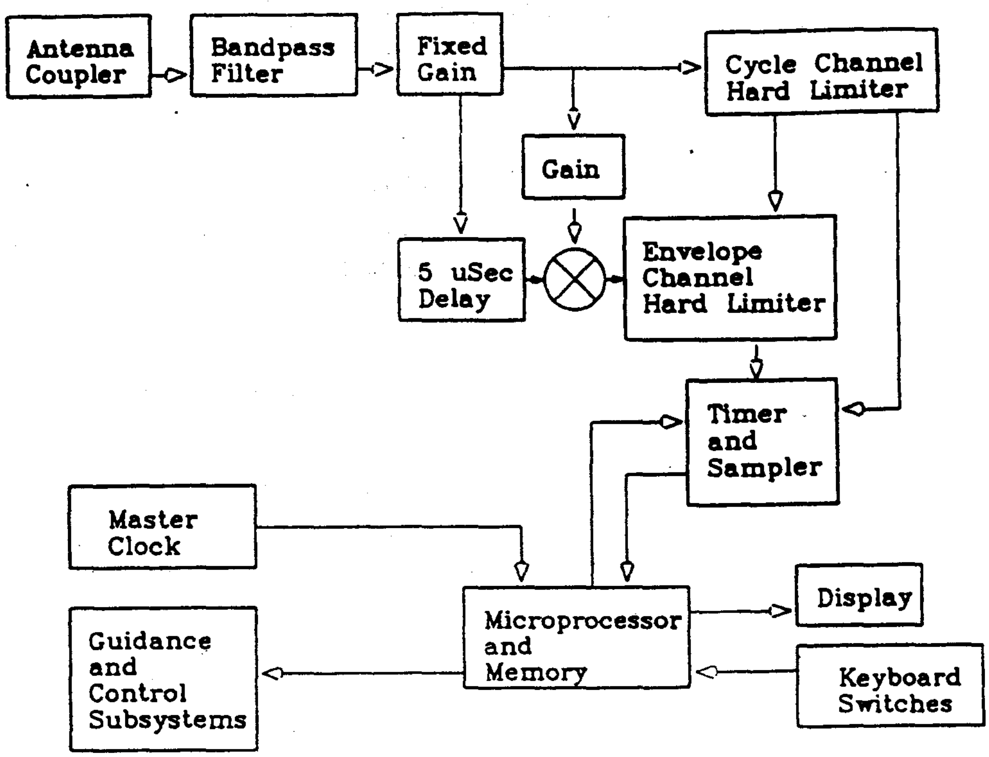

Fig. 1 Hard Limited LORAN Receiver Block Diagram

Hard-Limiting receivers quantize signals to one bit before processing with the analog carrier and envelope signals being created before separate hard-limiting. A variety of signal processing methods may be used on these signals in order to acquire the LORAN station TD information. Hard-limiting allows for a simple receiver design that rejects large amplitude burst noise. The cost of an error is the same from a large burst or relatively small burst, at worst only a sign change may occur. The hard-limit design suffers from the inability to reject CW interference and also neglects information which may provide more rapid acquisition.

QUANTIZING REQUIREMENTS for the LINEAR AVERAGING RECEIVER

Linear Averaging Digital receivers quantize the LORAN signal with multi-bit resolution and maintain an averaged waveform in memory. The quantizer (A/D converter) is similar to the hard limit receiver when the resolution is one bit and logically no additional information is obtained by this configuration. For additional increments in resolution, Figure 2 shows the digitized representation for 2 bits(2a), 4 bits(2b) and 6 bits(2c). In all representations, the quantizer clip level equals the LORAN pulse peak.

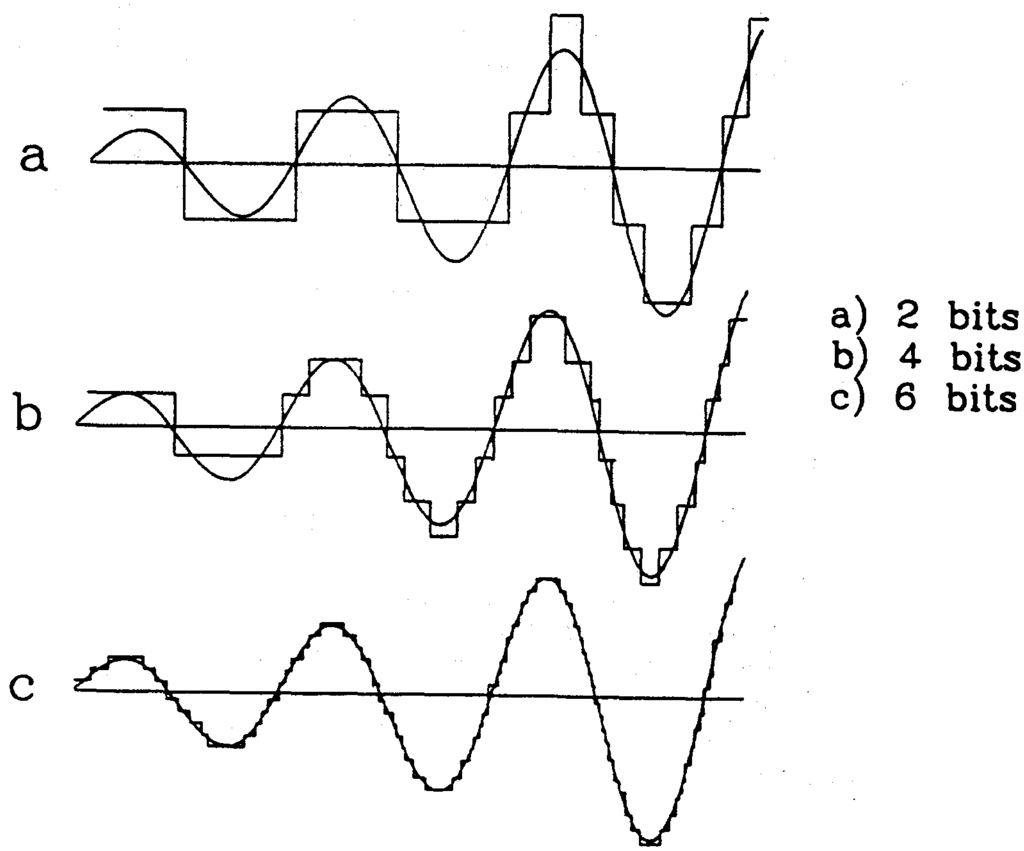

Fig. 2 Resolution for various A/D configurations

GAIN ZONES

For minimal quantizer bit resolution, it is important to properly frame the first 50 microseconds of the LORAN signal with regard to quantizer signal clip level. For this purpose, a means of dynamically adjusting the front-end gain is required and is accomplished with the microprocessor establishing Gain Zones for each station received, dependent on the on-going evaluation of the magnitude of the received signals. Figure 3 relates the method of establishing assigned zones of gain for the purpose of equalizing or normalizing quantizer resolution. Important features of the gain stages is that they do not cause the filter stages to ring for gain transitions and that the phase shift be minimal for every level of gain allowed.

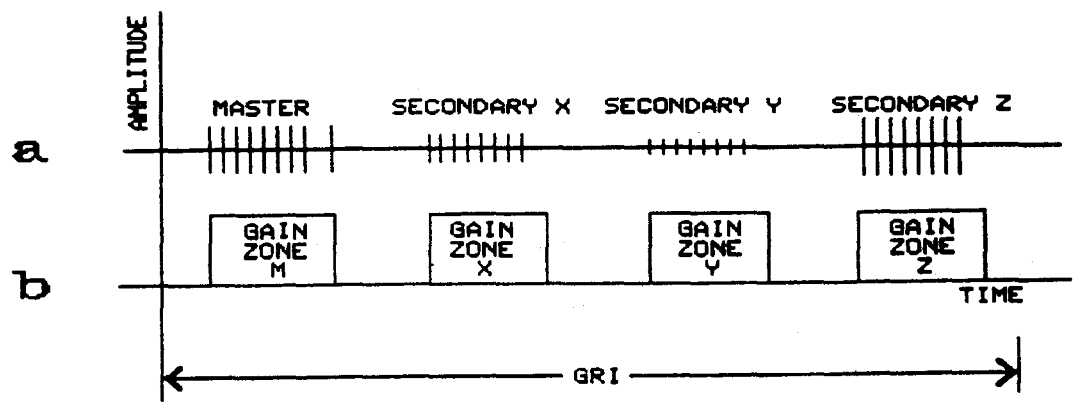

Fig. 3 GRI Gain Zoning

CLIP DETECTION

A major difference between the hard-limited and linear detector designs is in the treatment of burst or impulse noise. As previously discussed, a large impulse whether it be due to natural or manmade origin, would only contribute an error of one bit to a hard-limit signal average, but a linear detector allows the impulse to contribute a multi-bit error. One scheme to reduce the sensitivity of the Linear Averaging Digital receiver to large amplitude noise is to use the fact that the desired signal is framed to use most of the resolution the quantizer, with any larger signal or noise causing the clipping of the A/D output. Error contributed by the corrupted samples towards the average would then be limited. Even with this limiting process, it is undesirable to add clipped samples to the average so a further method is to detect the occurrence of an excessive number of clipped levels and then to discard the entire sampled signal before averaging.

AVERAGING

Linear averaging of the LORAN signal is a technique that has been used mostly on an experimental basis in the past. Operating on the basis that the phase coding of the signal repeats every second GRI, a very basic averaging receiver could be fabricated with a large acquisition memory and a highly stable clock. The repetition rate for each ensemble is thus equal to two GRI's and all phase codes will be additive regardless of their position within the GRI. A block diagram of this type of receiver is shown in Figure 4.

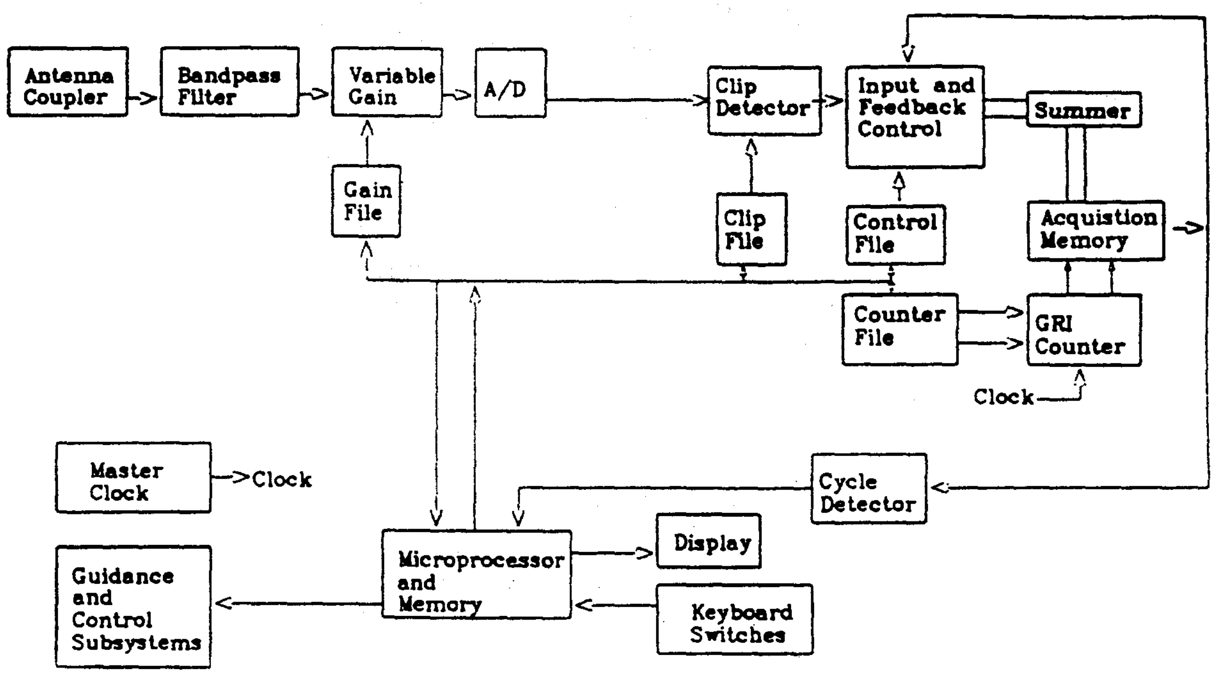

Fig. 4 Basic Averaging Receiver

By adding together a number of GRI's (limited only by the constraints of clock stability and memory width), the resultant signal would show improvement in the signal-to-noise similar to the simulated waveforms of figure 5. After, or possibly even during the signal acquisition phase, the output could be fed to a cycle detector for evaluation of the zero crossing points.

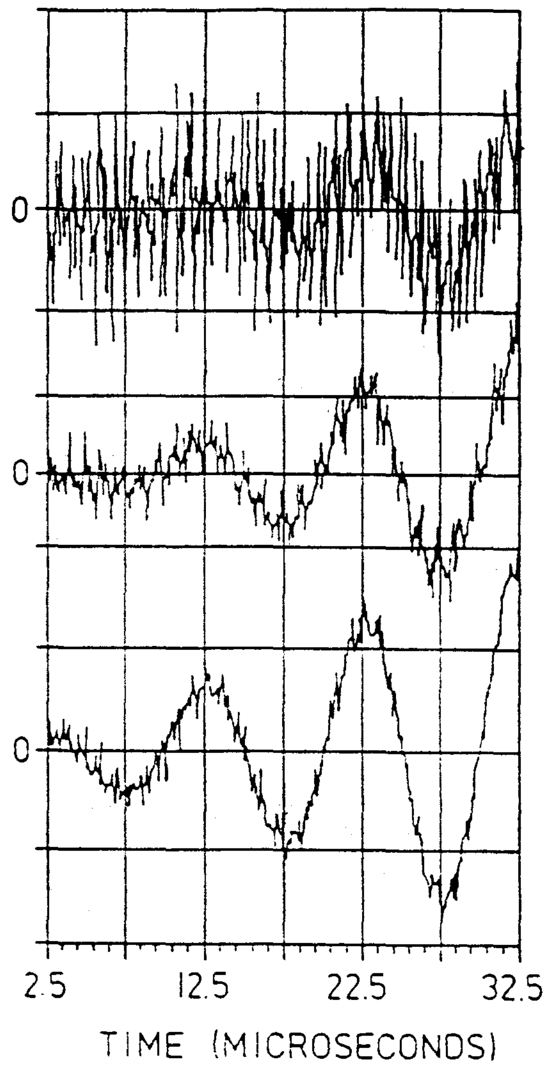

Fig. 5 Effects of Signal Averaging on Gaussian Noise

CLOCK SYNCHRONIZATION

Critical to the successful use of signal averaging techniques in LORAN receivers is the synchronization of the local GRI counter to the exact frequency of the GRI chain being used. Typical averaging intervals dictate short term clock stabilities of one part per million or better. Prior technologies have not allowed this type of performance at the low cost needed for a commercial product.

The clock synchronization method used in this design includes a processor controlled oscillator in conjunction with software algorithms to detect synchronization errors. Appropriate adjustments are then made on a real-time basis and the clock is literally phase locked to the strongest LORAN station's Cesium reference.

PHASE CONTROL

Much has been written on the LORAN phase coding characteristics and the built-in (and not quite optimal) ability to reduce the effects of cross-rate interference, CW interference and skywave contamination. Most of the concerns documented have been made with regard to the use of receiver phase strobing for the purpose of minimizing Cross Rate Interference through cross correlation processing techniques. Similar techniques are easily performed in the Linear Averaging Digital design. Figure 6 shows the usual phase coding scheme utilized in LORAN transmissions today.

	GROUP A										GROUP B									
	PULSE NUMBER										PULSE NUMBER									
	0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9
MASTER	+	+	−	−	+	−	+	−	N	+	+	−	−	+	+	+	+	+	N	−
SECONDARY	+	+	+	+	+	−	−	+	N	N	+	−	+	−	+	+	−	−	N	N

Fig. 6 LORAN Phase Patterns

In the design of this particular LORAN receiver, the phase coding is of critical importance for several reasons: 1) in the initial acquisition phase certain phase patterns can identify the position of the master and group codes within the GRI time frame; 2) in subsequent acquisition phases, the location of the slave stations can then found more readily with selective phasing of the input signal; 3) once all stations are identified as to their position spatially in time within the averaging interval, averaging of the pulse signals together within a pulse group is allowed.

The LINEAR AVERAGING DIGITAL RECEIVER

The final design configuration of the Linear Averaging Digital receiver includes all of the features previously described; GRI gain zoning, clip detection/rejection, phase toggling, clock synchronization, signal averaging and additional features not described herein.

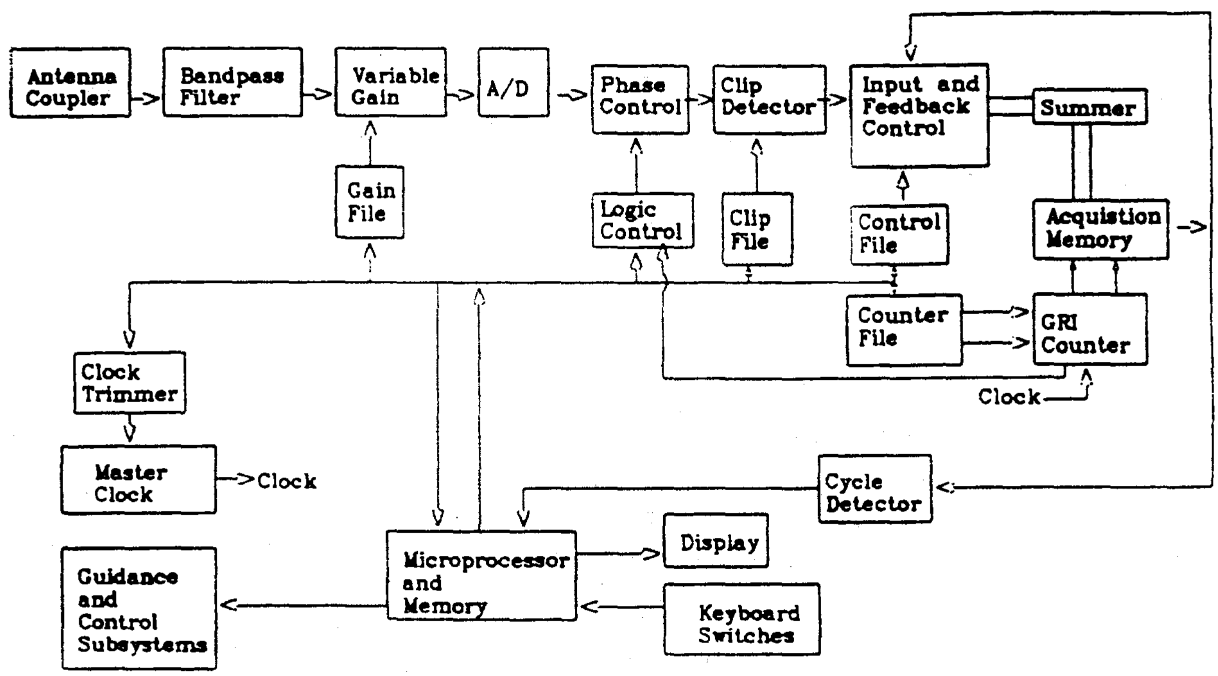

Fig. 7 Linear Averaging Digital Receiver Block Diagram

AUTOMATIC NAVIGATION with the LINEAR AVERAGING RECEIVER

The linear technology of this receiver makes it possible to track stations beyond 1000 nautical miles (1850 Km.). At more reasonable distances, cycle slip conditions are corrected in seconds to less than a minute.

Cycle position tracking is limited by CW interferers, statistical noise, cross rate interference, and skywave contamination. Adequate signal strength is not a problem! Contrary to some advertising claims, groundwave amplitudes are large, well in excess of 100uV/m even at 1100 nautical miles, for the weakest U.S. stations, but the noise is larger still, in the millivolts.

Cross rate interference is reduced by a broad notch at 100KHz. This distorts the pulses slightly, but the linear front end makes amplitude and phase available independently. There is enough information available to correct the distortion fully. With cross rate and narrowband (CW) interference, it is useful to average before signal processing so that the signal information is not swamped out.

The most serious limitation on tracking, even of moderately distant stations, is sky wave contamination, which appears as ECD; enough ECD to cause cycle slip unless it is corrected. At our location,(Madison, WI) for example, the skywave from Seneca routinely exceeds the Minimum Performance Standard values (12dB larger than groundwave and delayed 37.5uS), and Seneca is only 550 nautical miles (1000Km.) away. Some LORAN receivers track it quite poorly (especially at night) despite breathtaking advertising claims.

Figure 8 shows received groundwave data for Raymondville, Texas (1066 nautical miles away) normalized and fitted over the first 25uS to received data from Dana, Indiana. The skywave distortion can be seen (approximately) as the difference. The distortion is huge, and it begins very early, long before any 30 microsecond sampling point. Hard limit receiver designs will have great difficulty determining an accurate zero-crossing point on this signal.

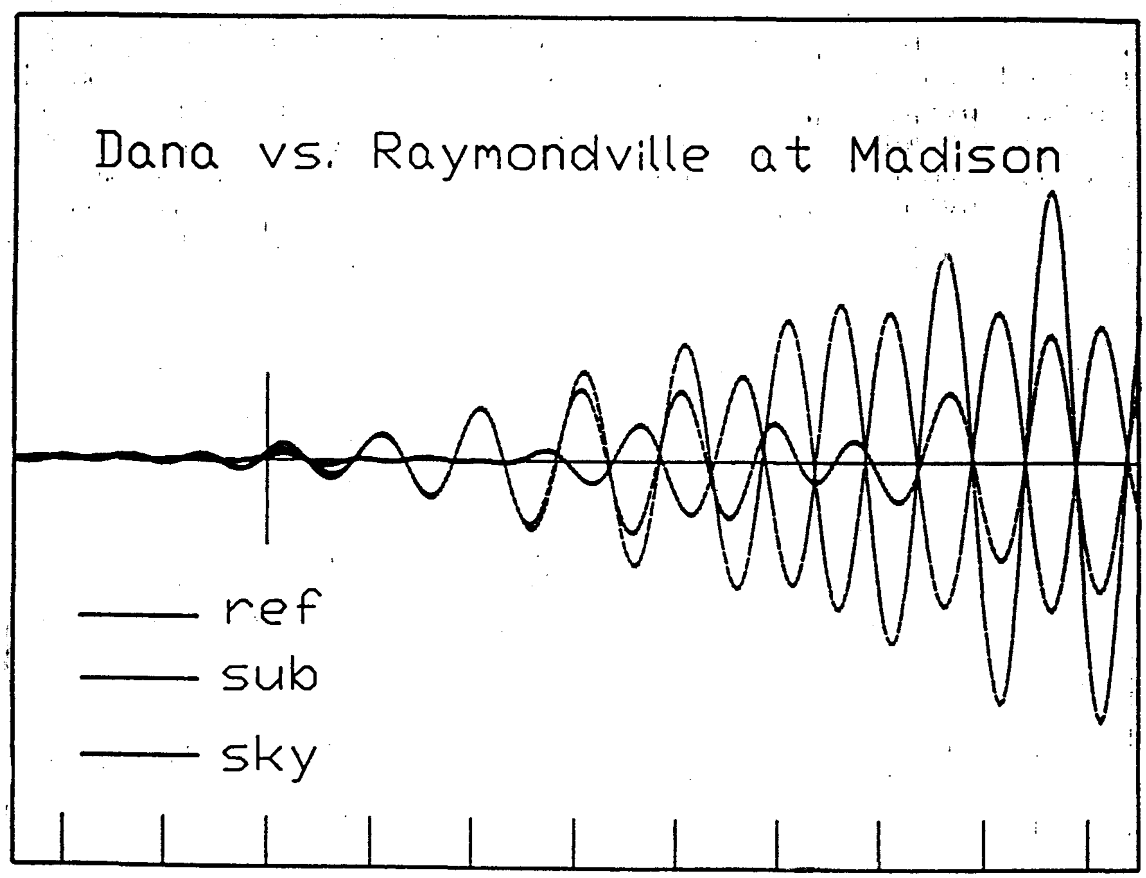

Fig. 8 Raymondville and Dana Data

Figure 9 shows comparative data (samples two minutes apart) from near Sawyerville, Illinois, fitted in the same way. Cross rate interference at this location is negligible (less than 0.6%) and we apparently have a skywave fluctuation early in the waveform. We are only 212 nautical miles (393 Km.) from Dana, with around 50 millivolts of signal!

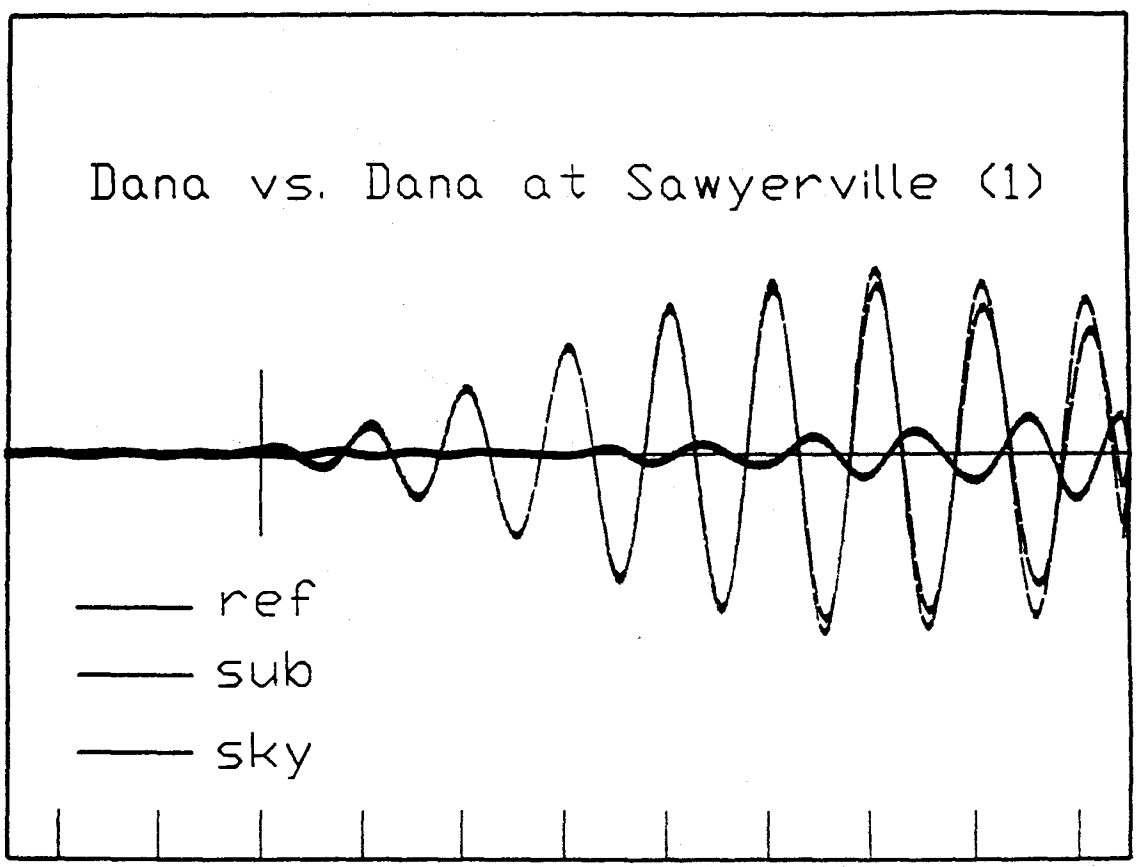

Fig. 9 Received Data, Sawyerville, IL

These figures illustrate why standard hard limit detection techniques often don't work well. The skywave contamination is simply inescapable. There is a front-end filter in use, so that both the pulse and the skywave begin 7-10uS earlier than their nominal starting points although this is not clearly visible at the scale of the figures. The portion of the groundwave which has both significant amplitude and is uncontaminated is essentially nonexistent.

The consequence of this condition is that many receivers have to average long enough to average skywave phases. It can take some receivers many hours, if ever, to correct a cycle slip. The test is simple: turn the receiver off, drive it two miles away, turn it on again, and see if it ever recovers. If it does, see if it also stays recovered.

The linear receiver normally recovers from cycle slip in 15 seconds to a minute for stations out to 850 nautical miles. All of the signal information is available for processing. It is free of the aliasing, second order distortion, and confusion of amplitude with phase, produced by hard limiting. Signal measurements are made primarily by cross-multiplying with carefully designed templates. The full, toleranced portion of the signal enters the calculations. Signal, noise and other amplitudes are available directly so that the averages weight correctly. Amplitude and phase are distinct, making good skywave correction possible.

PERFORMANCE OF A LINEAR AVERAGING RECEIVER

The receiver has a settling time typically less than 20 seconds and rarely exceeds 30 seconds during the daytime. Stations up to a distance of 1100nm can be tracked accurately since any skywave contamination is removed by software filters. The unit will locate and track signals as low as -15 dB in about two minutes.

The unit performs automatic GRI selection and, in fact, can be turned on anywhere in the world and it will determine its current location without user intervention.

PROPRIETARY DESIGN FEATURES

Three patents are in process with the basic patent on ensemble averaging having been issued. One of the patented items is the antenna. In a handheld unit, an antenna with a low driving point impedance is important to minimize capacitive coupling with people and objects near the antenna. One consequence of doing this is an antenna with a near zero impedance at zero Hertz. This eliminates any possibility of static build-up on the antenna.

The antenna needs to be only two to three feet long and the unit can be operated inside of the chain with a one foot antenna. We have found that holding the antenna nearly horizontal degrades the performance only slightly.

Six automatic notch filters have been incorporated together with a circuit which acts like a spectrum analyzer. Interferences can be detected and notched out in two seconds. The notches are 2KHz wide at the -3dB points, 200Hz wide at the -20dB points and have a minimum depth of -30dB.

A second order tracking loop takes into account the effects of system data smoothing and the effects of velocity on position using a modified Kalman filter.

All of the features and functions found on standard lorans have been incorporated except the ability to track sky waves. When one can track ground waves, why bother tracking sky waves?

NAVIGATIONAL EQUATIONS

The navigation equations are set up in a pseudo-ranging form and solved using a maximum likelihood method, depending on such factors as station geometry, signal strength and signal-to-noise ratio. GDOP calculations are made on each slave/master pair and are used to weigh the contribution of each station to the position calculation. A modified Andoyer-Lambert geodesic equation is used since it provides calculations nearly as good as the Sodona equation with less computer overhead. Errors for distances from typical loran stations amounts to 1 - 3 meters. The unit normally operates using a single GRI, however, the unit can operate using all the slaves from two GRI's. If required, the unit can be made to do its calculations in the typical three-station hyperbolic mode.

ADVANTAGES OF A LINEAR AVERAGING DIGITAL RECEIVER

What is the end result improvement in LORAN performance when the previous design features are incorporated in a LORAN receiver?

1)	Improvement in the rejection of continuous wave interference;	Phase toggling prior to adding a sample provides cancellation of most coherent interference.
2)	Increase in the extraction of the information content of the LORAN waveform;	Linear detection provides an inherent 3 to 6 db signal increase over hard-limited detectors.
3)	Speed of acquisition;	TD acquisition times of 15 to 20 seconds in typical signal areas.
4)	Sky waves and Cross Rate rejection	Sky waves and cross rate easily removed from linear signal.
5)	Improved accuracy;	Allows the unraveling of ground and sky waves by using cross correlation masks.
6)	Tracking of Russian Chay Ka Stations	Software masks can be changed depending on GRI.

TECHNOLOGY NECESSARY TO MAKE A LINEAR AVERAGING DIGITAL RECEIVER

How can today's technology make possible a high performance yet moderately cost effective LORAN receiver, i.e. a PERSONAL NAVIGATOR?

1) Through the use of multiple High Integration High Speed CMOS type Microprocessors that are available at relatively low cost.

2) By reducing the high component count/cost of a averaging receiver through the use of HCMOS VLSI parts.

3) Through the simplification of front-end circuit complexity with Standard Cell Analog CMOS Application Specific Integrated Circuits (ASICs).

4) Through the use of cost effective dynamic memory integrated circuits.

5) By fabricating such a receiver using surface mount component technology and automated assembly techniques.

LOSP: A LORAN-C RECEIVER SIMULATION PROGRAM

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ABSTRACT.

In the design of a Loran-C navigation receiver one of the most important design choices is that of a suitable receiver architecture. Such an architecture specifies what type of antenna, bandpass filter, signal processing algorithms etc. are used. The choice of a receiver architecture should be considered carefully because it determines largely the receiver quality and can be changed only at high cost afterwards; therefore a way to calculate quickly the properties of several different architectures would be a very helpful tool for a designer.

Because mathematical analysis of a complete Loran-C receiver is very complex if not impossible, a computer simulation program (called LOSP) for Loran-C receivers has been designed at the Delft University of Technology. It simulates a signal as can be received with a normal Loran-C antenna, the receiver front end with bandpass and notch filters, a digital-to-analog conversion and the consequent processing of the converted signals.

The formulae used to calculate the antenna signal and the receiver parts as e.g. the bandpass filter, are derived and the program structure is shown. Also, an example is given of the usefulness of the program in the analysis of signal processing techniques for interference suppression.

1. INTRODUCTION.

Loran-C, with its complex signal format and the presence of all kinds of dangers to its quality and reliability, presents some special challenges to designers of navigation receivers. A problem encountered very early in the design of a Loran-C receiver is the choice of a receiver architecture. The architecture determines which type of antenna, bandpass filter, interference suppression and signal processing algorithms are used.

This problem is especially challenging for two reasons. First, once a receiver architecture has been chosen, it is very costly and time-consuming to alter this choice. Second, with the introduction of Loran-C in Europe, new receiver architectures will be necessary, as the traditional ones do not perform optimally in the environment encountered here.

Much research work has been directed towards the optimal design of parts of Loran-C receivers: suitable active antennas, bandpass- and notch-filters, A/D converters (hard-limiting or linear) and all kinds of algorithms for acquisition and tracking of Loran-C signals. However, trying to understand what happens if all these "building blocks" are combined to form a complete receiver, is difficult. One could try to find a total "transfer function" of the receiver, with which the Time Of Arrival or Time Difference as experienced by the "receiver" can be calculated, with a well-defined signal at the antenna input. For practical receiver architectures this approach will quickly become so complicated as to be useless.

A much more viable way to gain understanding of the behavior of a complete Loran-C receiver, would be to write a computer simulation program. Such a program could "generate" signals coming from an imaginary antenna and calculate numerically the influence of each "building block" (e.g. filters, A/D conversion and tracking algorithms) on these signals. Developing formulae for these calculations is not too difficult, and the results of these calculations can be combined to yield the response of the total receiver architecture on an antenna signal.

So in order to be able to do research into receiver architectures, the Delft University of Technology started development of the simulation program LOSP, an acronym for LOran Simulation Program. This program runs on IBM- and compatible Personal Computers (XT or AT types).

2. *WHAT IS SIMULATED BY LOSP?*

Fig. 1.1 shows a complete navigation system, from a transmitter over a radio path to the receiver.

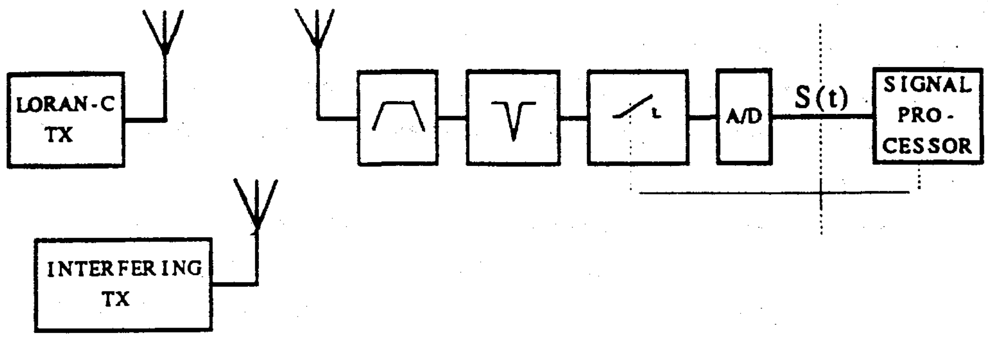


Fig. 1: Loran-C navigation system: transmitter, radio path and receiver.

The Loran-C transmitter generates a pure Loran-C burst, which will be contaminated on its way to the receiver by noise, interferences etc. The task of the receiver is to measure the Time Of Arrival (TOA) of the incoming Loran-C burst even under unfavorable circumstances. It consists of several "building blocks", as the example of fig. 1 shows. In order to be able to write a simulation program, one has to define first which "building blocks" are to be simulated.

In LOSP a general choice has been made to simulate all those receivers which have the commonly used architecture of fig. 1: analog bandpass- and notch-filters in the front end, some kind of A/D conversion (hard-limiter or linear) of the filtered signal and a (micro-)processor system used for the actual Time Of Arrival or Time Difference measurement. Note that all selectivity is assumed to be concentrated in the filter system; therefore amplifiers present in the receiver won't change any amplitude ratio's (e.g. SNR) and can therefore be neglected. It is assumed too that the receiver does not actually calculate a position in longitudes and latitudes; this is more a geodetic than an electronic problem and is therefore not implemented in LOSP.

As shown in fig. 1, simulation of the analog part of the receiver yields a signal S(t) going into the signal processor. This processor will take care of all algorithms necessary for locking onto the Loran-C transmission frame, identifying the proper cycle and measuring TOA's. So for proper receiver simulation LOSP has to be able to calculate the signal S(t) going into the signal processor at any time t, as well as the intermediate signals which are used to "build up" S(t). These are:

- A signal as transmitted by a standard Loran-C transmitter, with phase coding. For internal research purposes, a possibility to add Pulse Place Modulation to the 8 pulses in one GRI has been added. Note that for the purpose of this program (receiver analysis), it is enough to simulate one transmitter signal. Simulating more than one transmitter signal would not be useful, as the extra data would be used only in position calculations. These won't be simulated by LOSP anyway, as they present geodetic problems, not electronic problems.
- The influence of the radio path between transmitter and receiver on the Loran-C signal: Envelope-to-Cycle-Discrepancy (ECD), noise, interfering signals and skywaves.
- The influence of a filter system in the front end of a receiver on all incoming signals. In order to be flexible, there should be a choice of as many bandpass filters as possible and a possibility to add more than one notch filter.

Note that wherever suitable, LOSP keeps to the definitions of Loran-C and other signals as published in the Minimum Performance Standards (MPS) [1] of the Radio Technical Commission for Marine Services, Special Committee no. 70.

After the signal S(t) has been calculated, LOSP will execute the algorithms implemented in the signal processor of fig. 1. Because these algorithms can differ widely, the user of LOSP is not offered a choice at run-time, as this choice would have to be very limited. Instead, the user is offered a well-defined interface between the analog "receiver" part and the signal processing part of LOSP, with which he can write his own signal processing software to be included in LOSP.

3. *SIMULATION METHODS.*

3.1. *Introduction.*

In the previous chapter it has been shown that a very important task of LOSP is to calculate the signal S(t) going into the signal processor conform the USCG standards, at any time t. This signal consists of several parts: groundwave, skywave, interferences and noise. In a real receiver these signals are summed in the antenna and then filtered and processed. In LOSP, the signals are first filtered separately and then summed. Because the filter system is linear, this is completely legal; and filtering separately first and summing afterwards is easier and faster than summing first and filtering later.

So in order to calculate S(t), the parts which together form S(t) have to be calculated first and then summed. In order to be able to properly sum these "sub"-signals, a reference amplitude has to be established. In LOSP, the amplitude at the peak of the Loran-C groundwave burst at the receiver antenna is set to 1; the amplitudes of all other signals are referenced to this amplitude (incidentally, as LOSP does not simulate groundwave attenuation, the amplitude at the peak of the transmitted burst is 1 too in LOSP). Note however, that most Loran-C specifications are not referenced to the peak of the Loran-C burst, but to a continuous sine wave with the same amplitude as the envelope of the Loran-C burst at 25 μs. This value will be called Env_{25} in all following formulae, and for a peak amplitude of 1 it is about 0.506.

The four signal types of which S(t) is built up, are then:

- A filtered groundwave, optionally with ECD. The method used to calculate a filtered Loran-C burst with ECD is explained in § 3.2.
- A filtered skywave, again optionally with ECD. The filtered skywave is calculated in the same way as the filtered ground wave, and then multiplied with the sky-to-ground-wave ratio (this won't be changed by the filter system) and delayed with the skywave delay.
- The filtered interference signals. LOSP is designed to simulate Continuous-Wave Interferences (CWI) only, though later editions will be able to simulate Cross Rate Interferences (CRI) too. CWI signals can be written as:

$$S_{I,unfiltered}(t) = A \cdot \sin(\omega_I t + \varphi_I) \quad (1)$$

In this formula, ω_I and φ_I are specified directly by the user, but amplitude A has to be calculated from the specified Signal-to-Interference Ratio (SIR). For this calculation, the USCG definition of the SIR is used. This definition makes use of the value of the envelope of the burst at 25 μs:

$$A = \frac{Env_{25}}{10^{(\frac{SIR}{20})}} \tag{2}$$

with the SIR specified in decibels. The effect of filtering such a signal can be expressed as:

$$S_{I,filtered}(t) = A \cdot |H(j\omega_I)| \cdot \sin(\omega_I t + \varphi_I + \phi(\omega_I)) \tag{3}$$

with $|H(j\omega_I)|$ and $\phi(\omega_I)$ resp. the amplitude and phase transfer of the filter system at ω_I. The calculation of these filter parameters will be explained too in § 3.2.

- Filtered noise, specified and simulated according to the USCG specifications. The methods used to simulate noise in LOSP are explained in § 3.3.

3.2. Calculation of filtered LORAN-C bursts and simulation of filter systems in LOSP.

In LOSP, three kinds of filter calculations have to be done:

1. Calculation of amplitude- and phase-transfer of the filter at any frequency ω: $|H(j\omega)|$ and $\varphi(j\omega)$, for e.g. simulation of CWI-signals.
2. Calculation of the noise bandwidth of the filter: this is the bandwidth of a filter with a square amplitude transfer and the same noise power at its output as the filter selected in LOSP.
3. Calculation of the filtered Loran-C burst: phase transfer at the Loran-C transmitting frequency of 100 kHz and influence of the group delay on the Loran-C envelope.

A bandpass filter in LOSP is represented by the poles and zeros of the corresponding normalized low-pass filter. Data of these normalized low-pass filters can be found in all filter handbooks and therefore new filter types can be introduced relatively easily. A low-pass to bandpass transformation is then done on the filter selected for simulation, yielding complex conjugate pole- and zero-pairs $(p_i,\bar{p}_i)$ and $(z_i,\bar{z}_i)$. For each (optional) notch, one pole pair and one zero pair are added on the proper places. The general filter transfer function of the complete filter system is then:

$$H(s) = H \cdot \frac{s^{n-m} \cdot \prod_{i=1}^{m} (s-z_i)(s-\bar{z}_i)}{\prod_{i=1}^{n} (s-p_i)(s-\bar{p}_i)} \tag{4}$$

For a frequency ω, the amplitude- and phase-transfer functions are simply:

$$|H(j\omega)| = H \cdot \frac{\prod_{i=1}^{m} |j\omega-z_i|\,|j\omega-\bar{z}_i|}{\prod_{i=1}^{n} |j\omega-p_i|\,|j\omega-\bar{p}_i|} \tag{5}$$

$$\varphi(j\omega) = (n-m)\cdot\frac{\pi}{2} + \sum_{i=1}^{m} \Big(\varphi(j\omega-z_i)+\varphi(j\omega-\bar{z}_i)\Big) - \sum_{i=1}^{m} \Big(\varphi(j\omega-p_i)+\varphi(j\omega-\bar{p}_i)\Big) \tag{6}$$

and with these two formulae the calculation of amplitude- and phase-transfer for e.g. CWI-signals can be done.

For the calculation of the noise bandwidth, the amplitude transfer of the filter has to be integrated from (ideally) 0 Hz to ∞. With a noise source with power density = 1, connected to the filter input, this integral then yields the total noise power P_n at the filter output:

$$P_n = \int_0^{\infty} |H(j\omega)|^2 \, d\omega \tag{7}$$

This noise power has to be equal to that of a filter with transfer characteristic:

$$\begin{cases} |H(j\omega)| = 0 & 0 \le \omega < \omega_0 - \frac{1}{2}B_n \\ |H(j\omega)| = 1 & \omega_0 - \frac{1}{2}B_n \le \omega \le \omega_0 + \frac{1}{2}B_n \\ |H(j\omega)| = 0 & \omega_0 + \frac{1}{2}B_n < \omega \le \infty \end{cases}$$

with B_n the noise bandwidth to be calculated. Such a filter will have a noise power at its output of:

$$P_n = \int_0^{\infty} |H(j\omega)|^2 \, d\omega = \int_{\omega_0 - \frac{1}{2}B_n}^{\omega_0 + \frac{1}{2}B_n} d\omega = B_n \tag{8}$$

The noise powers of formulae (7) and (8) have to be equal, so the noise bandwidth simply becomes:

$$B_n = \int_0^{\infty} |H(j\omega)|^2 \, d\omega \tag{9}$$

For the calculation of a filtered Loran-C burst first the standard Loran-C burst is Laplace-transformed, then it is multiplied with the filter transfer of formula (4) and the result of this multiplication is transformed back from the Laplace- into the time-domain. This calculation is complex but contains only standard mathematics, and therefore here only the results will be shown.

The transmitted Loran-C burst is given by:

$$f_{Lu}(t) = (kt)^2 \cdot e^{-2kt} \cdot \sin(\omega_0 t) \tag{10}$$

with $k = \frac{1}{65\ \mu s}$ and $\omega_0 = 2\pi \cdot 100$ kHz. The Laplace-transform of this burst is:

$$\pounds\left\{ f_{Lu}(t) \right\} = j \cdot (ek)^2 \cdot \left\{ \frac{1}{(s-p_L)^3} - \frac{1}{(s-\bar{p}_L)^3} \right\} \tag{11}$$

with $p_L = -(2k \pm j\omega_0)$.

The filtered Loran-C burst can be calculated by multiplying (11) with (4) and transforming the resulting formula back to the time-domain. The result from this (complex) calculation is:

$$f_{Lf}(t) = 2 \cdot H \cdot (ek)^2 \cdot \left[\begin{array}{l} e^{-2kt} \cdot \sum_{x=1}^{3} \left\{ (-1)^{x-1} \frac{A_x}{(x-1)!} \cdot t^{x-1} \cdot \sin(\omega_0 t - \varphi_x) \right\} \\ \quad - \sum_{i=1}^{n} \left\{ e^{-\alpha_i t} \cdot A_i \cdot \sin(\beta_i t - \varphi_i) \right\} \end{array} \right] \tag{12}$$

with n the number of pole pairs in the filter system and parameters A_x, φ_x, A_i and φ_i functions of the filter poles and zeros. The formulae used to calculate these parameters are not given here, as they are rather complex. Parameters α_i and β_i in formula (12) are simply the real and imaginary parts of the filter poles p_i: $p_i = \alpha_i + j\beta_i$.

Formula (12) represents a filtered Loran-C burst without ECD. For the derivation of a formula of a filtered Loran-C burst with ECD the Laplace transform of such a burst has to be calculated again, that function has to be multiplied with the filter transfer function and the result must be transformed back into the time domain. The result of this complex calculation shows that ECD can be simulated by shifting the filtered envelope in formula (12) with respect to the filtered carrier, and using slightly different functions for the calculation of A_x, φ_x, A_i and φ_i.

3.3. Simulation of noise in LOSP.

According to the Minimum Performance Standards, two different noise sources can be used for simulation of Loran-C signals:

1. White noise. This noise is filtered with a single-resonator LC filter with a bandwidth of 30 kHz and the level of the filter output signal is used as a reference for SNR calculations.
2. Atmospheric noise, simulated by:
   - a noise source as described in point 1;
   - bursts of 100 kHz sine waves, lasting 30 μs each and distributed randomly in time according to a Poisson distribution.

   The two sources are added with a ratio of $\frac{0.1585}{0.8416}$ to simulate atmospheric noise.

It will be clear that the first method mentioned above, is easiest to implement and will be executed much faster by the computer. The only problem to be solved with this noise source is the effect of the 30 kHz LC filter. It will however be shown that at the sampling rates used in a typical Loran-C receiver, the only effect of filtering white noise will be to limit the noise power.

As mentioned in paragraph 3.1, in LOSP the signals used to simulate the total signal going into the signal processor, are calculated and filtered separately first and added afterwards. This means that the noise source used in LOSP should generate noise, not only filtered by a single-resonator LC filter of 30 kHz bandwidth, but filtered by the whole filter system used in the simulated Loran-C receiver (including the 30 kHz LC-filter). Such a filter system will have two effects on a noise signal:

1. Samples of pure white noise, transmitted through a filter, will have a correlation coefficient which is not zero. This means: when taking noise samples at regular distances, the value of a filtered sample will not only depend on the momentary value of the unfiltered noise signal, but also on the values of the previous noise samples.
2. The total noise power will be limited: ideal white noise has a constant power density from 0 Hz to infinity, while the filter will transmit only a part of this spectrum.

In a typical Loran-C receiver, samples of the antenna signal will be taken at distances around 1 ms. Filter theory, however, states that the correlation coefficient between signals coming out of the filter, will be approximately zero at sampling intervals of more than $\frac{1}{B}$, with B the -3 dB bandwidth of the filter. This would mean that even with a 1 kHz bandpass filter in the Loran-C receiver, samples taken at the Loran-C repetition rates will not be correlated. With the normal bandwidths in Loran-C receivers of 15 to 30 kHz, this will be even more so. So for samples taken at the burst repetition rates, one can safely take uncorrelated gaussian noise to simulate the noise coming out of the filter in a real Loran-C receiver.

Because of the above mentioned reasons and the wish to keep noise simulation in LOSP as efficient as possible, a choice was made to use uncorrelated gaussian noise at the filter output for noise simulation. The only problem not yet solved is the calculation of the proper variance or noise power σ^2 of the gaussian noise.

The noise power $\sigma_{LC30}{}^2$ of the antenna noise simulated according to the MPS, can be calculated easily (remember: in the MPS all amplitudes are referenced to the burst amplitude at 25 μs, which is equal to Env_{25} in LOSP):

$$\sigma_{LC30}{}^2 = \frac{\left(Env_{25}\right)^2}{2} \cdot 10^{\left(\frac{SNR}{10}\right)} \tag{14}$$

This is the power of the noise simulated according to the MPS at the <u>antenna input</u>. By dividing this power through the noise bandwidth of a 30 kHz LC filter, the power density N_0 of the antenna noise can be found:

$$N_0 = \frac{\sigma_{LC30}^{\ 2}}{B_{n,LC30}} \tag{15}$$

with $B_{n,LC30}$ the noise bandwidth of the filter used in the MPS specifications. This noise bandwidth can be calculated relatively easily and is found to be 47.124 kHz.

Once the noise power density of the antenna noise is found, the power of the noise after the filter system can be calculated easily:

$$\sigma_{filtered}^{\ 2} = B_{n,filter} \cdot N_0 \tag{16}$$

with $B_{n,filter}$ the noise bandwidth of the filter system (bandpass- and notch-filters) chosen by the user of LOSP. So, filtered noise in LOSP is simulated with uncorrelated gaussian noise with power (14 + 15 + 16):

$$\sigma_{filtered}^{\ 2} = \frac{B_{n,filter}}{B_{n,LC30}} \cdot \frac{\left(Env_{25}\right)^2}{2} \cdot 10^{\left(\frac{SNR}{10}\right)} \tag{17}$$

As formula (17) does indicate, every time the filter configuration is changed the noise bandwidth of the system has to be recalculated, because otherwise no proper noise simulation can be done.

The only problem still to be solved is how to generate uncorrelated gaussian noise. This is done in LOSP by generating and adding 12 random numbers with a pseudo-random noise generator. This technique has been described in among others [2] and yields a good approximation of a gaussian distribution with average $\mu = 6$ and standard deviation $\sigma = 1$. Both μ and σ can be scaled to the values wanted by the program designer.

As will be described in paragraph 3.4, LOSP can also take more than one "sample" per burst (in order to be able to do interference suppression or cycle identification) and in that case the uncorrelated noise model does not work. As stated, the minimum sampling distance for a correlation coefficient = 0 is $\frac{1}{B}$. With a bandpass filter of 20 kHz, this minimum distance will then become 50 µs, which is often more than the distance used between samples taken within one burst.

In order to solve this problem, an experimental correlated noise generator has been developed. This generator works only for samples taken within one burst; correlation between samples in different bursts is still assumed to be zero. As work on this generator is still continuing, no further details will be given here.

3.4. The time base used in LOSP.

Until now the methods used to calculate signal S(t) at any time t, have been explained. For calculating and displaying unfiltered and filtered waveforms, t can be increased linearly, which is rather easy. For use of LOSP in analysis of signal-processing algorithms however, a time base has to be established which determines at which moment t signal S(t) is sampled. The time base value can be changed by the signal processor in order to e.g. track a zero crossing. The time base implemented in LOSP works according to the following rules:

- Two coupled time bases are used:
  1. Time base T contains the time in microseconds from the start of the simulation on. This time base is used for all processes which are independent of the Loran-C burst generation.
  2. Time base SPP (acronym for Sample Point Position) contains the time in microseconds from the start of the current burst on. This time base is used for calculation of Loran-C signals.

  Fig. 2 shows how the time bases are used for the calculation of signal S(t).

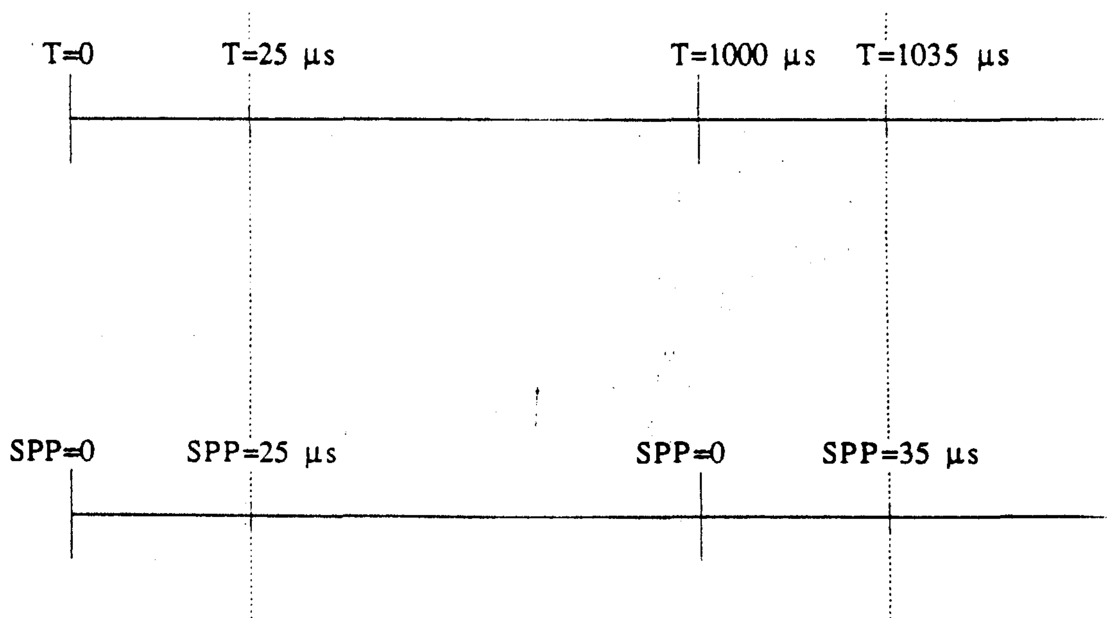


Fig. 2: Relation between the time bases used in LOSP.

As can be seen from fig. 2, as long as the sample point is stationary time base SPP won't change at all, while time base T will increase with 1 ms steps within a series of 8 bursts, and GRI - 7 ms while waiting for the next series of 8 bursts. Every time the sample moment is changed and SPP is increased or decreased (e.g. because of tracking action), time base T is changed with the same amount of time too.

- A "main sample" is taken every time a pulse is generated at the time stored in SPP, 8 samples per GRI at 1 ms spacing.
- Every time a main sample is taken, up to 10 relative samples can be taken too. These relative samples are taken at equal spacings of 5 μs and are located 2.5 + n • 5 μs (-10 <= n <= 10) from the main sample moment. This means that when the main sample moment is used for zero crossing tracking and a zero crossing has been found, the relative samples will be taken at the surrounding positive and negative tops of the sine wave. These samples can be used for interference suppression, cycle identification etc. Note that at the moment an experimental correlated noise model is used for noise simulation within one Loran-C burst.
- When pulse place modulation is applied, this means that the pulse is moved forward or backward in time. This is done by adding or subtracting the specified amount of time to the sample moment SPP.

Every time a set of samples has been taken, a procedure is called which contains the user-written signal processing software. This procedure can of course make use of all samples taken.

3.5. Block diagram of LOSP.

After the basic simulation methods as used in LOSP, have been described, a block diagram of the setup of LOSP can be drawn. As has been explained in the previous paragraphs, LOSP calculates the filtered signals separately and adds everything together behind the filter system. This signal then goes into the signal processing part. As shown in fig. 3, a menu control block has been added, which ensures that LOSP is easy and comfortable to use. Most simulation blocks in fig. 3 are connected to the menu block via a dashed line; this means that parameters of these blocks can be changed during program execution under menu control.

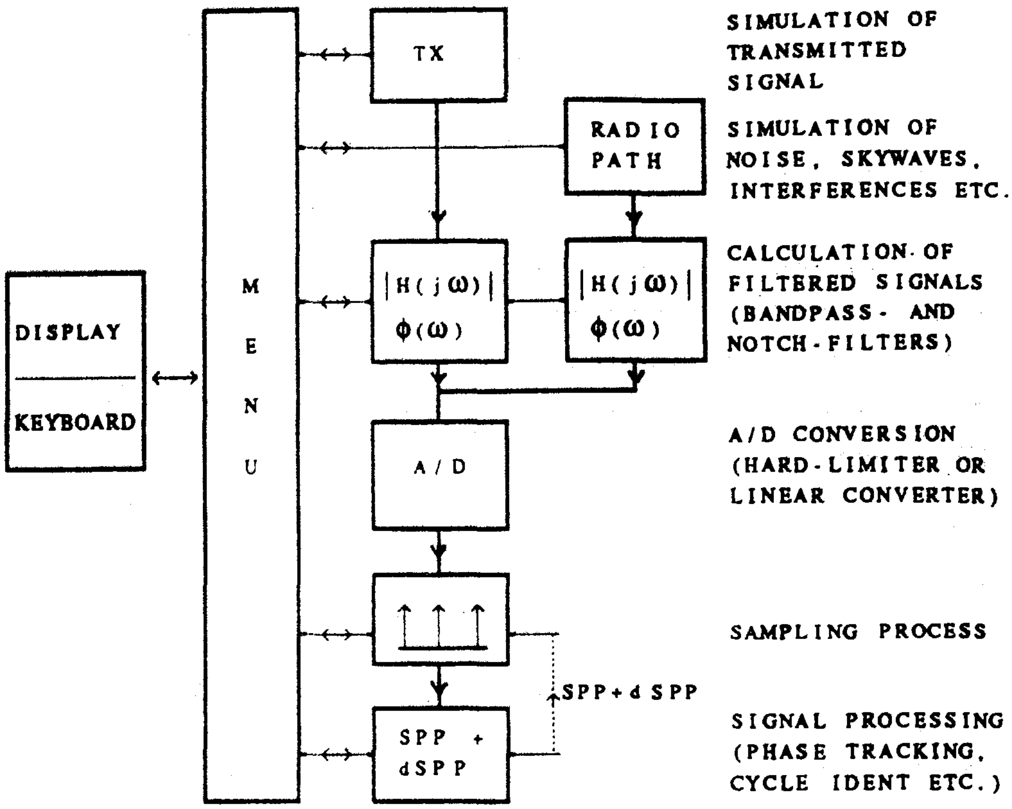


Fig. 3: Block diagram of Loran-C simulation program LOSP.

4. *APPLICATIONS OF LOSP.*

In this chapter an example of an applications of LOSP will be given, which will show its usefulness in the analysis of all kinds of signal processing algorithms. Such algorithms can include: locking onto a Loran-C transmission frame, identifying the cycle to be tracked, and tracking a zero-crossing. In this paragraph, attention will be focused on the use of LOSP in the analysis of receiver behavior if Loran-C signals are contaminated with CW interferences. A detailed theoretical analysis of problems caused by CW interferences can be found in [3] and the interested reader is referred to that publication. Here only some results will presented of simulations done with CW interferences as measured in Delft, The Netherlands.

In the example presented here, a setup is chosen with a Bessel filter with minimum group delay and a bandwidth of 20 kHz. The amplitude transfer of this filter is shown in fig. 4.

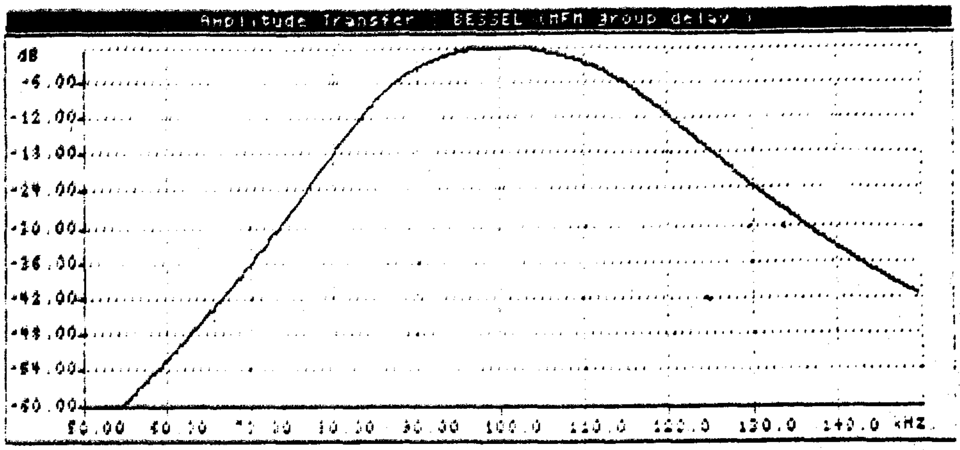
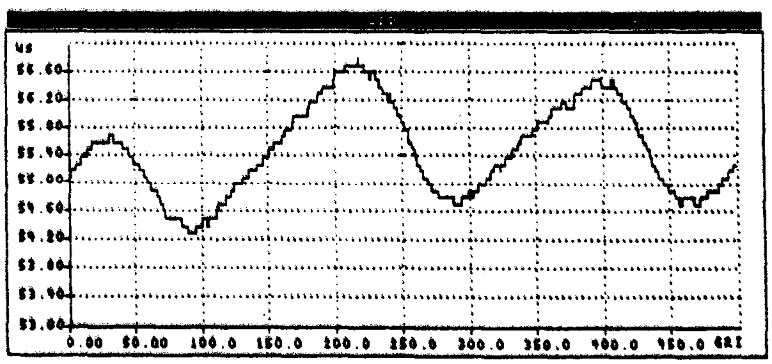


Fig. 4: Transfer function of a Bessel minimum group delay filter.

This filter has a zero-crossing at 55.08 μs, which is being tracked by the "receiver" in LOSP. It is assumed that the Loran-C signal comes from the Norwegian Sea Chain, with a GRI of 7970. One of the most dangerous interference signals found in Delft is a signal from a dutch DECCA transmitter at 115.552 kHz. Fig. 5 shows what happens to the tracking of the receiver if this (strong) signal is not properly suppressed.



operating conditions:

- SNR = 0 dB
- no skywaves present
- interference frequency: 115.552 kHz
- bandpass filter: Bessel, minimum group delay
- position of zero-crossing to be tracked: 55.08 us

Fig. 5: Effect of interference on tracking of zero crossing. The window shows the sample moment SPP (which should try to follow the zero crossing at 55.08 μs) with strong interference on 115.552 kHz.

The normal way to suppress an interfering signal as in fig. 4, would be to set a hardware notch filter on that frequency. However, other methods have been proposed as well, using software techniques to suppress interfering signals. One such method has been described in [4], and relies on the fact that interfering signals will either affect the even pulses (0, 2, 4, 6, 8, 10, 12 and 14) in a group of 2 GRI or the uneven pulses (1, 3, 5, 7, 9, 11, 13, 15). This depends on the number N, which is defined as:

$$N = 2 \cdot GRI \cdot f_{int} \tag{18}$$

with f_{int} the interference frequency. If N is even or nearly even, then the pulses with even numbers will be affected; if N is odd or nearly odd, then the pulses with odd numbers will be affected. So a way to suppress interference would be to take samples in either the even or the odd pulses. With an interference frequency of 115.552 kHz, N = 18418.9888 or nearly odd, so a way to suppress the interference would be to sample only the even pulses. This can be done easily with LOSP, and the result is shown in fig. 6.

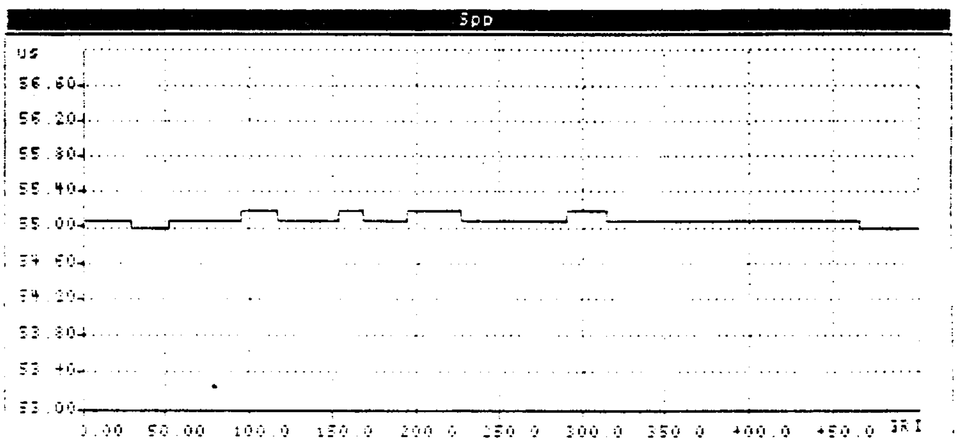


Fig. 6: Effect of sampling only even pulses in a GRI, with interference present at f = 115.552 kHz. Operating conditions are equivalent to those of fig. 5.

As can be seen, the oscillation present in fig. 5 due to the interference signal, has disappeared. What can be seen too is that the tracking has become quieter and slower, due to the fact that only 8 pulses per GRI are sampled instead of 16 and that therefore the information bandwidth is lower. This example is rather straightforward, but shows clearly the abilities of LOSP in analyzing all kind of signal processing techniques.

5. CONCLUSIONS.

Computer simulation of a complete Loran-C system (signal generation, propagation effects and receiver behavior) has proven to be a very powerful tool for research into Loran-C receivers architectures and design of receivers. The methods used for simulation of noise, filters etc. have been chosen in such a way that the calculations are not too complex for the computer but accurate enough for meaningful simulation. Because of this emphasis on computing efficiency, simulation can be done on personal computers, and a software package has been written implementing the simulation models on IBM and compatible PC's.

The program as presented here, is not complete. In future releases features like a correlated noise model with high computing efficiency and simulation of Cross Rate Interference will be included.

ACKNOWLEDGEMENTS.

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LORAN-C TIMING CONTROL AND/OR MONITOR TECHNIQUE

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ABSTRACT

This paper* presents a technique for developing "far field" signal equivalents for both local and remote Loran-C signals at the transmitting antenna location -- thus providing the capability to control and/or monitor Loran-C performance at the transmitter sites. Implementation of this technique can provide significant system monitoring advantages particularly if all stations use time of emission (TOE) control. It can provide:

- o the capability for full chain control and/or monitoring based on measurements made only at the transmitter sites.

- o accurate <u>real</u> <u>time</u> measurement of baseline electrical paths.

- o real time correction factors for area broadcast to improve system accuracy in all sectors.

- o simplified chain calibration by elimination of requirement to determine baseline length by baseline extension measurements.

An adjustment procedure (which can be automated) is described which insures integrity of the technique even with antenna detuning due to weather or other causes. The paper describes the implementation applicable to a transmitter station configuratiion utilizing a 625' top-loaded monopole and an AN/FPN-44A transmitter. However the technique is equally valid with all configurations of transmitters and transmitting antennas.

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* This paper reports on work done by the author and a former colleague, the late Milton Dishal, in the mid 1970's.

OBTAINING THE OPEN-CIRCUIT VOLTAGE AT THE BASE OF AN ANTENNA

The open-circuit voltage which would be developed at the base of the antenna if it were open circuited, will be used as a measure of the received radiation field.

The following paragraphs describe a circuit procedure which, with no high level RF switching required, allows one to obtain this open-circuit-voltage even though the antenna is fully connected to the n=3 (or n=2) output network being used for high power transmitting; that is, even though the antenna is not open circuited, but is instead fully resonated. Simply stated, the frequency selectivity of the input impedance of a network can be completly cancelled by using a properly-proportioned combination of voltage and current sampling. Indeed this same principle has been used in the AN/FPN-44A transmitter to cancel unwanted frequency selectivity within the feedback loop and achieve closed loop stabilization.

In this instance when we wish to use the transmitting antenna for receiving, the input impedance frequency selectivity we wish to cancel is that observed from the other end of the transmitter coupling network; that is, it is the frequency selectivity presented to the open circuit voltage which has been induced into the antenna by the remote field.

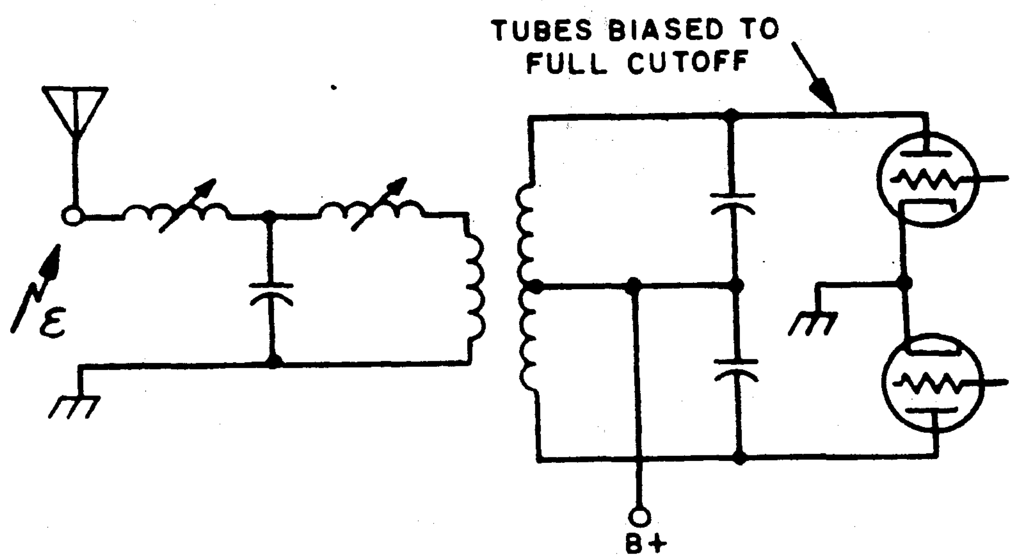

Figure 1: The n=3 circuit involved when the transmitting antenna is used for receiving.

If the antenna input impedance could be simulated by an equivalent circuit having a constant resistance preceding a purely reactive Foster or Cauer network, and if it were possible to physically contact the point immediately to the right of the equivalent antenna resistance, then Figure 2 shows the manner in which the voltage and current probing would be performed to make the total voltage labelled V_T be an exact replica of the open circuit induced voltage, $h_e\mathcal{E}$.

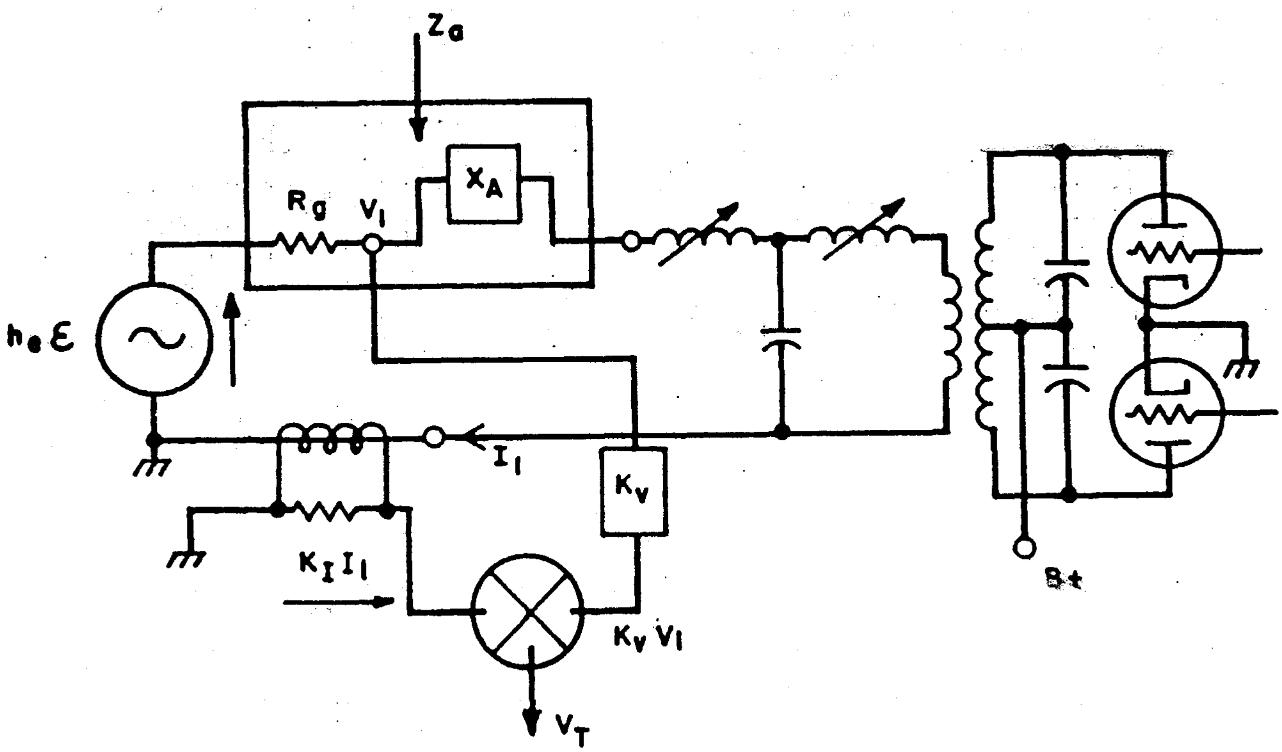

Figure 2: Simplified (but not realizable) circuit to produce replica of open circuit antenna voltage.

However, the antenna input impedance cannot be simulated by the equivalent of Figure 2; and even if it could, the point labeled V_1 in Figure 2 does not physically exist. Therefore the alternate configuration shown in Figure 3 will be implemented. The equivalent circuit shown in this illustration for the antenna will be discussed in detail in a later section of this paper.

Figure 3 illustrates the physically realizable sampling procedure which will be used, and which can be adjusted so that the V_T output from the sum circuit is an exact replica of the open circuit induced voltage $h_e \mathcal{E}$.

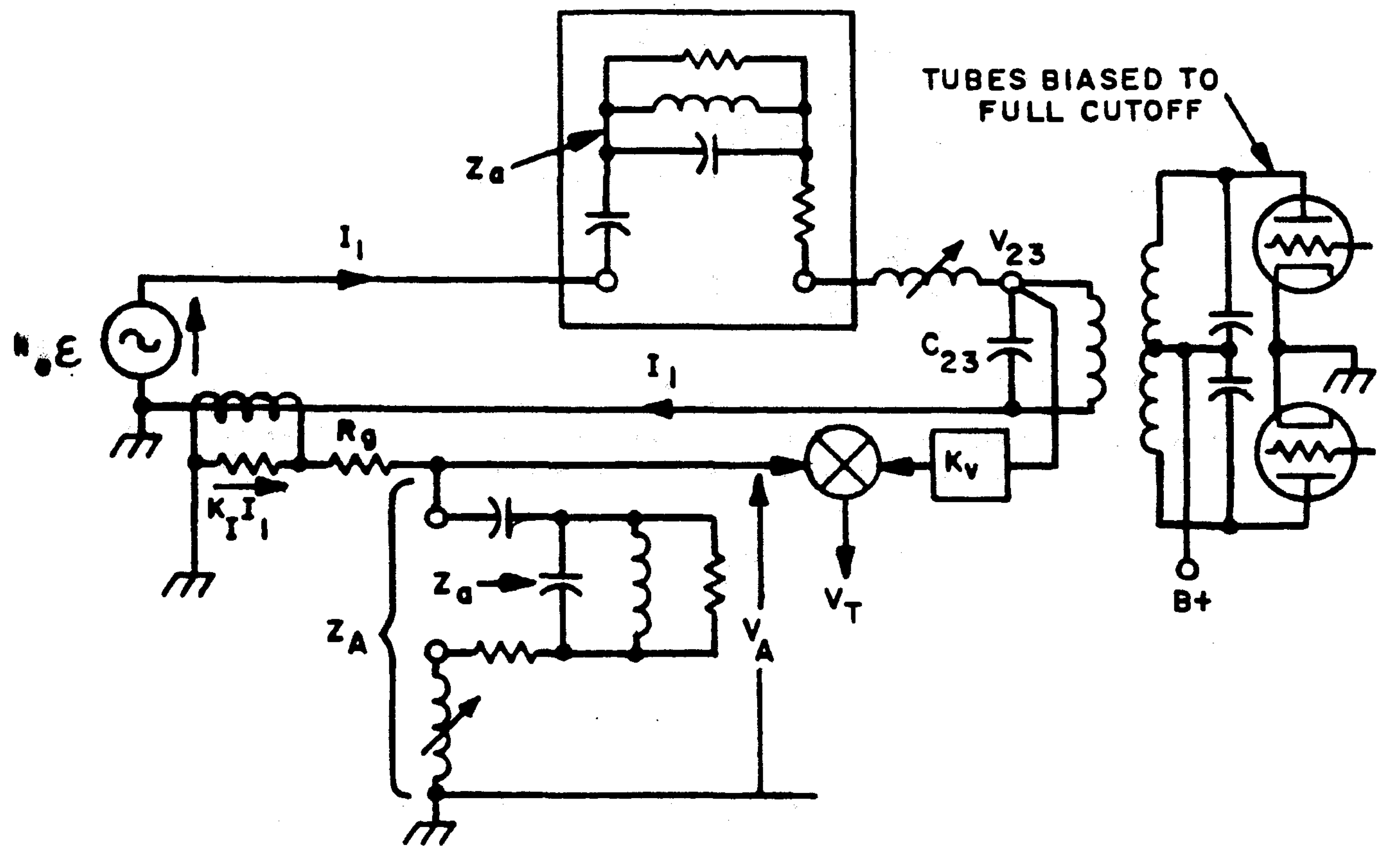

Figure 3: Physically realizable sampling procedure to obtain V_T output, an exact replica of open circuit induced voltage, $h_e \mathcal{E}$.

As observed in Figure 3, this procedure requires the use of an auxiliary "matching" circuit whose input impedance Z_A matches the total input impedance of the antenna plus its tuning coil. (A straightforward adjustment procedure is used which experimentally enables adjustment of the auxiliary matching circuit until it satisfactorily matches the antenna plus tuning coil impedance. Therefore, it is not a matter of hoping that one has satisfactorily matched the impedance; instead there is a solid experimental procedure for obtaining the satisfactory match.)

It is worthwhile to mathematically demonstrate the circuit relationships which must exist in order that V_T in Figure 3 will be proportional to the open-circuit induced antenna voltage $h_e \epsilon$.

In Figure 3, at the SUM port:

$$V_T = V_A + K_V V_{23} \tag{1}$$

In the antenna mesh of Figure 3:

$$V_{23} = h_e \epsilon - Z_A I_1 \tag{2}$$

Across the matching circuit of Figure 3:

$$V_A = \frac{Z_A}{R_g + Z_A} K_I I_1 \tag{3}$$

In the implementation, the R_g in Figure 3 is at least 20 times greater than Z_A even at the extreme ends of the frequency band of interest, (say 80 kHz and 120 kHz); thus for all first order phenomenon, Equation (3) becomes:

$$V_A = \frac{Z_A}{R_g} K_I I_1 \tag{3a}$$

Substitution of Equation (2) and Equation (3a) in Equation (1) produces Equation (4):

$$V_T = \frac{Z_A}{R_g} K_I I_1 + K_V \left[h_e \epsilon - Z_A I_1 \right] \tag{4}$$

$$= K_V h_e \epsilon + \left[\frac{K_I}{R_g} - K_V \right] Z_A I_1 \tag{4a}$$

Equation (4a) tells us that if we proportion K_I and K_V correctly, we can make the second term in Equation (4a) be zero, and then V_T will be a direct replica of $h_e \epsilon$ with a gain factor of K_V. From Equation (4a) we observe that for the previous statement to be true, we must make the bracketed expression in Equation (4a) be zero; that is, we must satisfy Equation (5):

$$\frac{K_I}{K_V} \pm R_g \tag{5}$$

We have described the need for, and use of, an auxiliary matching circuit whose input impedance matches the total impedance of the antenna plus its tuning coil. The very important practical point is that there is a solid experimental procedure which enables one to adjust the auxiliary matching circuit until it does satisfactorily match the actual antenna input impedance. The procedure is also used to monitor the match, so that any drifts in the actual antenna impedance will be tracked by the auxiliary matching circuit.

Figure 4 shows the simple circuitry involved in the experimental matching and monitoring procedure. With the circuitry of Figure 3 unchanged, we use the voltage developed across C_{23} by the normal transmitter signal. If the sampling network has been correctly adjusted in accordance with Equation (5), a broad-band null will be produced at V_T when the input impedance of the auxiliary matching circuit satisfactorily matches the input impedance of the actual antenna.

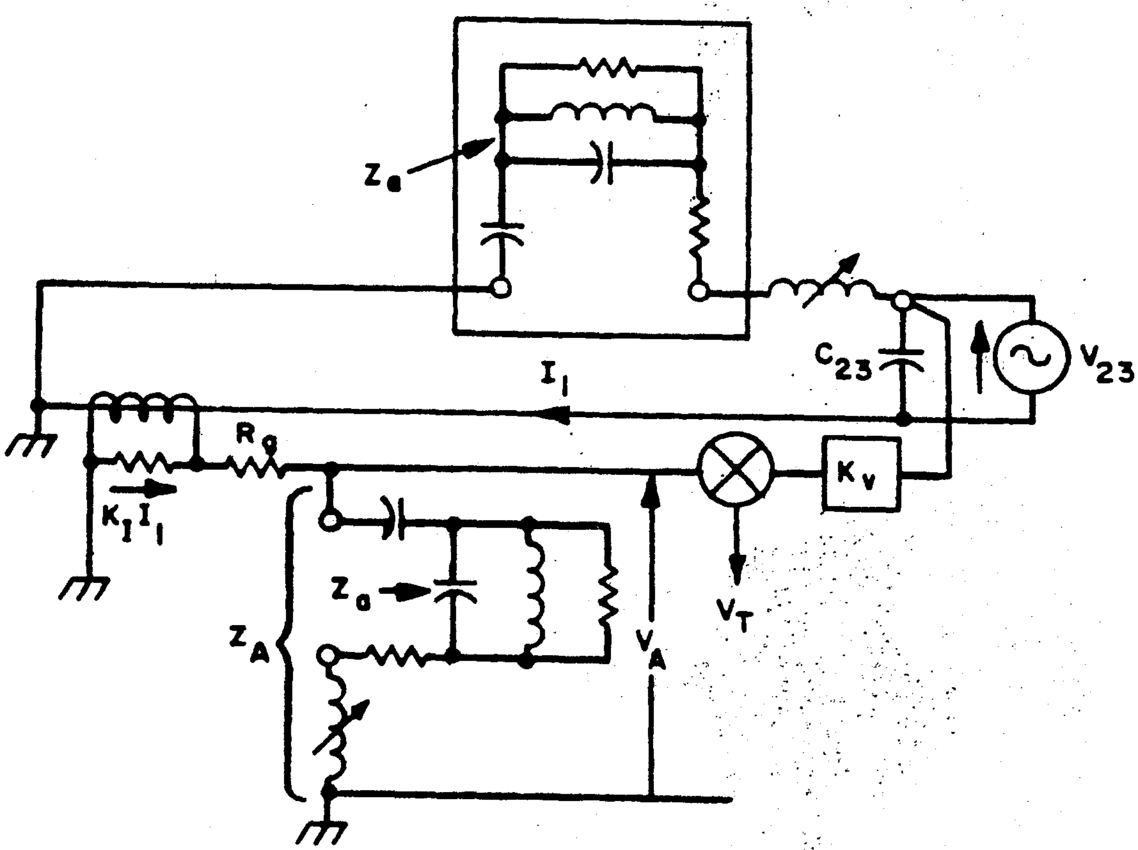

Figure 4: The auxiliary matching circuit is adjusted to produce a broad-band null when the normal transmitter signal produces its voltage across C

The mathematical proof of the correctness of this nulling procedure is simple and straightforward, and is presented here for the sake of completeness.

Equations (1), (3), and (3a) previously developed still apply exactly. Now paying careful attention to the arrow directions in Figure 4, we observe that:

$$I_1 = -\frac{V_{23}}{Z_A} \qquad (6)$$

Substitution of Equation (6) into Equation (3a) produces Equation (7):

$$V_A = -\frac{K_I}{R_g} V_{23} \qquad (7)$$

Substitution of Equation (7) into Equation (1) produces Equation (8):

$$V_T = \left[K_V - \frac{K_I}{R_g} \right] V_{23} \qquad (8)$$

In our circuit, we have carefully adjusted K_V and K_I to satisfy Equation (5). Of course this makes the bracketed expression in Equation (8) be zero, thus:

$$V_T = 0 \qquad (8a)$$

If K_V and K_I have been correctly proportioned a null of output from the circuit of Figure 4 will be obtained, each time the transmitter is driven, as long as the Z_A in the matching circuit and the Z_a plus the tuning coil of the actual antenna are correctly adjusted to be identical. This nulling procedure during the transmit time will be used to guarantee the correctness of the matching circuit.

OBTAINING THE RADIATED "FAR FIELD" AT THE BASE OF THE ANTENNA

The procedure used to obtain a network whose transfer impedance simulates the transfer impedance between antenna base current and resuting radiated far field is based upon the following basic concepts:

- In a network made up of pure reactances plus a single internal resistance, all the power delivered to this network must obviously be absorbed by that single internal resistance.

- If the real part of the input impedance to the previous network truly simulates the radiation resistance of the antenna, then, because of the previously expressed power relationship, the voltage across the single internal resistor in the previous network will truly simulate the phenomenon in the radiated far field from that antenna.

- o To simulate ground loses, copper losses, and dielectric losses, resistors must be added to the previous network in such a way that the total input resistance versus frequency is correctly simulated but the radiation variation with frequency is not disturbed.

A SIMPLE NETWORK SIMULATION OF THE 625′ TOP LOADED MONOPOLE

The report on Project W 215, performed by the U.S. Coast Guard at the Electronics Engineering Center in Wildwood includes a graph of the measured total input impedance of the 625-foot top-loaded monopole antenna. Total input impedance values obtained from this graph are listed in Table 1.

FREQUENCY (kHz)	INPUT IMPEDANCE (ohms)
50	1.0 - j205
75	1.5 - j91
100	2.5 - j16
125	4.0 + j47
150	6.8 + j108
200	17 + j245
300	210 + j1000

Table 1: Measured Values of the Total Input Impedance to the 625-foot Top-Loaded Monopole Antenna.

Figure 5 shows a network configuration and component values which matches the experimentally measured values of Table 1 to better that 3 percent up to 150 kHz. Because of this, the (V_E / i_a) of this network gives a very good approximation to the transfer impedance of the 625-foot top-loaded monopole (TLM) antenna.

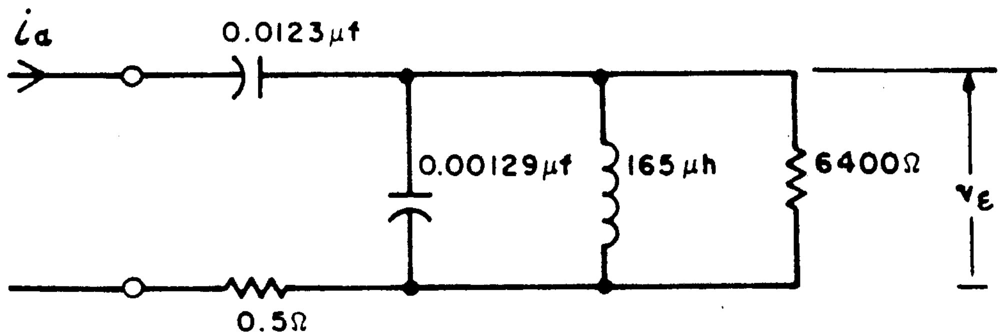

Figure 5: Network configuration and values that matches the total input impedance of the 625′ TLM.

Table 2 gives the total input impedance of the network of Figure 4.

FREQUENCY (kHz)	INPUT IMPEDANCE (ohms)
50	0.94 - j205.8
75	1.54 - j90.9
100	2.5 - j16.2
125	4.0 + j45.6
150	6.24 + j105.3
200	15.7 + j246.9
300	245 + j1184

Table 2: Total input impedance of the network of Figure 4.

The network of Figure 4 will be used to simulate both the input impedance and the transfer impedance of the 625′ TLM antenna.

INTEGRATION OF THE LOCAL AND FAR FIELD MONITOR SUBSYSTEM WITH AN/FPN-44A TRANSMITTER, 625′ TLM, AND RECEIVER SUBSYSTEM

Figure 6 shows how the circuitry and concepts which have been discussed could be combined with switching to send the local "far field" transmitted signal (the voltage V_6 proportional to the transmitted radiated field) to the monitor receiver subsystem during the local interval, and the remote received signal(s) (the voltage V_r proportional to the received open circuit radiation field) during the remote signal intervals.

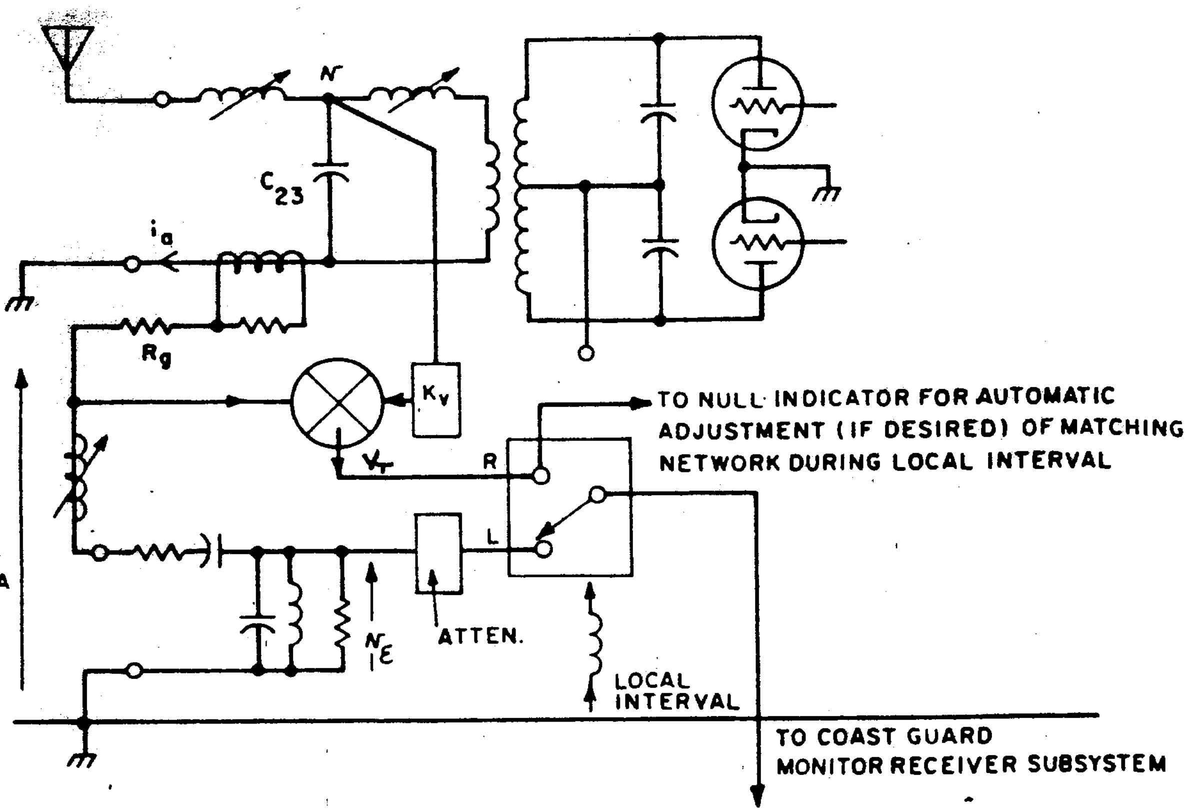

Figure 6: The remote signal circuit of Figure 3 and the local signal circuit of Figure 4 are combined with switching to complete "far field" probes at (and referenced to) the TLM location.

As previously mentioned, the value of Rg in Figure 6 is so great, compared to the input impedance to the network it is driving, that the network is effectively being driven with a constant current which is a replica of the actual antenna current being sampled by the current transformer.

A null indicator for manual or automatic adjustment of the auxilliary matching network during the local interval insures the integrity of the "far field" pickup of the remote signals at the TLM location. Note that both local and remote radiated field signals are phase-referenced to the geographical location of the 625′ TLM antenna.

SESSION 4

MARINE DEVELOPMENTS AND APPLICATIONS

LCDR GARY WESTLING
U.S. COAST GUARD

ASF Chartlets: A Picture Is Worth a 1000 Numbers

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Abstract

After five years of producing chartlets that show the Additional Secondary Factor (ASF) only where it was actually observed in the field, the Canadian Hydrographic Service (CHS) is in the final preparation stages of publishing the ASF corrections in a contoured map format throughout most Canadian Loran-C waters. The method of calculating the theoretical ASF (based on certain electrical properties) and then the incorporation of 100,000 data points of observed ASF data will be discussed as well as the visual presentation in map form. The impact and usefulness of such a product will also be discussed.

Background

During 1980 and 1981, the Radio Technical Commission for Marine Services' (RTCM) Special Committee No. 75 met to discuss the minimum performance standards for Loran-C coordinate converters. One of the most significant realizations of those meetings was the need for information about the Additional Secondary Factor (ASF) of each Loran-C rate. The Defense Mapping Agency (DMA) undertook to prepare booklets of ASF predictions throughout the coastal waters of the United States. Although Canada was not bound by any recommendation of the RTCM, the Canadian Hydrographic Service felt that providing similar information to Canadian mariners was necessary. However, after discussions within CHS and with several ship's captains, we considered that a map presentation was more useful than a digital one. Our reasoning was based on such points as:

- our publishing of Decca Fixed Errors (which are roughly akin to Loran-C ASF) in the form of correction tables was poorly received by the maritime public to the extent that they were not used,
- the Decca Company's publication of the same Decca Fixed Errors in map form was far more readable,

- condensation of information (particularly since we intended to go 200 miles off-shore),
- better portrayal of areas of rapid change versus areas of no change, and
- mariners probably have a better idea of where they are on a map than in a matrix of tabulated values.

One consideration was that we did not have a sophisticated ASF prediction package such as our colleagues at DMA had, but to more than offset that disadvantage, we had extensive data collection of observed ASF. By that time, the Loran-C public was well aware of the pitfalls of using only ASF predictions as was demonstrated by the early large scale charts near Los Angeles. We now know that phase recovery is underestimated off a rocky, low conductivity coastline and that the models also assume geometrical straight line propagation rather than wave propagation. This is particularly serious in the case of a transmission path grazing a coastline.

We had already begun making chartlets showing the actual observed ASF in the areas that we had surveyed, for internal inventory purposes; therefore, it was a relatively easy matter to improve the cartographic quality of these diagrams for publication. Over the past five years we have continued to add the new survey data to these chartlets and to publish them in a relatively timely manner.

Nevertheless, we felt that observed ASF chartlets were only an interim measure until we could provide a contoured format for the ASF correction. Now is the time to get away from interim measures and do the job properly!

Great Lakes

In the Great Lakes, we have extensive ASF observations throughout Lake Ontario, Erie, Huron and Georgian Bay, including the North Channel, and adequate information in Lake Superior. We also have National Ocean Survey and/or US Coast Guard data provided by DMA in Lake Ontario, Erie, St. Clair, Huron, Michigan and some very sparse data in Lake Superior. We were able to fit mathematical polynomials to this relatively dense data and present them in a contoured format on the chartlets. The preparation of the chartlets brought forth a problem that had been identified earlier in the 9960-Z ASF in Lake Huron near Point Clark where the American and Canadian data sets differed by about 1 microsec. That prompted a resurvey of the area in 1988 which has not completely resolved the problem.

Atlantic Coast & Gulf of St. Lawrence

Our data base of observed ASF in Atlantic Canada is probably our most extensive since this is a vast area; we have surveyed a great deal over a nine year period, including detailed observations in some test areas for special studies. Our surveys include the whole coast of Nova Scotia (including Sable I.), New Brunswick, Prince Edward Island, the Gaspé Peninsula, St. Lawrence River estuary, the Magdalen Islands, the Strait of Belle Isle, and selected areas of the coasts of Newfoundland. Along with this data, we also have GPS positioned data on Georges Bank and Doppler satellite positioned data scattered throughout the Scotia Shelf and Gulf of St. Lawrence. We have also received US Coast Guard data from New York City to Grand Manan.

In support of our off-shore multi-discipline surveys by using rho-rho Loran-C/Doppler Satellite/Doppler Sonar Log fixing, we developed an on-line Millington's Method ASF computation using the CIA digital coastline. We brought this ASF computation program into the office and improved it. We realize that there are perhaps more sophisticated ASF prediction techniques, however by using this method we have found that there is usually a systematic residual difference, around 0.5 microsec., between the computed and observed ASF that is almost a constant over a large area. We are exploiting the fact that the shape of the ASF surface is roughly correct but that the surface must be tacked down with groups of real ASF data. Because of this relationship between computed and observed ASF, we have developed a routine for applying this residual difference to the computed ASF values and to use these adjusted values as input to a lattice drawing routine or for contouring the ASF chartlets. Subjective judgment and experience are necessary in the application of the expected differences in areas where there are no observed data. The geographical variation of conductivity, the varying amount of land, and the wrong estimate of the conductivity cause only slowly varying residual differences which can be easily handled. What causes us more trouble is; 1) the fact that our prediction model underestimates phase recovery within a few wavelengths of a rocky coast, and 2) the fact that the model treats propagation in a straight line rather than wave motion which bends around corners.

Pacific Coast

Our data includes detailed surveys in Georgia, Juan de Fuca and Hecate Straits and the approaches to Prince Rupert as well as off-shore data based on Doppler satellite fixing. We also received from DMA detailed surveys in Juan de Fuca Strait and off-shore data presumably based on Doppler satellite fixing. During the off-shore surveys, using the same rho-rho Loran-C/Doppler satellite positioning system, it was found that the Millington's Method ASF computation routine sometimes gave unreliable answers because of the many fiords and islands. Also the topography contributed to significant delays that were not accounted for in the ASF computations. By using only the observed ASF data, we have been able to use the same methodology as in the Great Lakes; namely, the use of polymonials to express the ASF. For satisfactory results, the data upon which the polynomial is based must be adequately distributed over the region of interest and may not be adequate for prediction in areas with no surveys and is definitely not valid close in-shore where the ASF changes rapidly due to phase recovery. There is also the inability of the chartlets to show all this detail close to shore. Therefore, some areas have been identified with the note,"Insufficient data" and have also been ear-marked for surveys.

Publication

The observed ASF diagrams have been published in a Canadian Coast Guard publication "Radio Aids to Marine Navigation" which is required on board ships under the Charts and Publications Regulations promulagated under the Canada Shipping Act. The following contoured style ASF chartlets will supercede the observed ASF diagrams in Radio Aids to Marine Navigation:

Loran-C Rates:	Area:
5930 X & Y	West end of Nova Scotia,
5930 X & Y	South of Sable Island,
5930 X, Y & Z	Halifax to SW Newfoundland and to PEI,
5930 X, Y & Z	West part of Gulf of St. Lawrence,
5930 X, Y & Z	East part of Gulf of St. Lawrence,
5930 X, Y & Z	Southeast of Newfoundland,
5930 X, Y & Z	East of Newfoundland,
5990 X, Y & Z	Juan de Fuca and Georgia Straits,
5990 X, Y & Z	West of Vancouver Island,
5990 X, Y & Z	Queen Charlotte Sound,
5990 X, Y & Z	Hecate Strait & Dixon Entrance,
7930 W	Halifax to SW Newfoundland and to PEI,
7930 W	West part of Gulf of St. Lawrence,
7930 W	East part of Gulf of St. Lawrence,
7930 W & X	Southeast of Newfoundland,
7930 W & X	East of Newfoundland,
7930 W & X	Northeast of Newfoundland,
8970 X & Y	Lake Superior,
8970 X & Y	Lakes Huron & Erie and Georgian Bay,

9960	W & X	West end of Nova Scotia,
9960	W & X	West part of Gulf of St. Lawrence,
9960	W, X, Y & Z	Lake Huron, Erie & Ontario and Georgian Bay.

At present, only a few of the chartlets have been prepared and are available for constructive criticism, which we would be glad to receive. We have learned that it is best to have prototypes available for such a purpose since we do not necessarily think of all aspects on the first drafting.

Technical Concerns

We, the authors, are very concerned with the derivation of ASF and the use of it. We are looking at Loran-C as providing a positioning capability that will complement GPS - which we believe it is capable of doing in many areas. We also foresee that at least some of the future user public will have Electronic Chart Displays and that there will be a Loran-C coordinate converter as part of the positioning system. It therefore follows that ASF data is necessary to calculate the correct position. Consequently, accurate ASF is needed to produce a position without systematic biases that can be used in conjunction with GPS data. Therefore, such matters as the knowledge of the horizontal datum of the survey , error-free survey data, the integrity of the receivers used, the Loran-C transmitters and controlling TD's being correct have to be confirmed.

We are also concerned that the prediction techniques used by CHS and by others are not sufficiently realistic. The conductivities are selected very subjectively, topography is neglected, and dispersion, because there is a faster propagation path than the geodesic line, is never considered. Yet they all degrade the accuracy unless they are thoroughly mapped and appreciated. Even after an accurate position is determined, that position may be very wrong when applied to certain charts - at least in Canada and possibly elsewhere too. This is because a number of CHS charts are based on very old surveys and the geographic grid on those charts is not consistent with any geographic grid used today - be it North American Datum of 1927 or 1983 or World Geodetic System of 1972 or 1984. In fact, we are so concerned with the possibility that a user will use Loran-C correctly, apply the ASF correction correctly and determine an accurate position but will apply that position on one of these old charts and come to grief because of the inaccuracy of the horizontal grid of the chart that we plan to warn him that the ASF is INACCURATE so that he is duly cautioned. Of course, the mariner using GPS will have to be similarly cautioned.

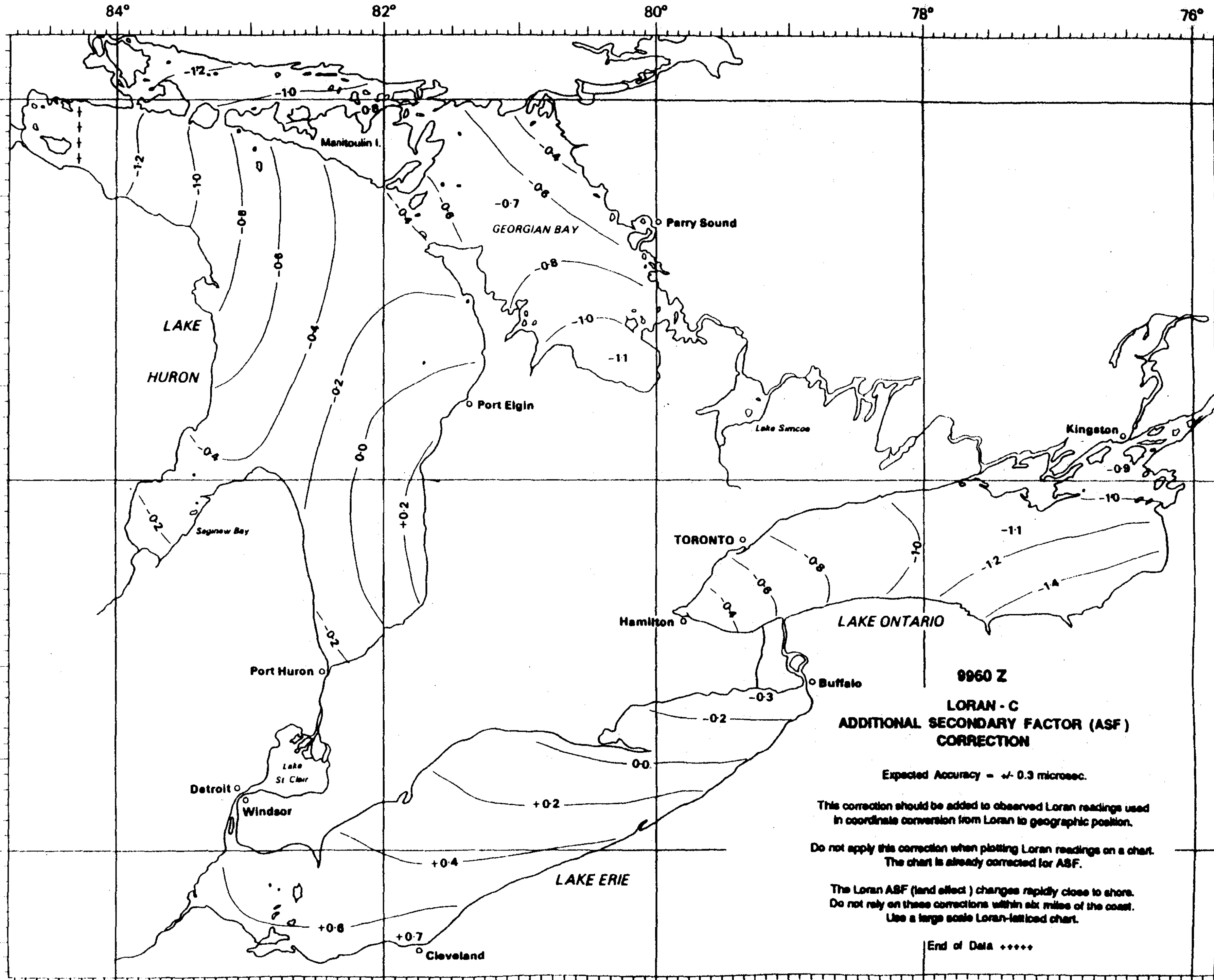
We also realize that we are preparing these chartlets at a scale of about 1:2,500,000 and at that scale we cannot display the intricacies along the coast line because detail is suppressed and some resolution is lost. Our tests have undeniably shown that there can be a rapid phase recovery near the coast of up to a full microsecond exceeding that predicted by Millington's Method. Hence we are planning a caution note to go on each ASF chartlet for the near-shore effects. We suggest that the large scale latticed charts should be used instead because the rapid change in the ASF has been included closer to the shore in the lattices than in the ASF chartlets. Also, the mariner might be induced to use his radar or make visual fixes.

There is a concern that is independent of chartlet scale. It is accepted mathematical practice that the accuracy of a contoured map is plus/minus half of the contour interval 95% of the time. Therefore, by the properties of a Gaussian distribution, the standard deviation is a quarter of the contour interval; or in the case of the area from Cape Sable to LaHave River (southwest of Halifax, N.S.), the 5930-Y ASF is 2.0 microsec ± 0.05 microsec. That accuracy is equivalent to 10 metres! Or, in other terms, the equivalent of a lattice line on a chart of 1:5,000 scale. This scares us because we would not think of latticing a chart at that scale! Therefore, an expected accuracy of ± 0.3 microsec is stated in the title block of each diagram. That value roughly accounts for the seasonal stability of the pattern, prediction techniques, and calibration survey accuracy. We are concerned that the mariner will select the wrong Time Difference pairs, but we also acknowledge that some manufacturers are writing sufficient software into their converters that the converter will know which Time Differences to use.

We invite you to make your comments known to CHS on our presentation of the ASF data and to express your suggestions on other forms of presentation of this data that might be useful to you. To those of the audience that are thinking of improving the Loran-C system by getting rid of the controlling monitors, we ask that you consider the fact that we have eleven years of TD calibration data at stake. Any change to the method of controlling the timing would change the location of the line of position which, in turn, changes its location on large scale charts. Also, because a timing change would allow users to select whatever station pairs he chooses, there would be an additional work-load of providing the ASF chartlets for the extra station pairs.

Conclusion

The Canadian Hydrographic Service will be publishing a whole new series of chartlets in the Radio Aids to Marine Navigation that will show Loran-C ASF in a contoured format. We believe that the data is accurate since it is based on surveyed ASF values and that it is provided in a meaningful yet compact manner for the user.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Saginaw Bay
Lake Simcoe
Kingston
TORONTO
Hamilton
LAKE ONTARIO
Port Huron
Buffalo
Lake St Clair
Detroit
Windsor
LAKE ERIE
Cleveland
-1·2
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-0·6
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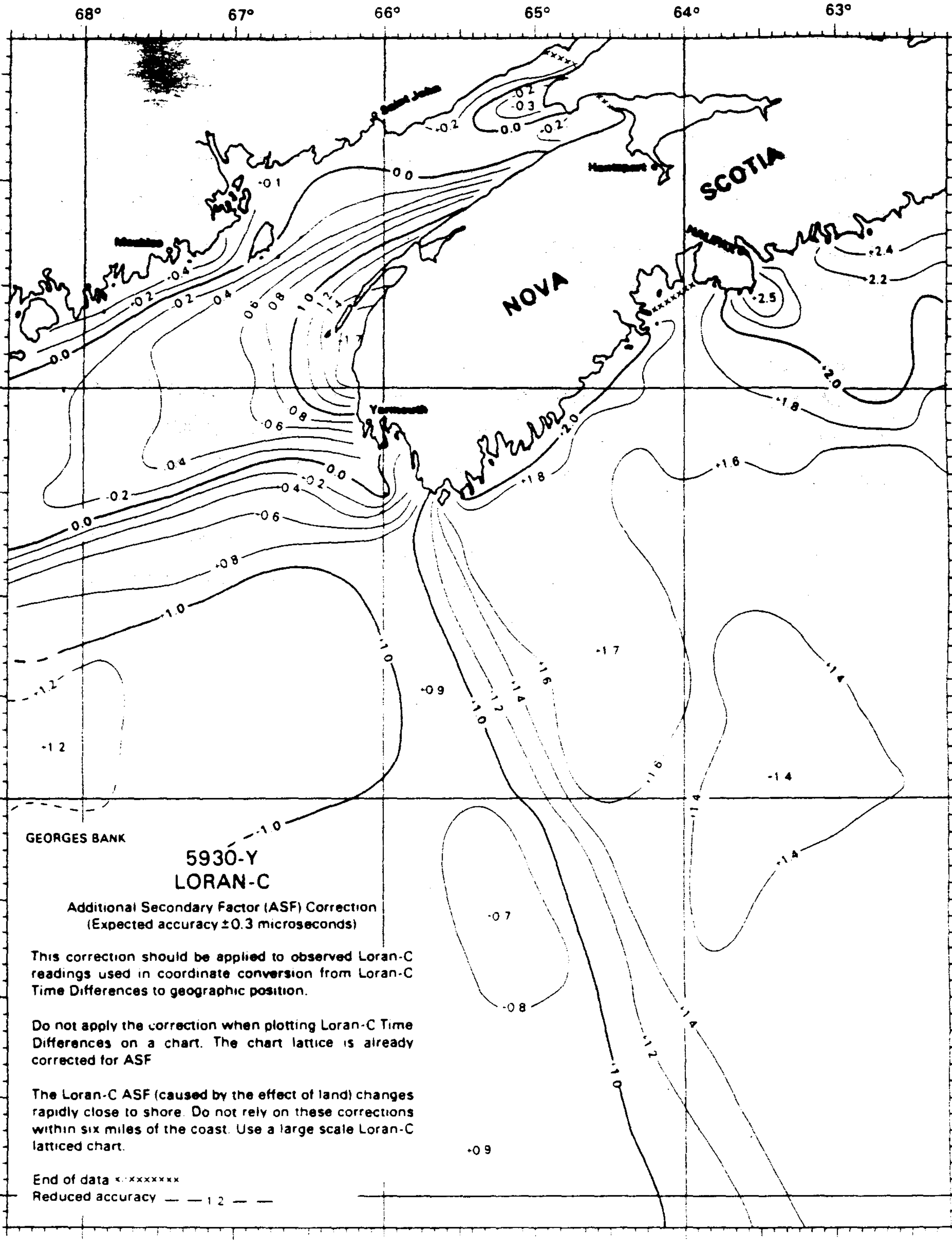
+0·2
-0·7
-0·8
-1·0
-1·1
-0·9
-1·2
-1·4
-0·3
+0·4
+0·6
+0·7
9960 Z
LORAN - C
ADDITIONAL SECONDARY FACTOR (ASF)
CORRECTION
Expected Accuracy = +/- 0.3 microsec.
This correction should be added to observed Loran readings used in coordinate conversion from Loran to geographic position.
Do not apply this correction when plotting Loran readings on a chart. The chart is already corrected for ASF.
The Loran ASF (land effect) changes rapidly close to shore. Do not rely on these corrections within six miles of the coast. Use a large scale Loran-latticed chart.
End of Data +++++

9960 Z



68°
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63°
45°
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43°
42°
41°
40°
NOVA
SCOTIA
Yarmouth
GEORGES BANK
5930-Y
LORAN-C
Additional Secondary Factor (ASF) Correction
(Expected accuracy ±0.3 microseconds)
This correction should be applied to observed Loran-C readings used in coordinate conversion from Loran-C Time Differences to geographic position.
Do not apply the correction when plotting Loran-C Time Differences on a chart. The chart lattice is already corrected for ASF
The Loran-C ASF (caused by the effect of land) changes rapidly close to shore. Do not rely on these corrections within six miles of the coast. Use a large scale Loran-C latticed chart.
End of data xxxxxxxx
Reduced accuracy — — 1 2 — —

5930-Y

Biographies

Speaker:

David H. Gray, M.A.Sc., Professional Engineer, Canada Lands Surveyor, has been with the Canadian Hydrographic Service since 1971 where he is a geodesy and radio positioning specialist. He has been responsible for Loran-C data analysis and has been officer in charge of several Loran-C surveys. He is also involved with conversion of charts to NAD83 and maritime boundary delimitations.

Co-author:

R. Michael (Mike) Eaton has been involved in Loran-C since 1971, first for offshore surveying and then in planning Loran expansion and in producing lattices to 2 mm accuracy for CHS charts of the Atlantic Region. He was awarded the WGA medal of merit in 1983.

Mike was educated in the UK, and has a physics degree from Dalhousie University, Halifax, Nova Scotia. He recently retired from the CHS, but continues to work on Loran ASF, and on the joint introduction of Navstar GPS and the Electronic Chart.

DIFFERENTIAL LORAN-C SYSTEM (DLCS) PROJECT

A STATUS REPORT

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Groton, CT 06340

ABSTRACT

The U. S. Coast Guard Research and Development Center is investigating ways to meet the 8 to 20 meter accuracy requirements in the Harbor and Harbor Approach (HHA) areas as outlined in the Federal Radionavigation Plan. One of the ways under examination is a Differential Loran-C System (DLCS). The R&D Center's project team has been working on the DLCS project for approximately four years and has made significant progress during the past year. This status report will summarize the DLCS installations and findings in Orange County, California, and on the Great Lakes. The paper will also cover the differential broadcast corrections and changes the R&D Center is recommending to the RTCM and the WGA to standardize DLCS broadcasts and make them compatible with other differential systems.

INTRODUCTION

The Coast Guard Research and Development Center has studied the stability and characteristics of the Loran-C Signal since 1977. In 1984, the R&D Center began investigating the use of Differential Loran-C as a way to meet the 8 to 20 meter accuracy requirements of the Federal Radionavigation Plan. The R&DC Project has installed Differential Loran-C Systems in New London, CT., Hampton Roads, VA., Orange County, CA., and near the St. Marys River in Michigan. The project team published a status report last year which reported on the success of these systems.[1]

The authors of this paper are officers or employees of the U. S. Coast Guard. The opinions or assertions contained herein are the private ones of the authors and are not to be construed as official or reflecting the views of the Commandant or the Coast Guard at large.

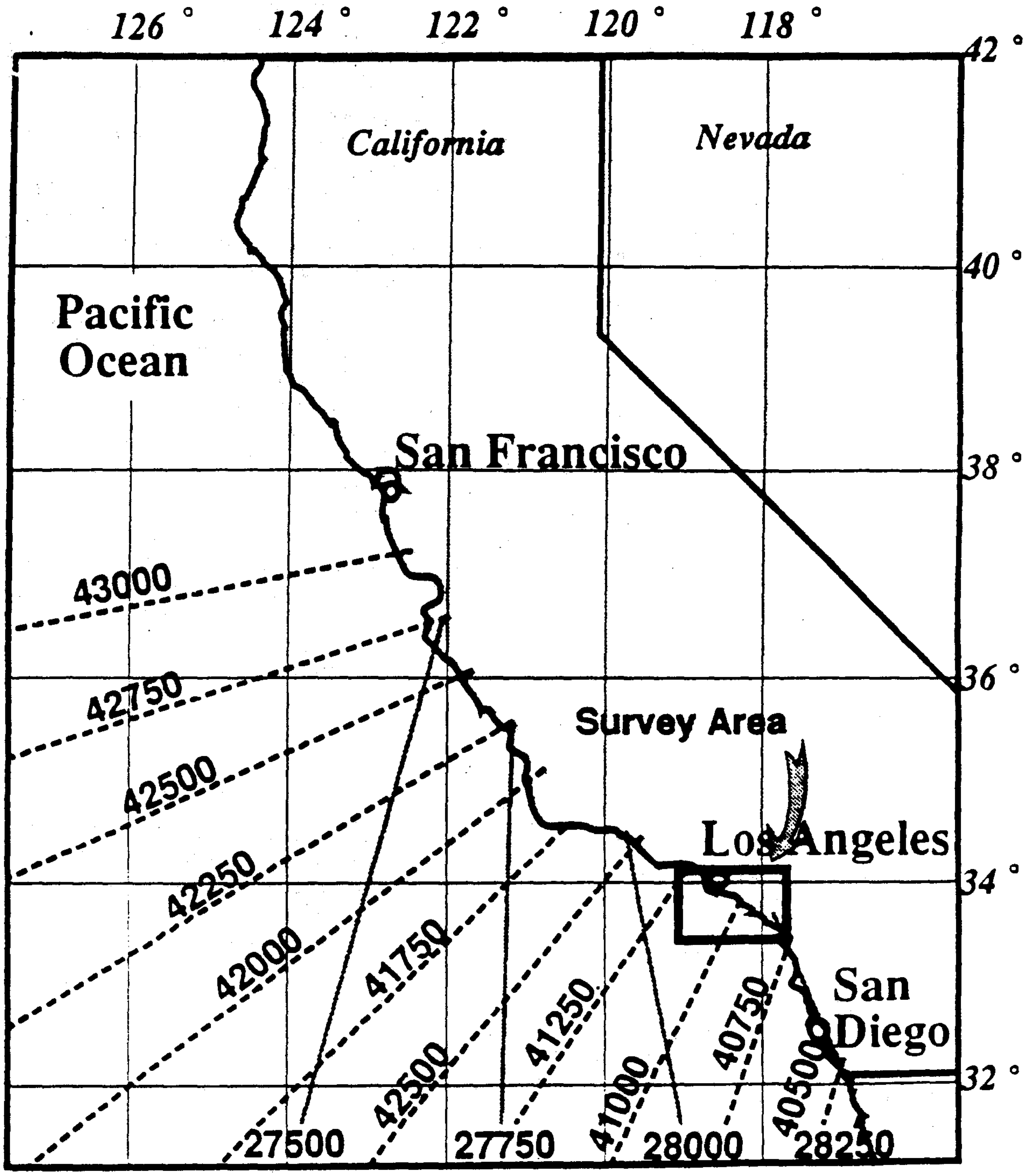
ORANGE COUNTY, CALIFORNIA, DLCS

The County Sanitation District of Orange County, California, has two out fall pipes for discharging sludge into the ocean. One of these pipes extends five miles offshore and terminates at a depth of two-hundred feet. Under a variance from the Environmental Protection Agency (EPA), the District was allowed to continue ocean discharge if they closely monitored ocean water quality and took bottom samples at fifty-three predetermined locations in the area near the out fall pipe. In order to comply with the provisions of the variance, the vessel taking the samples had to position itself within $\pm$ 12 meters of the predetermined location.

In 1986, Tetra Tech conducted a survey of possible positioning and surveying systems (conventional and electronic) to determine which systems could provide the necessary accuracy for positioning a vessel for purposes of obtaining these samples. This study concluded Loran-C could not meet the accuracy requirements in the Orange County, CA, area.[2] Figure 1 shows the area of interest and approximate Loran-C geometry. The poor crossing angles of the Loran-C time differences are primarily responsible for reduced accuracy in the Orange County, CA, area. The study also stated Differential Loran-C might provide the required accuracy, but more information was needed before Tetra Tech could properly evaluate DLC.

Orange County personnel, faced with very high costs using some of the positioning systems, wanted to explore DLC and determine if it could provide the necessary accuracy to meet EPA standards. In May, 1987, the R&DC project team installed a DLCS in Orange County and ran several tests. The initial results indicated DLCS might meet the EPA's accuracy requirements; Orange County personnel decided to investigate further and to validate DLCS fully.

In January, 1988, the R&DC project team and engineers from Tetra Tech conducted extensive accuracy validation tests in Orange County, California. Figure 2 shows the equipment configuration for the truth system and Loran-C data collection equipment.


126 °
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California
Nevada
Pacific
Ocean
San Francisco
Survey Area
Los Angeles
San
Diego
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Figure 1

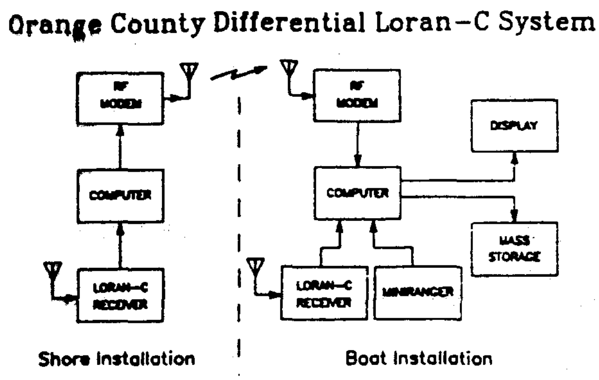

Figure 2

Based upon the May, 1987, experiment, the project team learned that one Differential Loran-C observation would not give them the necessary accuracy for EPA requirements. The team decided to try averaging several time difference observations to determine if this would improve the accuracy. This averaging or windowing process is illustrated in figure 3.

The width of the window (or number of observations to include in the average) was a key issue for the team. If the vessel taking the bottom samples were fixed to the bottom and would not move, a large window could give very accurate position information over a period of time. However, practicality dictates that a vessel not be fixed to the bottom, and a skilled seaman can only keep a vessel on station for short periods of time.

Figure 4 shows standard deviation of the X and Y values for DLC position as a function of window size. One can see that increasing the window size beyond 6 samples does little to improve the standard deviation of the smoothed data.

Figure 5 displays a scatter plot of miniranger positions and raw (i.e. window size of one) Differential Loran-C positions for a stationary vessel. Figure 6 shows the same data displayed in figure 5 except in this case the window size is set at six observations. The DLC data is more concentrated and shows a minor offset from the miniranger truth data.

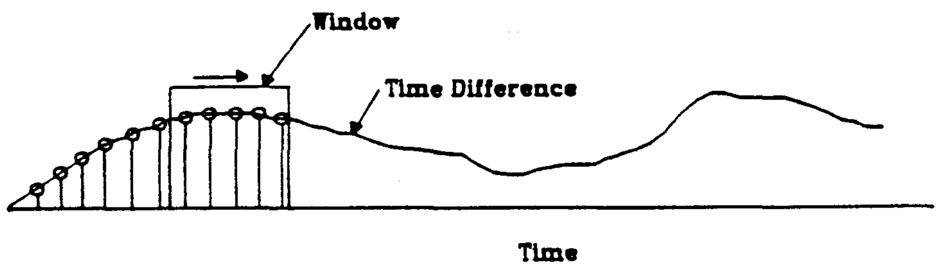

Figure 3

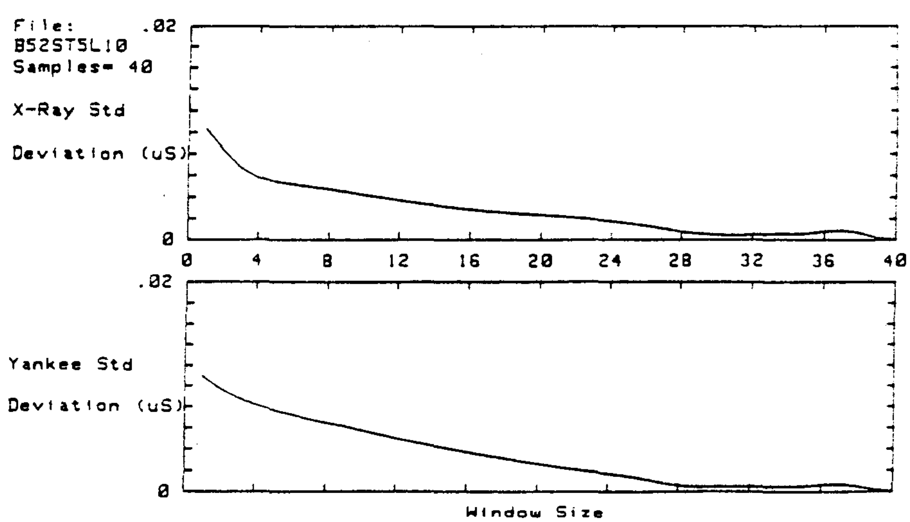

Figure 4

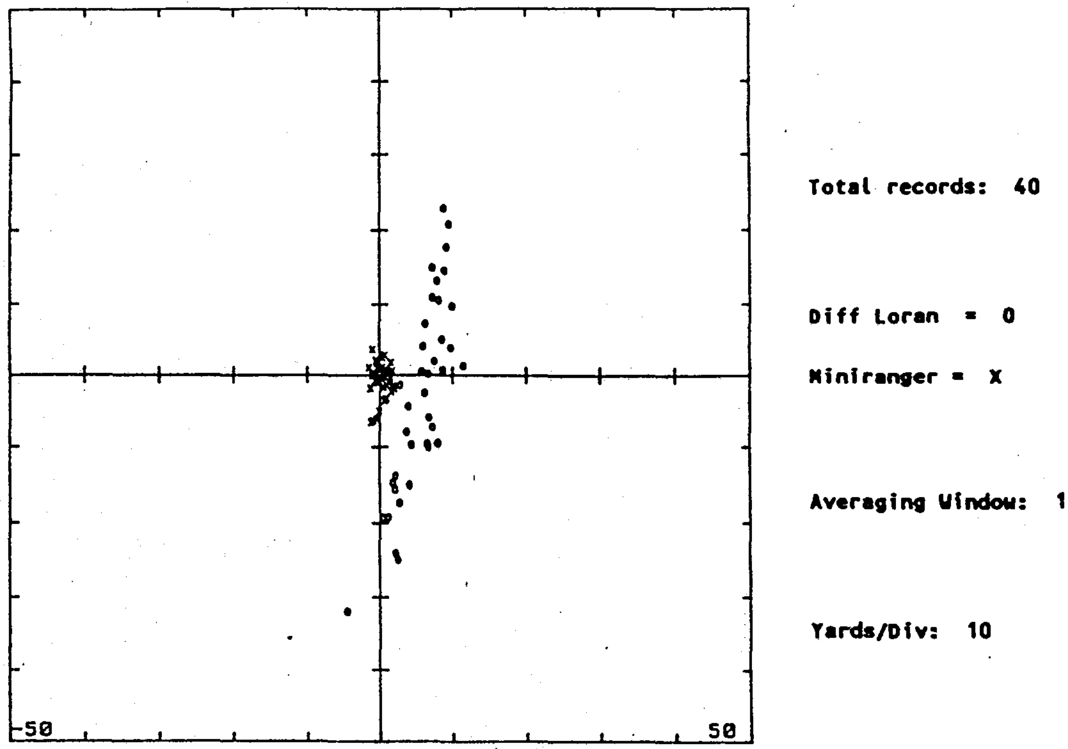

Figure 5
Stationary Data for
Miniranger and DLC
Window = 1

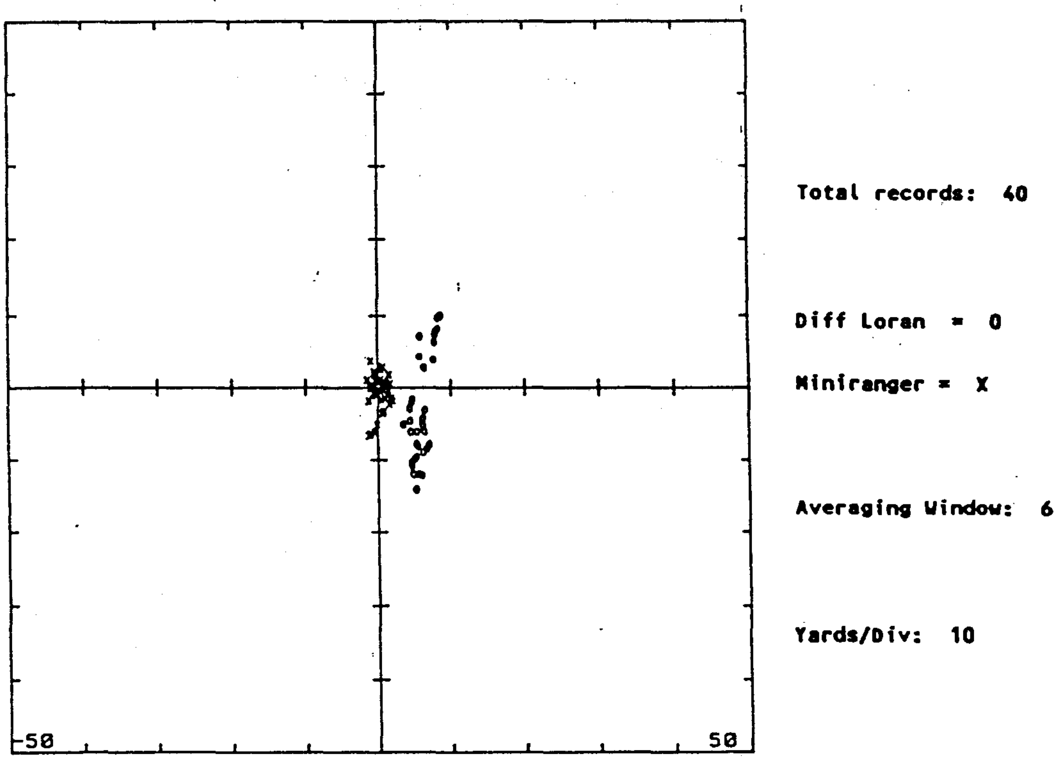

Figure 6
Stationary Data for
Miniranger and DLC
Window = 6

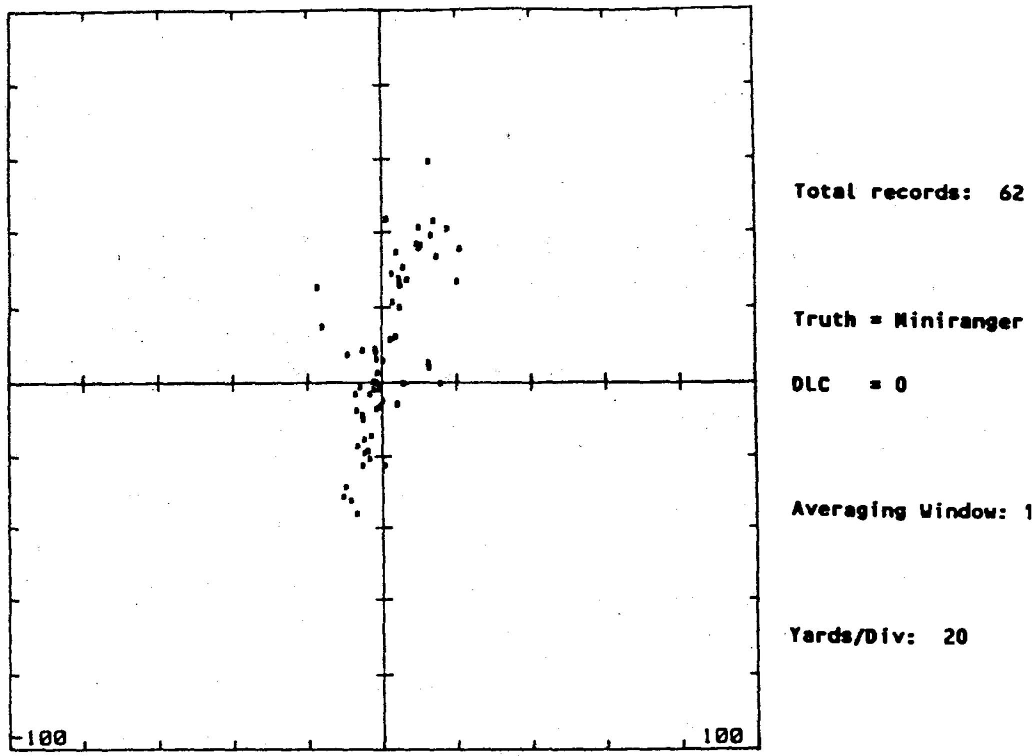

Figure 7
Dynamic Data for
DLC with Miniranger as Truth
Window = 1

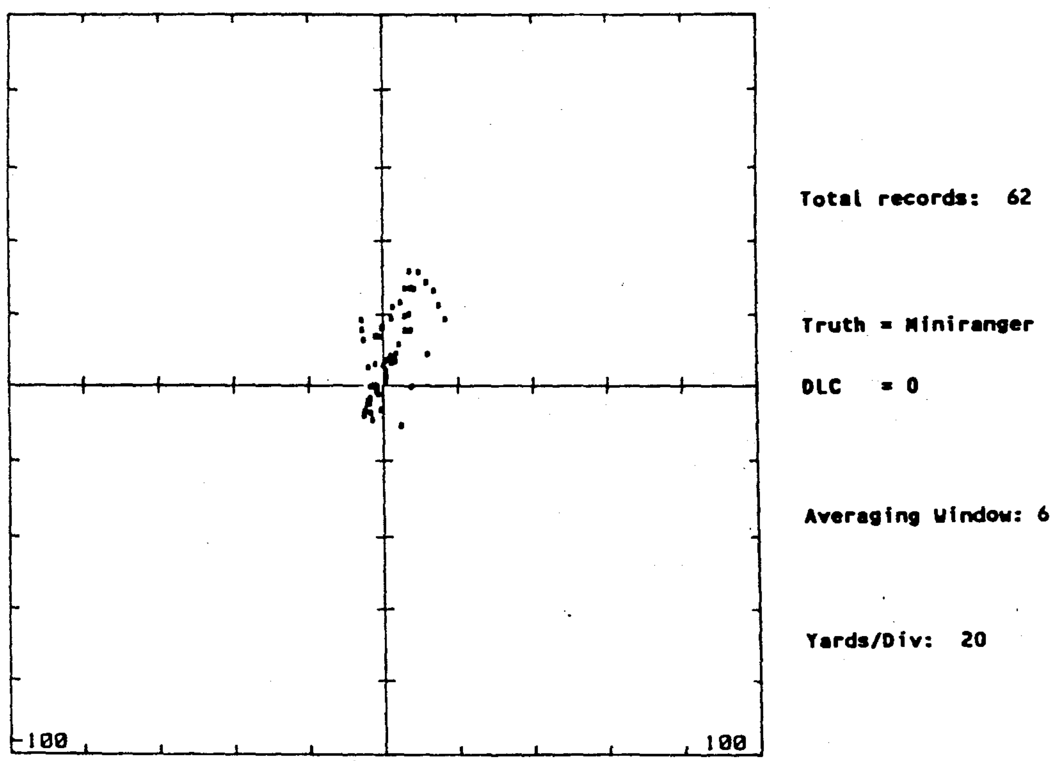

Figure 8
Dynamic Data for
DLC with Miniranger as Truth
Window = 6

Figure 7 displays a scatter plot of the difference between miniranger positions and raw (i.e. window size of one) DLC positions for a moving vessel. One might look at these results as the error between DLC and the truth system. Figure 8 shows the same data displayed in figure 7 except in this case the window size is set at six observations.

The test results shown in figures 7 and 8 were the first evaluation of DLC in a dynamic environment. The maximum error for the filtered data (i.e. figure 8) is approximately 30 yards and most of the points show an error of 20 yards or less. This method of filtering is good for stationary positioning, but introduces an additional lag in position information caused by the averaging. Performance can be improved dramatically for dynamic platforms by using more sophisticated filtering methods. One such method is to use a two state Kalman filter with DLC and ship's heading as inputs. The Kalman filter approach does not increase the lag of the position data but decreases the cross track excursions of the derived positions.

The initial results and findings of the Orange County, California, experiments were very encouraging. Tetra Tech, Inc., is performing an in-depth analysis of the data and will make a report to the EPA on their recommendations and conclusions.

SAULT STE. MARIE, MI DLCS

The USCGC BUCKTHORN is a 110 foot buoy tender whose operational area includes the St. Marys River from Lake Superior to Lake Huron. The St. Marys River is the main artery for large ships (1000 feet length, 105 feet beam) to transit between these two lakes. The river is narrow in many places with channel widths of 300 feet. This leaves little room for navigation or buoy placement errors.

The USCGC BUCKTHORN has historically used horizontal sextant angles to position buoys. Use of horizontal sextant angles provides a mechanism for obtaining a highly accurate position. One of the problems with using sextant angles is that this system requires surveyed markers along the shore. Many of these markers are being destroyed every year due to ice flows, river flooding, and building along the river frontage. Additionally, the derived position is no more accurate than the known positions of the markers. The project team found a few of the marks whose documented positions were wrong. Due to these reasons and others, there are not enough markers in some areas of the river to facilitate buoy placement using horizontal sextant angles. This prompted the USCGC BUCKTHORN to contact the R&D Center for assistance in positioning buoys using an electronic navigation system. The R&D Center installed a DLCS in response to this request. Figure 9 shows the St. Marys River DLCS installation.

St. Marys River Differential Loran-C System

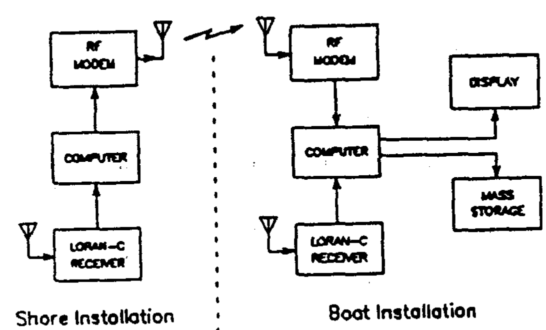

Figure 9

The differential monitor for the St. Marys River is located two miles from the A-1 chain monitor site at Dunbar Forest, MI. The 8970 LORAN-C chain is controlled to a 100 nanosecond tolerance which could cause approximately a 100 foot error in a receiver's position. This error is excessive for the narrow channels of the St. Marys River and is removed by the shore based differential monitor.

The position obtained from the DLC aboard the USCGC BUCKTHORN inputs to another R&DC project development, Automated Aids Positioning System (AAPS). AAPS is an integrated navigation and record maintenance system which is connected to the following sensors; ship's gyro, DLC, and Electronic Angle Measurement Devices (EAMD). Additional sensors such as GPS may be added. AAPS is capable of positioning the ship during the approach to the buoy by a visual display which is called the bull's eye or an 'AN position plot' which is shown in figure 10. This display is scaled automatically to show the ship on the screen as the approach is made to the buoy. When the ship is in the center of the bull's eye and the buoy is set, AAPS will automatically produce and Aid Positioning Record (APR) form and update the data base entries on that buoy. AAPS will also produce an 'AN error plot' (figure 11) which shows the error ellipse of the position fix in reference to the accuracy class of the buoy.

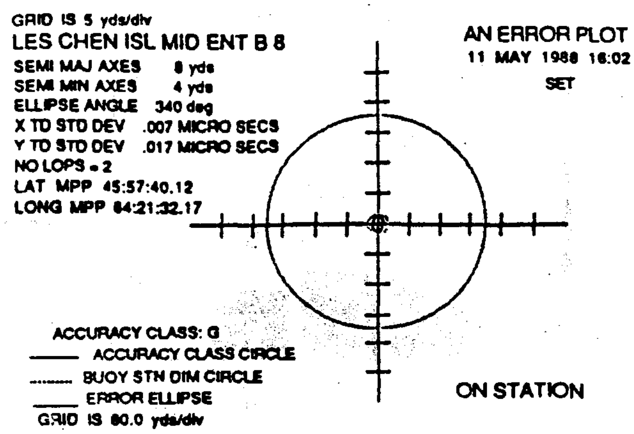

Figure 11

The use of Differential Loran-C with AAPS has demonstrated that the operating time of the USCGC BUCKTHORN can be reduced by 60 percent. Figures 12 and 13 show some preliminary data from testing done onboard the USCGC BUCKTHORN on two different days. These graphs show the approach and buoy setting times required for a typical navigation aid. The approach time consists of piloting from a point 2000 yds. away from the buoy's actual position (AP) to within 50 yds. of AP. Buoy setting time consists of maneuvering the vessel to drop the buoy within a circle around the AP; the radius is specified by the accuracy class of the buoy. The four different types of tests conducted were: 1) Approach using manually plotted bearings and Buoy setting using manually plotted horizontal sextant angles. 2) Approach using LORAN-C and Buoy setting using manually plotted horizontal sextant angles. 3) Approach using DLC sensor with AAPS display and Buoy setting using EAMDs with AAPS display. 4) Approach and Buoy setting using DLC sensor on AAPS display. Approach time and buoy setting time are indistinguishable operations in method 4.

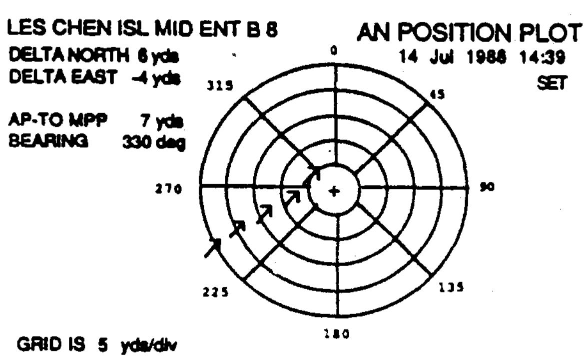

Figure 10

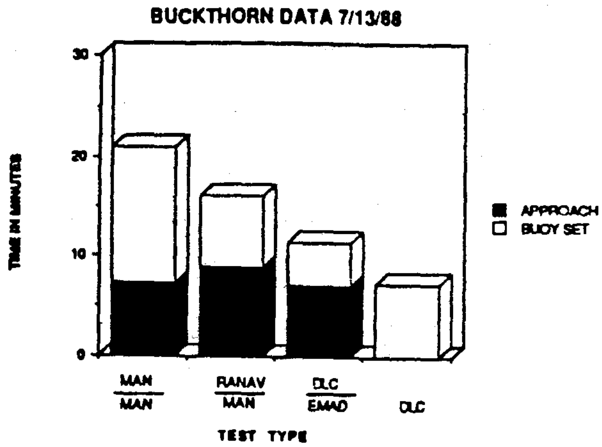

Figure 12

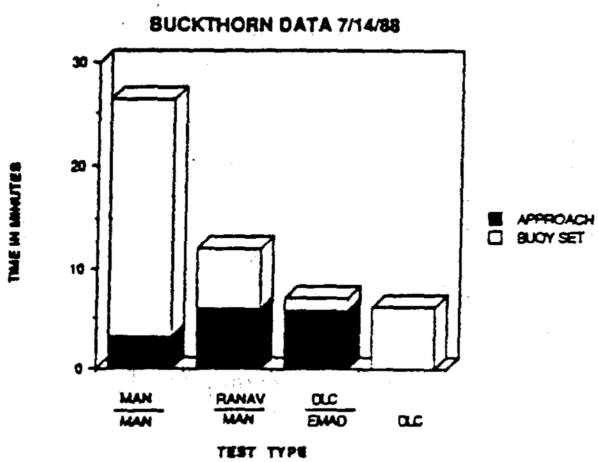

Figure 13

In the spring of 1987, the crew of the USCGC BUCKTHORN positioned and set 92 of their 268 buoys using DLC. In the spring of 1988, they increased the number of buoys set using DLC to 198. The USCGC BUCKTHORN has saved considerable time and operating expense with this system; this has allowed the vessel and crew to complete needed work which otherwise would have been performed by a contractor. If this system were made available to other buoy tenders, the Coast Guard could save considerable time and money.

STANDARDIZED DLCS BROADCASTS

Differential Loran-C has been shown to improve the accuracy of the Loran-C position, but the advent of GPS may negate any need for Loran-C in the future. For the near term, the accuracies offered by GPS are not within the reach of every boater. When GPS does become available (satellites up and equipment price down) the accuracy will be degraded by selective availability (SA) induced by the DOD. In the presence of SA, Loran-C can continue to compete with GPS as a precision radio navigation aid with a DLCS. In order to have a DLCS, corrections must be provided to the user equipment. The manner in which these corrections are provided is as numerous as the number of companies/manufacturers investigating their usage. Providing a universal method of correction broadcast promotes interoperability of DLC signals among various manufacturers' equipment which in turn enhances the attractiveness of a DLCS.

The nature of Loran-C signal propagation limits the area in which DLC corrections are valid (spatial correlation). For a given harbor or river, two or more DLC reference stations may be required to obtain the necessary accuracy. Simultaneous correction broadcasts from each station can be accomplished by time multiplexing the broadcasts on a single frequency or by assigning a different frequency to each reference station. Another method is to combine the corrections from all the reference stations in a DLCS network into one correction broadcast. This broadcast method is supported by the differential navigation message format of the Radio Technical Committee for Maritime Services, Special Committee 104 (RTCM SC-104).

The Coast Guard has been actively involved with the RTCM in the creation of a differential message format for the Differential GPS (DGPS) community.[3] Other forms of radionavigation can use this same message format for differential broadcast; the Coast Guard has proposed the adoption of DLCS correction messages by the RTCM. The use of the proposed RTCM standard for DLC would eliminate the need to generate and maintain a separate standard; this would save considerable time and resources. Presently there are four RTCM message types proposed for use with DLC. These message types have been given interim numbers of 60 through 63 by the RTCM SC-104.

The specifics of the RTCM SC-104 format can be found in reference 3. The proposed messages are;

Message Type 60 DLC Corrections

Figure 14 and table 14-1 present the content of message type 60. This is a primary message which provides the Time Difference (TD) corrections. The length of this frame is variable depending on the number of secondaries contained in the message. Only the corrections from one DLC reference station are sent in a single type 60 message. If the DLC network consists of multiple DLC reference stations, additional type 60 messages must be sent.

$$TD_p = TD_r + TD_c - TD_a \qquad (14a)$$

Equation 14a shows the application of this correction to the receiver TDs where TD_p is a theoretical or predicted TD received over an ideal all sea water path, TD_r is the actual received TD, TD_c is the TD corrections provided in message type 60 by the DLC reference station and TD_a is the ASF corrections for a given point. (The ASF corrections are discussed in more detail in conjunction with message type 63). Also provided is a 4 state age value for each correction which may be used by the provider to indicate usability of a TD pair.

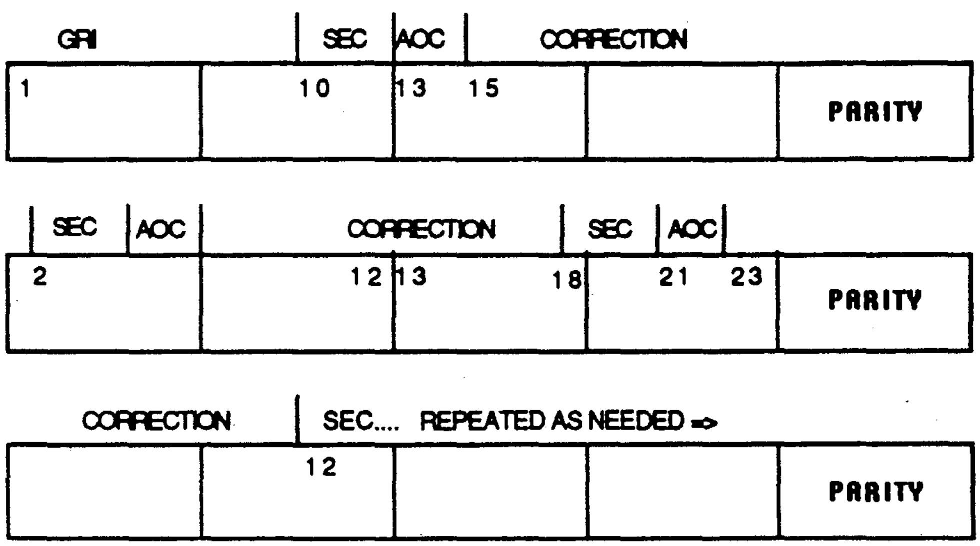

Figure 14 TYPE 60 MESSAGE FORMAT

TABLE 14-1 CONTENTS OF A TYPE 60 MESSAGE

PARAMETER	NO. OF BITS	SCALE FACTOR AND UNITS	RANGE
GROUP REPETITION INTERVAL (GRI)	9	10	4990 - 9990
SECONDARY ID (SEC)	3	see table 14-2	0 - 5
AGE OF CORRECTION (AOC)	2	provider dependent	0 - 3
CORRECTION	11	10^{-9} sec	$\pm$1023ns*
FILL		alternating 1's and 0's as required	

*2's complement

TABLE 14-2 SECONDARY ID

CODE	INDICATION
000	No further secondaries follow
001	Secondary V
010	Secondary W
011	Secondary X
100	Secondary Y
101	Secondary Z
110-111	Unused

__Message Type 61 DLC Reference Station Parameters__

Figure 15 and table 15-1 present the content of message type 61. This message contains information concerning the DLC reference stations of the DLC network.

The length of this frame is two words. Only the parameters for one DLC reference station are sent in a single type 61 message. If the DLC network consists of multiple DLC reference stations, additional type 61 messages must be sent.

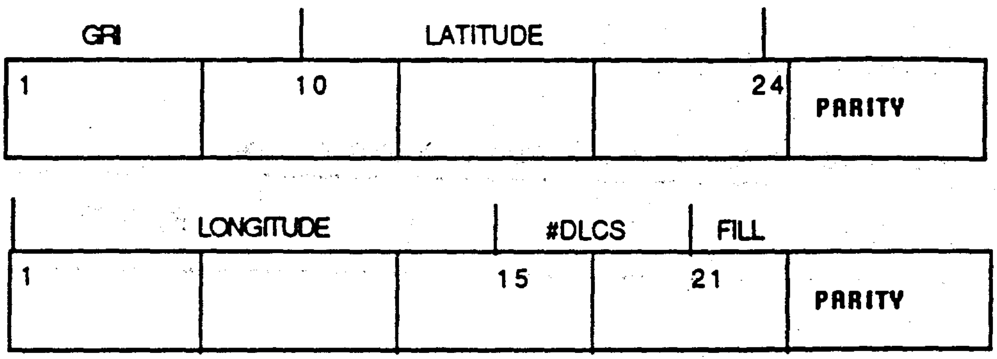

Figure 15 Type 61 MESSAGE FORMAT

TABLE 15-1 CONTENTS OF A TYPE 61 MESSAGE

PARAMETER	NO. OF BITS	SCALE FACTOR AND UNITS	RANGE
GROUP REPETITION INTERVAL (GRI)	9	10	4990 - 9990
LATITUDE	14	0.02°	± 90°*
LONGITUDE	15	0.02°	± 180°*
No. DLCS	6	1	1 - 64
FILL	4	alternating 1's and 0's	

*2's complement

Message Type 62 Signal Interference Message

Figure 16 and table 16-1 present the content of message type 62. This message provides information concerning interference frequencies which may exist in the area of the DLC network. Using programmable notch filters, receivers can use this information to enhance Loran-C reception by filtering extraneous noise sources. The length of this frame is variable depending on the number of interference frequencies broadcast. Each word can contain information for two interference frequencies. The frequency offset is from 100khz.

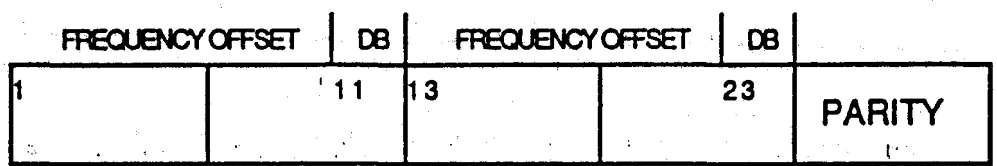

Figure 16 TYPE 62 MESSAGE FORMAT

TABLE 16-1 CONTENTS OF A TYPE 62 MESSAGE

PARAMETER	NO. OF BITS	SCALE FACTOR AND UNITS	RANGE
FREQUENCY OFFSET	10	0.1 khz	± 51.1 khz*
SIGNAL LEVEL (db)	2	see table 16-2	

* 2's complement

TABLE 16-2 SIGNAL LEVEL

CODE	INDICATION
00 - 11	Unassigned

Message Type 63 Additional Secondary Phase Factor (ASF) Table for Network Area

Figure 17 and table 17-1 present the content of message type 63. This message provides the ASF information for waypoints within the network area which tie Loran-C positions to a geodetic coordinate system. The ASF base line values are average ASF value for that secondary in the network coverage area. Delta ASF values are added to the Base line ASF values to obtain the Total ASF of the secondary at that waypoint. Total ASF values are subtracted from the receiver TDs to derive an all sea water path predicted TD. (see equation 14a) The length of this frame is variable depending on the number of waypoints to be broadcast. Each type 63 message contains at least 7 words (including header). Words 3 and 4 contain general data concerning all waypoints included in this broadcast. Words 5 through n contain the specific ASF data for each waypoint. If the number of waypoints contained within a network coverage area is large, this table may be broke into multiple broadcasts so as to avoid monopolizing the data link.

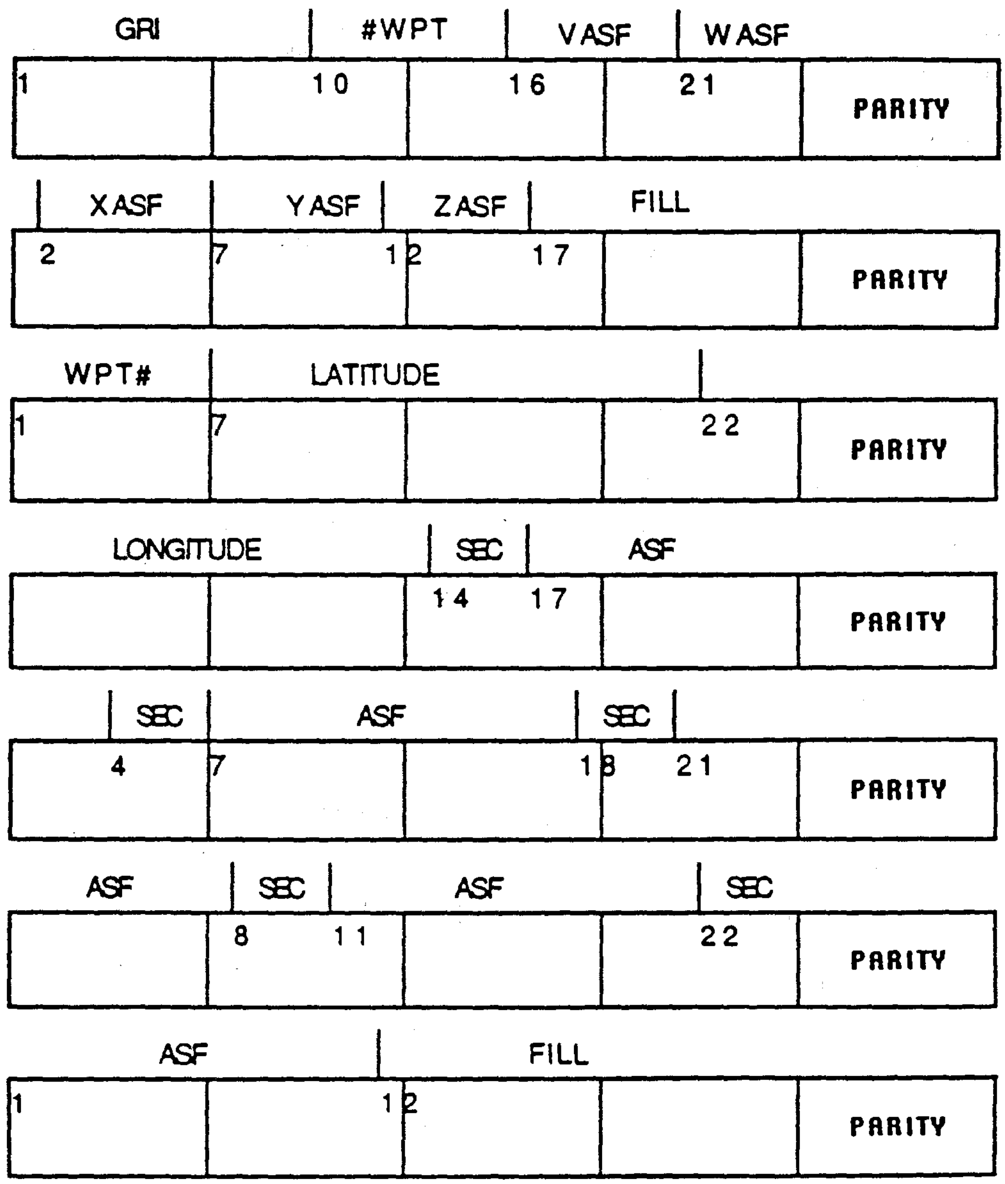

Figure 17 TYPE 63 MESSAGE FORMAT

TABLE 17-1 CONTENTS OF A TYPE 63 MESSAGE

PARAMETER	NO. OF BITS	SCALE FACTOR AND UNITS	RANGE
GROUP REPETITION INTERVAL (GRI)	9	10	4990 - 9990
NO. WAYPOINTS (#WPT)	6	1	1 - 64
ASF BASE LINE V (V BL ASF)	5	1^{-6} sec	± 15 usec
ASF BASE LINE W (W BL ASF)	5	1^{-6} sec	± 15 usec
ASF BASE LINE X (X BL ASF)	5	1^{-6} sec	± 15 usec
ASF BASE LINE Y (Y BL ASF)	5	1^{-6} sec	± 15 usec
ASF BASE LINE Z (Z BL ASF)	5	1^{-6} sec	± 15 usec
WAYPOINT NO. (WPT#)	6	1	1 - 64
LATITUDE	15	0.006°	± 90°*
LONGITUDE	16	0.006°	± 180°*
SECONDARY	3	see table 17-2	
DELTA ASF	11	1^{-9} sec	± 1023 ns*

* 2's complement

TABLE 17-2 SECONDARY ID

CODE	INDICATION
000	No further secondaries follow
001	Secondary V
010	Secondary W
011	Secondary X
100	Secondary Y
101	Secondary Z
110-111	Unused

CURRENT AREAS OF EVALUATION

The DLCS project team is currently providing the precision navigation sensor for conducting Q-route surveys in the New London Harbor. The navigation sensor being used is DLCS. Preliminary results of the data from a commercially available navigation package (QUILLS II) indicates a 5 - 20 meter correlation between DLCS and DGPS in WGS 84 coordinates. The project team is currently utilizing the RTCM format message to broadcast corrections and station information to the vessel. These corrections are carried on the same data link as DGPS corrections.

CONCLUSIONS

In several experimental systems, the project team has shown that with DLCS an operator can reliably obtain 8 to 20 meters accuracy. It also appears likely that an operator can achieve 8 to 20 meters absolute geodetic accuracy (in areas of good crossing angles and gradients). DLCS is a good candidate for filling the gap in precision positioning ability until DGPS is available full time. For the small boater or fishing fleet who may never be capable of affording a GPS receiver, DLCS can provide the repeatable level of accuracy which may be required, and it is available now. DLCS holds promise as a radionavigation aid in the setting and retrieving of Coast Guard buoys. The time saved can free up Coast Guard resources for other commitments.

FUTURE

The project plans to install and to operate a DLCS network in Puget Sound during 1989. Installation of this system will begin in late March, 1989, and be completed by June, 1989. The system is intended for use by the USCGC FIR in positioning buoys, but will be available to the public for use and evaluation. The system will consist of at least 3 DLC reference stations and the corrections from all stations will be broadcast over one data link using the RTCM message format. This system will be built to the current design specifications of the R&DC.

RECOMMENDATIONS

The authors strongly recommend that the WGA promote the development and implementation of Differential Loran-C as a navigational service in the commercial or government arena. If Differential Loran-C is to be a commercial service, then the WGA should support changes to existing laws and regulations. The authors further recommend that the WGA adopt a standardized format for the broadcast of Differential Loran-C information. These actions would aid the manufacturers of receiver equipment to work toward a common goal while holding down production and user costs. It is additionally recommended that the WGA push for a standardization of TD to LAT/LON conversion algorithms. If DLCS is to ever become a factor in obtaining absolute geodetic position accuracy, these algorithms must be common to all user equipment and Differential Loran-C reference stations.

BIOGRAPHICAL INFORMATION

Cordell S. Viehweg was commissioned in the U. S. Coast Guard in 1974, after graduating from the U. S. Merchant Marine Academy. He served 10 years in the Marine Inspection/Marine Safety field then attended California State University where he obtained his MS degree in Electronic Engineering. In 1986 he was assigned to the Coast Guard Research and Development Center, in Groton, Ct, and began work as a project engineer on the Differential GPS project. He is now serving as the Project Officer for the Differential LORAN-C project and the Automated Aid Positioning System project.

Robert D. Crowell initially joined the Coast Guard in 1969. After serving 3 years aboard the USCGC he was assigned to the Coast Guard Research and Development Center, in Groton, Ct. He finished his active duty tour in the Coast Guard in 1973 and became a civilian employee at the R&D Center. While working at the R&D Center, Mr. Crowell has had experience working on such diverse systems as; Loran-C, Distress Alerting and Locating System (DALS), Harbor Monitor System (HMS), Automatic Aid Positioning System (AAPS), Precision Intracoastal Loran Translocator (PILOT) and Differential Loran-C (DLCS). He is currently assigned to the DLCS and AAPS projects.

Alex Averin joined the Navy in 1969 as an electronics technician and served for 7 years before joining the Coast Guard. He was commissioned in 1982. His Loran-C experience includes a tour of duty at Marcus Island, Japan in 1980 and a tour at Iwo Jima, Japan in 1987. His duties at the R&D Center include collection and analysis of data from two R&D monitor sites in Alaska and development work with digital charts.

Ronald H. Frazier was commissioned in the U. S. Coast Guard in 1971, after graduating from the U. S. Coast Guard Academy. After two years of sea duty, he attended MIT and received the SM and EE degrees in Electrical Engineering in 1975. He is presently assigned at the Coast Guard Research and Development Center, in Groton, CT, as the Electronic Branch Chief. Previous Coast Guard tours involving Loran-C have included the Electronics Engineering Center in Wildwood, NJ, Coast Guard Headquarters, and Coast Guard Activities Europe, London, UK. He is presently an MBA Candidate through RPI.

References

[1] Blizard, Matthew M., "Update: Differential Loran-C System", Proceedings of the Sixteenth Wild Goose Association Technical Symposium, October, 1987.

[2] Muellenhoff, Dr. W. P. "Evaluation of Survey Positioning Methods for Nearshore Marine and Estuarine Waters", Tetra Tech, May, 1986.

[3] RTCM Special Committee No. 104, 'RTCM Recommended Standards for Differential NAVSTAR GPS Service, March 1, 1988.

Geometric Dilution of Precision

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ABSTRACT

The effects of geometry on position uncertainty for two dimensional radionavigation sytems is investigated. Both hyperbolic and direct ranging, or rho-rho, system types are covered. Expressions for the distance root mean square (dRMS) error measure are derived. Geometric Dilution of Precision (GDOP) is extracted from the dRMS expressions as a dimensionless quantity providing a relative measure of position accuracy. The angles used to formulate the GDOP expressions are fully discussed. The most critical of these angles is the crossing angle formed by the system lines of position (LOP's).

INTRODUCTION

No attempt has been made to research the historical development of the GDOP concept; Swanson[1] has presented this aspect quite well. The authors of this paper presume that the fundamental concept of GDOP is familiar to our readers. With the advent of satellite navigation and other three dimensional sytems, however, GDOP can be formulated in different ways. In addition, time measurements constitute an additional variable in GDOP for direct ranging systems. GDOP for the three dimensional direct ranging system incorporates geometric effects in the "horizontal" plane of latitude and longitude, the vertical direction for altitude, and in time space. Modern terminology has evolved to the point where we have Horizontal Dilution of Precision (HDOP), Vertical Dilution of Precision (VDOP), and Time Dilution of Precision (TDOP). Furthermore, Position Dilution of Precision (PDOP) is commonly used to combine HDOP and VDOP or to address the coordinate space versus time space. How each of these contribute to GDOP overall are summarized below:

Three Dimensional Direct Ranging System

$$(GDOP)^2=[(HDOP)^2+(VDOP)^2]+(TDOP)^2=(PDOP)^2+(TDOP)^2$$

Two Dimensional Direct Ranging System

$$(GDOP)^2=(HDOP)^2+(TDOP)^2=(PDOP)^2+(TDOP)^2$$

Two Dimensional Hyperbolic System

$$(GDOP)^2=(HDOP)^2=(PDOP)^2$$

For the two dimensional systems, therefore, PDOP is identical to HDOP. In the hyperbolic mode of the two dimensional system, GDOP, PDOP and HDOP are all identical. The balance of this paper, with respect to the terminology just described, will address HDOP.

We will now derive an expression for dRMS from which we will extract the dimensionless HDOP factor. Our derivations will be based upon the area of position uncertainty associated with the variables used to determine a position fix. We will use the loran triad system for the two dimensional hyperbolic case with time differences (TD's) as the variables and then proceed to the direct-ranging system.

TWO DIMENSIONAL HYPERBOLIC

The loran triad system consists of a Master transmitter (M) and two Secondary transmitters (A and B) generically illustrated in Figure 1. Emphasis is placed on the quadrant designations for the receiver (or observer) location in this triad system for the discussions that follow. Receivers (R_n) are illustrated in the four quadrants with n=1,2,3,4 labelled clockwise from True North. Quadrant 1 is the triad's primary service area defined by the sector bounded by both baselines and an included angle of <180 degrees. Quadrants 2 and 4 are the sectors between a baseline and a baseline extension. Quadrant 3 is the sector lying between both baseline extensions.

Figure 2 shows a receiver located in Quadrant 1. The angles between the lines of bearing (geodesics) to the Master and to the Secondaries are labelled α and β. The bisector of these angles gives the line of bearing for the respective Line of Position (LOP) at the receiver location. LOP's are shown by dotted lines, and the angle between the LOP's is the crossing angle (Γ). For the case illustrated, Γ is equal to $(\alpha+\beta)/2$.

Figure 3 depicts the area of position uncertainty where the TD variances (σ) in microseconds have been converted to distance (d) in meters from the loran gradients:

$$d = \sigma \cdot V^{\circ}/\mathrm{Sin}\Phi \tag{1}$$

In equation (1), Φ, is the angle at the receiver's location between the LOP and the geodesic to the Master (M); V° is the time-difference velocity along the baseline, about 150 meters/microsecond. The crossing angle (Γ) in is the sum of Φ_A and Φ_B which, in the illustrated case, is identical to $(\alpha+\beta)/2$.

The line R in Figure 3 is dRMS which is formulated from the root sum square value of two components d_A and $(d_{B1}+d_{B2})$ as expressed in equation 2:

$$\mathrm{dRMS}^2 = R^2 = (d_A)^2 + (d_{B1}+d_{B2})^2 \tag{2}$$

Using the angle, ψ, which is related to Γ by:

$$\psi = 90 - \Gamma \tag{3}$$

we find:

$$d_{B1}=d_A \mathrm{Cos}\,\varphi \tag{4}$$

$$d_{B2}=d_B/\mathrm{Cos}\,\varphi \tag{5}$$

Substitution of (4) and (5) into (2) and using trigonometric identities gives:

$$dRMS^2=(1/\mathrm{Sin}^2\Gamma)[d_A^2+d_B^2+2d_Ad_B\mathrm{Cos}\Gamma] \tag{6}$$

The complete expression when equation (1) is used for d_A and d_B is:

$$dRMS^2=(V^\circ/\mathrm{Sin}\Gamma)^2[(\sigma_A/\mathrm{Sin}\Phi_A)^2+(\sigma_B/\mathrm{Sin}\Phi_B)^2+2\sigma_A\sigma_B\mathrm{Cos}\Gamma/(\mathrm{Sin}\Phi_A/\mathrm{Sin}\Phi_B)] \tag{7}$$

If we assume a correlation coefficient of 0.5 affecting the last term in the brackets and assume equal TD variances, we have the classic expression used in generating coverage diagrams:

$$dRMS=(\sigma\cdot V^\circ/\mathrm{Sin}\Gamma)[(1/\mathrm{Sin}\Phi_A)^2+(1/\mathrm{Sin}\Phi_B)^2+\mathrm{Cos}\Gamma/(\mathrm{Sin}\Phi_A\cdot\mathrm{Sin}\Phi_B]^{\frac{1}{2}} \tag{8}$$

From either (7) or (8), HDOP is extracted using only the trigonometric terms leaving a dimensionless quantity:

$$HDOP=(1/\mathrm{Sin}\Gamma)[1/\mathrm{Sin}^2\Phi_A+1/\mathrm{Sin}^2\Phi_B+\mathrm{Cos}\Gamma/(\mathrm{Sin}\Phi_A\mathrm{Sin}\Phi_B]^{\frac{1}{2}} \tag{9}$$

For the case of a receiver in Quadrant I or in Quadrant III (see Figure 1), when the line of bearing to the Master is situated between both LOP's, the crossing angle will be the sum of Φ_A and Φ_B. But when a receiver is located in Quadrants II and IV, the line of bearing to the Master is not situated between both LOP's. Figure 4 illustrates the relationships for a Quadrant 4 case. For this case the crossing angle is given by:

$$\Gamma = \Phi_A-\Phi_B = \alpha/2 - \beta/2 \tag{10}$$

and for the Quadrant II case, it can be shown that:

$$\Gamma = \Phi_B-\Phi_A = \beta/2 - \alpha/2 \tag{11}$$

With the definitions given for α and β, it should be clear that the LOP's crossing angle is not always ½ their sum. It is always true, however, that the crossing angle always can be unambiguously determined by taking the difference between the bearings of the LOP's.

TWO DIMENSIONAL DIRECT RANGING

The situation is slightly different with the direct ranging mode. In the first place, the gradient for the LOP's is invariant and Equation 1 becomes:

$$d = \sigma V^\circ \tag{12}$$

reflecting a constant gradient with respect to distance from the transmitter site.

Figure 5 is an exagerrated illustration of the direct ranging case where Γ is the crossing angle and the line R is the dRMS obtained from the root sum square of d_A, and $(d_{B1}+d_{B2})$. From Figure 5 and trigonometric identities:

$$dRMS^2=(1/\mathrm{Sin}\Gamma)^2[(d_A)^2+(d_B)^2+2d_Ad_B\mathrm{Cos}\Gamma] \qquad (13)$$

Using the gradient relationship, assuming equal variances, and a correlation coefficient of 0.5 to complete the expression:

$$dRMS = (\sigma \cdot V^{\prime}/\mathrm{Sin}\ \Gamma)\cdot(2+\mathrm{Cos}\ \Gamma)^{\frac{1}{2}} \qquad (14)$$

$$HDOP = (1/\mathrm{Sin}\ \Gamma)\cdot(2+\mathrm{Cos}\ \Gamma)^{\frac{1}{2}} \qquad (15)$$

DISCUSSION

To illustrate the circumstance of ignoring the quadrant identity for the hyperbolic system, a simple analysis was conducted for GRI 9940. In this analysis, the crossing angle was determined in two ways: (1) as ½ the sum of the angles α and β, which we contend is not always correct, and (2) from the difference in the bearings of the LOP's. Figure 6 (not to scale) shows the two paths of movement in an easterly direction: (1) from Portland at about 45° North latitude to 110° West longitude, and (2) from 47° North to the same longitude. Both cross the 9940W baseline moving from region I to region II; the latter being close to the secondary transmitter at George. Figures 7 showS the difference between the crossing angle, dRMS, and HDOP, respectively, for the southerly path. Figures 8 shows the same differences for the northerly path. In each of these figures the solid line results from method (2) above while the dotted line is from using method (1).

The derivations given above for both dRMS and HDOP are representative of position errors due to geometric effects. HDOP is a dimensionless quantity extracted from the appropriate expression for dRMS; the latter is an uncertainty measure in the form of a circle's radius. For the hyperbolic system, we have stated that the quadrant relationship of the position is transparent when the angular quantities are determined from the bearings of the lines. Since these bearings can be determined using the Sodano methodology (Reference 1) and the two principal components of dRMS can be calculated, the error elipse is calculable. The dRMS components are the semi-major and semi-minor axes of the error ellipse. In the opinion of the authors, the error ellipse provides a much more comprehensive understanding of the position uncertainty because of the directionality knowledge contrasted to the circular dRMS. This knowledge of the directionality relationship can sometimes be put to advantage which the authors intend to investigate by modelling.

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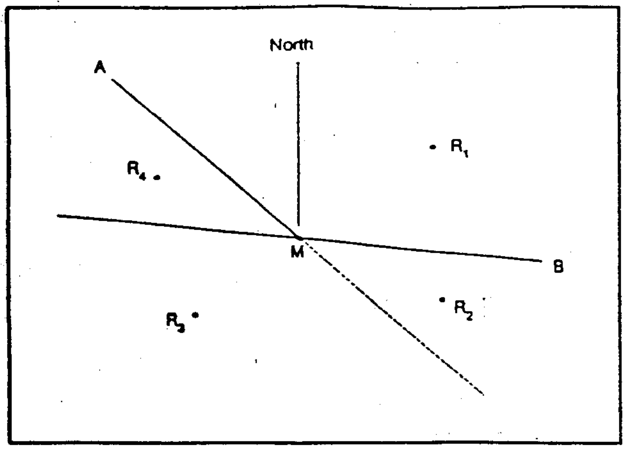


FIGURE 1.
LORAN Triad Geometry

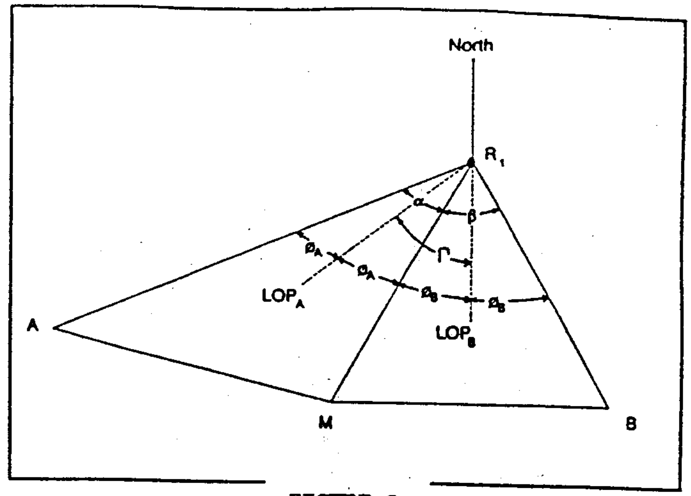


FIGURE 2.
Receiver in Quadrant 1

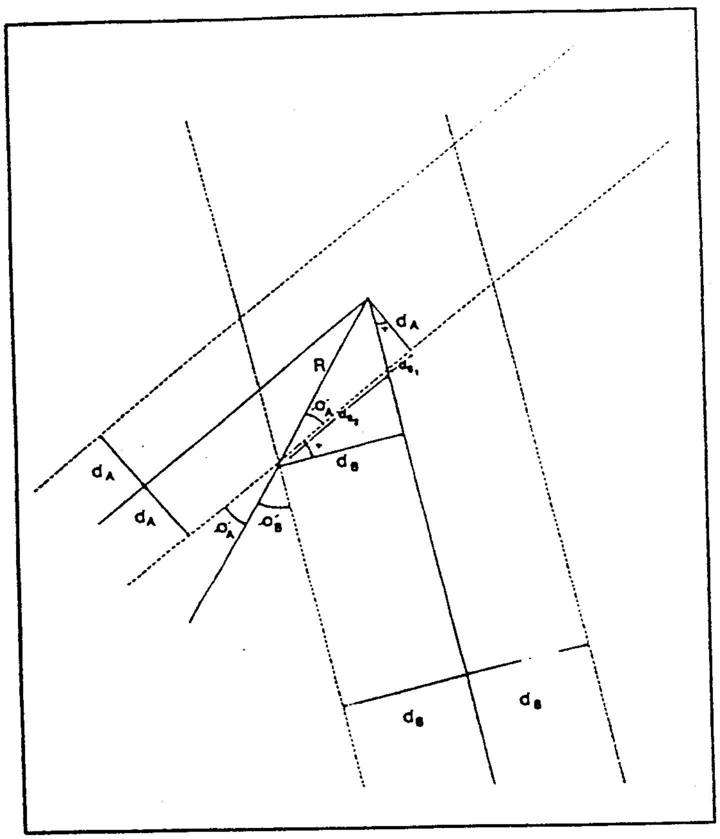


FIGURE 3.
LOCAL AREA OF POSITION UNCERTAINTY (HYPERBOLIC)

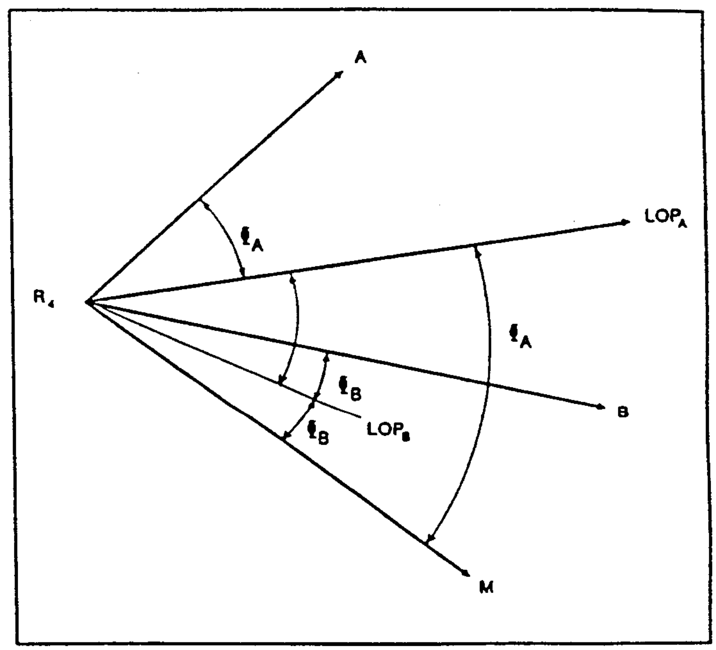


FIGURE 4.
LORAN Triad Quadrant IV Representation

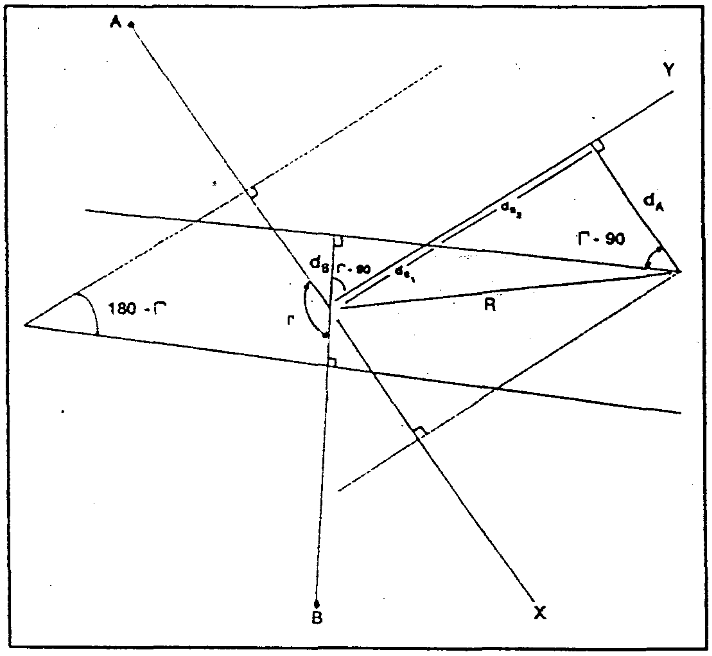


FIGURE 5.

LOCAL AREA OF POSITION UNCERTAINTY (RHO-RHO)

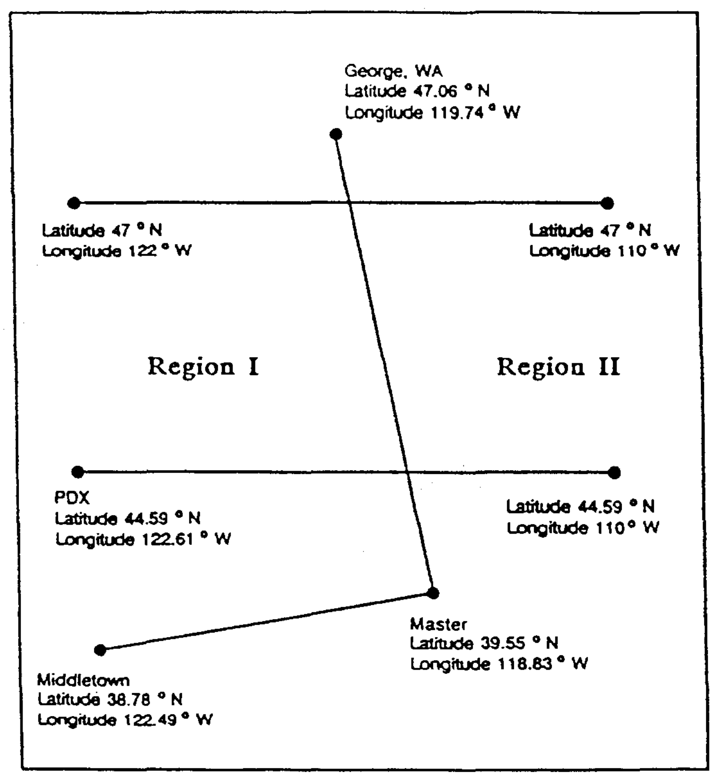


FIGURE 6.

HYPOTHETICAL PATHS FOR GRI 9940 ANALYSIS

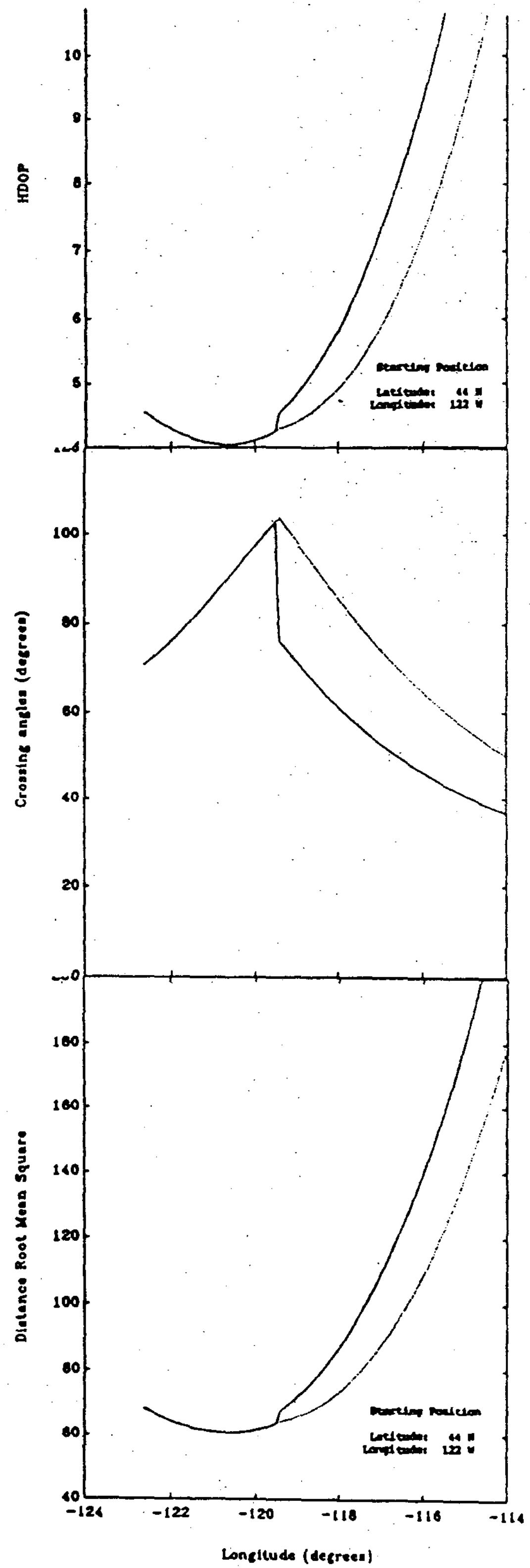


FIGURE 7.

SOUTHERLY PATH

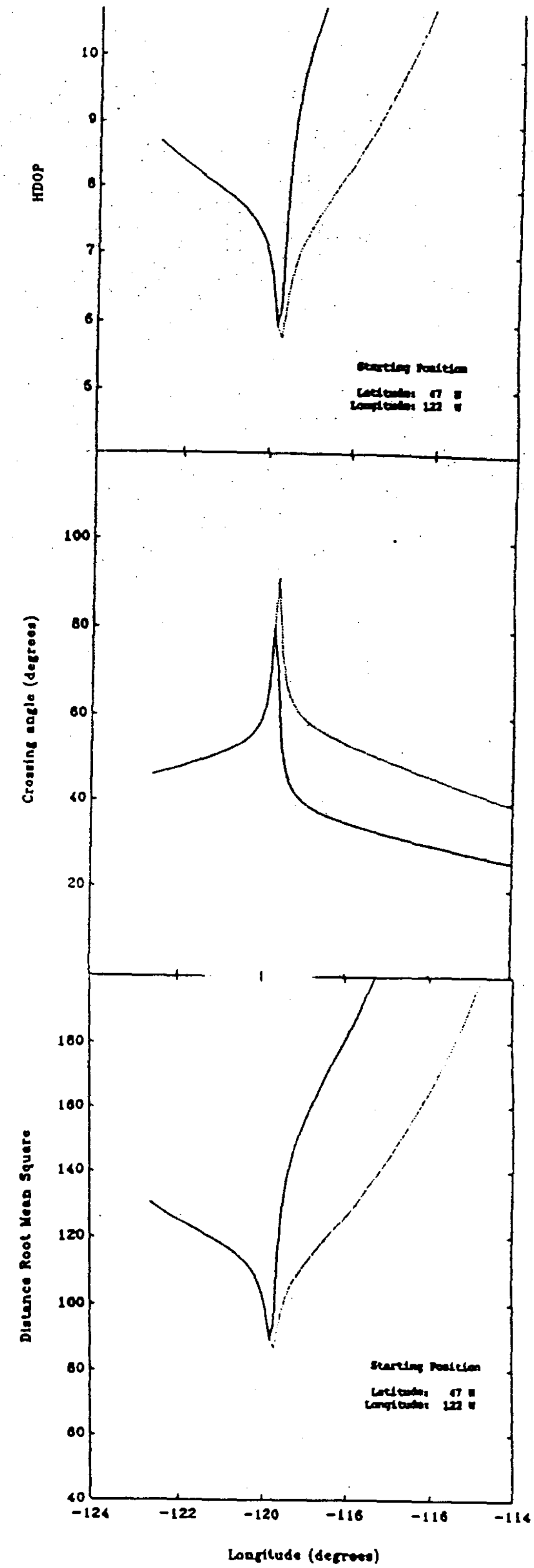


FIGURE 8.

NORTHERLY PATH

COAST GUARD ISSUES

FOREIGN

FAR EAST - COMMANDO LION
- ROK 1 YEAR OVERLAP

- NORWESTPAC

ACTIVITIES EUROPE - (PRE - AND POST-1994)

LORSTA SYLT & FRG

MEDSEA- TALKING W/ITALY & TURKEY
SPAIN - EXPECTING TO
START TALKS SOON

US/USSR JOINT OPERATIONS -

NEXT MEETING IN U.S. IN SUMMER

COAST GUARD ISSUES

DOMESTIC

MIDCONTINENT EXPANSION PROJECT (FAAMEP)

PT CLARENCE - TOK BASELINE (FAA) -

ON-AIR
FAIRBANKS MONITOR INSTALLED

LORAN-C SYNCHRONIZATION (LAW) -

M 100 ns - EECEN PROJECT
NEUS & USNO EXPERIMENT

S 100 ns EFFECTS STUDY -
R&DCEN CONTRACT

METHODS OF 30 ns LORAN/GPS
COMPARABILITY- R&DCEN & EECEN

COAST GUARD ISSUES

INTERNAL

A76 REVIEW OF LORSTA

TOK - OTH-B RADAR INSTALLATION

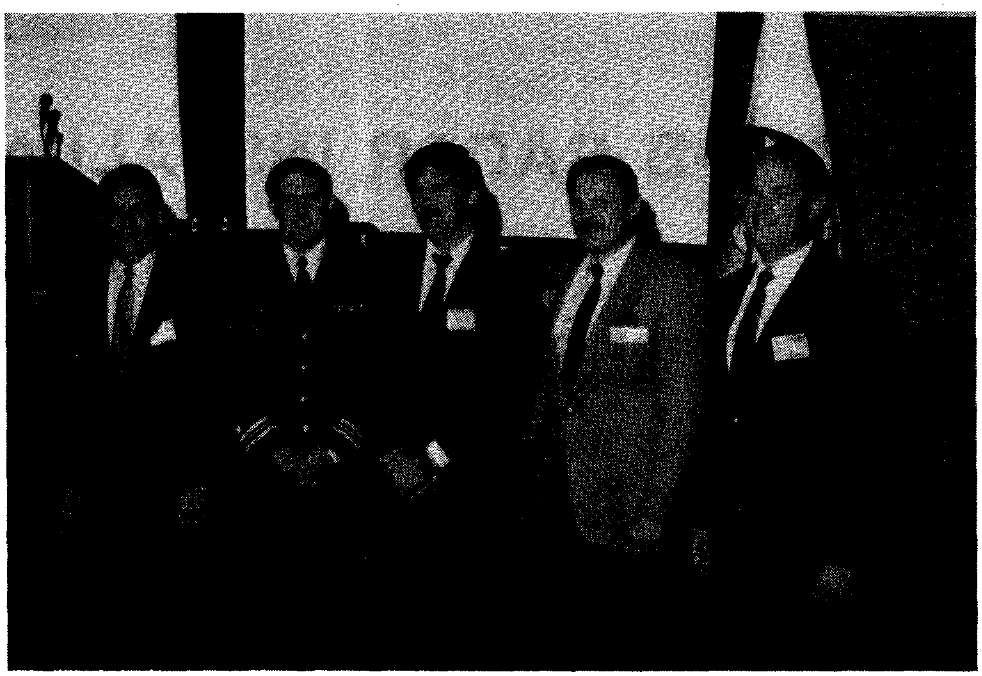
EQUIPMENT REPLACEMENT
SYSTEMS ANALYSIS &
FUTURE ARCHITECTURE

COVERAGE DIAGRAM GENERATOR
AUTOMATED
STANDARDIZED AND "BLESSED"

SESSION 5

TERRESTIAL DEVELOPMENTS AND APPLICATIONS

LARRY CORTLAND
II MORROW INC.



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LORAN-C's FUTURE ROLE IN AUTOMOBILE NAVIGATION

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ABSTRACT

As measured by market penetration, Loran-C has become the technology of choice for automatic vehicle location monitoring (AVLM) systems. This success results from the availability of low-cost computerized receivers that generally perform well in the land mobile environment. Numerous manufacturers are beginning to integrate dead-reckoning backup to provide continuous location information in even the most difficult urban settings, and the U.S. Coast Guard is investigating Navstar GPS time synchronization of master stations for cross-chain tracking which will give further improvements in accuracy. These improvements, along with the completion of continental U.S. coverage in the early 1990s, assure a large share of the expanding AVLM market, and make Loran-C an increasingly attractive option for general automotive navigation applications.

The current directions of worldwide automobile navigation system development suggest that dead reckoning with map matching may become a common denominator in system design, and that system differentiation may be primarily in the means used for absolute location updates and for the communication of real-time traffic data to on-board routing subsystems. The presently identified alternatives for location updates are proximity beacons and radio navigation. Proximity beacons have the advantage of simultaneously providing traffic data communications, but their outlook is dimmed by the high costs of instrumenting the street and highway infrastructure. The principal radio navigation candidates for location updating are Navstar GPS and Loran-C. GPS's promise of high accuracy and worldwide coverage once the satellites are fully deployed is tempered by uncertainties in availability and cost. Loran-C is a mature low-cost technology that can provide adequate accuracy for automobile navigation location updates but has limited geographic coverage, a drawback that will soon be eliminated in the United States.

This paper reviews the status and directions of automobile navigation system development, and describes the potential role of Loran-C in future systems.

INTRODUCTION

On-board navigation and information systems for future automobiles will automatically keep the driver informed of current location, deduce best routes to specified destinations taking into account current traffic and road conditions, and provide turn-by-turn route guidance according to where the automobile is along the route. These systems have been developed during the 1980s to the point that we are now at the threshhold of large-scale introductions that will occur during the early 1990s. Although most of the underlying technology originated in the U.S., most actual system development to date has occurred in Europe and Japan.

Automobile navigation and information systems are distinctly different from maritime and aerospace navigation systems because automobiles are constrained to operate primarily within defined road networks. Rather than dealing with traditional position fixes in terms of latitude and longitude, automobile location and guidance information must be specified in terms of street name, intersection, etc. if it is to be useful to the ordinary driver. Consequently, state-of-the-art automobile navigation systems invariably use digitized map information.

In virtually all of the latest European and Japanese systems, digitized map information is also used with map-matching algorithms to correct dead-reckoning calculations of vehicle position and, in the process, maintain precise knowledge of where the vehicle is along a particular road. Dead reckoning with map matching is also regarded as the preferred systems approach by leading U.S. motor companies (1).

In some European and Japanese systems, proximity beacons are expected to be installed throughout the road networks to provide occasional absolute position fixes and, of equal or greater importance, to communicate real-time traffic information to aid the on-board systems in generating optimal route guidance instructions to direct the driver to a desired destination. Proximity beacons, which involve a significant investment in special infrastructure, are not included in all system concepts being pursued in Europe and Japan, and are not a part of current system concepts in the U.S. RDS (Radio Data System, which uses available sideband of regular commercial FM radio stations) and teleterminals (a cellular-like digital radio network) are being tested as alternative traffic data communication links in Europe and Japan respectively.

Although the U.S. has not yet focused on a particular type of communication link for providing traffic data to on-board systems, it appears unlikely that proximity beacons will be used because of the formidable task of instrumenting the infrastructure. It follows that automobile systems based on dead reckoning with map matching will need an alternate method of obtaining absolute position fixes to avoid the tedious manual resetting that would otherwise be required on occasions when the systems lose track of location because of dead-reckoning anomolies or poor map data. At present, it appears that Loran-C will be one viable option for this location role in the U.S. once continental coverage is complete.

AUTONOMOUS NAVIGATION SYSTEMS

Autonomous navigation systems are self-contained within the vehicle, and are capable of performing useful functions even in the total absence of external navigation signals or other information from proximity beacons and land- or space-based radio transmitters. Three categories of autonomous systems have appeared during the 1980s.

Directional Guides

Several relatively simple directional guides were introduced in Japan (2) and West Germany (3) from 1981 through 1986, but, because their capabilities were limited compared to more sophisticated systems on the horizon, most of them have been withdrawn from the market. Nonetheless, this category of system is worthy of description because it introduces dead reckoning concepts to which other features may be added to develop autonomous electronic map and route guidance systems.

The principal components of a directional guide include heading and distance sensors, a microprocessor, a keypad or other input means, and a display unit. The driver enters the coordinates of the origin and destination, the microprocessor computes the vector connecting the two, and the display indicates the "crow flight" distance and direction to the destination. As the vehicle travels from the origin, signals from the distance sensor (usually derived from the speedometer cable) and the heading sensor (typically a solid state flux-gate magnetic compass) are used for dead-reckoning computations of the updated position of the vehicle and the corresponding distance and direction to the destination.

Dead reckoning is the process of determining a vehicle's location and heading relative to an initial position by integrating measured increments and directions of travel. The dead-reckoning sensors most commonly used in automobile navigation systems were developed long before the automobile itself (4). These include the odometer (~50 B.C.), the differential odometer (~300 A.D.), and the magnetic compass (~1200 A.D.). The differential odometer is essentially a pair of odometers, one for a wheel on each side of the vehicle. Real-time computer analysis of differential odometer signals yields information on heading changes as well as distance travelled.

Dead-reckoning accuracy decreases continuously with distance travelled. For example, systems based on the odometer and magnetic compass typically accumulate one mile of error per 50 to 150 miles driven. Thus dead-reckoning navigation systems require periodic reinitialization to a known position.

Electronic Maps

Dead-reckoning errors notwithstanding, a simple directional guide keeps the driver informed of distance and direction to the destination. However, since the vehicle is usually unable to travel the "crow flight" path, the usefulness of this information is diminished unless the driver has sufficient knowledge of the road network to devise a rational route to the destination. More advanced systems thus include a road map display that indicates the position of both the vehicle and the destination in the road network.

The first such system to be marketed was the Honda Electro Gyrocator in 1981 (5). This system used a gas-rate gyro and odometer to compute and display the vehicle path on a CRT screen. A transparent map overlay of appropriate scale was used to show the road network. This pioneering system was soon superceded by systems which use digitized road maps.

With state-of-the-art systems, digital road maps may be automatically selected according to the vehicle's location, shown on a CRT screen or flat display panel, and zoomed to the best scale for a particular situation. Vehicle location as well as destination may be indicated by symbols, and roads and streets may be shown with various intensities or colors to indicate classification. The most recent dead reckoning system to be introduced with a sophisticated electronic map display is the Electro Multivision available in Japan on the Toyota Crown (6). The Electro Multivision, which includes color TV, radio with cassette player, and CD player, is the first system to reach the market with CD-ROM for storing nationwide roadmaps, highway guides and dealer information (7). A single CD-ROM can store 550 MBytes of data, enough for an entire country.

In addition to providing the driver with a view of the road network, the on-board availability of vector encoded digital maps enables map matching, a software pattern-recognition process which continuously correlates measured vehicle path with the road network and thus prevents the accumulation of dead-reckoning error. In map matching, the pattern of the vehicle's path is analyzed as a sequence of vectors deduced from any of a variety of dead-reckoning processes. As the vehicle travels, its measured vector sequence is continuously compared with the digital map. Each time a turn is executed whose sense, magnitude, and location closely approximate those of a mapped turn, the vehicle is presumed to be at the mapped location. The matching process thus removes any dead reckoning error accumulated since the last turn (4).

The first commercially available electronic map navigation system based on dead reckoning augmented by map matching is the Etak Navigator™ marketed in California starting in 1985. The Etak system uses a flux-gate magnetic compass as well as differential odometer for dead reckoning, and uses 3.5-MByte tape cassettes to store digital map data approximately equivalent to two paper street maps (8). The vehicle's location relative to its surroundings is continuously displayed on a monochrome CRT map presentation which may be zoomed to different scales. A fixed symbol below the center of the CRT represents the vehicle position, and points to the top of the display indicating vehicle heading. As the vehicle is driven, the map scrolls and rotates about the vehicle symbol to maintain an orientation corresponding with the driver's view through the windshield. The destination, which is input by street number and name or by street name and nearby cross street, is shown on the Etak screen as a flashing star.

Route Guidance Systems

Accurate electronic map displays, while far more useful than simple directional guides, have two shortcomings as autonomous navigation systems. First, the driver must view a busy display which some critics consider to be a potentially dangerous distraction from the driving task. Second, it is up to the driver to devise the most appropriate route and then follow it to the destination. Both problems are solved by the addition of algorithms for devising the best route to an input destination and for issuing real-time route guidance instructions to prompt the driver turn-by-turn over the route. Once the driver specifies destination and routing criteria (fastest, shortest, scenic, etc.), the route guidance software makes all navigation decisions, freeing the driver to concentrate on driving safely. Explicit route guidance may be in the form of spoken instructions, displayed symbols (e.g., arrows shaped according to the maneuver), and/or displayed text messages.

Real-time route guidance over preplanned routes by an autonomous dead-reckoning/map-matching system was first demonstrated in the 1970s (9, 10). The first autonomous system to demonstrate on-board generation of best routes as well as real-time route guidance was Micropilot, a 1981 prototype that used an Apple computer to calculate the quickest route between an input starting point and destination (11). Digitized voice was used to give turn instructions as each junction along the route was approached based on position estimated from simple odometry alone.

Although none have yet reached the market, there are several recent examples of advanced autonomous route guidance systems. Philips' CARIN (12) was the first developmental system to use CD-ROM for storage of digital map data. The vehicle navigation subsystem employs dead reckoning (differential odometer and electronic compass based on the magneto-resistance effect) augmented by map matching. The system includes a route-search algorithm and provides step-by-step route guidance. In the original test and demonstration version, a color CRT map display shows vehicle location relative to the surroundings, and synthesized voice instructions prompt the driver when operating in the route guidance mode. The latest version has a flat-panel display for symbolic route instructions in addition to synthesized voice, and includes a CRT map display only as an option. Philips proposes to equip CARIN with an RDS (radio data system) receiver so that broadcast traffic information may be taken into account in route selection (13).

Blaupunkt's EVA (14) is an autonomous map-matching system which uses a differential odometer and includes route-search software to generate an optimum route to coded input destinations. Turns at intersections, lane changes, etc. are specified on an LCD in the form of simplified diagrams which show lane boundaries and arrows to indicate the path to be taken. Synthesized voice capability is included, and is used to confirm destination entries as well as to articulate turn-by-turn real-time route guidance instructions. The first version, which has been tested and demonstrated since 1983, stores a digital map of the test city in EPROM. An enhanced version under development uses CD-ROM for map storage. Production versions of EVA may include an RDS receiver for traffic information.

Nissan's NAV (15) also uses dead reckoning with map matching autonomous navigation. Map data is stored in a 1M-bit ROM. Optimal routes are computed in two stages using a skeletal network for the initial calculations, and then interpolating using a more detailed network. The route is traced on a CRT map display, and special screens guide the driver through intersections along the way.

Autonomous route guidance systems, by definition, require no infrastructure support for the basic location and navigation functions, including route guidance based upon static or historical information. However, for maximum route guidance effectiveness, it is highly desirable for autonomous navigation systems to have access to information on current traffic conditions in the area being travelled. This, in turn, requires infrastructure support of two types. The first is for collecting information on traffic conditions and the second is for communicating this information to the on-board systems.

One of the most popular means under consideration for transmitting such data to autonomous navigation systems aboard vehicles in Europe is RDS. Since RDS uses side-band capacity of existing FM radio stations, it has the advantage of low implementation costs and of not requiring additional frequency allocations. Car radio receivers may be readily adapted to receive and decode RDS transmissions for input to the navigation system. General RDS test broadcasts are underway in several European countries, and RDS experiments in the Netherlands already include the transmission of traffic data (13).

Another communications approach that is suitable for autonomous navigation systems is the teleterminal being promoted in Japan by the AMTICS project (16). AMTICS (Advanced Mobile Traffic Information & Communications System), which has the objective of providing on-board traffic and navigation information by integrating a variety of subsystems, was established by the National Police Agency (NPA) through the Japan Traffic Management and Technology Association in cooperation with the Ministry of Posts and Telecommunications (MPT) at the beginning of 1987. An experimental pilot system will be started in Tokyo this year, and the first commercial operation may be as early as 1990. A display screen in each equipped car will show traffic information gathered at control centers and broadcast to the cars using a mesh of cellular-like teleterminals each with a range of approximately 3 km. Teleterminals are relatively small, and may be mounted atop buildings or at other locations to form a mesh with approximately 3-km spacing. Packet data transmission technology is used, and there is a capability for addressing messages to individual vehicles. Operation in at 800 MHz with data rates of 4800/9600 bps.

Project Pathfinder, a demonstration of the use of in-vehicle traffic information in conjunction with autonomous navigation systems, is being included in the Los Angeles "Smart Streets" project. Pathfinder is a joint undertaking of the California Department of Transportation (Caltrans), the Federal Highway Administration, and General Motors. Traffic data collected by conventional means will be augmented and communicated (via two-way packet radio) to approximately 25 vehicles equipped with the Etak Navigator described elsewhere in this paper. While the Etak system does not provide route guidance *per se*, software modifications will superimpose real-time traffic information on the electronic map display so that the driver can take it into account in route planning. The communication link will also be used to relay recent travel experience of Etak-equipped vehicles to the traffic data center for additional information on traffic conditions.

RADIONAVIGATION SYSTEMS

Radionavigation, which is commonly used for aerospace and maritime navigation, is becoming of more interest for land vehicles with the expanding coverage of land masses by Loran-C and with the advent of satellite positioning systems. Radionavigation has the inherent advantage of providing absolute location information. Its major drawbacks are that radio signals may be blocked or reflected by man-made structures in urban areas and by rugged terrain, and that radio receivers are subject to interference from various sources. Another drawback is the present high cost of satellite receivers, but this problem should be ameliorated when the systems come into large-scale use.

In most cases, the availability of radionavigation signals depends upon land- or space-based navigation transmitter facilities operated by government entities. In the United States, radionavigation policy and planning is established by the Department of Defense (DOD) and the Department of Transportation (DOT), and is promulgated by the Federal Radionavigation Plan (FRP) which is updated every two years (17). Other than the obvious requirement for external radionavigation signals, the infrastructure support requirements for radionavigation systems are identical to those discussed above for collecting and transmitting real-time traffic data to autonomous navigation systems for dynamic route guidance.

Loran-C

Although Loran-C has been used for decades for marine and aircraft navigation, and has often been considered as a possible basis for automatic vehicle location monitoring systems, dependable cost-effective Loran-C receivers designed specifically for the hostile electromagnetic environment encountered by land vehicles have become available only in the last several years. Results of performance testing of state-of-the-art Loran-C receivers in the Boston area in 1985 indicated that terrestrial navigation was feasible when signal coverage is adequate (18). Examples of state-of-the-art Loran-C AVLM systems are reported by Janc (19), Bronson, et al. (20), and by Carter and Warburton (21).

Loran-C AVLM systems, unlike the obsolescent electronic signpost approach to AVLM, have the advantage of not requiring infrastructure support other than the existing Loran-C transmitter chains operated by the U.S. Coast Guard which is now installing mid-continent chains to complete nationwide coverage in the United States. European coverage is presently limited to the Mediterranean area and northern part of Europe, including the recently introduced French-operated chain. A European Working Group, formed to continue Loran-C service after 1994 when the U.S. Coast Guard plans to discontinue overseas Loran-C operation following completion of the Navstar GPS system (17), is considering expanding European converage.

Each Loran-C chain of 3 to 5 stations transmits time-synchronized groups of pulses at approximately 100 KHz. The time difference between arrival of pulses from the master and each secondary station describes a hyperbolic line of position. A Loran-C receiver measures the time difference of two or more master-secondary pairs, and the intersection of the lines of position defines the receiver's location. Time differences are usually transmitted from the vehicle to the monitoring dispatch office for conversion to location coordinates which are used to show vehicle location on a CRT map display. Most systems include driver-operated switches for reporting status as well as location. Land mobile radios, which many fleet operators already have installed for voice communications, are often fitted with modems to transmit vehicle location data to the dispatch office.

With the availability of high-performance Loran-C receivers at moderate cost, the types and number of AVLM installations have proliferated in the United States. Although Loran-C has not yet been seriously pursued as a basis for automobile navigation, the experience base being acquired through AVLM, along with the expanding geographical coverage and successful integration with various dead-reckoning techniques (22), make it probable that Loran-C will be used in some future automobile navigation systems.

Since 1983 General Motors Corporation has tested and demonstrated Loran-C and other navigation systems installed in an automobile (23). In addition to Loran-C, the systems include Navstar GPS, and a flux-gate compass and odometer sensor for dead reckoning. This test configuration, shown in Figure 1, permits the relative evaluation of three independent or integrated approaches. The few satellites currently deployed limits GPS signal availability to approximately 4 hours per day. Loran-C is used at other times to demonstrate radiolocation along with the integrated map display. Both Loran-C and GPS automatically shift to dead reckoning when their signals are obscured or when an unreasonable vehicle location is indicated by Loran-C or GPS.

In 1985, Nissan Motor Co. developed a special delivery van with Loran-C navigation and route-assistance features (24). The hardware configuration is shown in Figure 2. The van is equipped with software to provide route guidance as well as to manage the delivery of goods. The van equipment is supported by computer files downloaded by floppy disk from the main distribution computer to identify customer stops to be served on a given run. An in-vehicle color CRT displays a delivery list, delivery sequence, maps, etc., to facilitate deliveries in the most efficient order and along the best route. The Nissan Delivery Van was developed as a special project for Seibu Department Stores and, contrary to implications in some published accounts, was intended primarily for promotional purposes rather than as a prototype for a fleet of such vehicles.

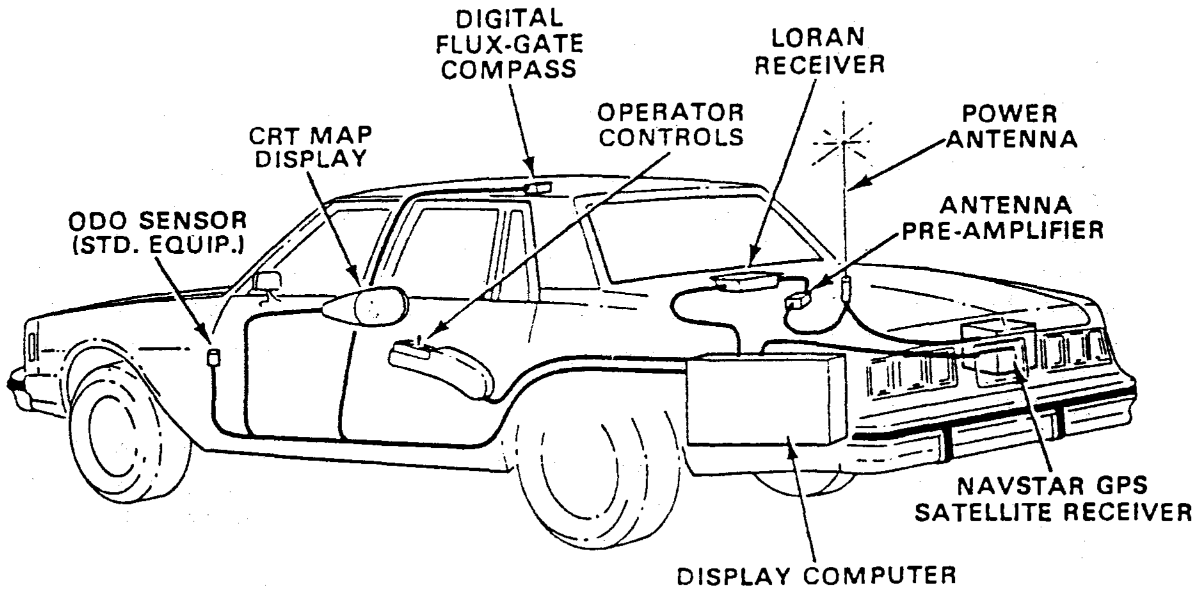

Figure 1. General Motors Navigation Test Vehicle

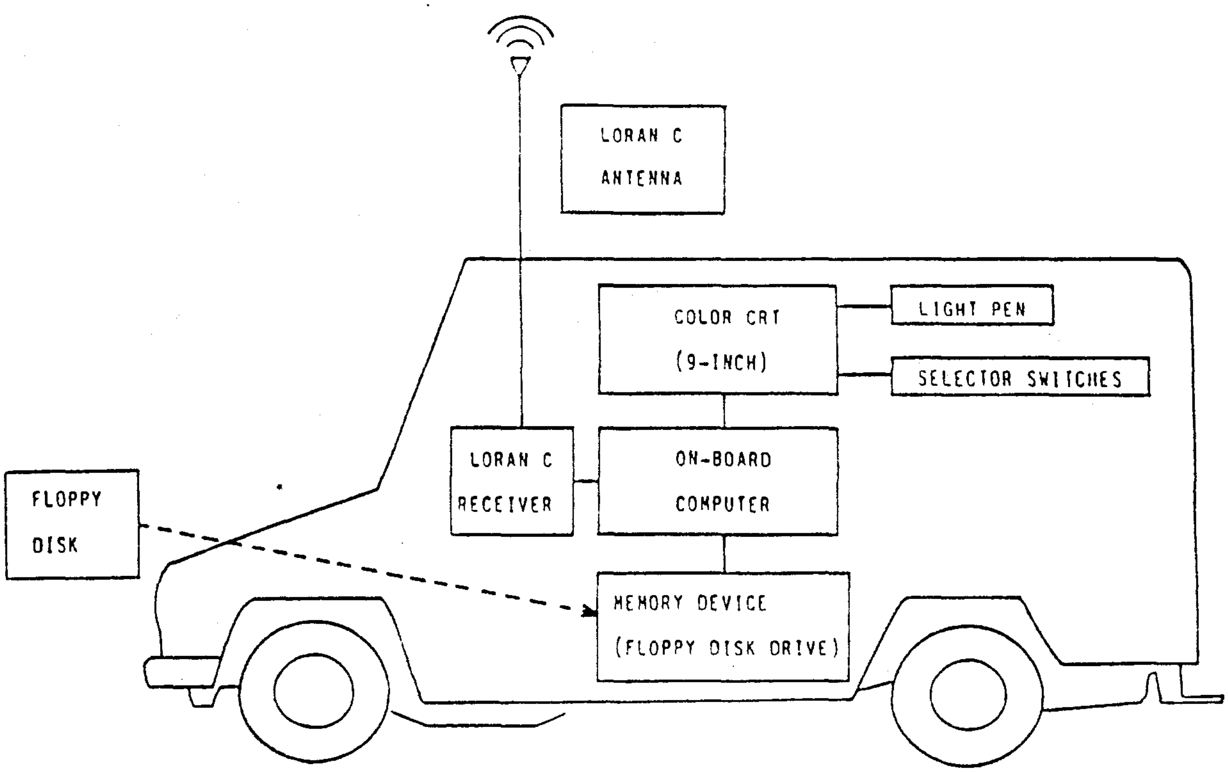

Figure 2. Nissan Delivery Van with Navigation System

Satellite

The Navstar Global Positioning System (GPS) (17) has received considerable attention as a basis for automobile navigation. Although the present focus is on Navstar, the older Transit satellite system has also been considered. The Transit satellite navigation system, implemented by the U.S. Navy in 1964 and scheduled to be phased out in 1996 (17), has several satellites logitudinally-spaced in polar orbits at a height of approximately 1,075 kilometers to give worldwide, albeit intermittent, coverage. Each satellite transmits information which, in combination with Doppler analysis, permits calculation of receiver location by interative solution of a set of equations. Since a Transit satellite is not always in range, vehicle systems based on Transit must include dead reckoning for continuous determination of position between satellite passes.

Ford Motor Company demonstrated the integration of Transit satellite navigation with dead reckoning for automobiles with an operational system installed in the Concept 100 car in 1983 (25). This system periodically obtained accurate position fixes from the Transit navigation satellites to update the primary location from the dead-reckoning subsystem. The dead-reckoning calculation was based on odometer signals and a flux-gate magnetic compass which was software compensated for magnetic field pertubation by the vehicle. The vehicle's position was tracked on a map displayed on a color CRT with touch-screen controls.

The U.S. Department of Defense's Navstar GPS, which is still in the implementation stage with 24 (21 plus three operating spares) satellites to be launched into 12-hour orbits by the mid-1990s, has received most attention as a possible basis for automobile navigation. When the GPS satellite constellation is complete, any point on earth will always be within range of at least four Navstar satellites. A GPS receiver could accurately determine its three position coordinates by analyzing the travel time of signals from only three satellites if the receiver's clock is precisely synchronized with the atomic clocks that time the satellite signals. However, given the timed signals from four satellites, the GPS receiver solves a system of four equations for its three position coordinates and the error of its less precise quartz clock. Locations may thus be determined to within approximately 10 meters using P-Code signals intended for government authorized applications. Less precise C/A-Code signals for general use will permit location determination to within approximately 100 meters. Differential GPS, which uses a broadcast correction derived from a local receiver at a precisely known location, can increase the C/A-Code accuracy to within a few meters.

Navstar GPS was the basis for CLASS (Chrysler Laser Atlas and Satellite System), a navigation system included in a concept car displayed at the 1984 World's Fair in New Orleans (26). CLASS included a nationwide set of AAA maps stored in image form on a video disc, and software for automatically selecting and displaying on a color CRT the map area incorporating the vehicle's current location as indicated by a cursor.

Although GPS has good potential accuracy and will provide continuous coverage, auxiliary dead reckoning is required in automobile applications to compensate for signal loss due to shadowing by buildings, bridges, foliage, mountainous terrain, etc. Dead reckoning may be used as a secondary system to maintain location information in the absence of GPS satellite signals or, alternatively, dead reckoning may be used as the primary vehicle location method with GPS employed as the secondary system to make position updates when usable signals are available. For example, a Nissan system relies upon dead reckoning whenever satellite position data disagree by 2 km or more, or if two consecutive satellite measurements taken at one second intervals exceeds the amount of vehicle movement indicated by dead reckoning (27).

A Department of Transportation evaluation of radionavigation for land vehicles notes that, because of differing ellipsoidal reference systems, the task of relating GPS (as well as Loran-C) location to local maps is formidable (18). Hence map-matching may be useful with GPS as well as with dead reckoning. In fact, one Japanese automobile navigation system, the MAPIX-III (28) already integrates dead reckoning, GPS and map matching. GPS signals, when available, provide absolute location which is reconciled with dead reckoning and matched to specific roadways included in the map data base.

PROXIMITY BEACON SYSTEMS

The proximity beacon approach to vehicular navigation uses strategically located short-range transmitters, and the very reception of their location-coded signals indicates the receiving vehicle's instantaneous location. In route guidance applications, proximity beacons transmit routing and traffic information as well as location, and may include two-way communications with equipped vehicles.

The widest initial application of proximity beacon technology was for AVLM systems such as those used for monitoring the location and status of transit buses from a central dispatch office. In this type of application, an on-board system receives and stores a location code as the vehicle passes a proximity beacon or "electronic signpost." Upon periodic polling, the last beacon location and possibly the distance or time since passing the beacon are automatically radioed to the dispatch computer.

Several variations of the proximity beacon approach have been investigated for interactive route guidance (29). Typically, the driver enters a destination code for automatic transmission to a roadside unit as an equipped vehicle approaches instrumented intersections. The roadside unit, which may be networked with a traffic management system, analyzes the destination code and instantly transmits route instructions for display on the vehicle's panel. Alternatively, the roadside unit may only transmit its location to the vehicle where an on-board computer, using stored road network data, will generate instructions for continuing the route from the identified location. The proximity beacon approach, inactive in the U.S. since the demise of the ERGS project (30) in 1970, has undergone further development in West Germany, the U.K. and Japan.

A state-of-the-art example of proximity-beacon route guidance systems is ALI-SCOUT, a joint project of the Federal Republic of Germany, Siemens, Volkswagen, Blaupunkt and others (31). ALI-SCOUT combines certain characteristics of autonomous systems in that, while dependent upon proximity beacons, the in-vehicle equipment includes dead-reckoning and map matching features that permit autonomous navigation between beacons which, consequently, may be spaced at greater intervals.

The ALI-SCOUT vehicular equipment receives approximately 8 KBytes of area road network data and recommended route data when passing strategically-located infrared beacons. Simplified graphic driving directions to the input destination are presented in real time on a dashboard LCD. As an equipped vehicle passes each beacon, it transmits to the beacon stored data on its travel history since passing the last beacon. The equipped automobiles thus serve as traffic sensors. ALI-SCOUT is undergoing large-scale field testing in the LISB (Leit- und Information System Berlin) project in West Berlin starting this year. Beacons are installed at 20 percent of the traffic lights, and 700 equipped automobiles will be used in the tests.

In 1986, the U.K. Department of Transport proposed Autoguide, a proximity beacon project starting with an early demonstration of interactive route guidance and traffic management in London (32). Autoguide is a system for helping drivers find their way through the primary road network. A route computer is mounted in the vehicle and the driver enters the destination and, possibly, preference for the type of route -- the driver might want the quickest, or the shortest (the two are not necessarily the same), or have some other requirement such as "no motorways." Either visually or using synthesized speech, the computer then gives easy-to-follow instructions during the journey. The on-board computer communicates with infrared beacons near main junctions. As in the case of ALI-SCOUT, the beacon transmits electronic map data including up-to-the-minute routing advice to the vehicle, and the vehicle transmits its travel history since passing the last beacon. Autoguide communications standards are being coordinated with the West German group developing ALI-SCOUT.

In Japan, the vehicle navigation systems approach currently being tested by the Ministry of Construction (MC) in the Road/Automobile Communications System (RACS) project depends upon proximity beacons for communicating traffic data and other information to on-board systems (33). Although the vehicular systems of several manufacturers participating in the program have autonomous navigation capabilities based on dead reckoning and map matching, proximity beacons are used for updating vehicle location as well as for communications.

Infrastructure requirements are heaviest for proximity beacon navigation and route guidance systems because of the requirement for equipped vehicles to pass beacons locations at frequent intervals as they travel about. In addition to the real-time traffic data collection requirements for dynamic route guidance using autonomous and radionavigation systems, dynamic route guidance with proximity beacons also requires wire-line or other communication links between the beacons and the central traffic data system. Thus, including the beacons themselves, the infrastructure expense is far greater for proximity beacon systems than for autonomous systems. Nonetheless, conventional wisdom has traditionally held that route guidance systems which distribute most of their intelligence at the roadside rather than aboard individual vehicles leads to the minimum overall system cost because there are far more vehicles to be outfitted than there are junctions to be instrumented with beacons.

However, it should be noted that designing for the lowest overall system cost is not necessarily the most effective way to proceed because this incurrs heavy infrastructure expense which must be paid out of public funds unless some kind of user fee scheme is devised to transfer this expense to the owners of equipped vehicles. In addition, if vehicle units have no independent capability in the absence of proximity beacons, there will be no incentive for their purchase before sufficient infrastructure is in place, and even then the units will be useless when driving outside of instrumented areas. Upgrading of in-vehicle equipment would tend to occur gradually as vehicles are replaced, whereas upgrading of infrastructure equipment would probably be at infrequent intervals once the installations are in place. The argument for intelligent infrastructure rather than intelligent vehicles is further diminished by the continuing downward spiral in the cost of microelectronics aboard individual vehicles.

FUTURE SYSTEMS

Autonomous vehicular navigation systems are expected to come into widespread use between now and the year 2000. These systems will use digital maps for map matching to enhance dead reckoning accuracy and for computing optimal routes for automatic route guidance. Some systems will optionally display the digital maps for orientation and reference purposes. Lack of widespread availability of standardized digital maps will slow the market penetration of autonomous systems for the next few years.

As shown by the dashed lines in Figure 3, the architecture of the autonomous systems will accommodate the addition of optional receivers or transceivers to take advantage of whatever type of traffic data communications scheme is available in the country or region in which equipped vehicles operate. Possibilities include RDS, teleterminals, and satellites, as well as adaptations of cellular telephone. Although proximity beacons (radio frequency, microwave, infrared, etc.), will give way to map matching for position updating, and to radionavigation for reinitialization, the proximity beacon concept is sufficiently well entrenched that it may persist in some areas as a first generation communications link. However, by 2010, standardized infrastructure to provide traffic data for dynamic route guidance will be in place in most high traffic density regions of the world, and the majority of new vehicles will be equipped to receive this information.

The autonomous systems will also be able to use optional radionavigation receivers as "locator sensors" to avoid the need for manual

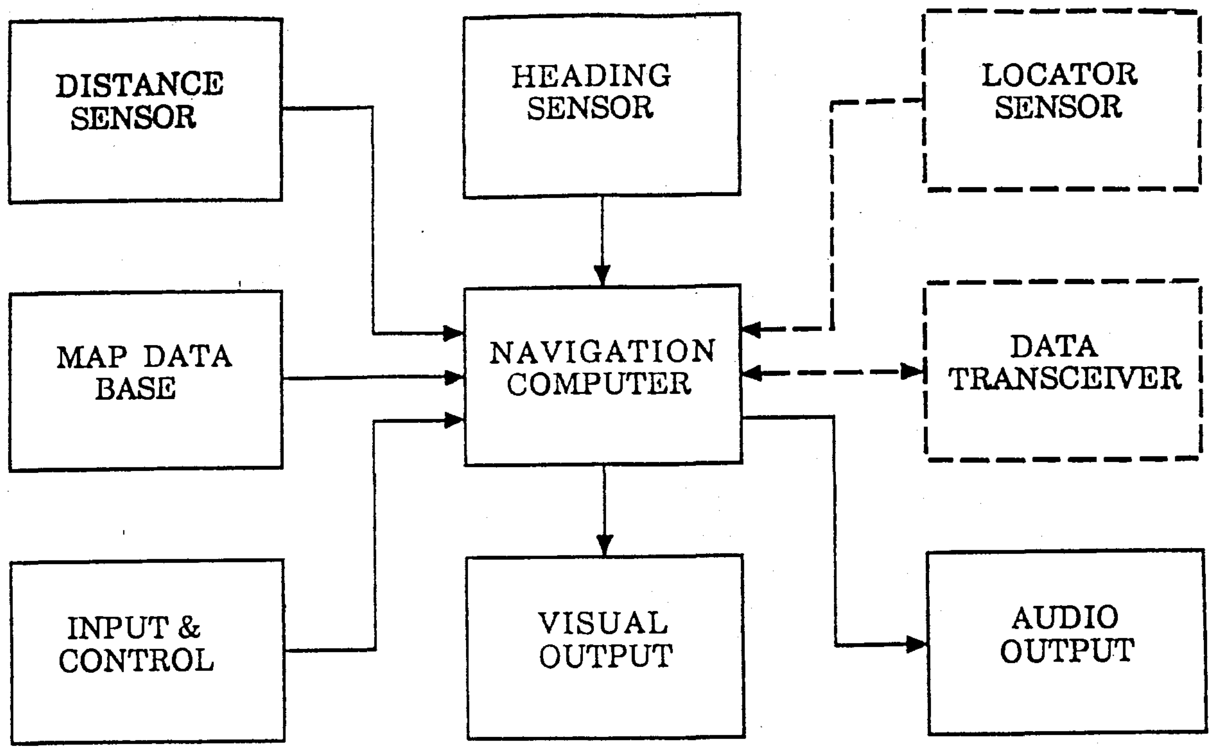

Figure 3. Future System Configuration

reinitialization (i.e., telling the system where it is) on infrequent occasions when dead reckoning anomalies or erroneous map data confuse the software. Navstar GPS will be a universal option, and Loran-C will be an option in regions where signals are available. As receiver prices are reduced through volume production, they will begin to appear as standard equipment. But even then, the basic navigation systems may be characterized as autonomous because they can operate effectively in the event radionavigation signals are not available, as well as in areas where traffic information is not collected and broadcast.

The principal argument for the radionavigation role in future automobile navigation and route guidance systems being for automatic reinitialization is that, once all the features required to make a radionavigation system perform well under all circumstances are added, the satellite or Loran-C receiver could be turned off and the system would continue to perform quite well until reinitialization is required. Specifically, dead reckoning is required because useful radionavigation signals are not always available, particularly in urban areas. On-board digital maps are also required to relate location coordinates to the real world because location coordinates, however, accurate, are of little value to the driver. In addition, on-board map data are required for route generation and route guidance. With these elements in place, only software additions are required to match vehicle location with the digital map, thus overcoming minor map errors as well as location errors.

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BIOGRAPHICAL SKETCH

Robert L. French is a physicist (MS, Vanderbilt University) who has worked with vehicular technology for 20 years. In the 1970s he headed a minicomputer systems integration firm and directed software development for dispatch, tollway, and vehicular control applications. He developed and patented the first autonomous in-vehicle route guidance system based on map matching concepts. As an independent consultant during the 1980s he has assessed alternative technologies, organized conference sessions, conducted seminars, promoted standards development, and provided consultation and information services relating to vehicular navigation and location systems. His clients include major automotive, electronic, cartographic, transportation, and communications organizations in the U.S., Canada, Europe and Japan. Mr. French's memberships include the IEEE Vehicular Technology Society and Aerospace and Electronics Systems Society, SAE Automotive Navigational Aids Standards Committee, TRB Communications Committee, Institute of Transportation Engineers, Institute of Navigation, Royal Institute of Navigation, Wild Goose Association, and World Future Society.

Envelope-to-Cycle Difference (ECD) Predictions for the Mid-Continent Loran-C Chains

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Abstract

In conjunction with the Federal Aviation Administration (FAA), the United States Coast Guard (USCG) is proceeding with the development of two new Loran-C Chains that will become operational in the early 1990s in the mid-Continent region of the United States. Contrary to the more traditional role of providing navigational capabilities to the mariner, these new chains are being established for the aviation community as well as an ever increasing number of terrestrial users. Signal propagation paths associated with these chains will be overland. One key Loran-C parameter that must be correctly developed and controlled to allow proper operation of the system, is the Envelope-to-Cycle Difference (ECD). This parameter has proved to be one of the most difficult to measure, define, explain, and to understand. Behavior of ECD is influenced by the propagation path, with more severe changes observed when the signal travels overland. A definition of ECD is provided, its importance is discussed, and control techniques are presented. Extracts of recently collected ECD data from the mid-continent region are included, and finally, through the use of conductivity data, predictions are made as to what ECD values are anticipated when each of the new chains become operational.

Introduction

The forerunner of the present day long-range navigation (loran) system was developed during World War II to meet the needs of the Navy during convoy operations and to provide all-weather navigation for military aircraft. At the close of the war, some 70 loran transmitting stations were in operation, providing over 60 million square miles of coverage [1]. This system was known as Loran-A. In the late 1950's, as efforts continued to improve coverage and navigational accuracy, a new form of loran was developed. The new system, called Loran-C, co-existed with Loran-A well into the 1970's. When United States Coast Guard Loran-A operations were discontinued in 1980, Loran-C took over the role as the primary land-based navigation system serving the marine community. A review of the present day Loran-C chains indicates that the principle user considered during the planning stages was the mariner.

The development of low cost, microprocessor-based receivers over the last ten years has resulted in a significant increase in the number of Loran-C users, both in the marine environment and elsewhere. Today, Loran-C chain planning has progressed to the point where the U.S. Coast Guard, in conjunction with the Federal Aviation Administration (FAA), is preparing to construct two new Loran-C chains for the mid-continent region of the Continental U.S. (CONUS). The project is called the Mid-Continent Expansion Project (MEP). If no delays are encountered during the construction phase, the two new chains will become operational in the fall of 1990. The names of the two new chains are Southern Continental U.S. (SOCUS), and Northern Continental U.S. (NOCUS). The SOCUS chain will consist of six transmitting stations, three new stations and three stations from adjacent existing chains that will be dual-rated. The NOCUS chain will be made up of four stations, two new stations (one new dual-rated with the SOCUS chain) and two stations from adjacent chains also being dual-rated. Control of these new chains will be accomplished by five new monitor sites. The two chains, the monitor sites and their respective monitoring responsibilities, are shown in Figure 1.

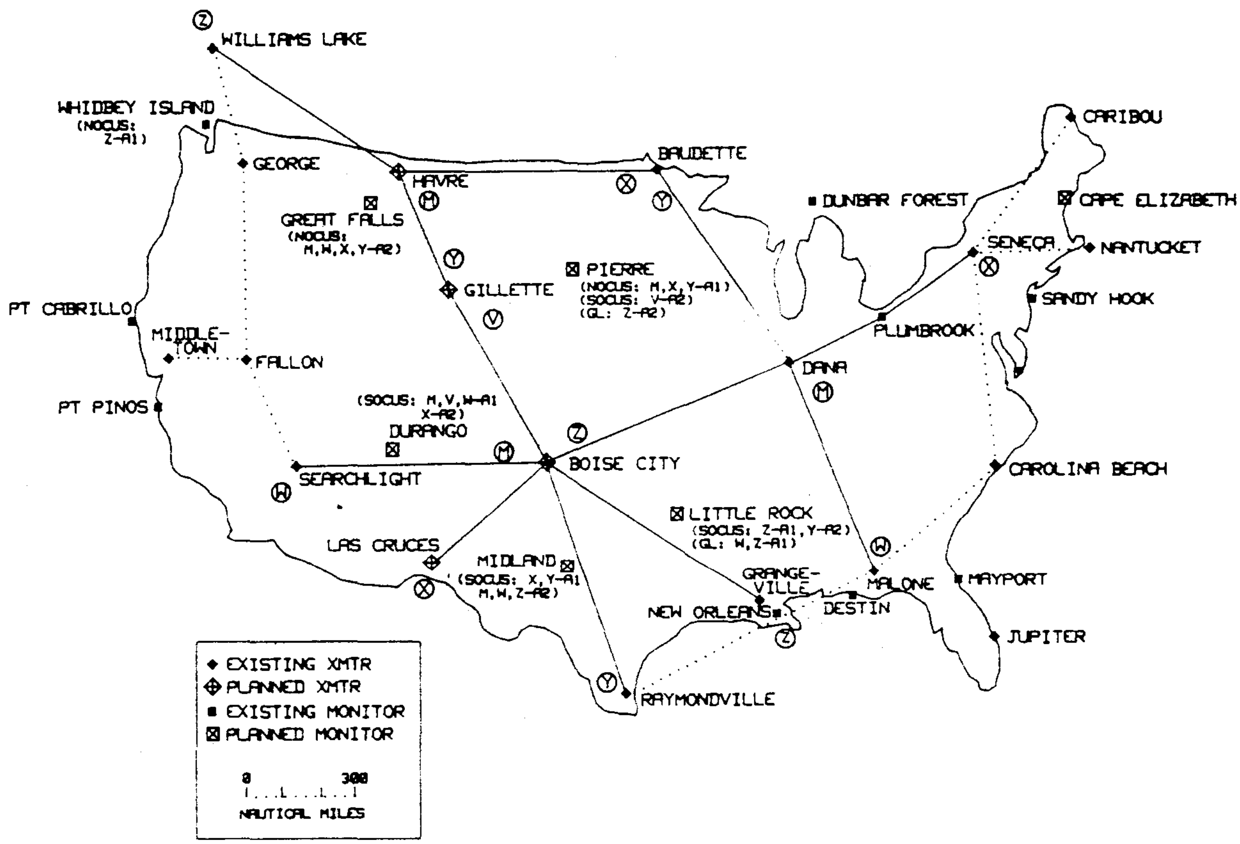

Figure 1
Proposed SOCUS and NOCUS Chains

Loran-C Control

Two basic requirements necessary for the proper operation of the Loran-C system are precise control of the time each transmitter outputs a pulse group, and control of the transmitted pulse shape. Monitoring and control of these two key parameters is necessary to ensure that receivers can properly determine and precisely measure time difference values. Timing, or phase control of U.S. Coast Guard operated Loran chains is accomplished by Loran-C receivers installed in the service areas. These monitor sites are called Alpha-1 and Alpha-2 sites. Alpha-1 sites are the primary monitor sites with fixed reference time differences assigned. Alpha-2 monitor sites are standby, or secondary sites. At Alpha-1 sites, control is maintained by adjusting the transmission of the secondary stations so that the reference numbers are maintained within limits, typically ± 100 nanoseconds. With regard to pulse shape, transmitting stations are responsible for the generation of pulses with the prescribed phase code, power level, pulse-to-pulse compatibility and a parameter known as Envelope-to-Cycle Difference, or ECD.

ECD Definition

Envelope-to-Cycle Difference (ECD) is defined in [2]:

> "ECD is the time relationship between the phase of the RF carrier and the time origin of the envelope waveform." [2]

This definition is explained as follows:

A single Loran-C pulse is described by the equation

$$\mathbf{i(t,tau) = f(t,tau)sin(\omega t)} \qquad (1)$$

where **i(t,tau)** is the antenna current as a function of time, **t**, with **tau** representing the ECD.

f(t,tau) is an amplitude function dependent on **t** and **tau** that modulates a sinusoid with a frequency of 100kHz. This amplitude modulating function has the form:

$$\mathbf{f(t,tau) = A^2(t-tau)\ exp\ [-2(t-tau)/65]} \qquad (2)$$

where **t** and **tau** are in microseconds

Figure 2 shows a single Loran-C pulse with **tau** equal to 0. Also drawn is the first derivative of the modulating function **f(t,tau)**. Phase modulation of the sinusoid is assumed to be zero and the 100kHz frequency is therefore maintained throughout the pulse, e.g. all zero crossings occur at 10-microsecond intervals.

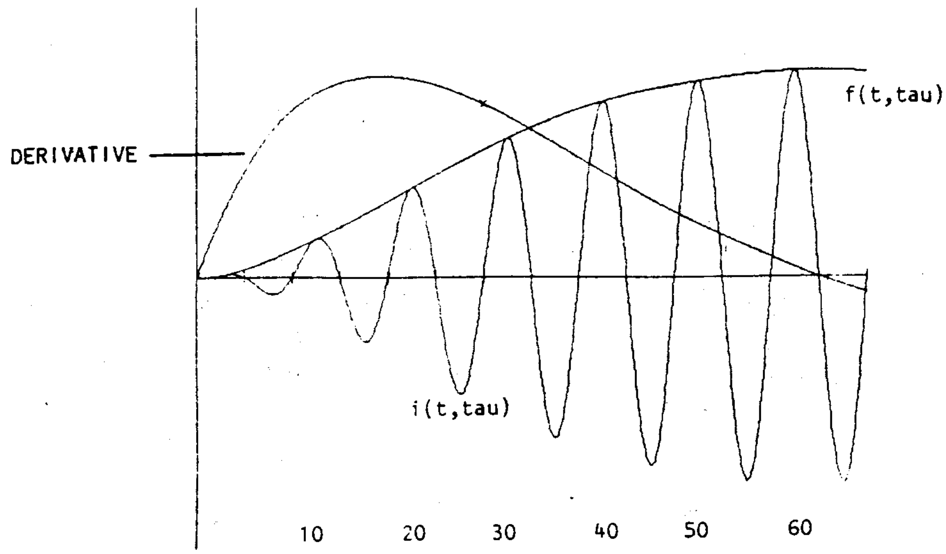

Figure 2
Zero ECD Loran-C Pulse

If a poll of the Loran-C user population were made and they were asked what ECD was, it is almost a certainty that a significant majority of the users would not even know that the term was associated with Loran-C. Their receivers most likely don't display it, and accompanying literature, if mentioning it at all, won't explain why it is important. So the question becomes; "Why is this term important?"

To answer, first a brief review of the principle behind Loran-C. Precise time measurement, which is converted to range information for positioning, is obtained by cycle-matching Loran-C signals. To ensure that loran receivers consistently identify the proper cycle, or track point, the Loran-C pulse must be formed in such a way as to provide sufficient energy so that receivers can distinguish between the relatively predictable ground wave and contamination from delayed skywaves. A very rapidly rising pulse, a square wave for example, would ensure this; but spectral requirements which specify that 99% of the radiated Loran-C power exist in the band 90 to 110 kHz would be violated.

The Loran-C pulse, described by equation (1), offers a good compromise between bandwidth and rise time. The positive-going 30- microsecond zero-crossing is the track point designated for cycle matching. The problem for a receiver is how to distinguish between the 30- microsecond positive-going crossover and the one corresponding to the 20- or 40-microsecond point. This is not accomplished by simply counting subsequent crossovers until the proper one is reached. Signal-to-noise ratio (SNR) levels even at relatively short distances from the transmitter eliminate this possibility. The alternative to cycle counting, is pulse shape matching. The first derivative of equation (2), **f(t,tau)** is shown superimposed on the zero-ECD Loran-C pulse in Figure 2, and gives an indication of how the pulse shape changes with time.

Once a Loran-C pulse is radiated from the antenna, it is affected by attenuation along the propagation path. Higher frequencies are attenuated more as a function of distance relative to lower frequencies, leading to pulse shape distortion. In the case of the Loran-C pulse, higher frequency components add sharpness to the pulse leading edge and contribute to the rapid rise of the pulse. Considering the effect of propagation path attenuation, a receiver processing a distorted pulse could mistakenly select an envelope track point that is different from the standard phase track point. The 40-microsecond point rather than the 30-microsecond point for example. So, Why is ECD important? The answer is that receivers use the envelope shape, which is a function of ECD, in the cycle selection process. If ECD is significantly different from those values anticipated by the receiver, the probability of improper cycle selection, more commonly called "cycle slip", is significantly increased. The result will be serious positioning error.

One example concerning ECD and its importance to proper cycle selection is highlighted as follows: In late 1985, as a result of a request from the European Loran Working Group, the U.S. Coast Guard's Activities Europe (ACTEUR) office directed the experimental dual-rating of Loran-C Station Sylt, Germany. This dual-rating effort was conducted in order to develop a Loran-C triad using the two French (8940) stations and Sylt, Germany. The drive behind this effort was the evaluation of Loran-C as a navigational aid in northwestern Europe. Almost immediately after declaring the chain available for user evaluation in mid-November 1985, reports were received in ACTEUR complaining of cycle slips. Investigations revealed that the French stations, which are used in the rho-rho mode of navigation, were transmitting an ECD not consistant with that of Loran Station Sylt. This did not create a problem for rho-rho users since their receivers were specifically calibrated for that system. The experiment was halted in late December of 1985 until the ECD problem could be resolved. As of this date, no additional tests have been conducted on this experimental triad [4].

ECD Measurement:

A number of important facts concerning ECD are listed as follows [2]:

1) The ECD of a transmitted loran pulse is determined by measuring the amplitudes of the first eight half-cycle peaks of the transmitting antenna ground return current. The deviations relative to an ideal pulse as described in equation (1) are computed using a minimum mean-square error (MMSE) over ECD and pulse peak amplitude [3].

2) An antenna ground return current with 0 ECD will result in a radiated E-field with an ECD of positive 2.5 microseconds in the far field close to the station.

3) The relationship between ECD and distance for an all-seawater path is approximated by the empirical equation:

$$ECD = 2.5 + NECD - 0.0025d \qquad (3)$$

where NECD = nominal ECD of the transmitting station antenna ground return current determined using the technique described above.

d = distance in nautical miles from the transmitting station.

Equation (3) was determined during an extensive set of measurements taken off the East Coast in December of 1977 using a calibrated Austron 5000 receiver. The standard deviation of the resulting ECD estimates was approximately .5 microseconds.

The above relationship shows that for an all-seawater path, the ECD at 1000 nautical miles from a transmitting station (with 0 ECD at the antenna ground return current) will be close to zero. If a user's receiver is adjusted to optimize cycle selection for 0.0 ECD, then it is convenient that at distances from the transmitter where SNR values are low, the resultant ECD value will be best-suited for the cycle selection process.

In the period from 1977 to 1979, a number of changes concerning the Coast Guard's monitoring and controlling of ECD were being implemented. They were:

- An improved piece of equipment was developed to monitor the transmitted ECD in real time. The device, known as the Electrical Pulse Analyzer (EPA), monitors and displays the ECD of the antenna ground return current and the peak current of selected pulses and half cycles. This device is still in use today.

- As a result of the EPA, the development of the ECD calculation routine, and other timing equipment improvements, Coast Guard Loran-C transmitting stations were adjusted to ensure that transmitted ECD values were nominally set at zero (with some exceptions). This was done based on the relationship shown in equation (3) as well as the Coast Guard's radio navigation policy that Loran-C transmitting stations will adjust transmitted ECD values to provide ECD in the coastal service area in the range ± 2.5 microseconds [5].

- A new chain control receiver was being deployed. This receiver, the Austron 5000, was first used on the West Coast and Canadian West Coast Chains [6]. It provides an "envelope number" that is easily converted to ECD. Service area ECD is monitored with limits of ± 1.5 microseconds applied to a Controlling Standard ECD (CSECD). Testing completed at the USCG Electronics Engineering Center (EECEN) in the late 1970's indicated that a calibrated Austron 5000 exhibited small errors in ECD over the range of -4 to +4 microseconds as shown in Figure 3[7].

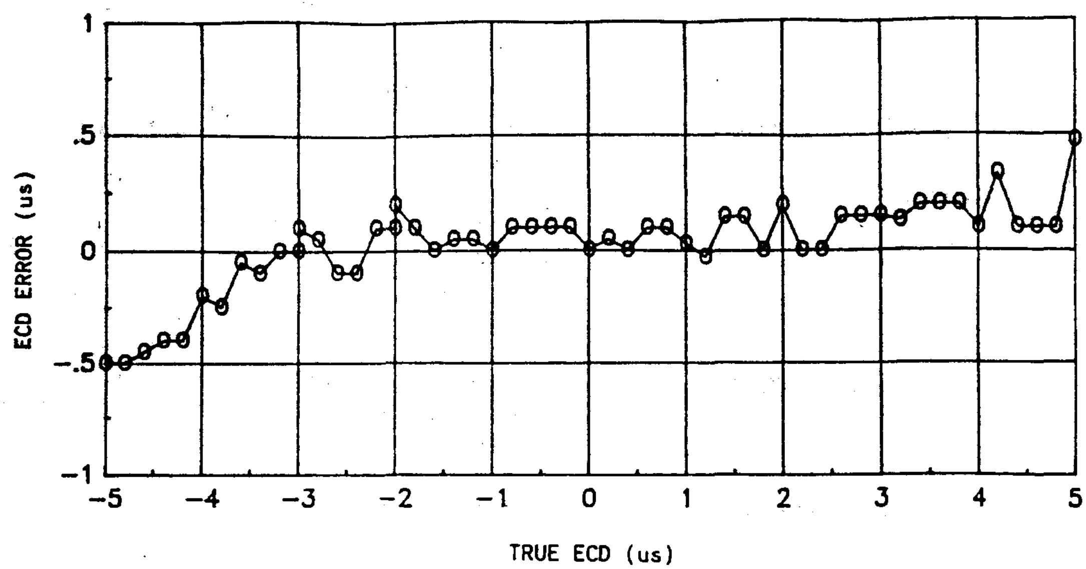

Figure 3
Austron 5000 ECD error versus Absolute ECD

ECD Overland Effects

My discussion of propagation-induced effects on ECD so far has been limited to an all-seawater path. Considering the traditional role of Loran-C for the marine community, this would usually be the dominant propagation path encountered by the majority of Loran-C users. However, as discussed in many earlier technical papers, the ECD of Loran signals propagating overland are not as well behaved as they are for Loran-C signals propagating over seawater. For example, during the early period of operation for the West Coast and Canadian West Coast chains problems with cycle slips were reported in some areas. Propagation effects caused by the mountains of the west coast had distorted the signals so that resultant ECD values in portions of the primary coverage area were lower than desired. To compensate for this distortion, the transmitted nominal ECDs (NECDs) were adjusted positively at a number of transmitters. For example, stations in these two chains with NECDs other than 0 microseconds are:

Williams Lake, BC, Canada	+1.0	Canadian West Coast Chain (5990-M)
George, Washington	+0.5	Both Canadian West Coast and the U.S. West Coast Chains. (5990-Y and 9940-W)
Middletown, California	+0.5	U.S. West Coast (9940-X)
Fallon, Nevada	+1.0	U.S. West Coast (9940-M)

During the planning stages of the Saudi Arabia chains overload propagation effects on ECD were considered. As a result, an ECD prediction scheme was developed. Figure 4 and equation 4 present the results of that prediction scheme [8]. The equation, as presented here, is in matrix form.

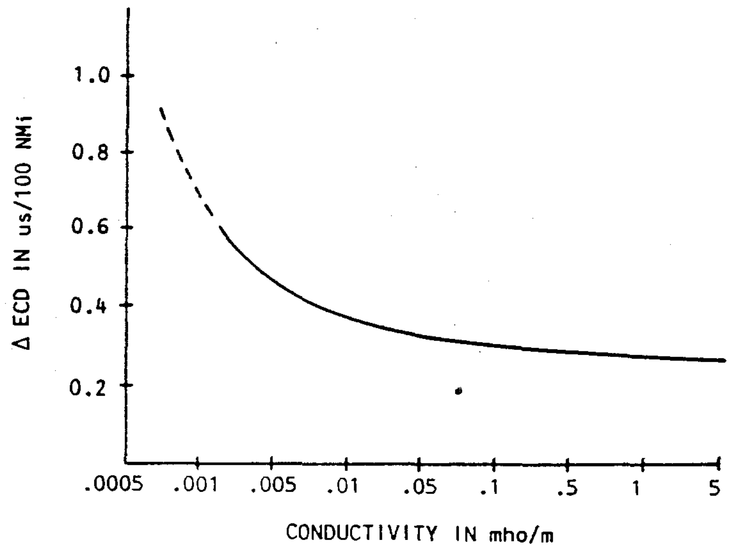

Figure 4
Change in ECD(microseconds/100NM)
versus
Path Conductivity(mho/meter)

$$\underline{\mathrm{ECD}}(n) = \underline{2.5} + \underline{\mathrm{NECD}}(n) - \underline{\underline{A}}*\underline{C} + \underline{e}(n) \qquad (4)$$

Where $\underline{\mathrm{ECD}}(n)$ = a vector of resultant ECD values for **n** stations. Units are: microseconds

$\underline{2.5}$ = a vector reflecting the 2.5 microsecond shift between antenna current and radiated fields

$\underline{\mathrm{NECD}}(n)$ = vector of transmitted ECD for **n** stations (Nominal ECD)
Units are: microseconds

$\underline{\underline{A}}(n \times 6)$ = Matrix of path segment lengths
Units are: nautical miles

$\underline{C}(6 \times 1)$ = Vector of Delta ECD values relative to path segment lengths
Units are: microseconds/nautical mile

$\underline{e}(n)$ = Vector of errors
Units are: microseconds

In this paper, the results discussed in [8] are applied to the two MEP chains using conductivity contours, observed ECD data and a simple modeling technique.

Figure 5 shows conductivity contours for the Continental United States [9]. Conductivity values were determined for frequencies greater than Loran-C's 100KHz frequency, but previous work predicting Additional Secondary Phase Factor (ASF) Loran-C corrections using these contours proved quite successful and therefore, the contours are used here.

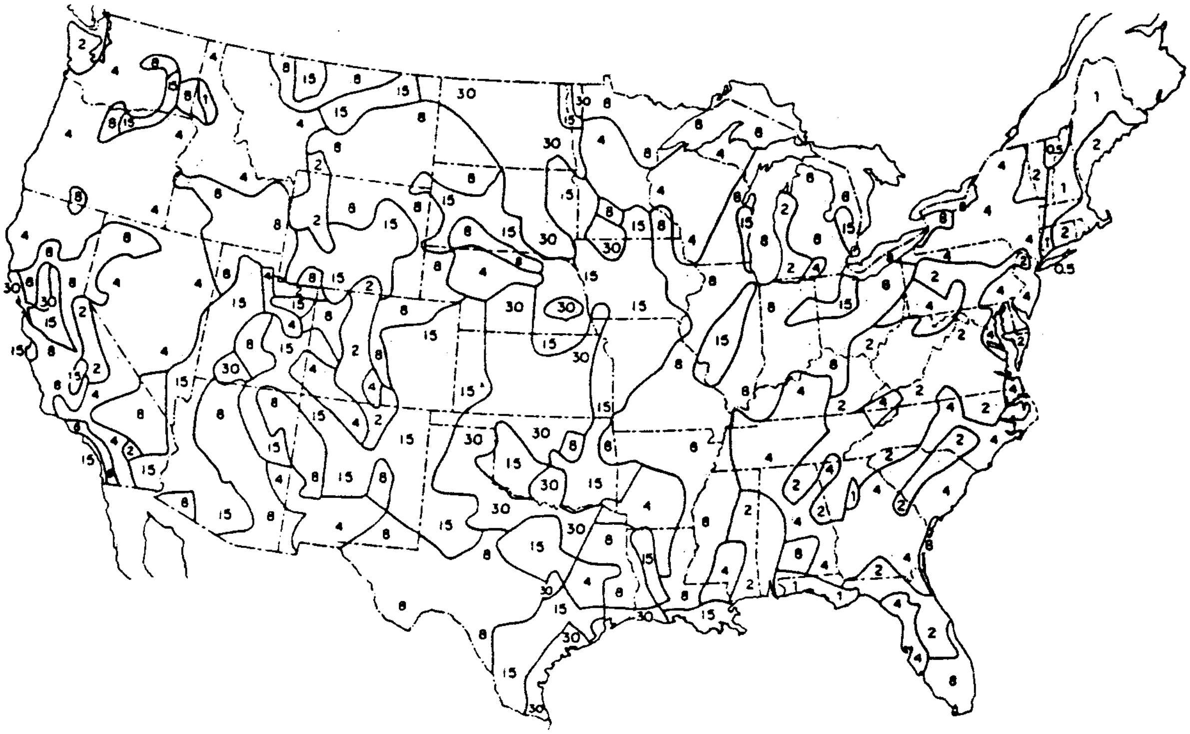

Figure 5
U.S. Conductivity Contours Units mmho/meter.
Seawater has a value of 5000mmho/meter

One final point made in [8] (and also mentioned in previous studies) concerns positive shifts in ECD values based on sharp changes in the terrain. These positive shifts (no magnitudes were reported) were observed within approximately one hundred miles of sharp terrain discontinuities. This observation will be discussed later.

Data Presentation

In July and September of 1988, engineers from EECEN conducted monitor surveys at six sites located in the FAA's Southwest and Northwest Mountain regions. Table 1 presents ECD data taken at these six sites. Included in Table 1 are: sites where monitoring was completed, date, station monitored, nominal ECD of the observed station, distance from the site to the station (in nautical miles), various path conductivity types and lengths (from Figure 5), calculated ECD for an all sea-water path, the calculated ECD using the relationship in equation (4), and the ECD measured with an Austron 5000 Loran receiver.

Units Site	Date	Station Observed	usec NECD	NM Distance to Station	Path segment(NM) Conductivity (mmho/meter) 1	2	4	8	15	30	usec Calc ECD Seawater	usec Calc ECD Land-Path	usec ECD Observed
Grand Junction Colorado	9/20-21/88	Fallon, NV 9940-M	+1.0	469	0	0	218	64	187	0	+2.33	+1.5	+1.9
		Searchlight, NV 9940-Y	0.0	366	0	0	0	79	230	57	+1.59	+1.1	+0.5
		Grangeville, LA 7980-W	-0.5	1013	0	70	201	147	442	153	0.0	+1.5	+1.2
		George, WA 9940-W	+0.5	679	0	0	287	312	80	0	+1.3	+0.2	0.0
		Middletown, CA 9940-X	+0.5	642	0	0	192	128	230	92	+1.4	+0.5	+0.9
Durango, CO	9/15-16/88	Searchlight, NV 9940-Y	0.0	360	0	0	48	142	170	0	+1.6	+1.1	+0.1
Little Rock, AR	7/14-15/88	Malone, FL 7980-M	0.0	421	0	110	145	166	0	0	+1.5	+0.6	+2.5
		Grangeville, LA 7980-W	-0.5	250	0	0	114	136	0	0	+1.4	+0.9	+2.1
		Raymondville, TX 7980-X	0.0	570	0	0	225	106	53	186	+1.1	+0.3	+2.2
		Malone, FL 8970-W	0.0	422	0	110	146	166	0	0	+1.5	+0.5	+2.2
		Dana, IN 8970-M	0.0	382	0	0	49	333	0	0	+1.5	+0.9	+2.1
Pine Bluff, AR	7/14-15/88	Malone, FL 7980-M	0.0	392	0	110	105	177	0	0	+1.5	+0.7	+2.1
		Grangeville, LA 7980-W	-0.5	213	0	0	77	136	0	0	+1.5	+1.1	+2.2
		Raymondville, TX 7980-X	0.0	550	0	0	117	117	112	204	+1.1	+0.5	+2.2
		Malone, FL 8970-W	0.0	392	0	110	105	177	0	0	+1.5	+0.7	+2.2
		Dana, IN 8970-M	0.0	402	0	0	61	341	0	0	+1.5	+0.8	+2.1
Midland, TX	7/21-22/88	Malone, FL 7980-M	0.0	875	146	67	158	242	262	0	+0.3	-1.4	+2.1
		Grangeville, LA 7980-W	-0.5	590	0	0	0	343	247	0	+0.5	-0.3	+2.1
		Raymondville, TX 7980-X	0.0	397	0	0	0	209	141	47	+1.5	+1.2	+1.5
		Searchlight, NV 9940-Y	0.0	661	0	0	93	408	160	0	+0.8	-0.2	+0.5
Big Springs, TX	7/23-24/88	Malone, FL 7980-M	0.0	840	158	79	85	255	263	0	+0.4	-1.3	+2.6
		Grangeville, LA 7980-W	-0.5	555	0	0	30	277	183	65	+0.6	-0.1	+2.2
		Raymondville, TX 7980-X	0.0	390	0	0	0	195	122	73	+1.5	+1.0	+1.8
		Dana, IN 8970-M	0.0	821	0	0	0	328	237	256	+0.5	+0.4	+1.3

Table 1

ECD and PATH CONDUCTIVITY DATA AT SIX PROPOSED MEP MONITOR SITES

The total path lengths shown in Table 1 were computed from the latitudes and longitudes of each station and the latitudes and longitudes of the data collection sites. The path segments were obtained by plotting each station and monitor site on a photographically enlarged copy of Figure 5 and measuring the path length for each conductivity value encountered. Admittedly, a very rough approximation.

Relating Table 1 to equation (4), the **A** matrix is defined by the path segments for each conductivity value (1, 2, 4, 8, 15 and 30 mmho/meter). The **C** vector, is taken from the relationship shown in Figure 4. The **C** vector has values as shown below.

$$[\underline{C}]^T = [0.006,\ 0.0053,\ 0.0045,\ 0.004,\ 0.0038,\ 0.003)$$

units are: microseconds/nautical mile

The elements correspond to the conductivity values of 1, 2, 4, 8, 15, 30 mmho/meter respectively. The seawater prediction column in Table 1 was calculated by setting all values of the **C** vector equal to 0.0025 (from equation 2).

If the relation obtained in Figure 4 is valid, and there is a correlation between ECD change and path conductivity, then equation (4) can be used to compute the $\hat{C}$ vector that minimizes the error vector **e(n)**. It can be shown that the $\hat{C}$ vector that minimizes the error is described by the equation:

$$\hat{\underline{C}}(n) = [\underline{\underline{A}}^T\underline{\underline{A}}]^{-1}\ \underline{\underline{A}}^T\ [\underline{2.5} + \underline{NECD}(n) - \underline{ECD}(n)] \qquad (5)$$

Using the data collected, the resulting $\hat{C}$ vector has the components:

$$[\hat{C}]^T = [-0.0057,\ -0.0069,\ 0.0049,\ 0.001,\ 0.0041,\ -0.0039]$$

units are: microseconds/nautical mile

A literal interpretation of the model would imply that the path conductivities of 1, 2 and 30 mmho/meter don't decrease ECD but actually increase ECD in a positive direction. Path segments with conductivities of 4, 8 and 15 mmho/meter, decrease ECD similar to the relation shown in Figure 4. In fact, the magnitudes of the ECD changes per nautical mile for the **C** estimate vector for 4, 8, and 15 mmho/meter are relatively close in magnitude to those shown in Figure 4 (converting units to NM versus 100NM). Note that the majority of the paths for the limited database also fall in this range. The number of data sets having path segment conductivities in the 1, 2, and 30 mmho/meter range are fewer in number and this most likely accounts for the unusual sign and magnitudes of the estimate of the $\hat{C}$ vector. Clearly, more data is needed before a definitive statement can be made about the usefulness of this $\hat{C}$ vector modeling approach.

One item not accounted for in the ECD prediction approach described by equation (4), is the positive shift observed when Loran-C signals pass over sharp changes in terrain. If observable shifts do actually occur, they would most likely occur in the mountainous areas near the Durango and Grand Junction, Colorado sites. A review of the data in Table 1 neither supports nor weakens the shift concept: at a few sites, observed values are greater than predicted, while at some they are lower. One unusual pattern in Table 1, is the significantly positive values of ECD measured at the four southern central plains sites, namely, Little Rock, Pine Bluffs, Midland and Big Springs. The ECD of the observed signal from Grangeville (7980-W) is considerably more positive than predicted. Note that the nominal ECD at Grangeville (7980-W) is -0.5 microseconds [2]. Coast Guard chain management specifies tolerances of ±0.5 microseconds for the nominal ECD values. Therefore, it is possible that Grangeville is transmitting an ECD more positive than that indicated by the nominal value. In fact, all of the NECD values could be more positive (or negative) by .5 microseconds. Applying these limits to Table 1, and favoring the addition of .5 microseconds, the predicted values accounting for land path attenuation are closer to those observed but not in all cases. In some cases they are actually made worse.

Table 2 presents the proposed MEP monitor sites and their associated responsibilities (Alpha-1 control) for each of the SOCUS and NOCUS baselines. The additional Great Lakes baseline, and the change in control responsibilities for the existing Great Lakes Whiskey baseline (Dana to Malone) are also shown. For the two MEP chains, five new monitors are planned. The resulting baselines and the change of existing monitor responsibilities for the Great Lakes Whiskey baseline will result in 12 new Alpha-1 control responsibilities. Note that the Great Falls, Montana monitor, shown in Figure 1, is not mentioned in Table 2. Present planning calls for this site to be used only as an Alpha-2 monitor. Table 2 includes: total path length, path segments with respect to conductivity, seawater predicted ECDs, land path predicted ECDs (using the method described by equation 4), the predicted ECDs using the estimate $\hat{C}$ vector from equation (5), and observed ECD values for those existing stations that are presently transmitting on other rates. Note that nominal ECDs are assumed to be zero except for those existing stations having nominal ECDs other than zero, i.e Grangeville and Williams Lake. It is not a requirement that dual-rated stations have the same NECD for both rates, but in order to not change the observed ECDs, the existing NECDs are used in the calculations. Also note that ECD data for the proposed NOCUS-Z secondary (Williams Lake) was obtained from the existing Austron 5000 presently operating at Whidbey Island for the Canadian West Coast Chain.

Monitor Site	Station To Be Controlled	usec MECD	NM Distance to Station	Path segment(NM) Conductivity (mmho/meter) 1	2	4	8	15	30	usec Calc ECD Seawater	usec Calc ECD Land-Path	usec Calc ECD Vector C	usec ECD Obs
Little Rock Arkansas	Grangeville, LA (SOCUS-Z) (SOCUS-Z)	-0.5	250	0	0	114	136	0	0	+1.4	+0.9	+1.8	+2.1
	Boise City, OK (Great Lakes-Z)	0.0	532	0	0	53	331	148	0	+1.2	+0.4	+1.9	NA
	Malone, FL (Great Lakes-W)	0.0	421	0	110	145	166	0	0	+1.5	+0.6	+2.0	+2.5
Midland, TX	Raymondville, TX (SOCUS-Y)	0.0	397	0	0	0	209	141	49	+1.5	+1.0	+1.4	+1.5
	Las Cruces, NM (SOCUS-X)	0.0	238	0	0	351	74	29	0	+1.9	+1.5	+2.1	NA
Durango, CO	Searchlight, NV (SOCUS-W)	0.0	360	0	0	48	142	170	0	+1.6	+1.1	+2.4	+0.1
	Boise City, OK (SOCUS-M)	0.0	237	0	63	74	0	100	0	+1.9	+1.5	+1.9	NA
	Gillette, WY (SOCUS-V)	0.0	422	0	162	128	0	132	0	+1.4	+0.6	+2.7	NA
Pierre, SD	Gillette, WY (NOCUS-Y)	0.0	231	0	0	0	131	100	204	+1.9	+1.6	+1.5	NA
	Baudette, MN (NOCUS-X)	0.0	348	0	0	67	0	61	220	+1.6	+1.3	+1.3	NA
	Havre, MT (NOCUS-M)	0.0	478	0	0	0	316	162	0	+1.3	+0.6	+2.3	NA
Whidbey Island,	Williams Lake, Canada (NOCUS-Z)	+1.0	221	221	0	0	0	0	0	+2.9	+2.1	+4.7	+0.9

Table 2
MEP ALPHA-1 ECD PREDICTIONS

The ECD predictions using the estimate for the C vector are unrealistic in some cases but are presented here for completeness. It is hoped that additional data collection, planned for the spring of 1989 at sites in the coverage area of the future NOCUS chain, will help "round-out" the database and lead to further improvements in the prediction scheme.

Conclusions

ECDs predicted for the proposed MEP monitor sites using the approach presented in [8] indicate that at distances from the transmitters on the order of a few hundred miles, no ECD problems are likely. Observed data from Loran-C Station Searchlight, specifically at the Durango and Grand Junction sites, indicate that the predicted values may be optimistically positive. It is likely that when the SOCUS and NOCUS chains become operational, stations such as Searchlight, Las Cruces, Boise City, Havre, Gillette, and Williams Lake will have to be adjusted to transmit pulses with positive values of ECD so that proper cycle selection in the mountainous regions will be possible. At stations such as Raymondville, Grangeville and Baudette, nominal ECD values of 0.0 microseconds will be acceptable. In any event, additional data is needed and will have to be collected.

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Loran-C Applications to Terrestrial Vehicle Tracking

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ABSTRACT

The economic, safety, and control benefits of monitoring vehicles automatically has long been recognized. During the 1970's many studies were commissioned and a number of demonstration systems were implemented. By the beginning of the 1980's only a small number of Automatic Vehicle Monitor (AVM) systems were in operation due mainly to the cost and complexity of the system. Most of these early systems were of the Sign Post type.

The requirements and demands of the user of today has increased dramatically at an equal if not greater pace than the technological improvements and cost reductions of the equipment. An ever increasing number of terrestrial applications with their new and unique requirements has also challenged the Research and Development efforts for Vehicle Tracking Systems (VTS). Where the number of Loran-C receivers in the Aviation and Marine environments is limited by the number of aircraft and vessels, the number of potential users in the terrestrial environment is almost limitless; from the tracking of a small parcel pick-up and delivery truck in a small geographical area to the tracking of long haul trucks cross country. These factors have all set the stage for continued development and improvement in Loran-C based vehicle monitoring systems.

This paper will discuss in broad terms Loran-C based Vehicle Tracking Systems presently in use and their general application with regard to vehicle type and employment. At the conclusion a close overview of the Detroit Project will be presented supplemented with color slides to fully described this Automatic Vehicle Locating (AVL) System which tracks 760 Police, Fire and EMS vehicles and is integrated into a system supported by a pair of MicroVax Computers incorporating a Mobile Data Terminal (MDT) and a Computer Aided Dispatch (CAD). To date this is the most ambitious undertaking of its kind in this country and is scheduled to go into operation at the end of this month.

HISTORY OF LORAN VEHICLE TRACKING

In the early 1970's a small number of Loran tracking systems were developed to compete in the DOT/UMTA development studies to implement tracking of buses in large metropolitan areas. Although a small Phase I contract was awarded for wide area coverage in Los Angeles, no major systems were installed. The Loran receivers and base station computers were large, expensive and complex, while the Loran coverage was sparse in many areas of the United States.

By the early 1980's things had changed dramatically; Loran signals covered about 75 - 80% of the continental U.S.; new solid state Loran transmitters had been installed; microprocessor and LSI chip development had been designed into new sophisticated Loran receivers resulting in small, low cost units; base stations had been reduced to desk top computers or PC's displaying high resolution graphics on color monitors.

The first application of this technology at II Morrow was a system developed for the police department of Salem, Oregon. The design requirement was to display the location and status of 25 police vehicles on a detailed map of the city in the Dispatch Center. The color/graphic map display was to allow for 10 levels of detail to be selected by zooming in and expanding the area of interest. The active patrol car ID's were to be displayed on the map corresponding to their actual position while the color of the icon displayed was to be significant to the operation or deployment of the vehicle. The status of each vehicle was to be shown in a list on the left side of the map display. The dispatcher was also to have the option of viewing a table of data on all active vehicles. The table was to tabulate and display vehicle location to the nearest intersection or landmark, status, time of last position update, time of last status change, and each line was to be color coded to indicate emergency situations, Loran signal condition, and position data transmission condition. The location of each vehicle was determined by a Loran-C Receiver located in the trunk and connected to the two-way radio by an interface/modem board. Position data and voice commmunications shared this same channel.

In the three (3) year interval since this first VTS system was installed, a total of forty (40) II Morrow fleet management systems with over one thousand (1000) vehicles have been installed, not including the 760 AVL equipped vehicles in the Detroit Project to be described later. The types of systems break down as follows:

Ten (10) systems have been installed for Truck Dispatching and status reporting in the concrete and timber industries.

Eight (8) Law Enforcement systems have become operational in California, Florida, Louisiana and Oregon. All but one (1) are located in dispatch centers. The remaining one is installed in a mobile command center for undercover operations. As previously mentioned a major system is being installed in Detroit and is scheduled to become operational at the end of this month.

Five (5) systems have been installed for Security Operations ranging from marine vessel theft protection to nuclear plant security.

Five (5) systems are operating in the Trucking Industry including an eighty nine (89) vehicle system in Dallas, Texas for the U.S. Postal Service.

Four (4) systems are installed for U.S. Government Agencies.

Four (4) systems have been sent out of country for Foreign operations in Canada, Italy and Saudi Arabia.

Two (2) systems are installed in Public Transit bus systems in Champaign, Illinois and Sheboygan, Wisconsin.

Two (2) other systems use portions of the VTS for precise Oil Exploration and EMS STATUS operations.

VEHICLE TRACKING SYSTEM APPLICATIONS

A vehicle tracking system is able to provide a graphic and static display of the vehicle's position and this position information may be useful for several purposes. The majority of applications, however, fall into one or a combination of four main categories; (1) Reduced response time in being able to dispatch the closest vehicle to a desired location; (2) Optimization of a vehicle's operation by knowing in advance its time of arrival at a predetermined destination; (3) The ability to keep vehicles evenly spaced on a given route, usually on a given schedule, while entering or removing vehicles from the route as conditions require; and (4) The ability to integrate a large number of vehicle positions into a Computer Aided Dispatch (CAD) system and efficiently control their deployment to a degree that would be impossible for one or more human dispatch operators.

The underlying elements of each of the above categories is public safety or service in one form or another, and/or economics. Note also that the above categories cover both random as well as repetitive routing of vehicles where both can benefit from a vehicle tracking system. And finally a vehicle tracking system can provide historical data which may be archived for later retrieval for determining a vehicle's time of departure, time enroute, time stopped at a particular site or location, and time in a particular status. All of this information finds application in automated statistical record keeping and billing, and is a growing area which was not originally recognized as significant or important in the early days of vehicle tracking.

Category one deals with reducing response time by being able to dispatch the closest vehicle to a desired location. This obviously fits public safety from both a law enforcement as well as an emergency services aspect. It also tends to optimize the movements of a vehicle noted in category 2, thereby reducing the number of vehicles necessary to carry out any assigned workload. The primary underlying reason for police, fire and EMS to utilize vehicle tracking systems seems to be to reduce response time. Category one also fits a parcel pickup and delivery truck which is randomly routed at different times to pick up and deliver. A dispatcher who can graphically see in real time which truck is nearest to a newly designated pickup location can easily dispatch the appropriate vehicle, reduce response time and optimize each vehicle's operation.

Category two mainly attempts to optimize the use of the vehicle by knowing in advance its time of arrival at a predetermined location. This is the case of a cement truck, which itself is an extremely expensive vehicle and normally has a driver who is highly paid because of much overtime and usually favorable fringe benefits. For every minute the truck and driver are stopped and idle, the company is loosing money due to lost production. By closely scheduling loaded vehicles to arrive at a site at an exact time the operation of the vehicle and driver are obviously optimized. More important, by knowing in advance exactly when a truck is going to return to the plant for a new load, a new batch of concrete can be mixed in advance of the truck's arrival rather than waiting for the truck to arrive and then delaying the departure of the truck until the new batch is mixed and ready for loading. The movements of a long haul truck such as a loaded Moving Van can also be optimized by closely coordinating unloading services at each intermediate stop before its final destination. The more expensive the cost of the vehicle and driver, the greater the benefit to the company in optimizing the operation of the vehicle.

The third category obviously relates to mass transit where it is important to keep buses evenly spaced and on schedule on a predetermined route and then be able to add and remove buses as the number of riders changes throughout the day. The ability to maintain buses on schedule obviously results in increased ridership of the mass transit system with increased revenues to the transit company. Buses also fall partly into category two wherein the movements of the buses can be optimized by knowing their real time movements and being able to compensate for vehicle breakdowns or increased service requirements. The total number of buses necessary to carry out the operation can therefore be reduced to a minimum with a resultant reduction in capital equipment expenditures.

Finally, category four can relate to any of the previous categories when the number of vehicles becomes so large that attempting to direct, coordinate or monitor all their movements becomes an impossible task for the human mind, especially when the vehicles cannot be broken up into separate geographic areas. When a call for service is received for Police, Fire or EMS, the CAD which vehicles are appropriate to meet the call for service; ie, Police, Fire or EMS. Next the CAD determines which of these vehicles are closest taking into account one way streets, highways with limited access, median divider strips which may prevent a west bound vehcle from responding to an east bound call, and dead end streets which do not go through. Next the CAD determines the status of the closest appropriate vehicles; ie, is the driver of the vehicle on a coffee break, is the police officer out of the vehicle on traffic duty, is the vehicle temporarily out of service for repairs, etc. Next the CAD examines the suitability of resources on the vehicle to meet the call for service; ie, is the fire vehicle a Pumper when a Hook and Ladder is required, does the EMS vehicle have the particular type of medical equipment to treat cardiac arrest, etc. And finally after all this analysis of resources the CAD recommends to the dispatcher a vehicle to assign. This resource analysis closely describes the City of Detroit AVL Project where the city will direct and optimize the deployment and movement of about 760 Police, Fire and EMS vehicles. This type of system also lends itself to the data storage and archiving necessary for statistical record keeping mentioned above and Detroit is availing itself of this type of capability.

ADVANCEMENTS IN THE TOTAL LORAN-C SYSTEM

Loran-C is a mature but expanding system having been in place for some 30 years while there still continues to be an increase in the number of stations world wide as well as domestically. Loran-C is the least expensive electronic earth referenced navigation systems to operate and maintain, and has come a long way since the earlier days when Loran-A was considered the "poor man's electronic navigation system." None the less industry and other users are continuing to place continuing demands for improvement on our existing Loran-C system; (1) Increased accuracy, (2) Increased coverage, (3) Increased availability, (4) Increased reliability, and (4) Decreased cost to the user. With regard to vehicle tracking applications all of the above requirements are being met in varying degrees.

Looking first at position accuracy for vehicle tracking purposes, many users are demanding some form of differential correction to improve on the inherent errors present in the predictable mode. The City of Detroit Project is an example of such a requirement where an initial survey indicated that a 300 ft accuracy over 95% of the area could easily be met with a simple differential correction being applied to all reported vehicle positions in the Host Computer at the fixed end. Increased accuracy is also being addressed by manufacturers as a result of the proposed closing of the Mid-Continent Gap. With the availability of redundant chains in many areas, the use of Dual Chain tracking will find increased application over a large portion of the continental U.S. and this type of receiver is already being found on more and more manufacturers' drawing boards. With the increase in the number of redundant Secondaries available, an inexpensive Cross Chain tracking receiver can create pseudo Base Lines between Secondaries of different chains and greatly improve geometry in many areas. This Cross Chain tracking is only available in the inexpensive receiver if both Masters can be received or if the error in the Time of Coincidence (TOC) between the two Masters can be determined in some manner. The necessity to be able to receive both Masters obviously limits the areas where Cross Chain tracking is presently available in the inexpensive receiver. The U.S. Coast Guard at this time appears to be investigating more seriously the possibility of synchronizing the Master Stations of all Chains in some manner which would in affect eliminate the error in the TOC between the Masters and make an inexpensive Cross Chain tracking receiver (determination of any TD with only one Master signal available) a near term reality. While much of the pressure to synchronize Masters is coming from the aviation community, its implementation will also greatly improve the accuracy of positions in vehicle tracking. With the establishment of the North and South Central U.S. Chains and their eight (8) new base lines, as well as the possibility of greatly increasing the number of pseudo base lines in the foreseeable future through Cross Chain tracking, the accuracy of Loran-C will improve greatly over what is available even today in many areas. The addition of Dead Reckoning to enhance Loran-C may further improve the accuracy by as much as two fold in many areas and applications.

With regard to increased coverage within the limits of the continental U.S., the previous discussion of the closing of the Mid-Continent Gap should prove adequate for purposes of vehicle tracking at least in the near to mid term.

The question of improvements in Availability and Reliability can be handled together to some degree for purposes of this discussion. Both availability and reliability of Loran-C have been very high and have achieved a degree that probably cannot be improved appreciably at an acceptable cost. For purposes of vehicle tracking, the only complaint from industry relates to the individual station down time, either scheduled or emergency. In areas with a limited number of stations combined with poor signals and/or poor geometry, the loss of any single station, especially the Master, can be a serious obstacle to the satisfactory operation of the tracking system. This one shortcoming can at least be partially overcome through a redundancy of chains and/or secondary stations when operating with a Dual Chain or a Cross Chain type of receiver and multiple LOP fixes. As these new type receivers become more common in the market place, the question of Availability and Reliability becomes less critical.

The final question with regard to required improvements to the Loran-C system demanded by industry relates to decreased cost of mobile and fixed end equipment. As with so many other high-tech components and pieces of equipment, the price of chips has rapidly decreased and an ever increasing number of specialized chips are becoming available everyday. In a way this presents one of the most complex questions facing any manufacturer of Loran-C receivers used for vehicle tracking. If developed today, how long will it be before a specific Loran-C receiver becomes obsolete in the market place, and can a reasonable profit be realized in the mean time. The application of vehicle tracking is still in its infancy and with new applications "being dreamed up every day" there should be a sufficient market for new products to be developed in quantity at a reduced cost to be competitive in the market place. Conventional forms of vehicle tracking will feel the major impact of reduced cost of mobile-end Loran-C receivers first with more specialized or unique applications feeling less reduction in hardware cost for the mobile-end. Another factor which is acting to reduce the overall cost of vehicle tracking is the availability of low-cost computers. This means that industry has the ability to purchase a very competitively priced computer to meet his fixed-end needs for a graphic or static display of information and then purchase only the necessary software and high resolution monitor from a vehicle tracking system manufacturer. In the past two years alone II Morrow has seen a dramatic trend in the reduction in the hardware in the fixed-end coupled with a greatly increased capability and flexibility of operations through software development at the dispatch station. All at a considerable cost savings to the user over what such a system would have cost just a few years ago. Once again the City of Detroit Project is a classic example of a greatly enhanced operational capability of vehicle tracking through software development.

DEVELOPMENT OF INTEGRATED NAVIGATION SYSTEMS

II Morrow has been working on an integrated navigation system that incorporates various sensors with a Loran receiver. This Research and Development effort has resulted in better than expected results and serves as a stepping stone for further work in this area.

The majority of customers for the Vehicle Tracking System operate in urban environments which can cause problems for Loran only operation as discussed in the PLC section of this paper. In addition things like narrow streets between tall buildings, tunnels, railroad tracks, bridges, poor geometry and weak signals will all have varying effects on the Loran reception which will affect the position accuracy.

One approach to correcting for the adverse effects of these factors is to apply filtering techniques to limit their

influence. Another approach is to integrate a navigation device with good short term stability with long term Loran stability. Thus the use of Dead Reckoning (DR) to complement Loran should provide an improvement in poor signal areas. The Dead Reckoning system consists of an inexpensive, a two dimensional flux-gate compass and a pulse generating speed sensor. Basically, a processor reads the compass and speed sensor along with the Loran receiver. This information is feed to an adaptive algorithm to produce an improved position solution.
The heart of this integrated navigation system is an algorithm that monitors various sensors and determines which to use as the primary navigation source and how reliable it is. The algorithm works basically in two modes: (1) Dead Reckoning alone, and (2) Combination Dead Reckoning and Loran. When the Loran is determined to be temporarily unusable, the system uses the compass and speed sensor for positioning and navigation. When Loran is determined to be satisfactory, the system combines position reported by Loran, magnetic heading and speed sensor and produces a position via a progressive and adaptive filter. Even when Loran is selected and could provide sole position data, combining Loran with DR provides greatly enhanced position tracking and accuracy.

One of the most important features in this integrated system or any similar systems is the ability to judge the integrity of the Loran operation. When Loran signals are blocked by large structures the signal strength and/or the signal-to-noise ratio can reliably be used as indicators. However it is not as straight forward in the case of PLC, multipath, or skywave contamination. In the latter instances, it has been observed that these signal indicators are only marginal in interpreting signal quality or integrity. Combining signal strength and signal-to-noise ratio with envelope cycle difference (ECD), time difference (TD) rate of change, and jitter can help to improve the chance of accurately determining Loran signal integrity.

Because this is an integrated navigation system, independent characteristics among component systems should be exploited by using one system (sensor) to check the others; in this case to use DR sensors to check Loran integrity or to use Loran data to monitor and correct DR sensors. For this particular mix of sensors - Loran and flux-gate compass - caution has to be taken since they both can be corrupted by the same interfering sources, (ie. steel bridge, etc.). After numerous simulations and road tests, the results have been very encouraging. Preliminary data has indicated obvious and substantial improvements in tracking and accuracy over systems that use only Loran. Improvements in the order of 25 to 60% improvement have been observed.

Integrated navigation research is continuing at II Morrow. The challenge is to design and produce integrated navigation systems with a cost/performance ratio that is acceptable to the customer. With the near term addition of new Loran chains and the recent emergence of promising sensor technologies, the next few years will be very important and busy for the integrated navigation field.

POWER LINE CARRIER (PLC) INTERFERENCE CONSIDERATIONS

While Loran-C is susceptible to several types of both synchronous and asynchronous interference, Power Line Communication (PLC) is unique to terrestrial vehicle tracking systems. (Note: PLC interference has also been reported by aircraft pilots but is rare in comparison with terrestrial Loran-C use.) Power Line Communications may be conducted anywhere in the 9 - 490 KHZ band, but are most commonly found on frequencies divisible by 10 (ie, 80, 90, 100 KHZ, etc.) with a particularly high concentration between 60 KHZ and 140 KHZ and an <u>extremely</u> dense concentration around 100 KHZ. Most transmissions are of the continuous wave (CW) type on one or two frequencies. They consist of a continuous pilot carrier in the range of 1 to 10 watts with a keyed command carrier in the range of 10 to 100 watts. The lower power continuous pilot carrier is partiuclarly bothersome while the command carrier which is used for power switching and control purposes is used infrequently, is of very short duration and does not cause permanent interference. PLC has been around for many yhears and much of the equipment still found in operation is of the "6L6 vintage!" PLC is utilized primarily on high voltage transmission lines and seldom found on low voltage utility distribution systems. Fortunately, the major utilities are switching to the more modern and reliable micro-wave form of communications for power switching and control. This means that PLC on the higher voltage, longer transmission lines is being phased out first with a more gradual replacement on the lower voltage, shorter transmission lines. The range of PLC interference is obviously dependent upon many factors but can affect Loran-C reception for several blocks. PLC interference is also aggravated by the fact that transmissions lines many times are also found to carry impulse noise which many originate from almost any source. PLC interference is particularly harmful to terrestrial vehicle tracking systems where a high voltage transmission line runs parallel to a road or highway and the vehicle is continuously subjected to the interference and loses the Loran signal completely until the vehicle moves out of the area of interference associated with the power line. Overhead trolley car and electric bus power lines also are a major source of RFI and in many cases cause the Loran-C receiver to loose signals when the vehicle is driven close to or below these overhead lines. The U.S. Coast Guard is aware of PLC and its potential effect on terrestrial (and to a lesser degree aviation) Loran signals, and is working with the North American Electric Reliability Council (NERC) to try and resolve the problem. Well documented cases of PLC interfering with Loran-C signals are invited by the U.S. Coast Guard, Marine Radio Policy Branch who is seeking to eliminate or reduce such interference under 47 CFR 90.63g.

OVERVIEW OF DETROIT AVL SYSTEM

A major contract was awarded earlier this year by the City of Detroit to II Morrow, Inc., of Salem, Oregon for the installation and implementation of a Vehicle Tracking System (VTS) in conjunction with a Mobile Data Terminal (MDT) network and a Computer Aided Dispatch (CAD) System. This is the most ambitious undertaking of its kind to date and incorporates many innovative features not previously found in other systems. II Morrow is the Prime Contractor for the Vehicle Tracking System portion of the contract and is assisted by Advanced Control Technology, Inc., of Albany, Oregon as a Subcontractor.

The Detroit Project is comprised of approximately 760 Police, Fire and EMS vehicles which serve the City of Detroit. The position of each vehicle is determined by a Mobile Loran Receiver installed in each car or truck which transmits this information back to the Base Dispatch where the data is processed through a Micro Vax Computer and then displayed on 6 Police, 2 Fire and 2 EMS Graphic Work Stations. An additional 14 terminals are available for Supervisor personnel as well as "Hot Spares" for back up. While the initial system will be brought on line with a digitized map of the City of Detroit developed by II Morrow, ultimate plans call for a Geo Base file to be developed to create a computer drawn Map which will have full capability to interface with the CAD. This will allow for a full E-911 LAT/LON cross reference to street address. At the Dispatch end the AVL Communications Radios, Polling System, Micro Vax Computers, CAD and MDT are all fully duplicated for redundancy and have a back-up system design for the rerouting of data between the CAD, Micro VAX Computers and MDT should one of them become inoperative.

Each City vehicle in the Detroit Project is equipped with three totally separate and independent radio communications systems; namely one dedicated to voice communications, one dedicated to MDT data communications and one dedicated to AVL data communications. The total communications load between the Base Dispatch and vehicles could not possibly be carried out on one radio channel and while these three independent radio communications systems are initially expensive they have several very important benefits: (1) They provide a degree of redundancy and back up should one radio system fail; (2) They allow for simultaneous communications with a vehicle at times of critical operations; (3) They prevent an overload on any one system such as the MDT from adversely reflecting this overload onto another system such as the AVL; (4) They prevent the mixing of voice and data communications on the same channel or radio system which at best is marginally acceptable and causes the loss of many data transmissions; and (5) They optimize each system by preventing collisions or other interference from occurring between different systems operating on the same radio channel. Additionally, these radio communications systems are operating on different bands which provides a limited degree of frequency diversity and insures that all communications will not be lost with a vehicle due to operating conditions or limitations unique to one particular band. In an effort to reduce the number of antennas installed on each vehicle the antenna required for the Loran Receiver (receiving at 100 KHZ) was duplexed with the AVL Radio Communications (transmitting and receiving at 158 MHZ) into a single 21 inch trunk mount whip antenna.

The Polling requirements for the Detroit Project are quite unique in that they combine several types of vehicle polling into one system; ie, Police, Fire and EMS. Operationally this spans the spectrum of polling pursuit Police vehicles as often as once every three (3) seconds with Fire Trucks that may be in a stand by readiness condition and polled only once every ten (10) minutes. Due to the total number of vehicles being polled, two communications channels were required. The AVL system continuously determines the polling load on each channel and automatically moves polled vehicles from one channel to the other to balance out the load between them.

Although the City of Detroit is fairly small geographically, three Remote Receivers are used on one AVL Communications Channel and four on the other. A modified Voting technique is used to validate the received data message from the Mobile Units as well as to insure that each Remote Receiver is operating normally. The operation of both fixed end Transmitters are also monitored by the Remote Receivers to verify normal operation of the transmitters. The Main Transmitter is automatically shifted to the Standby if the Polled signal is found to be missing, corrupted or weak. With this redundancy of Transmitters and Receivers, the City of Detroit is assured of continuous AVL Communications at all times.

The Detroit Project is drawing considerable attention from other municipalities who are carefully weighing the benefits of such a system in their own community.

CONCLUSIONS

As the monitoring and dispatching capabilities of Loran-C based vehicle tracking systems become recognized, large new markets are opening up in such industries as long haul trucking, hazardous waste tracking, ambulance fleets, taxi fleets, courier and parcel pickup and delivery service companies. Since II Morrow Inc. was acquired by United Parcel Service (UPS), considerable attention is being given to the latter applications by this company. Military uses of Loran-C based vehicle tracking systems include weapons and munitions material transportation, war games and selected tactical applications. The immense popularity of airborne Loran-C receivers and the expanding applications of terrestrial vehicle tracking have contributed to the building of the two new Mid-Continent Chains.

In Europe as well as in the UK, land navigation and location technologies are seriously being studied for traffic control and fleet management purposes with varying degrees of success. For the general motoring public, in-vehicle navigation/display systems are also being developed by most of the world's automobile manufacturers for introduction in the 1990 time frame. Systems are being developed using Dead Reckoning, Beacons or Sign Posts, Map Matching, VLF/OMEGA, Transit or GPS satellites, Loran-C, or various combinations of these systems. Of all these systems, a Loran-C based system provides the most cost effective, accurate, reliable and maintenance free system of all, and where greater accuracy is required enhancement of Loran-C with such items as Dead Reckoning flux gates and speed sensors still provide the least expensive system to the user.

BIOGRAPHICAL INFORMATION

Ransom K. Boyce is a retired U.S. Coast Guard Commander having graduated from the U.S. Coast Guard Academy in 1958 with a BS in Engineering. He spent the majority of his Coast Guard career in the Aids to Navigation Program where he acquired his background in the field of LORAN-C. He has been with II Morrow, Inc. two years and is the Engineering Program Manager for Aviation, Marine and Vehicle Tracking Loran Products.

LORAN-C OSCILLATOR REQUIREMENTS

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ABSTRACT

The precision oscillator used by modern Loran-C receivers for time reference is the most expensive component in many designs, and, as such, has come under pressure by low-cost equipment manufacturers looking for ways to reduce their bill of material costs. Since stability is related to price, it is worthwhile to analyze the requirements to insure that the oscillator is not overspecified.

The affects of absolute oscillator accuracy on the raw acquisition of the loran signals, the phase-locking, and the TD measurement are described; changes of frequency with voltage and temperature are considered; and, finally, an implementation is shown using an oscillator with a stability specification of +/-25 ppm over the temperature range of -10 to 55 degrees centigrade.

INTRODUCTION

Before the fall of the dollar, many U.S. manufacturers of Loran-C Receivers, feeling the pressure from lower-priced but good quality Japanese products, remained competitive by reducing their manufacturing costs. Considerable engineering went into converting hardware to software and utilizing more powerful microprocessors with built-in timers, input/output and control bits, serial communications, retentive memory, and even analog-to-digital converters, all of which eliminated external hardware. A good example of this is the Motorola MC68HC11 Microcomputer (Reference 1) currently used by eight U.S. manufacturers for their newest Loran-C products; this processor can be programmed to do all the digital functions of a low- to mid-cost Loran-C receiver, even including driving a display and a keyboard leaving no digital parts to eliminate. Future efforts to reduce costs

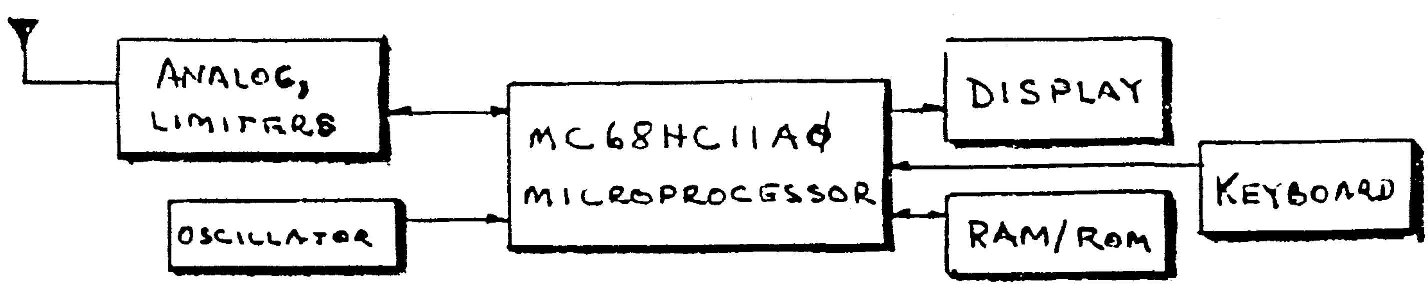


Figure 1. BLOCK DIAGRAM OF "SINGLE-CHIP" LORAN-C RECEIVER

must address the receiver's analog/filtering section, the display, packaging, or the precision oscillator. This paper explores the last possibility.

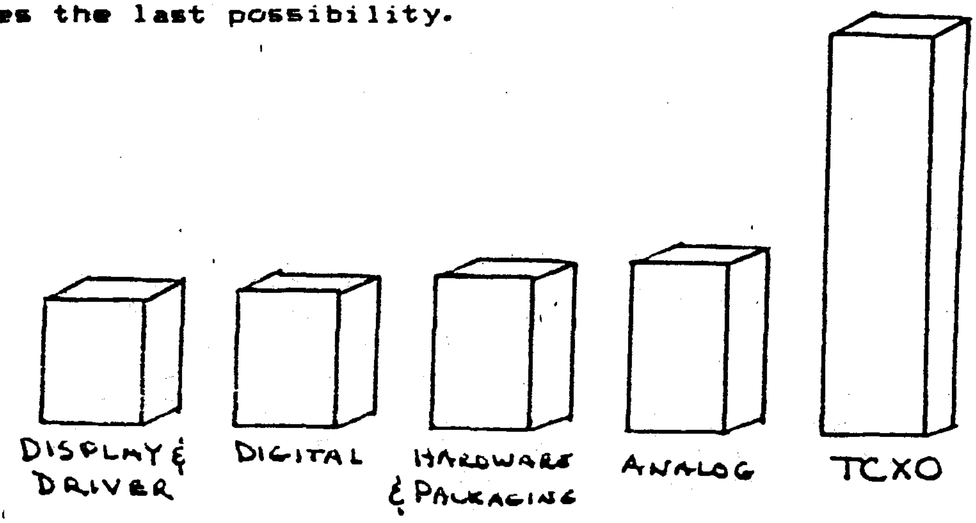


Figure 2. RELATIVE COSTS OF RECEIVER SECTIONS

THE OSCILLATOR PROBLEM

Ten years ago, precision oscillators with stabilities down to +/- 1 part per million over the range of -10 degrees centigrade to +55 degrees centigrade were common, with some even better. As prices for most components declined dramatically, the price of this oscillator looked grossly out of place in low-end

PART	COST	% OF BOM
Enclosure(s)	$ 6.00	6
Hardware	3.50	3.5
Connectors	2.00	2
PCB's	3.50	3.5
LCD	8.50	8.5
Display Driver	2.50	2.5
Keyboard	5.00	5
Microprocessor	7.50	7.5
RAM, ROM	4.50	4.5
Regulators	1.00	1
Power supply filter	5.00	5
Limiters	1.50	1.5
Analog components:		
75 capacitors	6.00	6
100 resistors	1.50	1.5
15 inductors	5.50	5.5
Transformers	4.00	4
10 transistors	2.50	2.5
Manual	2.00	2.0
Packaging	3.00	3.0
TCXO	25.00	25.0

Figure 3. HYPOTHETICAL $100.00 BILL OF MATERIAL RECEIVER

sets, and some manufacturers simply relaxed the requirements, using +/- 2 ppm and +/- 3 ppm oscillators over 0-50 degrees and, where possible, living with the consequences, thereby saving 50% of the oscillator cost. By the time they got to +/- 5 ppm, however, acquisition and phase lock became problems as well as the TD measurement error created just by temperature change. Investigating and solving these problems has led to the possibility of using much less expensive components: a +/- 25 ppm oscillator is one-tenth the cost of +/- 1 ppm. The next step, +/- 50 ppm, is the high end of off-the-shelf components (0.005%), the use of which would make the oscillator simply another part.

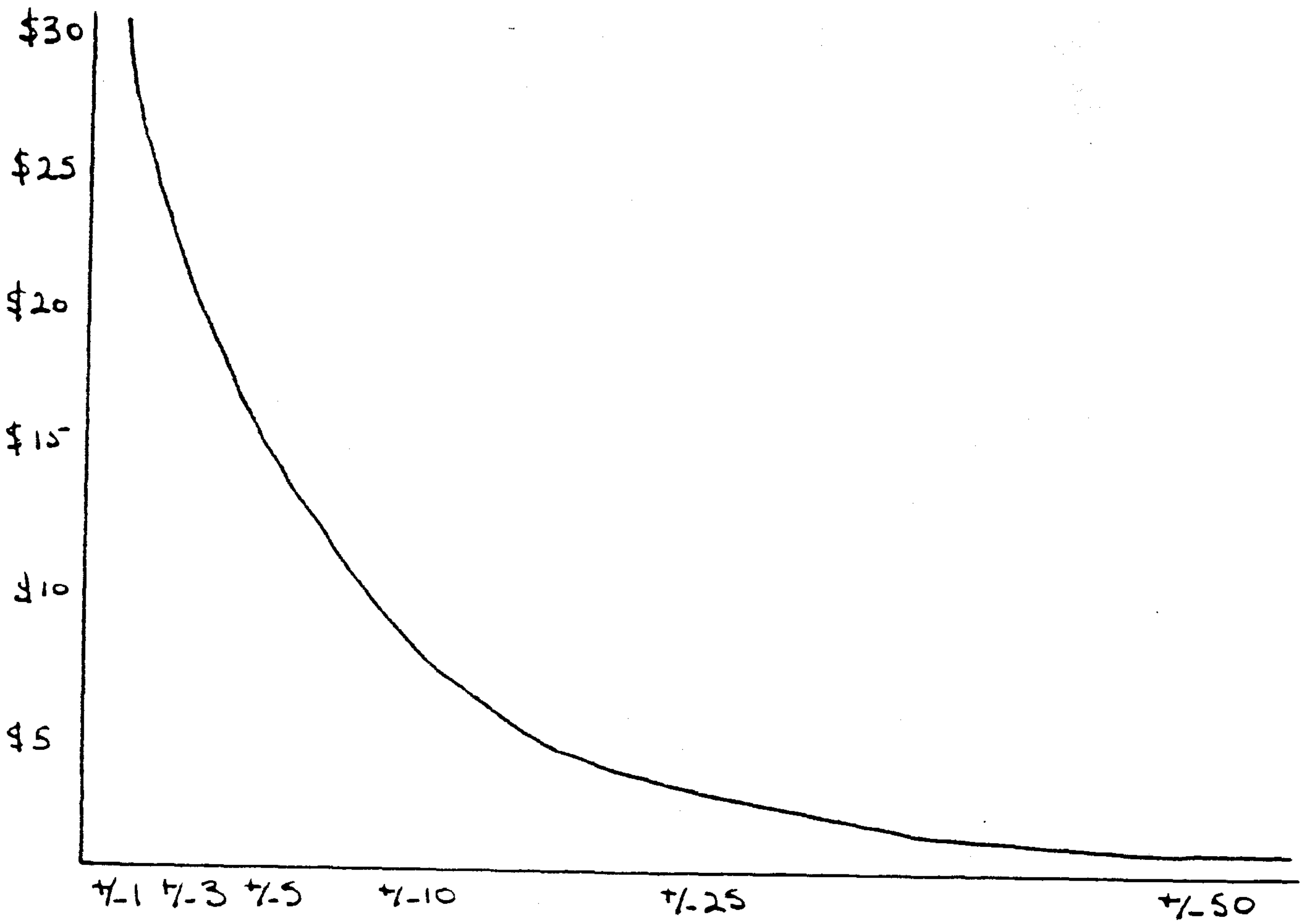


Figure 4. OSCILLATOR COST VS. STABILITY

STABILITY REQUIREMENTS

The actual frequency of the oscillator that provides the Loran-C with its timing reference is, within limits, unimportant; frequencies in use include 4 Mhz, 5 Mhz, 8 Mhz, 10 Mhz, 20 Mhz, and others. Whether the frequency is exactly, say, 10 Mhz or 10.000001 Mhz or 10.010000 Mhz or 10.123456 Mhz is immaterial because, if the actual frequency is known, the processor's software can adjust for any offset. And, _if_ the Loran-C receiver can somehow acquire and track (phase lock to) one Loran-C signal, the actual frequency of the receiver's oscillator can be measured and adjustments made so that _all_ signals can be tracked accurately. This is not usually done since a nominal 10 MHz oscillator is easier to come by than a 10.01 MHz oscillator, and, of course, the TD's need to be corrected as is shown later.

GRI	MICROSECONDS	COUNTS AT 10 MHz	EXTRA COUNTS NEEDED PER GRI AT 10,010,000 HZ
9960	99,600	996,000	996
9940	99,400	994,000	994
8970	89,700	897,000	897
7980	79,800	798,000	798
5990	59,900	599,000	599
5930	59,300	593,000	593

Figure 5. CORRECTING FOR AN "OFF-FREQUENCY" OSCILLATOR

The difficulty arises when the frequency _changes_ with temperature or voltage or age. There are three separate areas of operation, or processes, that are affected when the frequency is unknown: acquisition (search), phase lock (tracking), and measurement. For purposes of this paper, the following definitions are used:

ACQUISITION: the "coarse" identification of the loran signal;

PHASE LOCK: the "fine" identification of an edge of the signal;

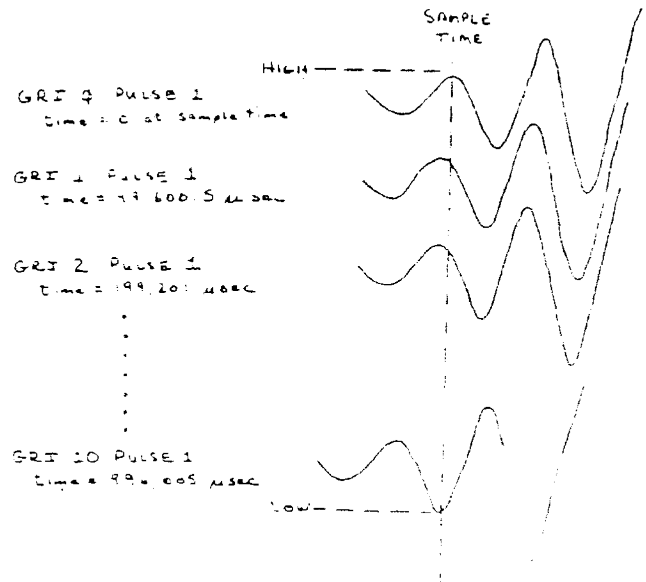
MEASUREMENT: the time between edges of the signals from different stations.

In this discussion, selection of the "proper" edge, i.e., "third cycle matching," is not considered, as that is an analysis of the _shape_ of the pulse not of the _timing_ between pulses or the isolation of a single edge. Each of the three processes defined is discussed separately.

ACQUISITION

Methods of acquisition (locating the Loran-C signal in time) are as varied as the number of designs. Commonly, many GRI's are used, averaging the signal response to eliminate the noise. This approach is most susceptible to changes in the frequency of the timing reference, and, the more GRI's that are used, the more stable the oscillator must be. A change of five ppm from what is expected will cause a five microsecond drift in ten GRI's which will make averaging unusable (averages to zero). A change of 50 ppm (from plus 25 to minus 25) will give a five microsecond error per GRI! Without predicting (or guessing) the frequency error, no averaging is possible with this amount of error. Due to the time consuming nature of averaging, a repeated trial-and-error approach is usually not desirable.

(Since many of the common rates are close to 100,000 microseconds (9960, 9940, etc.), this number will be used as a reference for simplicity. Although all the problems associated with oscillator frequency change are lessened for shorter rates (not the least of which is more signal per unit time), all the differences are less than 2:1, which is small compared to the magnitude of the errors considered.)



Figu e 6. APPARENT SIGNAL DRIFT AT 0.5 uSEC/GRI (5 ppm)

An aquisition method that uses but a single GRI, with or without a second GRI for correllation, is <u>independent</u> of the oscillator error up to hundreds of parts per million (+/-2.5 usec per 7 msec), and neither predicting nor guessing the frequency is necessary. Such an approach was developed by the author in the early 1980's and has been successfully used by more than ten companies in some two dozen products aggregating over 100,000 receivers. Persistence pays off in a noisy environment, because only a seven-millisecond relatively clear window is required for any one of the Loran-C signals--it only takes finding one to lock up the oscillator so that conventional averaging can be used.

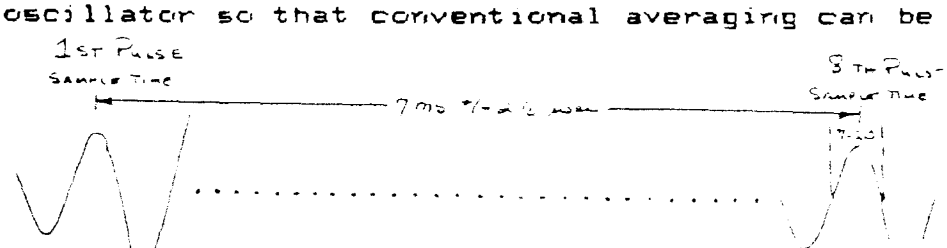


Figure 7. ACQUISITION IN ONE GRI.

PHASE LOCK

After the receiver has the approximate location of the signal, usually high into the best SNR portion, it must "lock" to an edge (zero-crossing) to make timing measurements between signals from different stations. A detailed discussion of phase lock loops is beyond the scope of this paper, but, without proof, it can be said that any loop has a lock range that cannot be exceeded, and, given the nature of the Loran-C signal, it must be less than five microseconds per GRI which is less than 50 ppm.

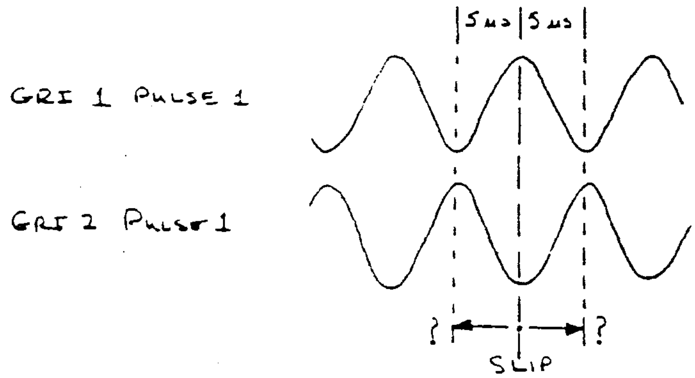


Figure 8. FIVE MICROSECOND SLIP PER GRI.

This requires an initial gain of one for the first order loop; in order to be stable, not to say useful, an adaptive filter is required and is used by most modern sets. To insure stability in the noisy Loran-C environment, a reliable loop would be less than that amount giving a practical lock-in range of 10-25 ppm.

Although a phase lock loop, however complex, may be designed to use a 25 ppm oscillator, a simpler loop may be enhanced by using the predictive techniques discussed later in this paper and will enable use of even less stable oscillators.

TD MEASUREMENT

With a +/- 5 ppm oscillator, a TD measurement of 50,000 microseconds uncorrected for oscillator error will be in error by +/- 0.25 microseconds due to the oscillator alone. Thus, sitting in one place, measuring a hypothetical TD of 50,000.0 when very hot, if the temperature decreases so the oscillator changes by its full stability, the measurement will change to 50,000.5 due to the change of oscillator frequency alone, in addition to whatever else the propagation does or the receiver does.

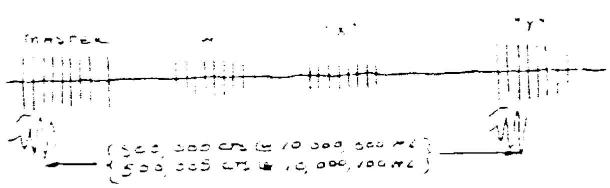


Figure 9. TD ERROR DUE TO OSCILLATOR OFFSET

This is, however, the easiest problem to solve because Loran-C receivers are excellent measurers of the oscillator error. Simply taking the velocity term of the set's phase-lock loop, normalizing it for the GRI, and multiplying it by the TD measurement will give the TD error which can be algebraically added to the TD.

$$TD_{COR} = TD_{MEAS}\left(1 + k \cdot \Delta osc\right)$$

Figure 10. TD CORRECTION FOR OSCILLATOR ERROR.

This makes the assumption that the velocity component due to movement is negligible. In boats this is true: at 50 knots directly on a baseline, the movement error is approximately 1 ppm which is less than 0.1 microsecond in 50,000. For aircraft usage, however, correcting the TD only for "apparent" oscillator error will produce a lag in the TD value by up to 0.4 microseconds. Fortunately, this too is easily corrected with some additional arithmetic. Using the TD gradients computed in the latitude-longitude solution and the actual motion of receiver computed from the position filter, the composite oscillator error is broken into oscillator "errors" in the direction of each TD. After the individual station velocities are subtracted from the calculated components, the true oscillator error is computed. (This calculation requires separate phase lock loops for each station, as is the case for most modern receivers.)

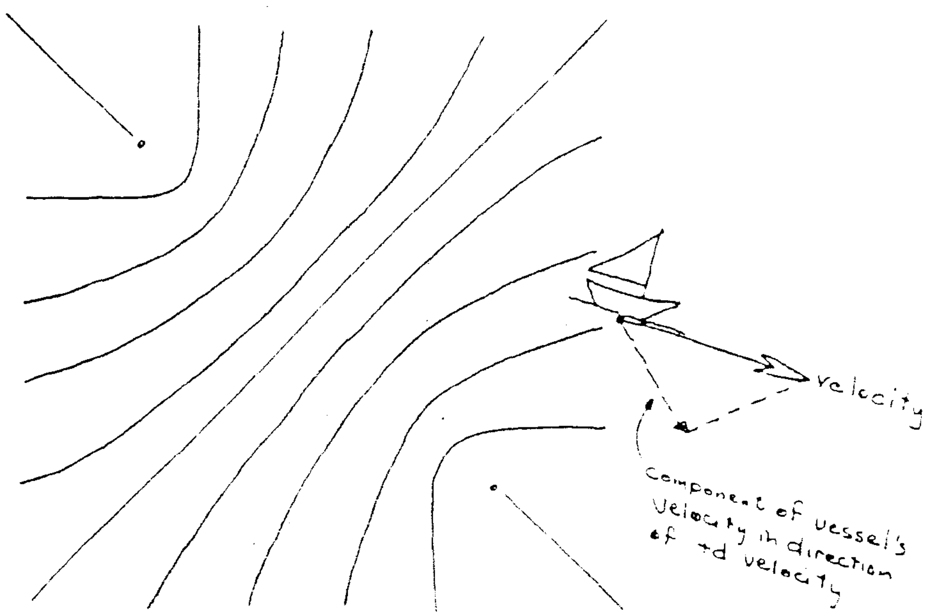


Figure 11. CORRECTION OF TD VELOCITY FOR VEHICLE MOTION.

GUESSING AND PREDICTING

If the process design being used doesn't solve the problems for acquisition and phase locking, there are still methods to anticipate them. The first (and cheapest) is to guess at an error and try it; if unsuccesful at acquisition, guess again. Depending on the range of the process and the "instability" of the oscillator, up to some number of attempts "n" will yield the result. The drawback of this approach is how long it takes to guess right, which in actuality is <u>only</u> a point-of-sale problem--the guessing time is typically less than the cycle select time which the user already waits for.

The "guess" approach can normally be speeded up simply by starting at the last (turn-off) value, which makes the reasonable showroom assumption that the turn-on temperature is the same as the turn-off temperature. This is the simplest (and cheapest) of various predictive schemes.

The major variation in frequency is due to temperature change. If the receiver has a method of measuring the temperature, a highly accurate prediction may be made once one point on the frequency-temperature curve is known. Actually the problem isn't even that difficult because the temperature does <u>not</u> need to be known absolutely, only relatively. So, if the processor has a built-in analog-to-digital converter (as the MC68HC11 has) a very simple circuit (worth ten cents) can be used to measure changes in temperature and very reliably predicting the turn-on frequency. Updating the temperature end points (as an A/D value) with the normalized oscillator error (corrected for the GRI so that the GRI may be changed) allows a very simple algorithm to predict a very accurate oscillator error for the "current temperature."

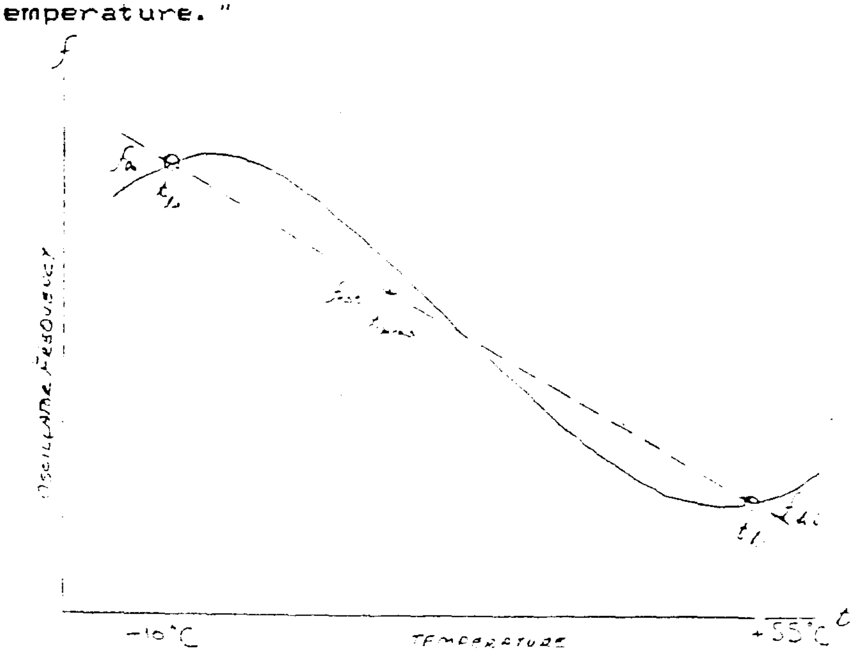
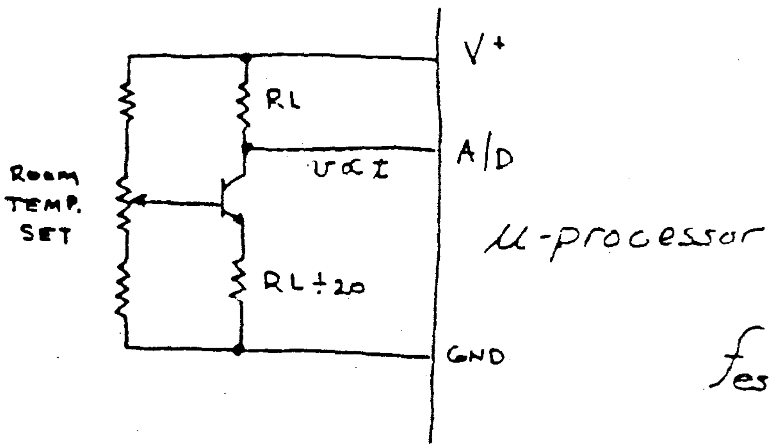


Figure 12. TYPICAL CRYSTAL OSCILLATOR FREQUENCY-TEMPERATURE CHARACTERISTICS

TEMPERATURE CHANGES, AGING, AND ACCELERATION

A change in the oscillator frequency due to aging, if it is large enough to be noticed, is easily accomodated by the continual recalibration technique described above. An acceleration (starting, stopping, and/or changing direction) appears to an operating receiver like the frequency change due to a temperature change (without the temperature change). This error can be accomodated by the phase-lock loop either within the tracking lock-in range, or, if extreme, the adaptive filter can be designed to accommodate the change as is commonly done with aircraft receivers. This is typically a non-problem: a ten degree centigrade change in temperature in one hour for a +/- 25 ppm oscillator is only 0.001 microsecond per GRI (approximately), hopefully well within the phase-lock loop response; 0-60 in zero time (on a baseline) produces a velocity of nearly 0.2 microseconds per GRI--in 28 GRI's the uncorrected error would reach five microseconds and the tracking would slip a cycle. Using a five second time constant loop filter, the first order loop gain would need to be at least 0.02, which, to the author, seems to be less than a minimum number anyway. All boat and all practical aircraft accelerations are within this; to achieve a 900-knot standard rate 180 degree turn on a baseline would require an adaptive filter to increase the first order loop gain during the acceleration.



$$f_{est} = f_{lo} + \left[\frac{(t_{mrs} - t_{lo})(f_{hi} - f_{lo})}{(t_{hi} - t_{lo})} \right]$$

Figure 13. SIMPLE (RELATIVE) TEMPERATURE MEASUREMENT CIRCUIT.

EXAMPLE

A new, low-cost Loran-C receiver based on the ideas of this paper has been introduced for 1989. The specification of its oscillator is +/- 25 ppm over the operating temperature range. In addition, the oscillators have no frequency adjustments and are received with room temperature frequencies up to 175 Hertz off (plus and minus) their nominal frequency of 8 Mhz.

Since the individual oscillator frequencies are not predictable, the first factory turn-on must go through a guess approach or allow technician input of the current frequency. Once, however, the receiver achieves phase lock on some loran signal, it goes through a self-calibration sequence which is continuously updated when the receiver is operating. Since waypoints, routes, and start-up data are stored in non-volatile RAM, it is a simple matter to save the "end-points."

CONCLUSION

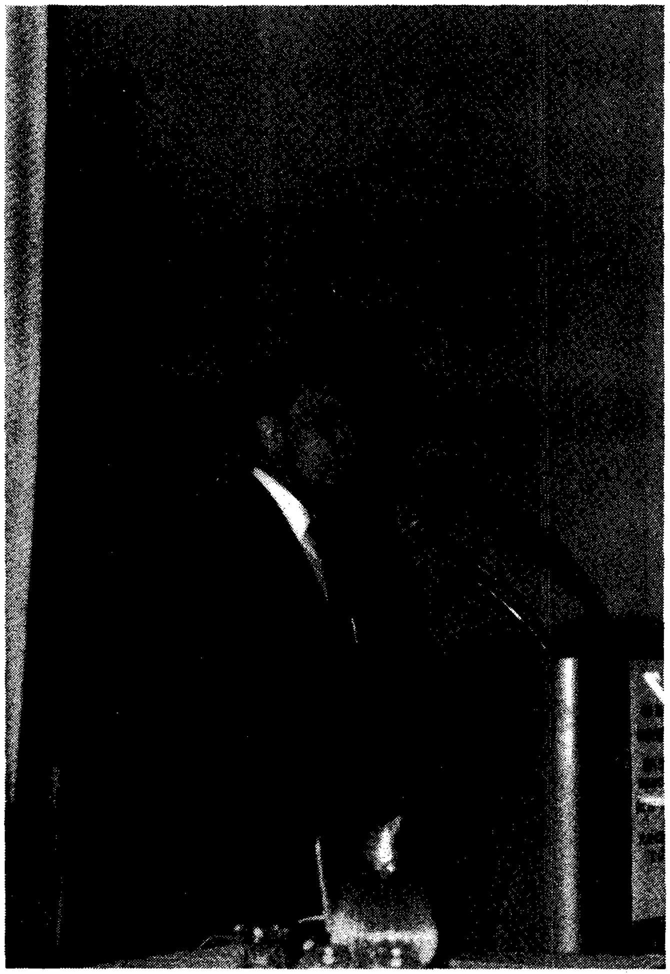
The oscillator stability for the Loran-C timing reference has always been specified to very tight tolerances because the necessary software processes for acquisition, phase locking, and TD correction had not been developed to adjust for the offsets. Although the TD correction is not difficult, a one-GRI acquisition and a sophisticated adaptive phase lock loop is required to tolerate an "instability" to +/- 25 ppm over the operating temperature range with no degradation of specifications in low-priced sets. Adding a rudimentary temperature measurement capability to predict the oscillator offset can extend the range even further without a loss in acquisition and phase lock.

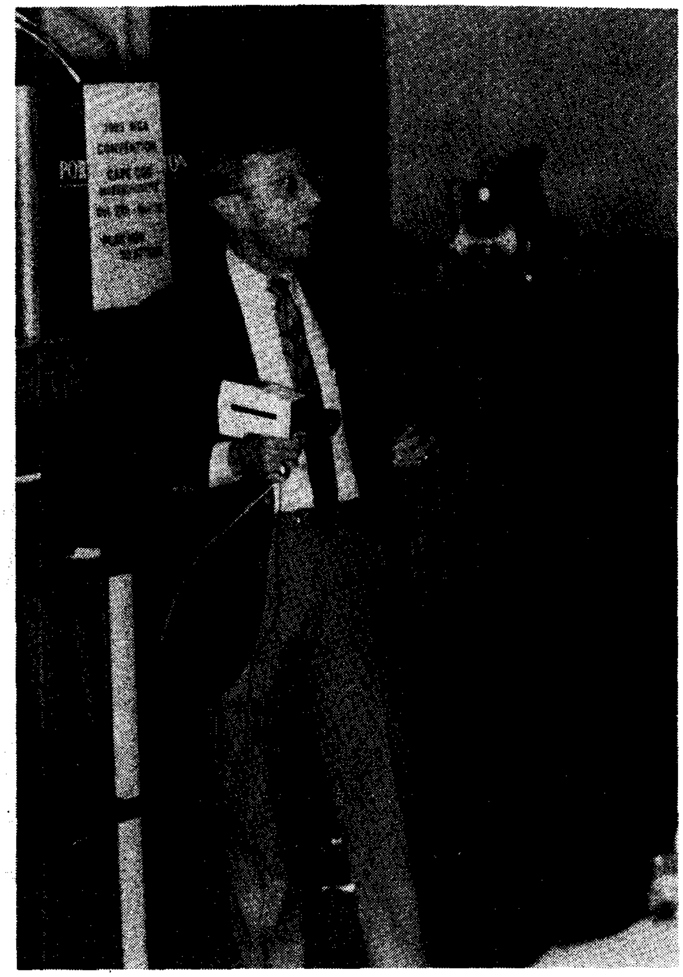
Reference 1. "Single-Chip Loran-C Transducer" Jesse Pipkin, Wild Goose Association Technical Symposium, October, 1988.

Reference 2. "Design of Phase-Locked Loop Circuits" Howard M. Berlin, Blacksburg Continuing Education Series

JESSE PIPKIN

Jesse Pipkin is a real-time signal processing specialist. His introduction to Loran (A) was in the United States Air Force where he served as a Navigator and used loran during hun.
His introduction to Loran (A) was in the United States Air Force where he served as a Navigator and used loran during hundreds of trans-Atlantic and trans-Pacific flights. He has been involved in Loran-C equipment design for the last ten years, concentrating the last three on his "Single-Chip Loran-C Transducer" (Wild Goose Association Technical Symposium, October, 1986). He received the BSEE from the University of Florida and did graduate electronic design work at the University of California, Berkeley. His designs are used by more than a dozen companies involved in both marine and avionics applications.

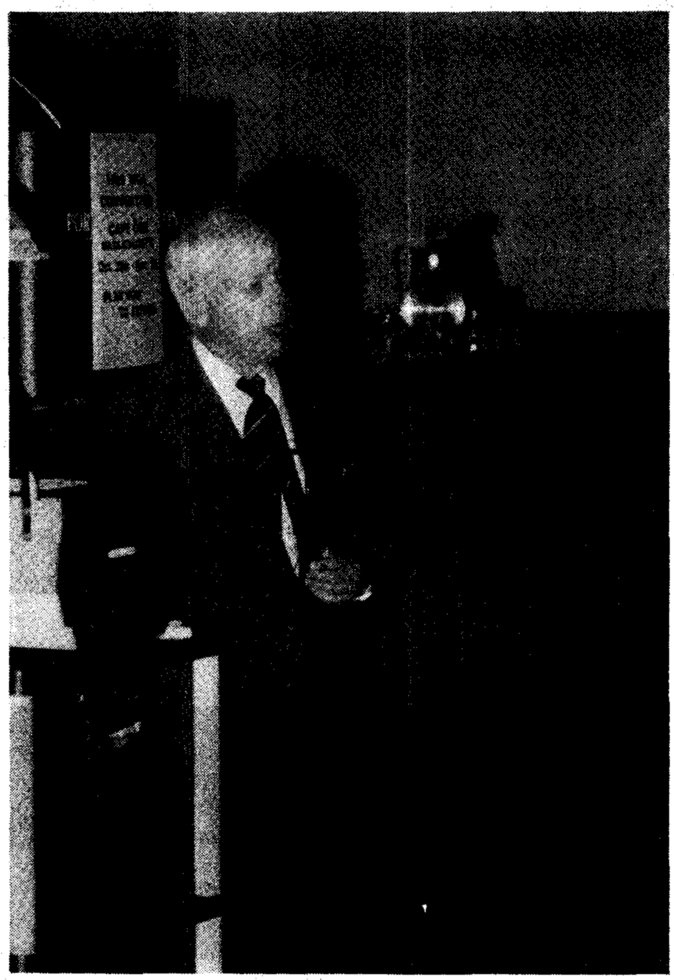




SESSION 6

LORAN AND GPS INTEROPERABILITY

MAJ William Polhemus (USAF Retd.)
Polhemus Associates Inc.



NAVIGATION SYSTEMS INTEROPERABILITY

Bradford W. Parkinson

Stanford University

October 26, 1988

OUTLINE:

- Define Interoperability
- Potential Benefit Areas for POS/NAV Users
- Matrix of Combinations
- Interesting Combinations
- Some Conclusions -- Where are We Going...

  Should We Go?

POS/NAV Interoperability

" Use of Two Or More Systems

to Provide Complementary Capabilities

with Enhanced User Benefits."

or:

" Use of Two or More Systems

to Provide Symbiotic (Cooperative) Capabilities

with Enhanced User Benefits."

Potential Benefit Areas:

COVERAGE:

-- Geographic
-- Daily Time
-- Evolutionary Time
(Improvements with Time)

ACCURACY:

-- Position
- Absolute/Relative
- 2D/3D

-- Velocity (Absolute)
- Low Dynamic
- High Dynamic

RELIABILITY

-- OUTAGES
- Probability
- Notification

COST

FOR 1991 L = Local N = Not Deployed *** Exc (3 met) ** Good (30 met) * Fair (300 met) - Deficient	COVERAGE			DYNAMIC ACCURACY						RELIABILITY				
				POSITION				VEL		Outages		Degrad		
	GEOGRAPHIC	DAILY TIME	EVOLUTIONARY TIME	ABS	REL	2D	3D	L.DYN.	H.DYN.	PROB.	NOTIF.	PROB.	NOTIF.	CO
DIFF GPS	- L/ND	++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	++
DOP RADAR	+++	+++	+++	+	++	++	-	++	++	++	+++	++	+	+
GPS	+++	++(+)	+++	+ (+)	++ (+)	++	++	+++	+++	+++	++	++	++	+++
INS (After 1 hr/)	+++	+++	+++	+	++	++	-	++	++	++	-	++	-	-
LORAN	++	+++	+++	+	++	+	-	+	-	+++	++	+++	++	+++
MLS / ILS	+ L	+++	+++	++ +	++ +	++ +	++ +	+	+	++ +	++ +	++ +	+++	++/ +++
OMEGA	+++	+++	+?	+	+	+	-	-	-	++	++	+	++	+++
TRANSIT	+++	+	-	+	+	+	-	-	-	+	-	++	-	++
VOR / DME	+ L	+++	+++	+	+	+	-	-	-	+++	+++	+++	+++	+++

QUALITATIVE VALUE OF INTEROPERABILITY	DIFF GPS	DOP RADAR	GPS	INS (After 1 hr/)	LORAN	MLS / ILS	OMEGA	TRANSIT	VOR / DME
DIFF. GPS									
DOP. RADAR									
GPS	+++ Natural	++							
INS (After 1 hr/)	+++	+	+++						
LORAN	+++		+++	+	+++ X Chain				
MLS / ILS		+		++	++				
OMEGA				++ Ocean		+			
TRANSIT							+		
VOR / DME		+		++	++	++	+		

ꞁOR 1991

= Local

= Not
ꞁployed

*** Exc (3 met)
** Good (30 met)
* Fair (300 met)
- Deficient

	COVERAGE			DYNAMIC ACCURACY						RELIABILITY				
				POSITION				VEL		Outages		Degrad		
	GEOGRAPHIC	DAILY TIME	EVOLUTIONARY TIME	ABS	REL	2D	3D	L.DYN.	H.DYN.	PROB.	NOTIF.	PROB.	NOTIF.	COST
ꞁPS	+++	++(+)	+++	+ (+)	++ (+)	++	++	+++	+++	+++	++	++	++	+++
NS (After 1 hr/)	+++	+++	+++	+	++	++	-	++	++	++	-	++	-	-

GPS / INS

GPS Can Provide

-- 10 Meter Accuracy Usually
-- Bounding of INS Drifts
-- Calibration for INS Parameters
(Gyro Drift/Accelerometer Bias, etc.)
-- Integrity Checking of INS (KAL 007)

INS Can Provide

-- Velocity Aiding for GPS Tracking Loops
-- Inertial Flywheel if GPS is Jammed
-- Coverage for Outages
-- Integrity Checking

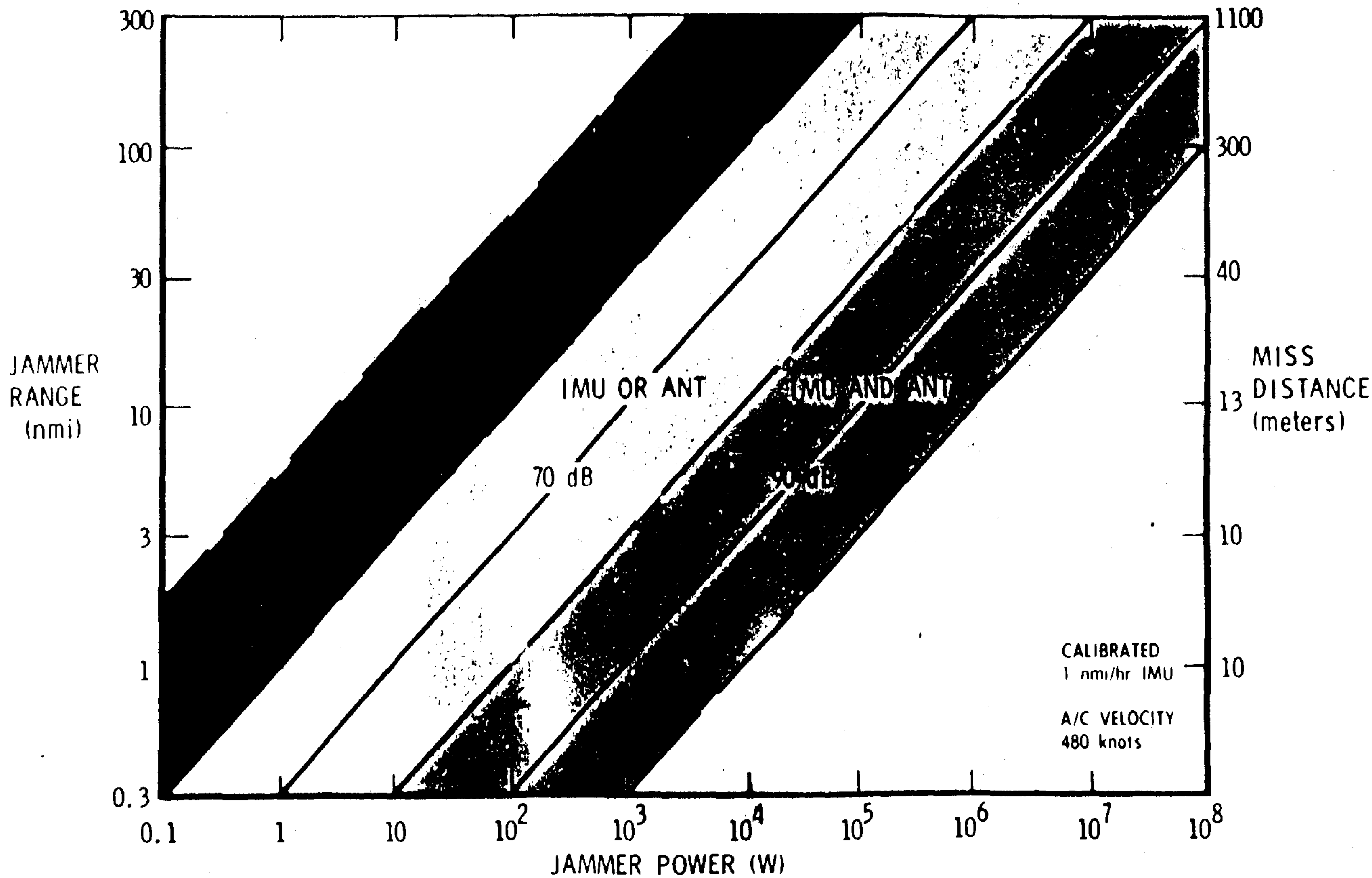
Common Systems Cost Savings

-- Cheaper INS Components (Strap Down)
-- Sharing of Sub-systems

- Clock
- Computer
- Control Display

10/88nvtc

GPS ECCM


300
100
30
10
3
1
0.3
JAMMER
RANGE
(nmi)
1100
300
40
13
10
10
MISS
DISTANCE
(meters)
IMU OR ANT
IMU AND ANT
70 dB
90 dB
CALIBRATED
1 nmi/hr IMU
A/C VELOCITY
480 knots
0.1
1
10
10^2
10^3
10^4
10^5
10^6
10^7
10^8
JAMMER POWER (W)

FOR 1991 L = Local N = Not Deployed *** Exc (3 met) ** Good (30 met) * Fair (300 met) - Deficient	COVERAGE			DYNAMIC ACCURACY						RELIABILITY				
				POSITION				VEL		Outages		Degrad		
	GEOGRAPHIC	DAILY TIME	EVOLUTIONARY TIME	ABS	REL	2D	3D	L.DYN.	H.DYN.	PROB.	NOTIF.	PROB.	NOTIF.	COST
GPS	+++	++(+)	+++	+ (+)	++ (+)	++	++	+++	+++	+++	++	++	++	+++
LORAN	++	+++	+++	+	++	+	-	+	-	+++	++	+++	++	+++

LORAN / GPS

GPS Can Provide

- Master Station Synchronization
- Periodic Accurate Coverage
- Precise Velocity
- Airborne Calibrations of LORAN (ASF)
- Ocean Area Coverage

LORAN Can Provide

- Early, Wide-Area Continuous Coverage
- Integrity Checking for GPS (Receiver Autonomous)
- Failure Backup

Synchronized LORAN / GPS Provides

- Additional Ranging Signals / Smart Filter Accuracy
- Control/Display Cost Savings

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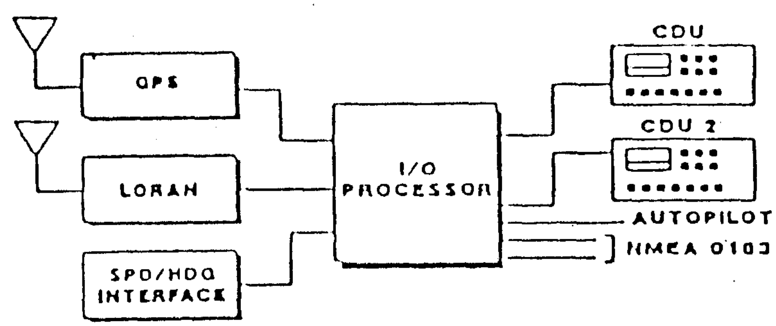
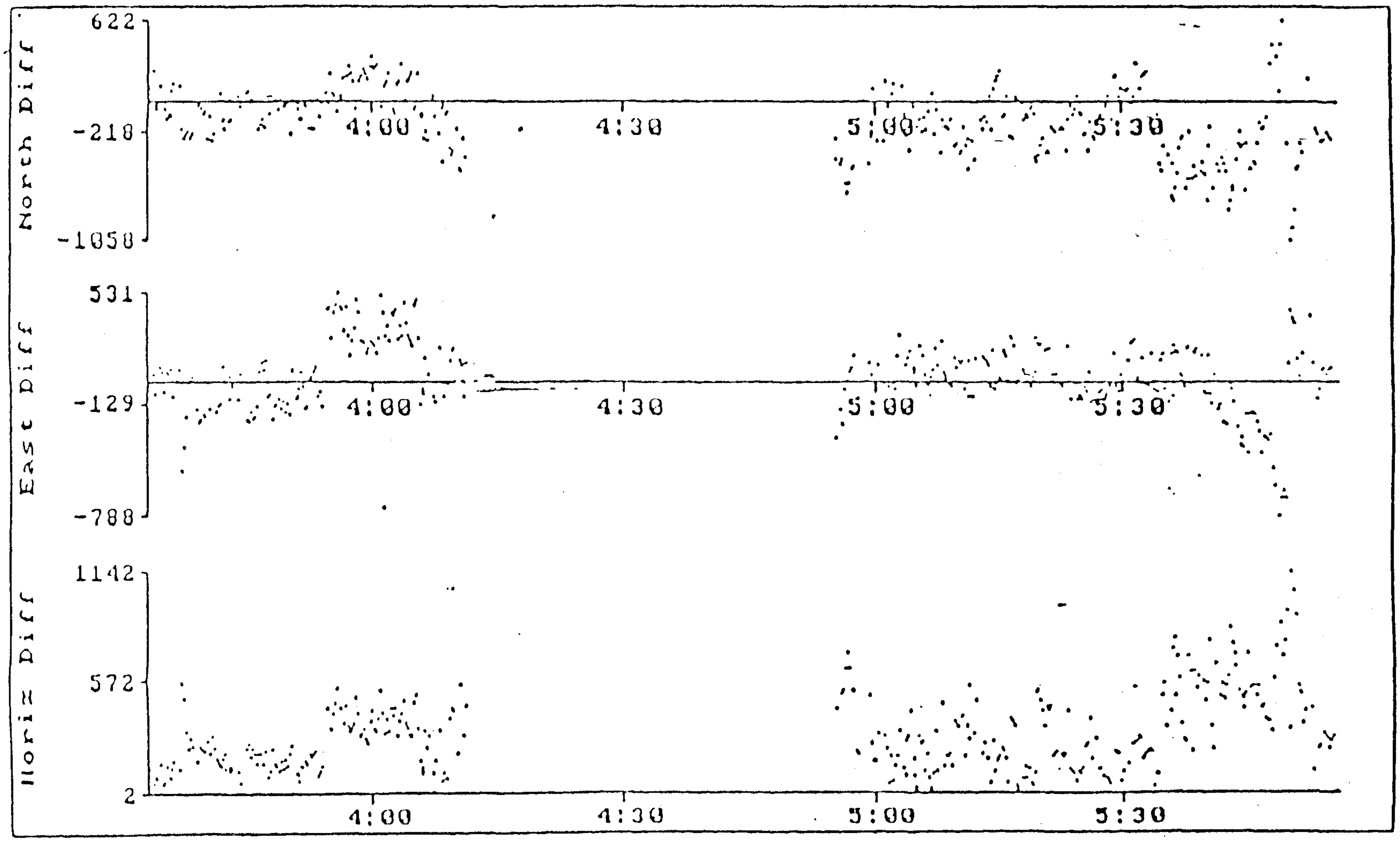
10X Block Diagram



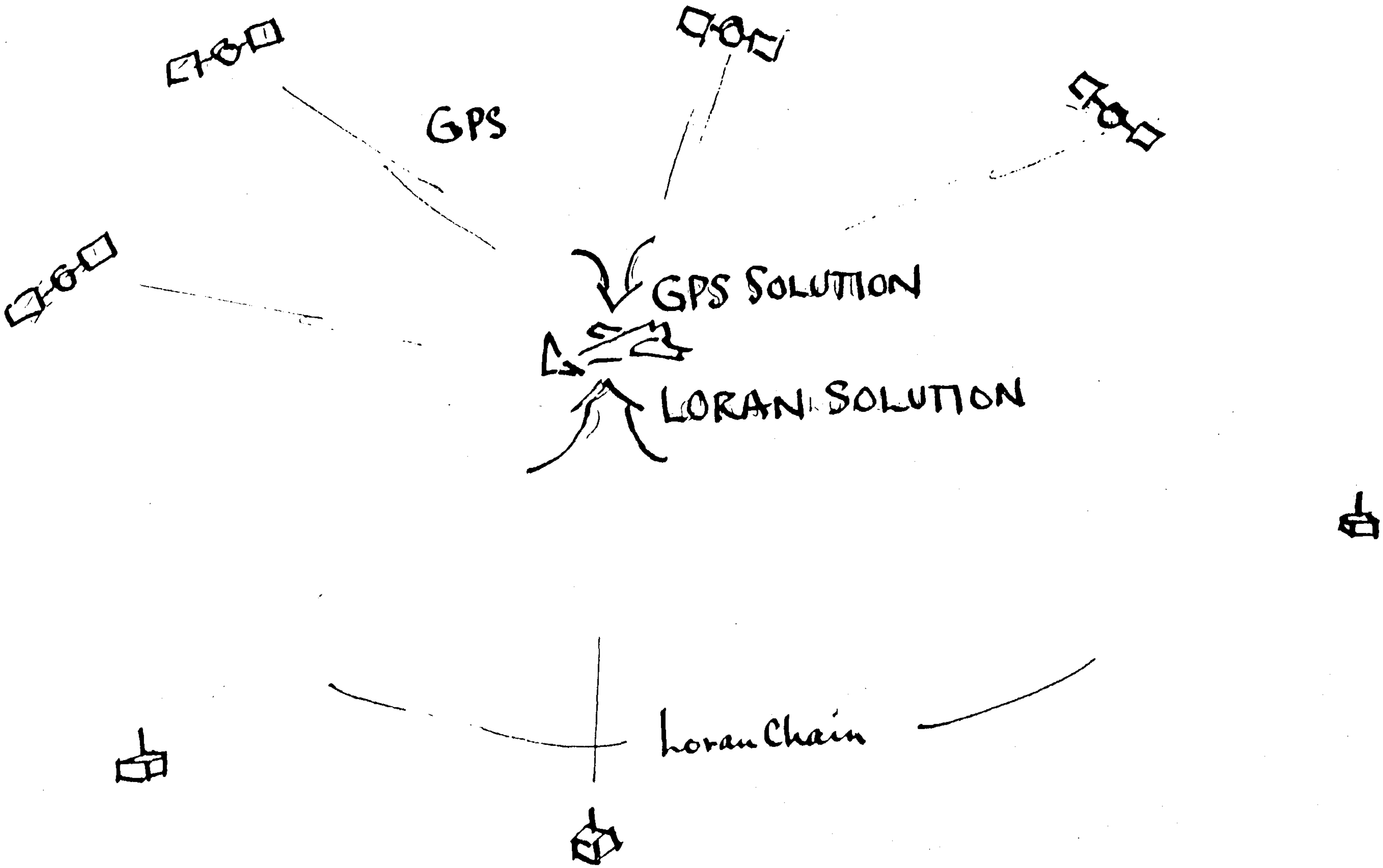


Loran/GPS Difference on a Trip from San Francisco to San Diego

GPS INTEGRITY

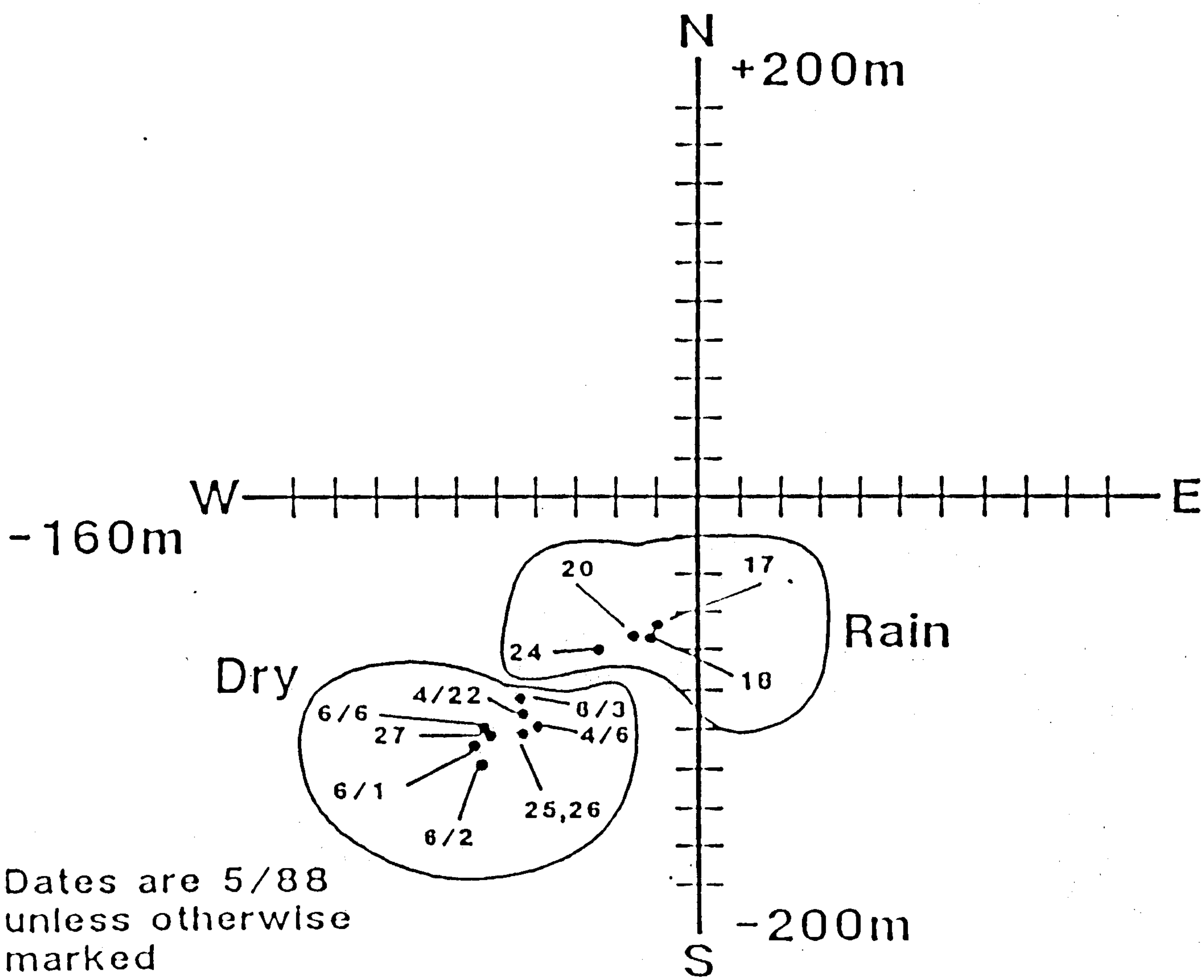
- **National Notification**
  (The Integrity Channel / GIC)

- **Receiver Autonomous Integrity Monitoring**
  (RAIM)



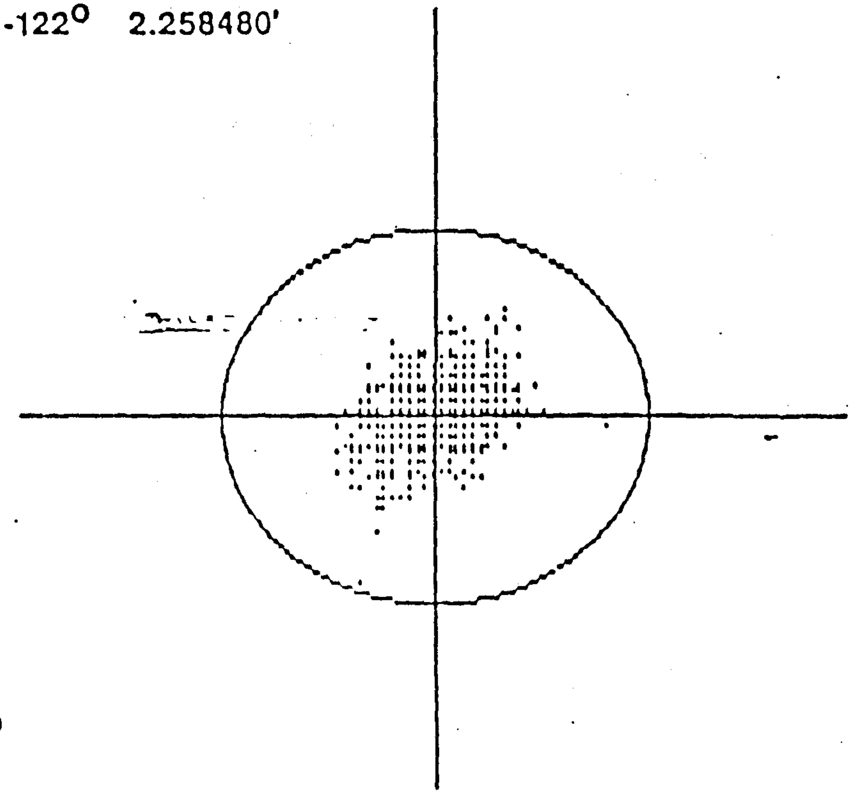
SYSTEM CONCEPT #1

ASF Corrections over 1 month



Center at: Latitude 37° 23.567986'

Longitude -122° 2.258480'



Datum: WGS 84

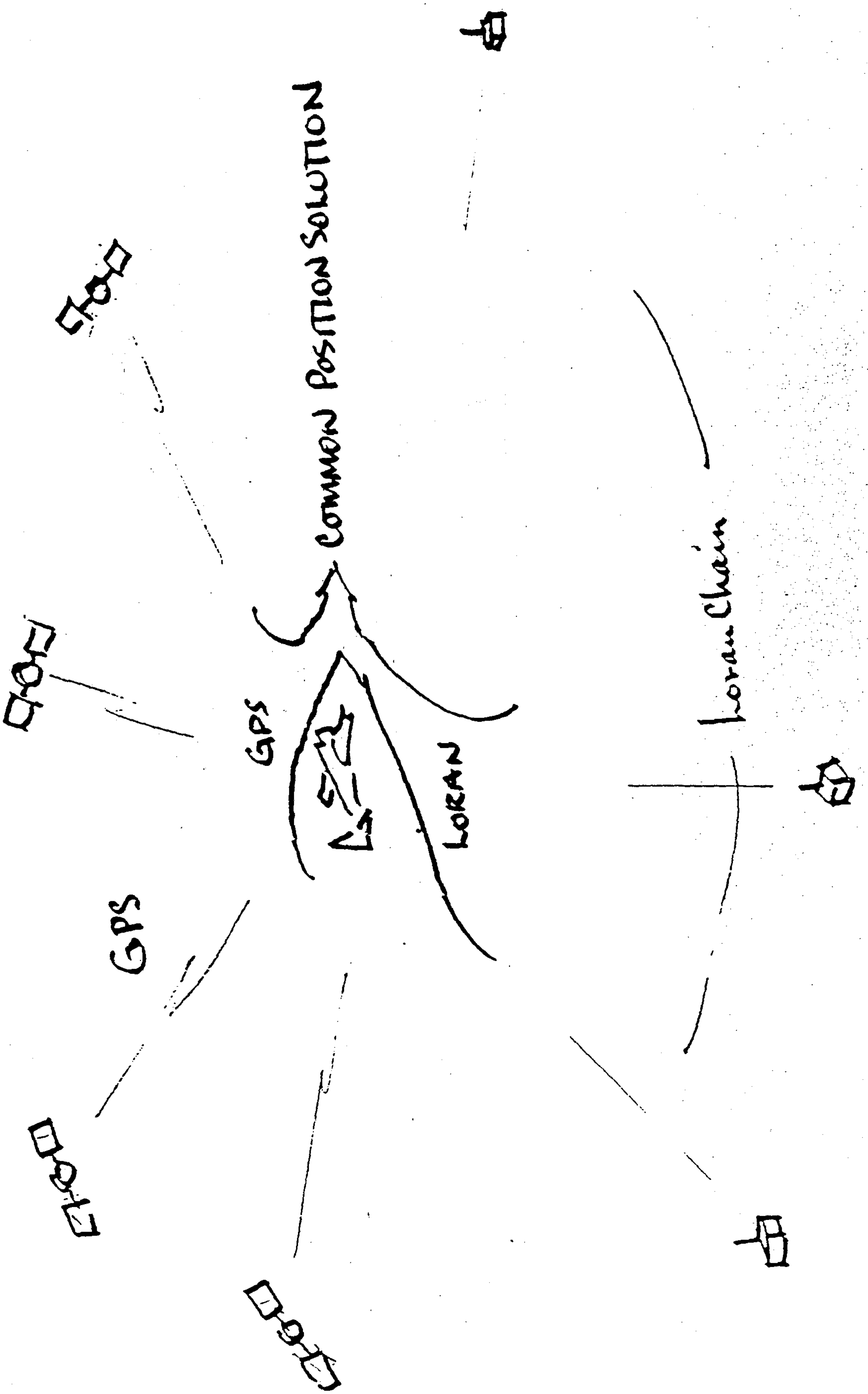
File: 0423gps.cap

RMS Distance: 7.15m

Center to Mean: 2.03m

Radius of Circle: 40.0m

Three Days of GPS and GPS Corrected Loran



SYSTEM CONCEPT #2

$$
\begin{bmatrix}
\bar{e}_{1S}^{T} & 1 & \emptyset \\
\bar{e}_{2S}^{T} & 1 & 0 \\
 & \vdots & \\
\bar{e}_{1L}^{T} & 0 & 1 \\
 & \vdots &
\end{bmatrix}
\begin{bmatrix}
\bar{R}_{u} \\ B_{uS} \\ B_{uL}
\end{bmatrix}
=
\begin{bmatrix}
\boxed{\bar{e}_{1S}^{T} \mid 1} & & & \emptyset & \\
 & \boxed{\bar{e}_{2S}^{T} \mid 1} & & & \\
 & & \ddots & & \\
 & \emptyset & & \boxed{\bar{e}_{1L}^{T} \mid 1} & \\
 & & & & \ddots
\end{bmatrix}
\cdot
\begin{bmatrix}
\bar{R}_{1S} \\ B_{1S} \\ \bar{R}_{2S} \\ B_{2S} \\ \vdots \\ \bar{R}_{1L} \\ B_{1L} \\ \vdots
\end{bmatrix}
-
\begin{bmatrix}
\rho_{1S} \\ \rho_{2S} \\ \vdots \\ \\ \rho_{1L} \\ \vdots
\end{bmatrix}
+
\begin{bmatrix}
\nu_{1S} \\ \nu_{2S} \\ \vdots \\ \\ \nu_{1L} \\
\end{bmatrix}
$$

$$
\bar{\bar{G}} \cdot \bar{X} = \bar{\bar{A}} \cdot \bar{S} - \bar{\rho} + \bar{\nu}
$$

$$
E\left[\bar{\nu}\bar{\nu}^{T}\right] \triangleq \mathrm{Cov}(\bar{\nu}) =
\begin{bmatrix}
E(\nu_{1S}\nu_{1S}) \ldots & & E(\nu_{iS}\nu_{jL}) \\
 & E(\nu_{1L}\nu_{1L}) \ldots & \\
 & &
\end{bmatrix}
$$

This is assumed to be:
$$
= \begin{bmatrix}
\bar{\bar{I}}\sigma_S^2 & \bar{\bar{0}} \\
0 & \bar{\bar{I}}\sigma_L^2
\end{bmatrix}
$$

The Combined Measurements

$$\hat{X} = \left[G^T \operatorname{cov}^{-1}(v)\, G \right]^{-1} G^T \operatorname{cov}^{-1}(v) \left[\bar{\bar{A}} S - \bar{\rho} \right]$$

The Combined Solution

Caveats / Comments:

-- *Front End Calibrations* B_{us} / B_{ul}

-- *Integrity by Looking at Residuals*

-- *Stability of Intersystem Biases*

CONCLUSIONS:

-- LORAN / GPS Interoperability Very Desirable

- Accuracy
- Coverage
- Integrity

-- Further Measurements are Needed

-- Costs Can Potentially Be Reduced

- Control Display Unit
- Oscillator
- Navigation Computer

INTEGRATION AND INTEROPERABILITY

of

OMEGA, G.P.S. and LORAN - C.

Abstract:

The three radio navigation systems: Omega, G.P.S. and Loran -C should be thought of as a combined set of three integratable and interoperable radio navigation systems (i.e. three parts of a whole) in the future and not as three competing systems. Each system has its advantages and disadvantages. By making use of the advantages, it is possible to build a superior navigation system.

This paper is intended to be a discussion of such a system and of some of the interesting related data.

The views expressed here are those of the author and not necessarily those of Canadian Marconi Company.

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Integration and Interoperability

of

Omega, G.P.S., and Loran - C

Introduction

The only wide range radio navigation systems available today are Loran - C, Omega and in the future: G.P.S. Other systems such as the DECCA network (analogous to Loran-C) are highly localized and outside this discussion. In fact, of these only Omega and G.P.S. provide true world coverage, and G.P.S. is not quite here yet. I should like to also point out here that the views expressed are mine and not necessarily those of Canadian Marconi Company.

There are a number of real or potential G.P.S. systems, including the U.S.S.R. GLONASS system, the proposed GEOSTAR navigation system which can only be made worldwide if GEOSTAR expands its coverage to the whole globe, and the recently proposed INMARSAT navigation addition to the international communications satellite system that has been around for many years mainly for the marine community. It is now also being developed for airline use. Finally, we have the NAVSTAR G.P.S. which is the system being implemented by the U.S. Armed Forces for their own use, but which will also provide a less accurate signal accessible by civilian users. More of this later. For purposes of todays discussion, we shall only consider the NAVSTAR system since it is the only system for which actual information is available and for which manufacturers are actively designing and building equipment.

At present, system integration has been persued by the avionics manufacturers for very practical reasons, but system interoperation is still a very new field and experimental in nature. Never-the-less, the combination of integration and interoperation can provide some surprising benefits.

Integration

The larger world of aircraft navigation equipment users has developed a real and growing demand for multisensor systems. An example of such a system is the Canadian Marconi Company CMA - 900 Navigation Management System (Fig. 1.). Here we have a number of separate sensors, each providing an estimate of the aircraft position to a central computer which accepts some, rejects others on the basis of the phase of flight and the quality of signals. Some signals, such as DME or Loran-C or, at present and for some time, G.P.S., are relatively localized. Never-the-less, they can provide a considerable improvement on flight path accuracy over such systems as INS or OMEGA, which are the only truly world-wide navigation systems operationally available today.

I do not intend to deal with INS (Inertial Navigation Systems) here, other than to say they are very expensive, and commercial versions have an accuracy drift rate of typically two miles per hour. DME (Distance Measuring Equipment) offers accuracies of better than a tenth of a mile, but signal coverage is not generally available outside the U.S.A., Europe and the most heavily populated areas of the rest of the world. It is not suitable for trans-oceanic flying, but is usefull for updating Omega and INS system positions where available.

Omega has its own weaknesses, such as less than desireable signal coverage in some areas, notably in the area around Winnipeg (the infamous Winnipeg hole) over to Chicago and partly down the Mississippi Valley. Advances in Omega signal receivers and signal processing software, coupled with the use of the U.S. Navy VLF signals, have largely eliminated this difficulty. Other signal anomaly areas have been discovered, but are being successfully dealt with on an on-going basis by the manufacturers. Canadian Marconi Company maintains a computerized signal processing laboratory and a set of airborne signal recorders for this purpose.

Loran - C provides good accuracy where signals are good, but like the little girl with the curl in the middle of her forehead, when it is bad, it is very very bad. Unfortunately, it is also relatively expensive and it may be impossible to try to blanket the world with stations. Despite this, Loran - C signals can and do permit excellent navigation in the U.S. east, west and southern coasts and parts of Europe. As the U.S. mid-continent gap is closed the entire nation will be covered. Great, but only of marginal value to Africa or South America or China, or even northern Canada.

G.P.S. is the critical factor that can tie the three radio based systems into a cohesive total which is greater than the sum of its individual parts.

Combining the calculated position outputs of a number of sensors in a Kalman, least-mean-squares, or similar filter, even with some intelligent data selection, is still only integration: i.e. each sub-system is still essentially independent. Interoperablity can remarkeably improve navigation reliability. You can have integration without interoperability, but you can't have interoperability without integration.

Interoperability

Interoperability makes use of signals available in one sub system to improve on the reliability or accuracy companion system.

Omega/G.P.S.

Canadian Marconi has designed a G.P.S. sensor that can be plugged inside the CMA - 771 system. (Fig. 2). Another unit can be mounted beside the Omega RPU as in Figure One. Once the GPS receiver is installed for position calculations, it is fairly easy to pick the timing signal off the GPS data stream (Fig. 3) and use it to stabilize the Omega system internal clock. This is like having an atomic clock on board. As a result, in the absence of three Omega stations, a rho-rho type of navigation for a period of time becomes possible. Alternately, with three or more Omega stations, position accuracy is enhanced for up to 30 minutes, even if all G.P.S. signals disappear. In the event that full NAVSTAR satellite coverage is not available, due to poor area coverage such at the artic latitudes, or a satellite fails (Yes, it will happen!), the Omega can act as an integrator to prevent drastic dislocations in the flight track.

Figure 4A shows a typical three station hyperbolic Omega position fix. A recent development now adds to the interesting possibilities. The Omega station timing clocks have been synchronized to each other and to the G.P.S. satellites via the G.P.S time signals. As a result, it will be possible to develop a line of position from a combination of one Omega and one G.P.S. station. (Fig. 4B) This is an obvious advantage in the event of a paucity of signals from one or both systems. This is not to be confused with the simpler but less effective approach in which complete lines-of-position (LOP's) from each sub-system or sensor is combined with the LOP's of another sub-system sensor. This latter technique is presently in use by CMC and has proven to provide very smooth transitions from one mode of flight to another (i.e. trans oceanic Omega to continental DME.)

Loran-C and G.P.S.

By synchronizing the G.P.S. and Loran-C time clocks, master and slave stations in a chain as well as other chains can be used in conjunction with each other for greatly expanded coverage and signal reliability. The interoperability of Loran-C and G.P.S. is simular to that described for Omega. Of course with all three systems synchronized, LOP's could be generated using mixes of all three types of transmitted signals. (Fig. 5)

I'm sure that the details of Loran-C and G.P.S. integration and interoperability are covered in much greater detail by some of the other speakers today.

CMA-900

As mentioned earlier, the CMA-900 represents an ideal system in which Omega, G.P.S. and Loran-C can be integrated and made interoperable. A brief overview of this system may be of interest to attendees at this conference. Please remember, this

equipment is aimed at the larger corporate aircraft, commercial carrier and military markets, not the smaller single engine users, therefore flexibility and reliability are more important than extreme small size, weight and cost.

The CMA-900 represents the company's latest approach to the design of an airborne navigation management system using the application of state-of-the-art technologies for a break-through in size, weight, flexibility and reliability (Fig. 6) for this class of equipment. But, first allow me to digress by describing what we mean by a Navigation Management System or N.M.S., since similar functions are also performed by what we call a Flight Management and Control System or FMCS. There appears to be considerable confusion on this point. Basically a full FMCS automaticaly controls all the flight functions of an aircraft in three dimensions. That is, it provides for lateral and vertical navigation from one place to another. Lateral navigation is parallel to the earth's surface. Vertical navigation often includes the appropriate cruising altitude for maximum fuel economy, shortest flight time or simply a pre-defined altitude. In addition, it also controls the thrust of the engines through an electro-mechanical connection referred to as auto-throttle to vary the speed of the aircraft through the air. It also provides display of the take-off speeds for the pilot for the specific aircraft, i.e. V1, VR, V2.

An N.M.S. basically navigates in only the lateral dimension. Tell the system where you are, where you want to go, and it will automatically plot a course to get you there in the most direct manner; unless the operator inserts special considerations, such as deviations from this direct or great circle path called waypoints or parallel offsets or airways, etc. The N.M.S. differs from a standard airborne Omega system in that it optimally combines the inputs at any given time from one or more navigation sensors to provide a more accurate and reliable position calculation. It also selects among these sensors for the most appropriate type for a particular phase of the flight. For normal cruise, Omega/VLF would be appropriate; for landing and take-off, MLS or ILS and DME are more appropriate; for terminal area operation, DME is usually most appropriate. An N.M.S. also frequently provides specific range computation, that is a calculation of estimated range based on fuel flow and operator inserted values of fuel quantity.

A navigation management system is not specific to a particular airframe and engine configuration whereas an FMCS invariably is closely tied to the specific engine, airframe and flight characteristics of the particular aircraft type.

The CMA-900 was designed to span the requirements of a basic navigation system with only two or three sensors and only horizontal navigation: through the capabilities of a full N.M.S. as described above and with the potential power to develop into an FMCS in the future. This great range of capability with a low economic overhead is possible only through the extensive application of recent developments, such as semi-rigid printed circuit boards, surface mount components (Figure 6), and special design integrated circuit gate arrays. It is a modular expansion approach to the use of multiple sensors (Figure 7) coupled to a control and display terminal carefully engineered designed to simplify the operator's work load and minimize "heads-down time" in the cockpit. It also minimizes the on-going training of pilots, a serious problem with some of the more sophisticated systems on the market. (Particularly Flight Management and Control Systems).

More specifically, these technical advances have enabled Canadian Marconi to design a system that, although it is extremely small and light, is able to provide

- an extensive internal data base capable of storing up to 35,000 waypoints, flight plans, VOR's, flight data, etc., plus a
- comprehensive interface capability including provision for both digital and analog interfaces to control the operation of and display the outputs from multiple aircraft systems, including cockpit instrumentation, maintenance functions and the various navigation systems such as Omega/VLF, GPS, MLS, DME, IRS, Loran-C, etc. These functions are controlled by an
- advanced color graphic and alpha/numeric display (Fig. 8) capability in the control terminal. This is combined with high display readability and easy to use single function alpha/numeric and control keys plus software programmed/display linked "soft" keys. This "smart" control terminal (Multi-Function Control and Display Unit-MFCDU) is also capable of handling a significant number of interfaces to systems other than the CMA-900 NMU.

This capability of the MFCDU to directly interface with other systems, while not specific to today's discussion, is of interest because it potentially allows the system to be applied in a very unique way. If a "Flight Critical" sub-system such as a Microwave Landing System (MLS) is to be incorporated into the overall NMS package, it can be accomplished without the complexities involved in declaring the entire system to be "Flight Critical". An MLS, because of the extra reliability required during the crucial landing and take-off phases of 10

flight, has extra reliability and redundancy conditions imposed on it. In the CMA-900, the MLS sensor can be connected to the control and display unit(s) through one of its multi-function interface ports. Thus, only the terminal and the MLS need be considered "critical" to the landing and take-off process, considerably simplifying the installation and its operation, lowering the cost and weight and improving overall reliability.

The CMA-900 Navigation Management System sets a new standard for smaller size and flexible expandability while remaining light in weight: under 20 pounds for the basic system. It is the flexibility which can enable implementation of interoperability as well as integration.

Before concluding this paper, I feel it is appropriate to raise a few thoughts on GPS NAVSTAR that need resolution before it can become a really useful international navigation signal source. I have no axes to bear in this since my company designs and manufactures both Military P code and commercial C/A code receivers.

The GPS NAVSTAR system cost is extremely high. While it is currently funded by the U.S. Congress through the USAF, the "user shall pay" concept is still very much alive. A comparison of signal coverage (transmitter) costs by the U.S. Coast Guard indicates that

- G.P.S. costs about $30 per square mile

- Loran-C costs about $2 to $3 per square mile.

- Omega costs about 10 cents per square mile.

Who will eventually pay the bill? NAVSTAR satellites are also expected to be required replacement at a rate of three per year (at about $16M each) when the full constellation is in place due to failures. These failures also impact signal availability while the replacement is being manouvered into place.

Area coverage of the satellites should be better now that they will be boosted in higher orbits. However, the polar regions will still be poorly served. Crucial for many airlines in transpolar routes.

International acceptance of a system under the control of the U.S. military establishment is being seriously questioned. Recent events have indicated that the civil applications of NAVSTAR fall far down the list of priorities of the Pentagon.

As a result, approval of the GPS NAVSTAR as a "sole means" of navigation system is a long way off, if it ever does happen. Therefore, combining the use of its signals with Omega or Loran-C is most appropriate. By integrating the three sensors, the size and weight of the resultant package can be reduced. By further developing the interoperability of these systems, a more reliable and accurate system can be derived, even though the full acceptability of the G.P.S. NAVSTAR system (or its alternates) may be in question.

<u>Side Issues</u> -

Following are four side issues that may also be of interest.

. <u>Omega station saving</u> -

GPS will save money through use of the G.P.S. timing signals via receivers at each station. The Coast Guard up to now had to transport a special calibrated atomic clock time standard across the world to recalibrate each station on a regular basis. At a rate of one station per month: very expensive!

. <u>G.P.S. Accuracy</u>

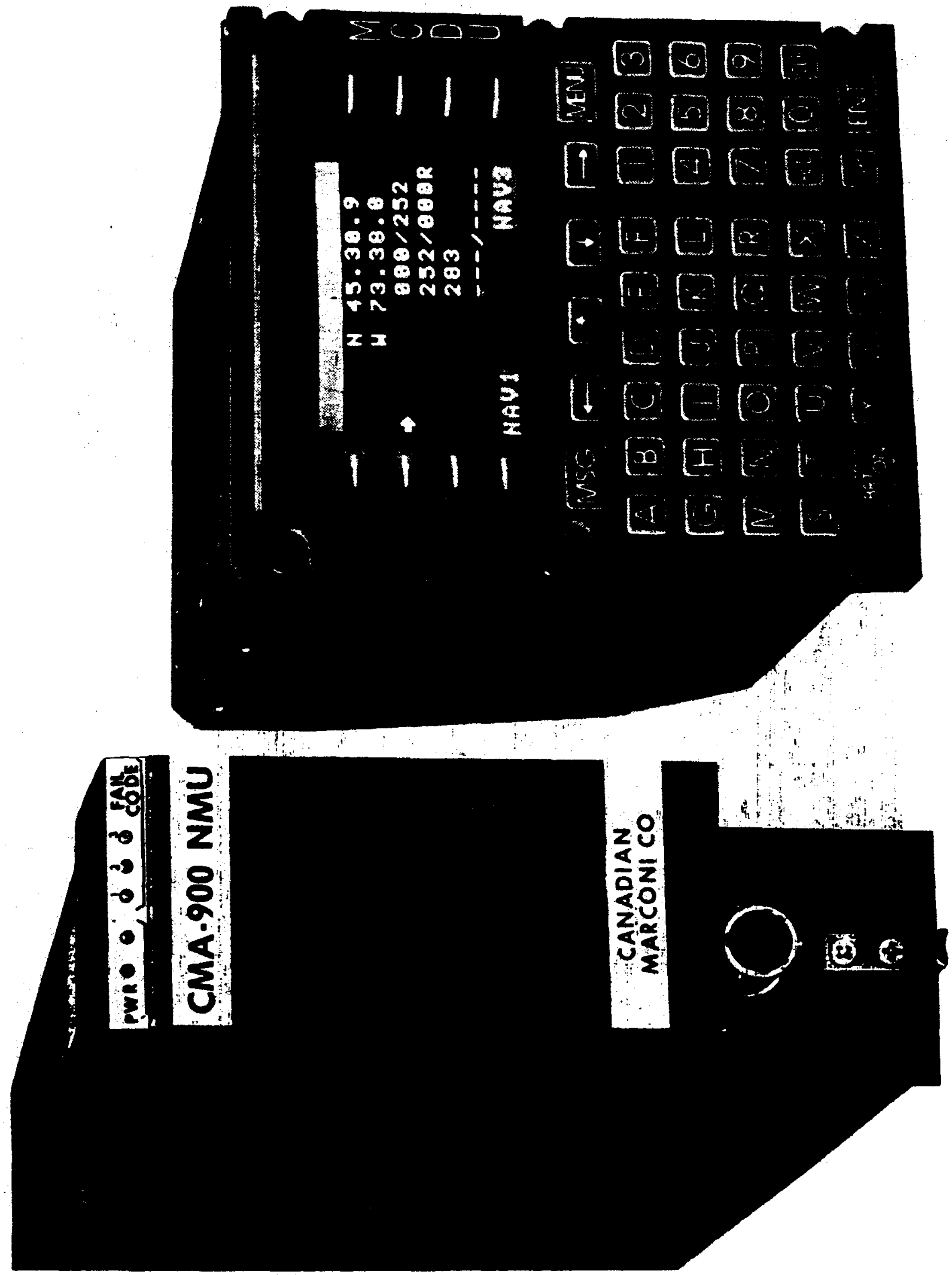
No doubt G.P.S.NAVSTAR is potentially a great navaid. C.M.C. experience shows 2D accuracy of <u>3 to 5</u> meters in a P-Code 5 channel receiver and 20-30 meters in a 2 channel C/A code signal receiver. The C\A code signal is to be degraded to allow only 100 meters accuracy when the full constellation is up- still very good!

. <u>Omega accuracy improvement</u> -

With G.P.S. timing signals to improve Omega Rx clock accuracy, navigation accuracy should be improved to 0.75 to 1.0 N. Miles instead of the present 1.5 to 2.0 N. Miles.

. <u>G.P.S. Military</u> -

G.P.S. signals are easy to block in times of conflict by relatively low power above user aircraft altitude levels. Omega is almost impossible to jam. (Ref. J. Saganowich, G. Litchford, Fort Monmouth).


CMA-900 NMU
PWR
FAIL CODE
CANADIAN
MARCONI CO
MCDU
N 45.30.9
W 73.30.0
NAV1
NAV3

and is a growing area which was not originally recognized as significant or important in the early days of vehicle tracking.

Category one deals with reducing response time by being able to dispatch the closest vehicle to a desired location. This obviously fits public safety from both a law enforcement as well as an emergency services aspect. It also tends to optimize the movements of a vehicle noted in category 2, thereby reducing the number of vehicles necessary to carry out any assigned workload. The primary underlying reason for police, fire and EMS to utilize vehicle tracking systems seems to be to reduce response time. Category one also fits a parcel pickup and delivery truck which is randomly routed at different times to pick up and deliver. A dispatcher who can graphically see in real time which truck is nearest to a newly designated pickup location can easily dispatch the appropriate vehicle, reduce response time and optimize each vehicle's operation.

Category two mainly attempts to optimize the use of the vehicle by knowing in advance its time of arrival at a predetermined location. This is the case of a cement truck, which itself is an extremely expensive vehicle and normally has a driver who is highly paid because of much overtime and usually favorable fringe benefits. For every minute the truck and driver are stopped and idle, the company is loosing money due to lost production. By closely scheduling loaded vehicles to arrive at a site at an exact time the operation of the vehicle and driver are obviously optimized. More important, by knowing in advance exactly when a truck is going to return to the plant for a new load, a new batch of concrete can be mixed in advance of the truck's arrival rather than waiting for the truck to arrive and then delaying the departure of the truck until the new batch is mixed and ready for loading. The movements of a long haul truck such as a loaded Moving Van can also be optimized by closely coordinating unloading services at each intermediate stop before its final destination. The more expensive the cost of the vehicle and driver, the greater the benefit to the company in optimizing the operation of the vehicle.

The third category obviously relates to mass transit where it is important to keep buses evenly spaced and on schedule on a predetermined route and then be able to add and remove buses as the number of riders changes throughout the day. The ability to maintain buses on schedule obviously results in increased ridership of the mass transit system with increased revenues to the transit company. Buses also fall partly into category two wherein the movements of the buses can be optimized by knowing their real time movements and being able to compensate for vehicle breakdowns or increased service requirements. The total number of buses necessary to carry out the operation can therefore be reduced to a minimum with a resultant reduction in capital equipment expenditures.

Finally, category four can relate to any of the previous categories when the number of vehicles becomes so large that attempting to direct, coordinate or monitor all their movements becomes an impossible task for the human mind, especially when the vehicles cannot be broken up into separate geographic areas. When a call for service is received for Police, Fire or EMS, the CAD which vehicles are appropriate to meet the call for service; ie, Police, Fire or EMS. Next the CAD determines which of these vehicles are closest taking into account one way streets, highways with limited access, median divider strips which may prevent a west bound vehcle from responding to an east bound call, and dead end streets which do not go through. Next the CAD determines the status of the closest appropriate vehicles; ie, is the driver of the vehicle on a coffee break, is the police officer out of the vehicle on traffic duty, is the vehicle temporarily out of service for repairs, etc. Next the CAD examines the suitability of resources on the vehicle to meet the call for service; ie, is the fire vehicle a Pumper when a Hook and Ladder is required, does the EMS vehicle have the particular type of medical equipment to treat cardiac arrest, etc. And finally after all this analysis of resources the CAD recommends to the dispatcher a vehicle to assign. This resource analysis closely describes the City of Detroit AVL Project where the city will direct and optimize the deployment and movement of about 760 Police, Fire and EMS vehicles. This type of system also lends itself to the data storage and archiving necessary for statistical record keeping mentioned above and Detroit is availing itself of this type of capability.

ADVANCEMENTS IN THE TOTAL LORAN-C SYSTEM

Loran-C is a mature but expanding system having been in place for some 30 years while there still continues to be an increase in the number of stations world wide as well as domestically. Loran-C is the least expensive electronic earth referenced navigation systems to operate and maintain, and has come a long way since the earlier days when Loran-A was considered the "poor man's electronic navigation system." None the less industry and other users are continuing to place continuing demands for improvement on our existing Loran-C system; (1) Increased accuracy, (2) Increased coverage, (3) Increased availability, (4) Increased reliability, and (4) Decreased cost to the user. With regard to vehicle tracking applications all of the above requirements are being met in varying degrees.

Looking first at position accuracy for vehicle tracking purposes, many users are demanding some form of differential correction to improve on the inherent errors present in the predictable mode. The City of Detroit Project is an example of such a requirement where an initial survey indicated that a 300 ft accuracy over 95% of the area could easily be met with a simple differential correction being applied to all reported vehicle positions in the Host Computer at the fixed end. Increased accuracy is also being addressed by manufacturers as a result of the proposed closing of the Mid-Continent Gap. With the availability of redundant chains in many areas, the use of Dual Chain tracking will find increased application over a large portion of the continental U.S. and this type of receiver is already being found on more and more manufacturers' drawing boards. With the increase in the number of redundant Secondaries available, an inexpensive Cross Chain tracking receiver can create pseudo Base Lines between Secondaries of different chains and greatly improve geometry in many areas. This Cross Chain tracking is only available in the inexpensive receiver if both Masters can be received or if the error in the Time of Coincidence (TOC) between the two Masters can be determined in some manner. The necessity to be able to receive both Masters obviously limits the areas where Cross Chain tracking is presently available in the inexpensive receiver. The U.S. Coast Guard at this time appears to be investigating more seriously the possibility of synchronizing the Master Stations of all Chains in some manner which would in affect eliminate the error in the TOC between the Masters and make an inexpensive Cross Chain tracking receiver (determination of any TD with only one Master signal available) a near term reality. While much of the pressure to synchronize Masters is coming from the aviation community, its implementation will also greatly improve the accuracy of positions in vehicle tracking. With the establishment of the North and South Central U.S. Chains and their eight (8) new base lines, as well as the possibility of greatly increasing the number of pseudo base lines in the foreseeable future through Cross Chain tracking, the accuracy of Loran-C will improve greatly over what is available even today in many areas. The addition of Dead Reckoning to enhance Loran-C may further improve the accuracy by as much as two fold in many areas and applications.

With regard to increased coverage within the limits of the continental U.S., the previous discussion of the closing of the Mid-Continent Gap should prove adequate for purposes of vehicle tracking at least in the near to mid term.

The question of improvements in Availability and Reliability can be handled together to some degree for purposes of this discussion. Both availability and reliability of Loran-C have been very high and have achieved a degree that probably cannot be improved appreciably at an acceptable cost. For purposes of vehicle tracking, the only complaint from industry relates to the individual station down time, either scheduled or emergency. In areas with a limited number of stations combined with poor signals and/or poor geometry, the loss of any single station, especially the Master, can be a serious obstacle to the satisfactory operation of the tracking system. This one shortcoming can at least be partially overcome through a redundancy of chains and/or secondary stations when operating with a Dual Chain or a Cross Chain type of receiver and multiple LOP fixes. As these new type receivers become more common in the market place, the question of Availability and Reliability becomes less critical.

The final question with regard to required improvements to the Loran-C system demanded by industry relates to decreased cost of mobile and fixed end equipment. As with so many other high-tech components and pieces of equipment, the price of chips has rapidly decreased and an ever increasing number of specialized chips are becoming available everyday. In a way this presents one of the most complex questions facing any manufacturer of Loran-C receivers used for vehicle tracking. If developed today, how long will it be before a specific Loran-C receiver becomes obsolete in the market place, and can a reasonable profit be realized in the mean time. The application of vehicle tracking is still in its infancy and with new applications "being dreamed up every day" there should be a sufficient market for new products to be developed in quantity at a reduced cost to be competitive in the market place. Conventional forms of vehicle tracking will feel the major impact of reduced cost of mobile-end Loran-C receivers first with more specialized or unique applications feeling less reduction in hardware cost for the mobile-end. Another factor which is acting to reduce the overall cost of vehicle tracking is the availability of low-cost computers. This means that industry has the ability to purchase a very competitively priced computer to meet his fixed-end needs for a graphic or static display of information and then purchase only the necessary software and high resolution monitor from a vehicle tracking system manufacturer. In the past two years alone II Morrow has seen a dramatic trend in the reduction in the hardware in the fixed-end coupled with a greatly increased capability and flexibility of operations through software development at the dispatch station. All at a considerable cost savings to the user over what such a system would have cost just a few years ago. Once again the City of Detroit Project is a classic example of a greatly enhanced operational capability of vehicle tracking through software development.

DEVELOPMENT OF INTEGRATED NAVIGATION SYSTEMS

II Morrow has been working on an integrated navigation system that incorporates various sensors with a Loran receiver. This Research and Development effort has resulted in better than expected results and serves as a stepping stone for further work in this area.

The majority of customers for the Vehicle Tracking System operate in urban environments which can cause problems for Loran only operation as discussed in the PLC section of this paper. In addition things like narrow streets between tall buildings, tunnels, railroad tracks, bridges, poor geometry and weak signals will all have varying effects on the Loran reception which will affect the position accuracy.

One approach to correcting for the adverse effects of these factors is to apply filtering techniques to limit their

influence. Another approach is to integrate a navigation device with good short term stability with long term Loran stability. Thus the use of Dead Reckoning (DR) to complement Loran should provide an improvement in poor signal areas. The Dead Reckoning system consists of an inexpensive, a two dimensional flux-gate compass and a pulse generating speed sensor. Basically, a processor reads the compass and speed sensor along with the Loran receiver. This information is feed to an adaptive algorithm to produce an improved position solution.
The heart of this integrated navigation system is an algorithm that monitors various sensors and determines which to use as the primary navigation source and how reliable it is. The algorithm works basically in two modes: (1) Dead Reckoning alone, and (2) Combination Dead Reckoning and Loran. When the Loran is determined to be temporarily unusable, the system uses the compass and speed sensor for positioning and navigation. When Loran is determined to be satisfactory, the system combines position reported by Loran, magnetic heading and speed sensor and produces a position via a progressive and adaptive filter. Even when Loran is selected and could provide sole position data, combining Loran with DR provides greatly enhanced position tracking and accuracy.

One of the most important features in this integrated system or any similar systems is the ability to judge the integrity of the Loran operation. When Loran signals are blocked by large structures the signal strength and/or the signal-to-noise ratio can reliably be used as indicators. However it is not as straight forward in the case of PLC, multipath, or skywave contamination. In the latter instances, it has been observed that these signal indicators are only marginal in interpreting signal quality or integrity. Combining signal strength and signal-to-noise ratio with envelope cycle difference (ECD), time difference (TD) rate of change, and jitter can help to improve the chance of accurately determining Loran signal integrity.

Because this is an integrated navigation system, independent characteristics among component systems should be exploited by using one system (sensor) to check the others; in this case to use DR sensors to check Loran integrity or to use Loran data to monitor and correct DR sensors. For this particular mix of sensors - Loran and flux-gate compass - caution has to be taken since they both can be corrupted by the same interfering sources, (ie. steel bridge, etc.). After numerous simulations and road tests, the results have been very encouraging. Preliminary data has indicated obvious and substantial improvements in tracking and accuracy over systems that use only Loran. Improvements in the order of 25 to 60% improvement have been observed.

Integrated navigation research is continuing at II Morrow. The challenge is to design and produce integrated navigation systems with a cost/performance ratio that is acceptable to the customer. With the near term addition of new Loran chains and the recent emergence of promising sensor technologies, the next few years will be very important and busy for the integrated navigation field.

POWER LINE CARRIER (PLC) INTERFERENCE CONSIDERATIONS

While Loran-C is susceptible to several types of both synchronous and asynchronous interference, Power Line Communication (PLC) is unique to terrestrial vehicle tracking systems. (Note: PLC interference has also been reported by aircraft pilots but is rare in comparison with terrestrial Loran-C use.) Power Line Communications may be conducted anywhere in the 9 - 490 KHZ band, but are most commonly found on frequencies divisible by 10 (ie, 80, 90, 100 KHZ, etc.) with a particularly high concentration between 60 KHZ and 140 KHZ and an extremely dense concentration around 100 KHZ. Most transmissions are of the continuous wave (CW) type on one or two frequencies. They consist of a continuous pilot carrier in the range of 1 to 10 watts with a keyed command carrier in the range of 10 to 100 watts. The lower power continuous pilot carrier is partiuclarly bothersome while the command carrier which is used for power switching and control purposes is used infrequently, is of very short duration and does not cause permanent interference. PLC has been around for many yhears and much of the equipment still found in operation is of the "6L6 vintage!" PLC is utilized primarily on high voltage transmission lines and seldom found on low voltage utility distribution systems. Fortunately, the major utilities are switching to the more modern and reliable micro-wave form of communications for power switching and control. This means that PLC on the higher voltage, longer transmission lines is being phased out first with a more gradual replacement on the lower voltage, shorter transmission lines. The range of PLC interference is obviously dependent upon many factors but can affect Loran-C reception for several blocks. PLC interference is also aggravated by the fact that transmissions lines many times are also found to carry impulse noise which many originate from almost any source. PLC interference is particularly harmful to terrestrial vehicle tracking systems where a high voltage transmission line runs parallel to a road or highway and the vehicle is continuously subjected to the interference and loses the Loran signal completely until the vehicle moves out of the area of interference associated with the power line. Overhead trolley car and electric bus power lines also are a major source of RFI and in many cases cause the Loran-C receiver to loose signals when the vehicle is driven close to or below these overhead lines. The U.S. Coast Guard is aware of PLC and its potential effect on terrestrial (and to a lesser degree aviation) Loran signals, and is working with the North American Electric Reliability Council (NERC) to try and resolve the problem. Well documented cases of PLC interfering with Loran-C signals are invited by the U.S. Coast Guard, Marine Radio Policy Branch who is seeking to eliminate or reduce such interference under 47 CFR 90.63g.

OVERVIEW OF DETROIT AVL SYSTEM

A major contract was awarded earlier this year by the City of Detroit to II Morrow, Inc., of Salem, Oregon for the installation and implementation of a Vehicle Tracking System (VTS) in conjunction with a Mobile Data Terminal (MDT) network and a Computer Aided Dispatch (CAD) System. This is the most ambitious undertaking of its kind to date and incorporates many innovative features not previously found in other systems. II Morrow is the Prime Contractor for the Vehicle Tracking System portion of the contract and is assisted by Advanced Control Technology, Inc., of Albany, Oregon as a Subcontractor.

The Detroit Project is comprised of approximately 760 Police, Fire and EMS vehicles which serve the City of Detroit. The position of each vehicle is determined by a Mobile Loran Receiver installed in each car or truck which transmits this information back to the Base Dispatch where the data is processed through a Micro Vax Computer and then displayed on 6 Police, 2 Fire and 2 EMS Graphic Work Stations. An additional 14 terminals are available for Supervisor personnel as well as "Hot Spares" for back up. While the initial system will be brought on line with a digitized map of the City of Detroit developed by II Morrow, ultimate plans call for a Geo Base file to be developed to create a computer drawn Map which will have full capability to interface with the CAD. This will allow for a full E-911 LAT/LON cross reference to street address. At the Dispatch end the AVL Communications Radios, Polling System, Micro Vax Computers, CAD and MDT are all fully duplicated for redundancy and have a back-up system design for the rerouting of data between the CAD, Micro VAX Computers and MDT should one of them become inoperative.

Each City vehicle in the Detroit Project is equipped with three totally separate and independent radio communications systems; namely one dedicated to voice communications, one dedicated to MDT data communications and one dedicated to AVL data communications. The total communications load between the Base Dispatch and vehicles could not possibly be carried out on one radio channel and while these three independent radio communications systems are initially expensive they have several very important benefits: (1) They provide a degree of redundancy and back up should one radio system fail; (2) They allow for simultaneous communications with a vehicle at times of critical operations; (3) They prevent an overload on any one system such as the MDT from adversely reflecting this overload onto another system such as the AVL; (4) They prevent the mixing of voice and data communications on the same channel or radio system which at best is marginally acceptable and causes the loss of many data transmissions; and (5) They optimize each system by preventing collisions or other interference from occurring between different systems operating on the same radio channel. Additionally, these radio communications systems are operating on different bands which provides a limited degree of frequency diversity and insures that all communications will not be lost with a vehicle due to operating conditions or limitations unique to one particular band. In an effort to reduce the number of antennas installed on each vehicle the antenna required for the Loran Receiver (receiving at 100 KHZ) was duplexed with the AVL Radio Communications (transmitting and receiving at 158 MHZ) into a single 21 inch trunk mount whip antenna.

The Polling requirements for the Detroit Project are quite unique in that they combine several types of vehicle polling into one system; ie, Police, Fire and EMS. Operationally this spans the spectrum of polling pursuit Police vehicles as often as once every three (3) seconds with Fire Trucks that may be in a stand by readiness condition and polled only once every ten (10) minutes. Due to the total number of vehicles being polled, two communications channels were required. The AVL system continuously determines the polling load on each channel and automatically moves polled vehicles from one channel to the other to balance out the load between them.

Although the City of Detroit is fairly small geographically, three Remote Receivers are used on one AVL Communications Channel and four on the other. A modified Voting technique is used to validate the received data message from the Mobile Units as well as to insure that each Remote Receiver is operating normally. The operation of both fixed end Transmitters are also monitored by the Remote Receivers to verify normal operation of the transmitters. The Main Transmitter is automatically shifted to the Standby if the Polled signal is found to be missing, corrupted or weak. With this redundancy of Transmitters and Receivers, the City of Detroit is assured of continuous AVL Communications at all times.

The Detroit Project is drawing considerable attention from other municipalities who are carefully weighing the benefits of such a system in their own community.

CONCLUSIONS

As the monitoring and dispatching capabilities of Loran-C based vehicle tracking systems become recognized, large new markets are opening up in such industries as long haul trucking, hazardous waste tracking, ambulance fleets, taxi fleets, courier and parcel pickup and delivery service companies. Since II Morrow Inc. was acquired by United Parcel Service (UPS), considerable attention is being given to the latter applications by this company. Military uses of Loran-C based vehicle tracking systems include weapons and munitions material transportation, war games and selected tactical applications. The immense popularity of airborne Loran-C receivers and the expanding applications of terrestrial vehicle tracking have contributed to the building of the two new Mid-Continent Chains.

In Europe as well as in the UK, land navigation and location technologies are seriously being studied for traffic control and fleet management purposes with varying degrees of success. For the general motoring public, in-vehicle navigation/display systems are also being developed by most of the world's automobile manufacturers for introduction in the 1990 time frame. Systems are being developed using Dead Reckoning, Beacons or Sign Posts, Map Matching, VLF/OMEGA, Transit or GPS satellites, Loran-C, or various combinations of these systems. Of all these systems, a Loran-C based system provides the most cost effective, accurate, reliable and maintenance free system of all, and where greater accuracy is required enhancement of Loran-C with such items as Dead Reckoning flux gates and speed sensors still provide the least expensive system to the user.

BIOGRAPHICAL INFORMATION

Ransom K. Boyce is a retired U.S. Coast Guard Commander having graduated from the U.S. Coast Guard Academy in 1958 with a BS in Engineering. He spent the majority of his Coast Guard career in the Aids to Navigation Program where he acquired his background in the field of LORAN-C. He has been with II Morrow, Inc. two years and is the Engineering Program Manager for Aviation, Marine and Vehicle Tracking Loran Products.

LORAN-C OSCILLATOR REQUIREMENTS

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ABSTRACT

The precision oscillator used by modern Loran-C receivers for time reference is the most expensive component in many designs, and, as such, has come under pressure by low-cost equipment manufacturers looking for ways to reduce their bill of material costs. Since stability is related to price, it is worthwhile to analyze the requirements to insure that the oscillator is not overspecified.

The affects of absolute oscillator accuracy on the raw acquisition of the loran signals, the phase-locking, and the TD measurement are described; changes of frequency with voltage and temperature are considered; and, finally, an implementation is shown using an oscillator with a stability specification of +/-25 ppm over the temperature range of -10 to 55 degrees centigrade.

INTRODUCTION

Before the fall of the dollar, many U.S. manufacturers of Loran-C Receivers, feeling the pressure from lower-priced but good quality Japanese products, remained competitive by reducing their manufacturing costs. Considerable engineering went into converting hardware to software and utilizing more powerful microprocessors with built-in timers, input/output and control bits, serial communications, retentive memory, and even analog-to-digital converters, all of which eliminated external hardware. A good example of this is the Motorola MC68HC11 Microcomputer (Reference 1) currently used by eight U.S. manufacturers for their newest Loran-C products; this processor can be programmed to do all the digital functions of a low- to mid-cost Loran-C receiver, even including driving a display and a keyboard leaving no digital parts to eliminate. Future efforts to reduce costs

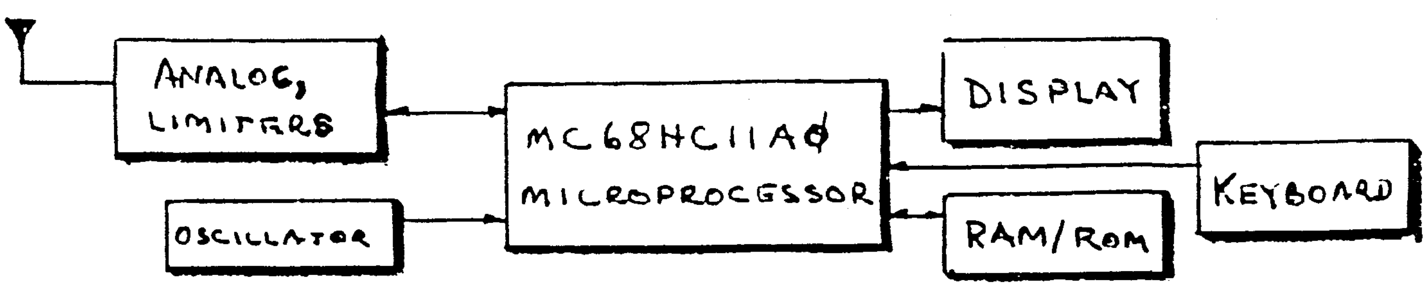


Figure 1. BLOCK DIAGRAM OF "SINGLE-CHIP" LORAN-C RECEIVER

must address the receiver's analog/filtering section, the display, packaging, or the precision oscillator. This paper explores the last possibility.

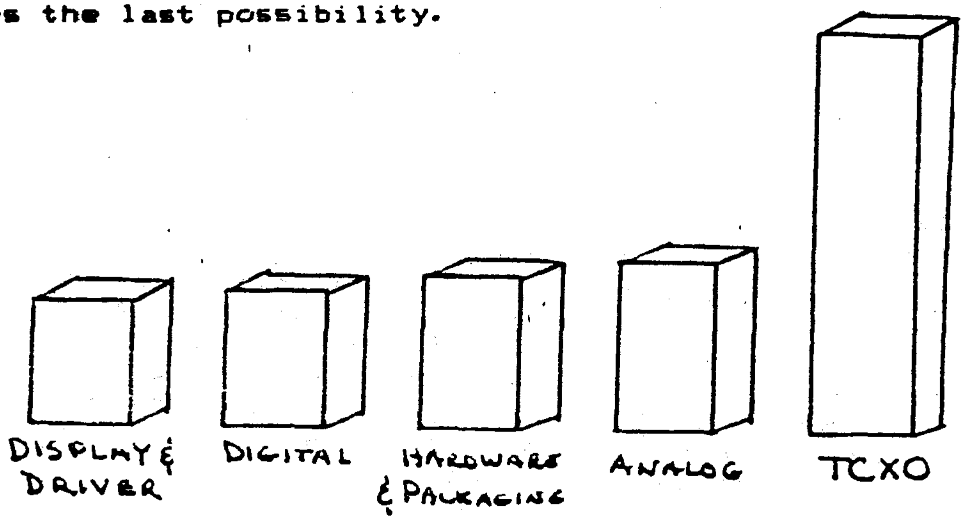


Figure 2. RELATIVE COSTS OF RECEIVER SECTIONS

THE OSCILLATOR PROBLEM

Ten years ago, precision oscillators with stabilities down to +/- 1 part per million over the range of -10 degrees centigrade to +55 degrees centigrade were common, with some even better. As prices for most components declined dramatically, the price of this oscillator looked grossly out of place in low-end

PART	COST	% OF BOM
Enclosure(s)	$ 6.00	6
Hardware	3.50	3.5
Connectors	2.00	2
PCB's	3.50	3.5
LCD	8.50	8.5
Display Driver	2.50	2.5
Keyboard	5.00	5
Microprocessor	7.50	7.5
RAM, ROM	4.50	4.5
Regulators	1.00	1
Power supply filter	5.00	5
Limiters	1.50	1.5
Analog components:		
75 capacitors	6.00	6
100 resistors	1.50	1.5
15 inductors	5.50	5.5
Transformers	4.00	4
10 transistors	2.50	2.5
Manual	2.00	2.0
Packaging	3.00	3.0
TCXO	25.00	25.0

Figure 3. HYPOTHETICAL $100.00 BILL OF MATERIAL RECEIVER

sets, and some manufacturers simply relaxed the requirements, using +/- 2 ppm and +/- 3 ppm oscillators over 0-50 degrees and, where possible, living with the consequences, thereby saving 50% of the oscillator cost. By the time they got to +/- 5 ppm, however, acquisition and phase lock became problems as well as the TD measurement error created just by temperature change. Investigating and solving these problems has led to the possibility of using much less expensive components: a +/- 25 ppm oscillator is one-tenth the cost of +/- 1 ppm. The next step, +/- 50 ppm, is the high end of off-the-shelf components (0.005%), the use of which would make the oscillator simply another part.

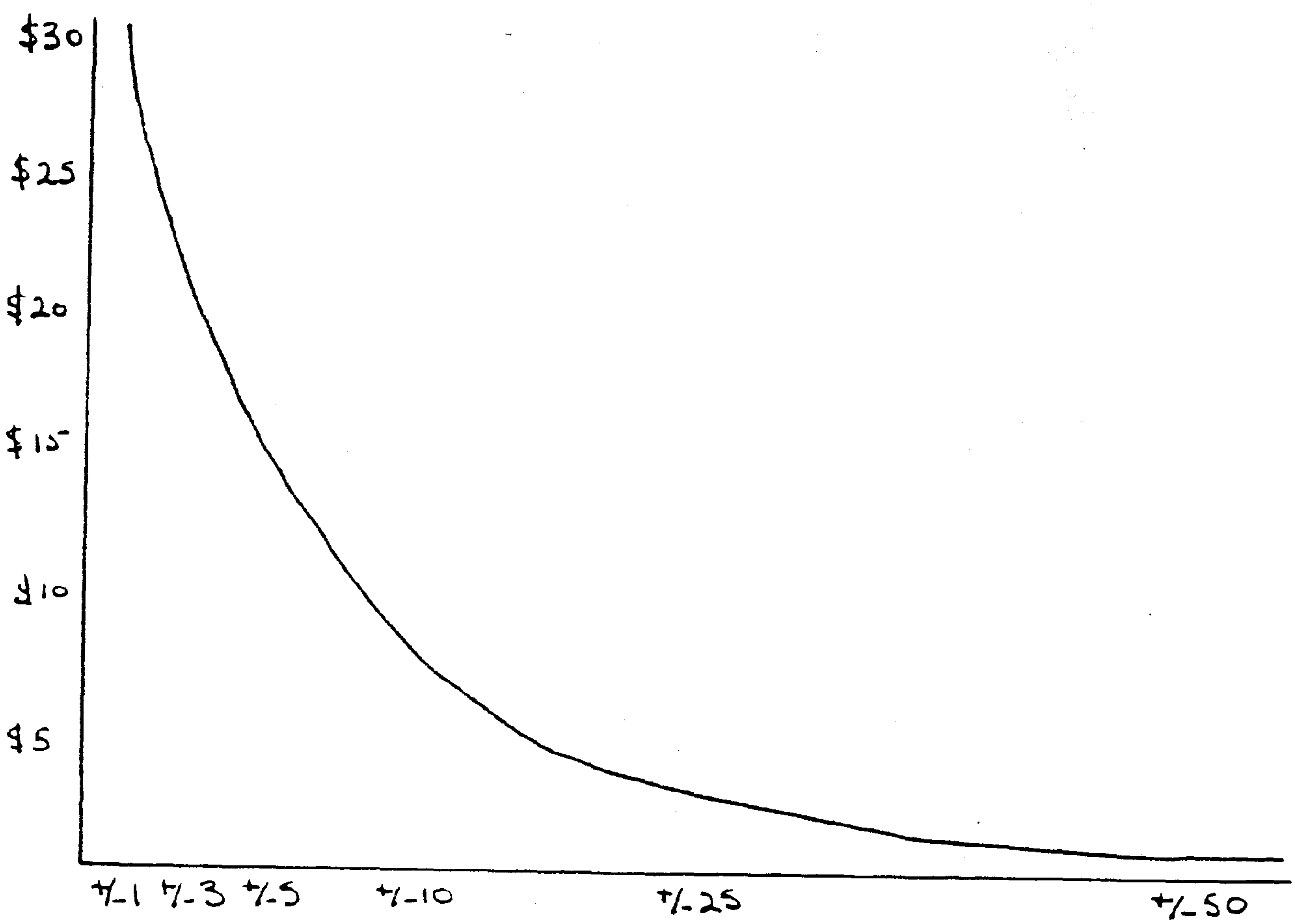


Figure 4. OSCILLATOR COST VS. STABILITY

STABILITY REQUIREMENTS

The actual frequency of the oscillator that provides the Loran-C with its timing reference is, within limits, unimportant; frequencies in use include 4 Mhz, 5 Mhz, 8 Mhz, 10 Mhz, 20 Mhz, and others. Whether the frequency is exactly, say, 10 Mhz or 10.000001 Mhz or 10.010000 Mhz or 10.123456 Mhz is immaterial because, if the actual frequency is known, the processor's software can adjust for any offset. And, _if_ the Loran-C receiver can somehow acquire and track (phase lock to) one Loran-C signal, the actual frequency of the receiver's oscillator can be measured and adjustments made so that _all_ signals can be tracked accurately. This is not usually done since a nominal 10 MHz oscillator is easier to come by than a 10.01 MHz oscillator, and, of course, the TD's need to be corrected as is shown later.

GRI	MICROSECONDS	COUNTS AT 10 MHz	EXTRA COUNTS NEEDED PER GRI AT 10,010,000 HZ
9960	99,600	996,000	996
9940	99,400	994,000	994
8970	89,700	897,000	897
7980	79,800	798,000	798
5990	59,900	599,000	599
5930	59,300	593,000	593

Figure 5. CORRECTING FOR AN "OFF-FREQUENCY" OSCILLATOR

The difficulty arises when the frequency _changes_ with temperature or voltage or age. There are three separate areas of operation, or processes, that are affected when the frequency is unknown: acquisition (search), phase lock (tracking), and measurement. For purposes of this paper, the following definitions are used:

ACQUISITION: the "coarse" identification of the loran signal;

PHASE LOCK: the "fine" identification of an edge of the signal;

MEASUREMENT: the time between edges of the signals from different stations.

In this discussion, selection of the "proper" edge, i.e., "third cycle matching," is not considered, as that is an analysis of the _shape_ of the pulse not of the _timing_ between pulses or the isolation of a single edge. Each of the three processes defined is discussed separately.

ACQUISITION

Methods of acquisition (locating the Loran-C signal in time) are as varied as the number of designs. Commonly, many GRI's are used, averaging the signal response to eliminate the noise. This approach is most susceptible to changes in the frequency of the timing reference, and, the more GRI's that are used, the more stable the oscillator must be. A change of five ppm from what is expected will cause a five microsecond drift in ten GRI's which will make averaging unusable (averages to zero). A change of 50 ppm (from plus 25 to minus 25) will give a five microsecond error per GRI! Without predicting (or guessing) the frequency error, no averaging is possible with this amount of error. Due to the time consuming nature of averaging, a repeated trial-and-error approach is usually not desirable.

(Since many of the common rates are close to 100,000 microseconds (9960, 9940, etc.), this number will be used as a reference for simplicity. Although all the problems associated with oscillator frequency change are lessened for shorter rates (not the least of which is more signal per unit time), all the differences are less than 2:1, which is small compared to the magnitude of the errors considered.)

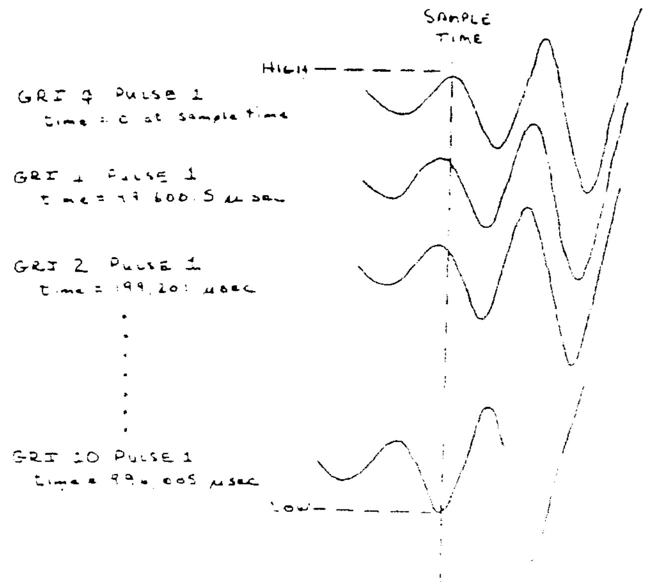


Figure 6. APPARENT SIGNAL DRIFT AT 0.5 uSEC/GRI (5 ppm)

An aquisition method that uses but a single GRI, with or without a second GRI for correllation, is <u>independent</u> of the oscillator error up to hundreds of parts per million (+/-2.5 usec per 7 msec), and neither predicting nor guessing the frequency is necessary. Such an approach was developed by the author in the early 1980's and has been successfully used by more than ten companies in some two dozen products aggregating over 100,000 receivers. Persistence pays off in a noisy environment, because only a seven-millisecond relatively clear window is required for any one of the Loran-C signals--it only takes finding one to lock up the oscillator so that conventional averaging can be used.

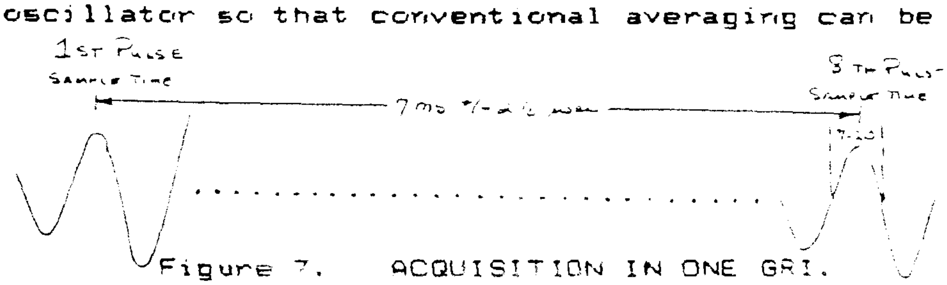


Figure 7. ACQUISITION IN ONE GRI.

PHASE LOCK

After the receiver has the approximate location of the signal, usually high into the best SNR portion, it must "lock" to an edge (zero-crossing) to make timing measurements between signals from different stations. A detailed discussion of phase lock loops is beyond the scope of this paper, but, without proof, it can be said that any loop has a lock range that cannot be exceeded, and, given the nature of the Loran-C signal, it must be less than five microseconds per GRI which is less than 50 ppm.

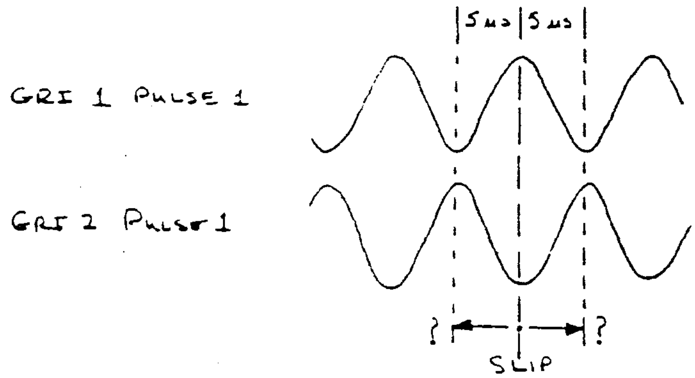


Figure 8. FIVE MICROSECOND SLIP PER GRI.

This requires an initial gain of one for the first order loop; in order to be stable, not to say useful, an adaptive filter is required and is used by most modern sets. To insure stability in the noisy Loran-C environment, a reliable loop would be less than that amount giving a practical lock-in range of 10-25 ppm.

Although a phase lock loop, however complex, may be designed to use a 25 ppm oscillator, a simpler loop may be enhanced by using the predictive techniques discussed later in this paper and will enable use of even less stable oscillators.

TD MEASUREMENT

With a +/- 5 ppm oscillator, a TD measurement of 50,000 microseconds uncorrected for oscillator error will be in error by +/- 0.25 microseconds due to the oscillator alone. Thus, sitting in one place, measuring a hypothetical TD of 50,000.0 when very hot, if the temperature decreases so the oscillator changes by its full stability, the measurement will change to 50,000.5 due to the change of oscillator frequency alone, in addition to whatever else the propagation does or the receiver does.

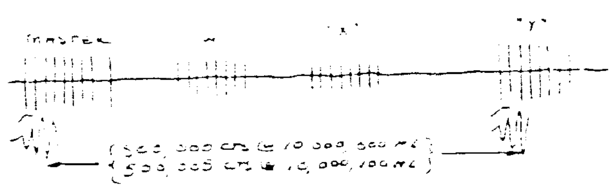


Figure 9. TD ERROR DUE TO OSCILLATOR OFFSET

This is, however, the easiest problem to solve because Loran-C receivers are excellent measurers of the oscillator error. Simply taking the velocity term of the set's phase-lock loop, normalizing it for the GRI, and multiplying it by the TD measurement will give the TD error which can be algebraically added to the TD.

$$TD_{COR} = TD_{MEAS}\left(1 + k \cdot \Delta osc\right)$$

Figure 10. TD CORRECTION FOR OSCILLATOR ERROR.

This makes the assumption that the velocity component due to movement is negligible. In boats this is true: at <u>50 knots</u> directly on a baseline, the movement error is approximately 1 ppm which is less than 0.1 microsecond in 50,000. For aircraft usage, however, correcting the TD only for "apparent" oscillator error will produce a lag in the TD value by up to 0.4 microseconds. Fortunately, this too is easily corrected with some additional arithmetic. Using the TD gradients computed in the latitude-longitude solution and the actual motion of receiver computed from the position filter, the composite oscillator error is broken into oscillator "errors" in the direction of each TD. After the individual station velocities are subtracted from the calculated components, the true oscillator error is computed. (This calculation requires separate phase lock loops for each station, as is the case for most modern receivers.)

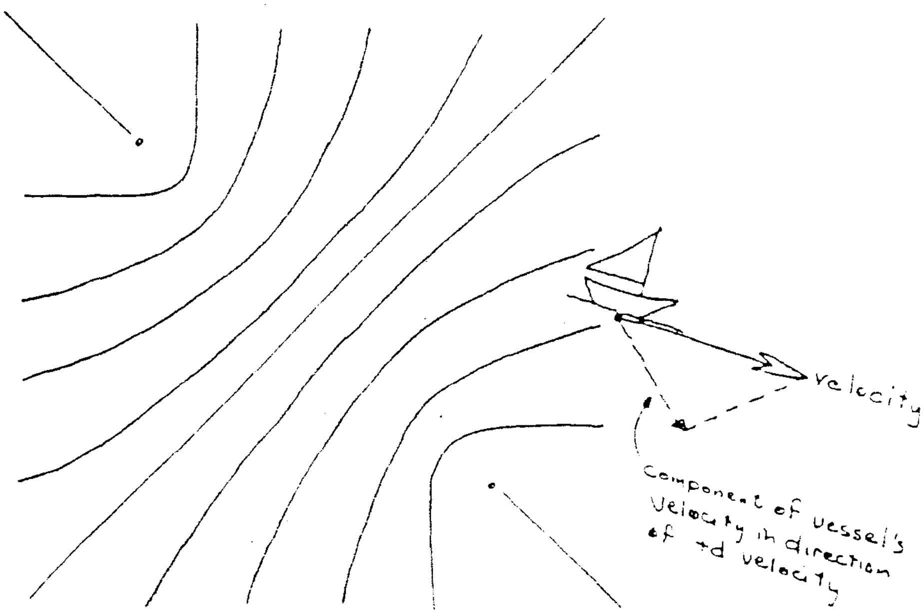


Figure 11. CORRECTION OF TD VELOCITY FOR VEHICLE MOTION.

GUESSING AND PREDICTING

If the process design being used doesn't solve the problems for acquisition and phase locking, there are still methods to anticipate them. The first (and cheapest) is to guess at an error and try it; if unsuccesful at acquisition, guess again. Depending on the range of the process and the "instability" of the oscillator, up to some number of attempts "n" will yield the result. The drawback of this approach is how long it takes to guess right, which in actuality is <u>only</u> a point-of-sale problem--the guessing time is typically less than the cycle select time which the user already waits for.

The "guess" approach can normally be speeded up simply by starting at the last (turn-off) value, which makes the reasonable showroom assumption that the turn-on temperature is the same as the turn-off temperature. This is the simplest (and cheapest) of various predictive schemes.

The major variation in frequency is due to temperature change. If the receiver has a method of measuring the temperature, a highly accurate prediction may be made once one point on the frequency-temperature curve is known. Actually the problem isn't even that difficult because the temperature does <u>not</u> need to be known absolutely, only relatively. So, if the processor has a built-in analog-to-digital converter (as the MC68HC11 has) a very simple circuit (worth ten cents) can be used to measure changes in temperature and very reliably predicting the turn-on frequency. Updating the temperature end points (as an A/D value) with the normalized oscillator error (corrected for the GRI so that the GRI may be changed) allows a very simple algorithm to predict a very accurate oscillator error for the "current temperature."

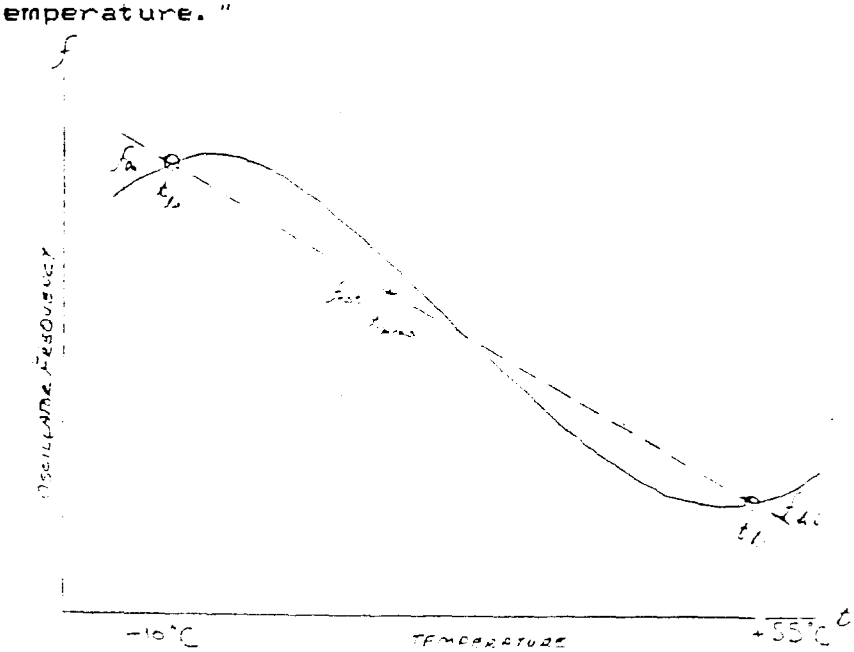


Figure 12. TYPICAL CRYSTAL OSCILLATOR FREQUENCY-TEMPERATURE CHARACTERISTICS

TEMPERATURE CHANGES, AGING, AND ACCELERATION

A change in the oscillator frequency due to aging, if it is large enough to be noticed, is easily accomodated by the continual recalibration technique described above. An acceleration (starting, stopping, and/or changing direction) appears to an operating receiver like the frequency change due to a temperature change (without the temperature change). This error can be accomodated by the phase-lock loop either within the tracking lock-in range, or, if extreme, the adaptive filter can be designed to accommodate the change as is commonly done with aircraft receivers. This is typically a non-problem: a ten degree centigrade change in temperature in one hour for a +/- 25 ppm oscillator is only 0.001 microsecond per GRI (approximately), hopefully well within the phase-lock loop response; 0-60 in zero time (on a baseline) produces a velocity of nearly 0.2 microseconds per GRI--in 28 GRI's the uncorrected error would reach five microseconds and the tracking would slip a cycle. Using a five second time constant loop filter, the first order loop gain would need to be at least 0.02, which, to the author, seems to be less than a minimum number anyway. All boat and all practical aircraft accelerations are within this; to achieve a 900-knot standard rate 180 degree turn on a baseline would require an adaptive filter to increase the first order loop gain during the acceleration.

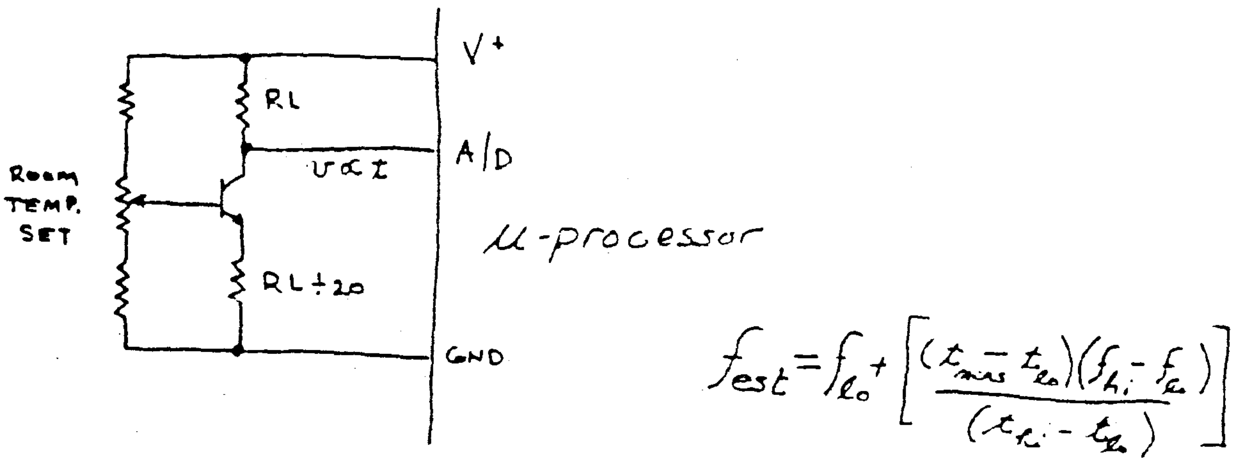


Figure 13. SIMPLE (RELATIVE) TEMPERATURE MEASUREMENT CIRCUIT.

EXAMPLE

A new, low-cost Loran-C receiver based on the ideas of this paper has been introduced for 1989. The specification of its oscillator is +/- 25 ppm over the operating temperature range. In addition, the oscillators have no frequency adjustments and are received with room temperature frequencies up to 175 Hertz off (plus and minus) their nominal frequency of 8 Mhz.

Since the individual oscillator frequencies are not predictable, the first factory turn-on must go through a guess approach or allow technician input of the current frequency. Once, however, the receiver achieves phase lock on some loran signal, it goes through a self-calibration sequence which is continuously updated when the receiver is operating. Since waypoints, routes, and start-up data are stored in non-volatile RAM, it is a simple matter to save the "end-points."

CONCLUSION

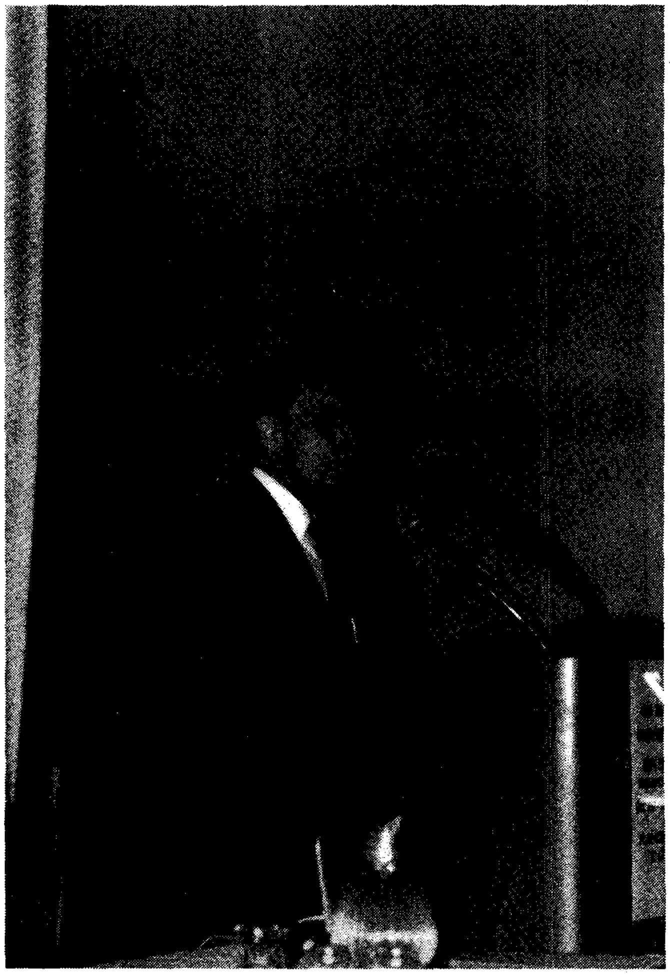
The oscillator stability for the Loran-C timing reference has always been specified to very tight tolerances because the necessary software processes for acquisition, phase locking, and TD correction had not been developed to adjust for the offsets. Although the TD correction is not difficult, a one-GRI acquisition and a sophisticated adaptive phase lock loop is required to tolerate an "instability" to +/- 25 ppm over the operating temperature range with no degradation of specifications in low-priced sets. Adding a rudimentary temperature measurement capability to predict the oscillator offset can extend the range even further without a loss in acquisition and phase lock.

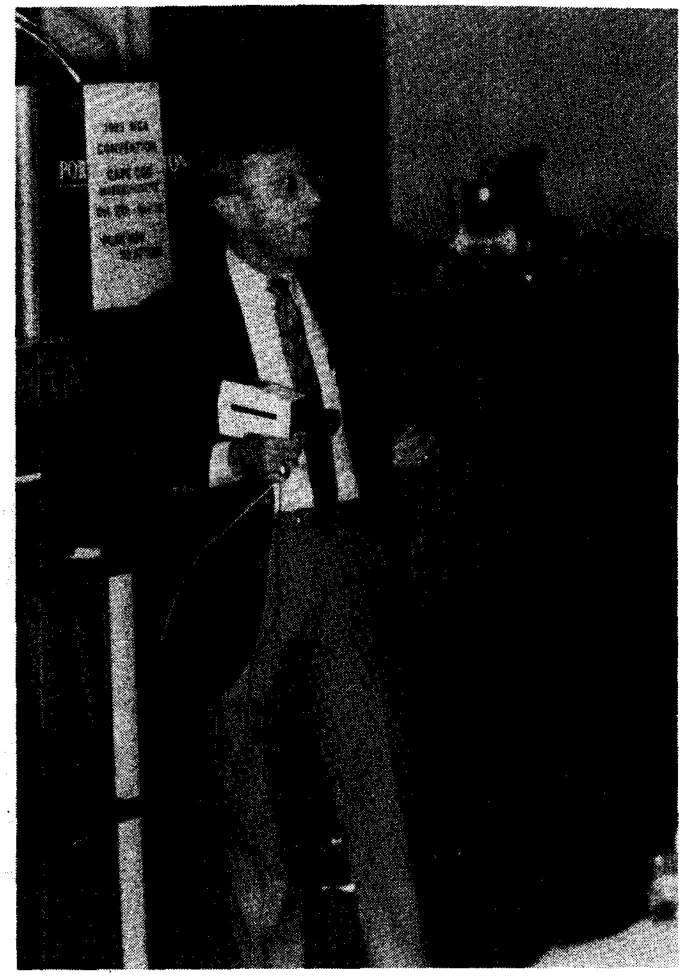
Reference 1. "Single-Chip Loran-C Transducer" Jesse Pipkin, Wild Goose Association Technical Symposium, October, 1988.

Reference 2. "Design of Phase-Locked Loop Circuits" Howard M. Berlin, Blacksburg Continuing Education Series

JESSE PIPKIN

Jesse Pipkin is a real-time signal processing specialist.
His introduction to Loran (A) was in the United States Air Force where he served as a Navigator and used loran during hun.
His introduction to Loran (A) was in the United States Air Force where he served as a Navigator and used loran during hundreds of trans-Atlantic and trans-Pacific flights. He has been involved in Loran-C equipment design for the last ten years, concentrating the last three on his "Single-Chip Loran-C Transducer" (Wild Goose Association Technical Symposium, October, 1986). He received the BSEE from the University of Florida and did graduate electronic design work at the University of California, Berkeley. His designs are used by more than a dozen companies involved in both marine and avionics applications.

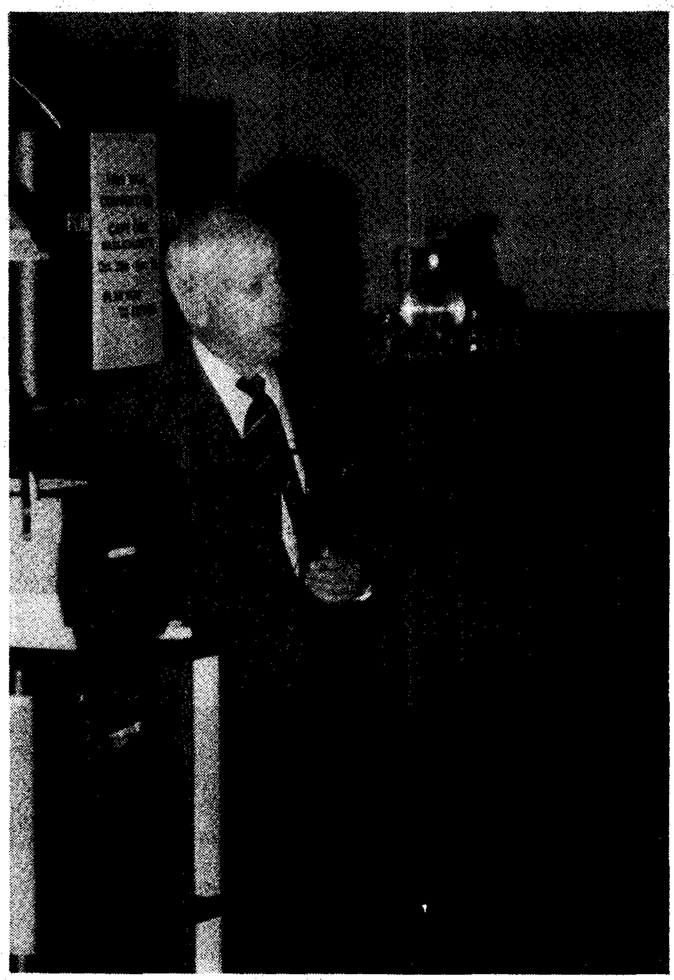




SESSION 6

LORAN AND GPS INTEROPERABILITY

MAJ WILLIAM POLHEMUS (USAF RETD.)
POLHEMUS ASSOCIATES INC.



NAVIGATION SYSTEMS INTEROPERABILITY

Bradford W. Parkinson

Stanford University

October 26, 1988

OUTLINE:

- Define Interoperability
- Potential Benefit Areas for POS/NAV Users
- Matrix of Combinations
- Interesting Combinations
- Some Conclusions -- Where are We Going...

  Should We Go?

POS/NAV Interoperability

" Use of Two Or More Systems

to Provide Complementary Capabilities

with Enhanced User Benefits."

or:

" Use of Two or More Systems

to Provide Symbiotic (Cooperative) Capabilities

with Enhanced User Benefits."

Potential Benefit Areas:

COVERAGE:

-- Geographic
-- Daily Time
-- Evolutionary Time
(Improvements with Time)

ACCURACY:

-- Position
- Absolute/Relative
- 2D/3D

-- Velocity (Absolute)
- Low Dynamic
- High Dynamic

RELIABILITY

-- OUTAGES
- Probability
- Notification

COST

FOR 1991 L = Local N = Not Deployed *** Exc (3 met) ** Good (30 met) * Fair (300 met) - Deficient	COVERAGE			DYNAMIC ACCURACY						RELIABILITY				
				POSITION				VEL		Outages		Degrad		
	GEOGRAPHIC	DAILY TIME	EVOLUTIONARY TIME	ABS	REL	2D	3D	L.DYN.	H.DYN.	PROB.	NOTIF.	PROB.	NOTIF.	CO
DIFF GPS	- L/ND	++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	++
DOP RADAR	+++	+++	+++	+	++	++	-	++	++	++	+++	++	+	+
GPS	+++	++(+)	+++	+ (+)	++ (+)	++	++	+++	+++	+++	++	++	++	+++
INS (After 1 hr/)	+++	+++	+++	+	++	++	-	++	++	++	-	++	-	-
LORAN	++	+++	+++	+	++	+	-	+	-	+++	++	+++	++	+++
MLS / ILS	+ L	+++	+++	++ +	++ +	++ +	++ +	+	+	++ +	++ +	++ +	+++	++/ +++
OMEGA	+++	+++	+?	+	+	+	-	-	-	++	++	+	++	+++
TRANSIT	+++	+	-	+	+	+	-	-	-	+	-	++	-	++
VOR / DME	+ L	+++	+++	+	+	+	-	-	-	+++	+++	+++	+++	+++

QUALITATIVE VALUE OF INTEROPERABILITY	DIFF GPS	DOP RADAR	GPS	INS (After 1 hr/)	LORAN	MLS / ILS	OMEGA	TRANSIT	VOR / DME
DIFF. GPS									
DOP. RADAR									
GPS	+++ Natural	++							
INS (After 1 hr/)	+++	+	+++						
LORAN	+++		+++	+	+++ X Chain				
MLS / ILS		+		++	++				
OMEGA				++ Ocean		+			
TRANSIT							+		
VOR / DME		+		++	++	++	+		

FOR 1991

= Local

= Not
ployed

*** Exc (3 met)
** Good (30 met)
* Fair (300 met)
- Deficient

	COVERAGE			DYNAMIC ACCURACY						RELIABILITY				
				POSITION				VEL		Outages		Degrad		
	GEOGRAPHIC	DAILY TIME	EVOLUTIONARY TIME	ABS	REL	2D	3D	L.DYN.	H.DYN.	PROB.	NOTIF.	PROB.	NOTIF.	COST
GPS	+++	++(+)	+++	+ (+)	++ (+)	++	++	+++	+++	+++	++	++	++	+++
NS (After 1 hr/)	+++	+++	+++	+	++	++	-	++	++	++	-	++	-	-

GPS / INS

GPS Can Provide

- -- 10 Meter Accuracy Usually
- -- Bounding of INS Drifts
- -- Calibration for INS Parameters
  (Gyro Drift/Accelerometer Bias, etc.)
- -- Integrity Checking of INS (KAL 007)

INS Can Provide

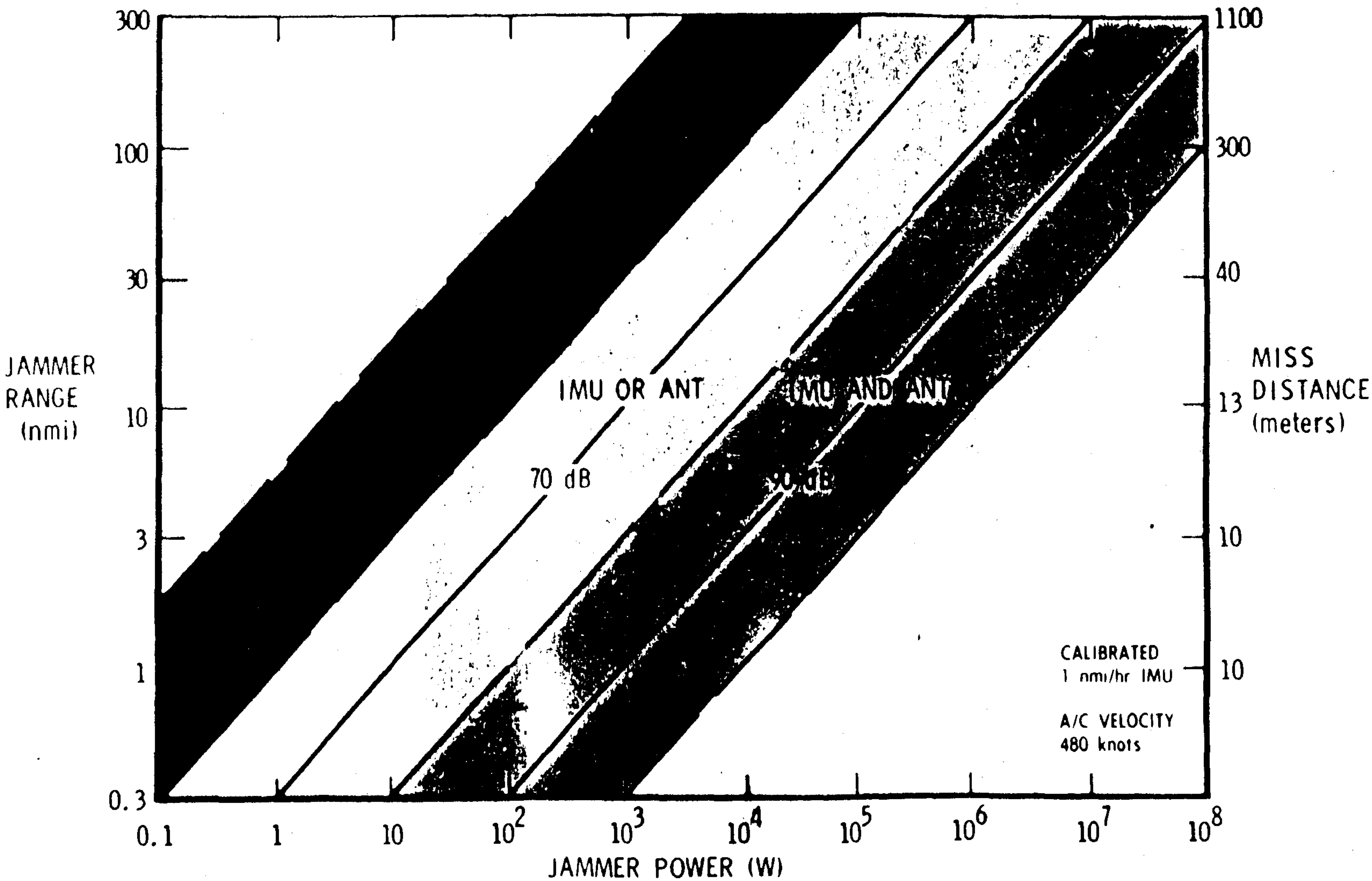
- -- Velocity Aiding for GPS Tracking Loops
- -- Inertial Flywheel if GPS is Jammed
- -- Coverage for Outages
- -- Integrity Checking

Common Systems Cost Savings

- -- Cheaper INS Components (Strap Down)
- -- Sharing of Sub-systems
  - Clock
  - Computer
  - Control Display

10/88nvtc

GPS ECCM



300
100
30
10
3
1
0.3
JAMMER
RANGE
(nmi)
1100
300
40
13
10
10
MISS
DISTANCE
(meters)
IMU OR ANT
IMU AND ANT
70 dB
90 dB
CALIBRATED
1 nmi/hr IMU
A/C VELOCITY
480 knots
0.1
1
10
10^2
10^3
10^4
10^5
10^6
10^7
10^8
JAMMER POWER (W)

FOR 1991 L = Local N = Not Deployed *** Exc (3 met) ** Good (30 met) * Fair (300 met) - Deficient	COVERAGE			DYNAMIC ACCURACY						RELIABILITY				
				POSITION				VEL		Outages		Degrad		
	GEOGRAPHIC	DAILY TIME	EVOLUTIONARY TIME	ABS	REL	2D	3D	L.DYN.	H.DYN.	PROB.	NOTIF.	PROB.	NOTIF.	COST
GPS	+++	++(+)	+++	+ (+)	++ (+)	++	++	+++	+++	+++	++	++	++	+++
LORAN	++	+++	+++	+	++	+	-	+	-	+++	++	+++	++	+++

LORAN / GPS

GPS Can Provide

- Master Station Synchronization
- Periodic Accurate Coverage
- Precise Velocity
- Airborne Calibrations of LORAN (ASF)
- Ocean Area Coverage

LORAN Can Provide

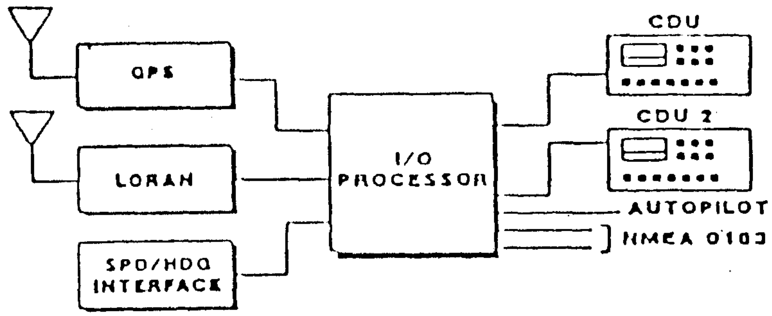
- Early, Wide-Area Continuous Coverage
- Integrity Checking for GPS (Receiver Autonomous)
- Failure Backup

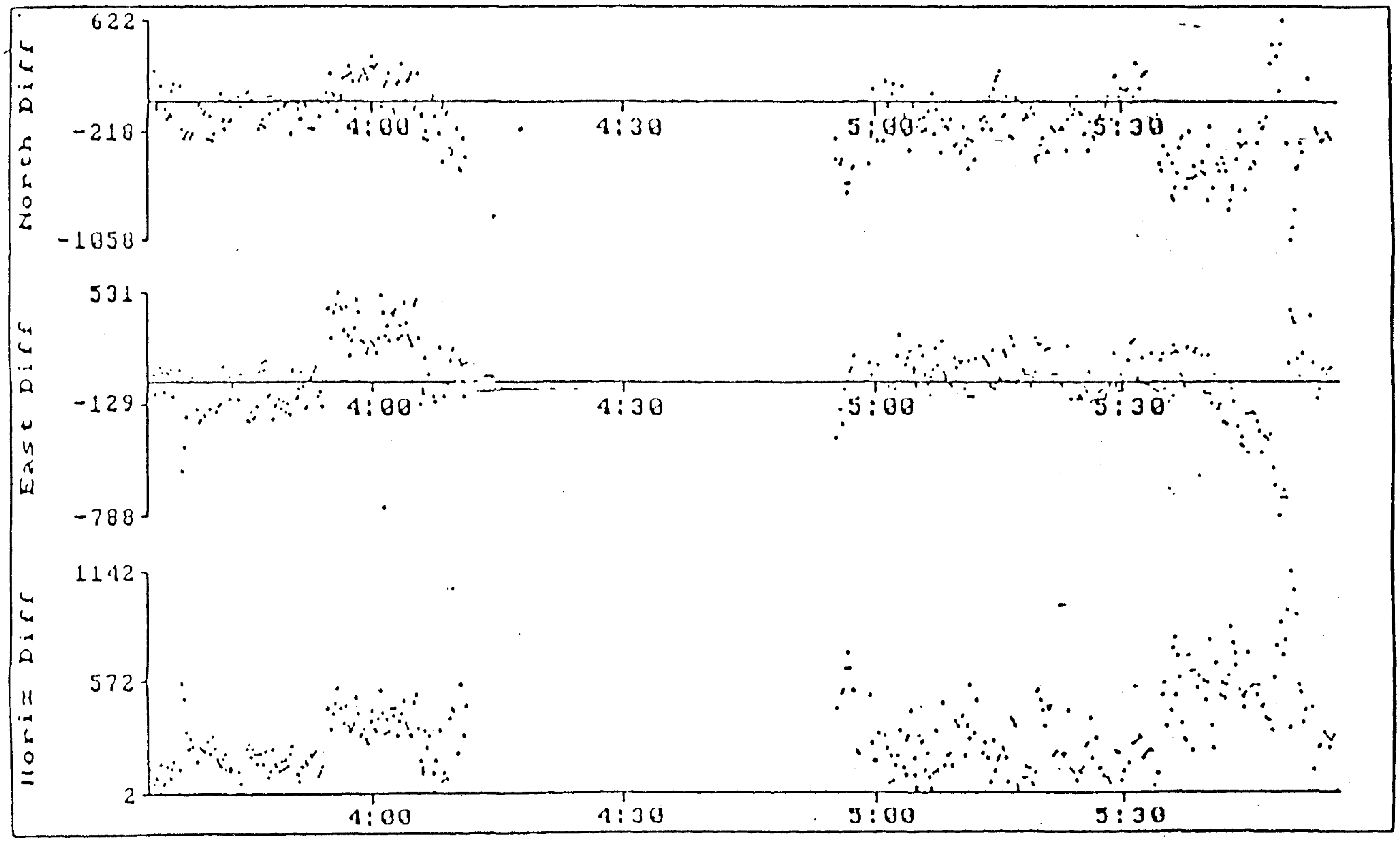
Synchronized LORAN / GPS Provides

- Additional Ranging Signals / Smart Filter Accuracy
- Control/Display Cost Savings

10/88nvtc

10X Block Diagram



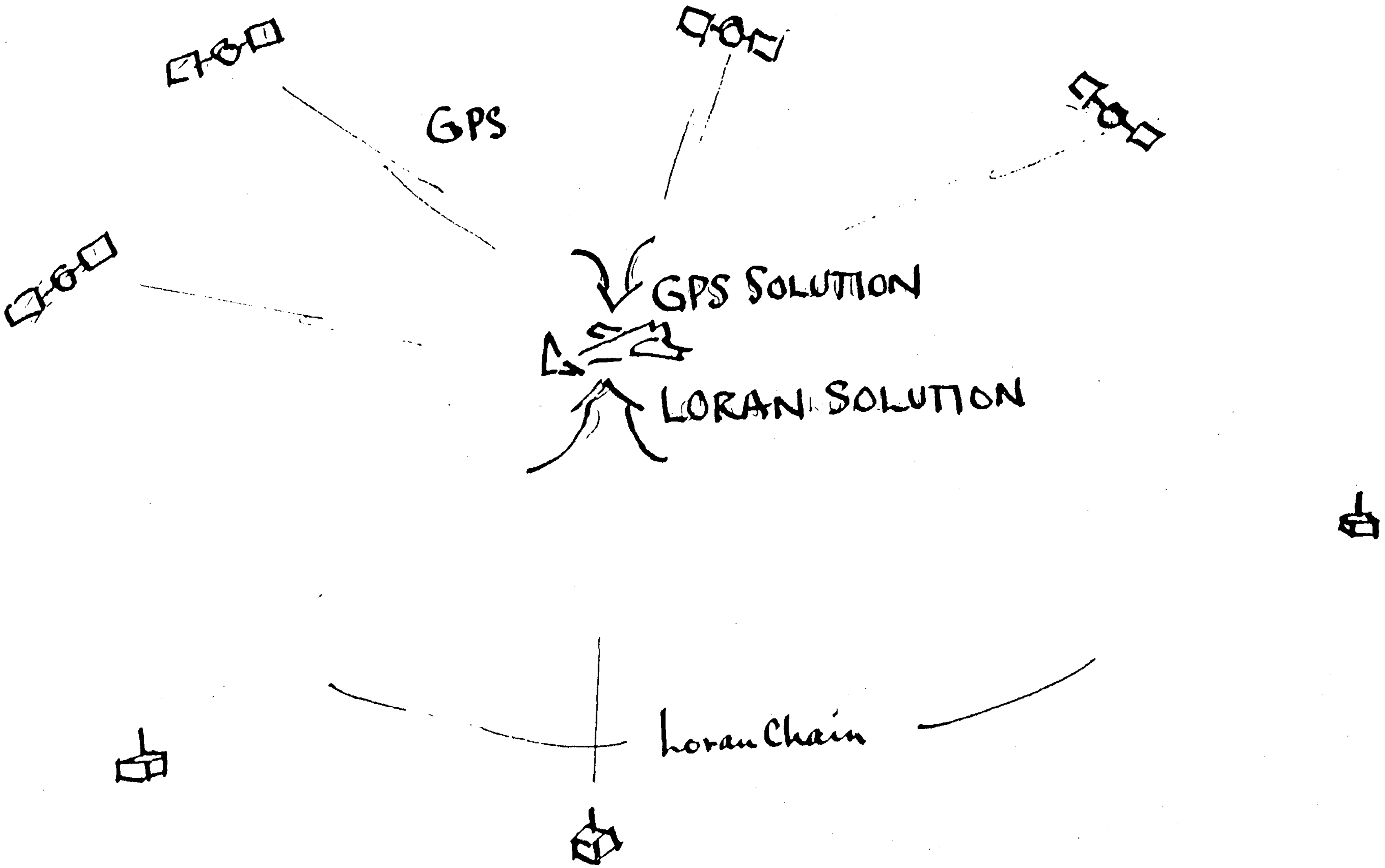


Loran/GPS Difference on a Trip from San Francisco to San Diego

GPS INTEGRITY

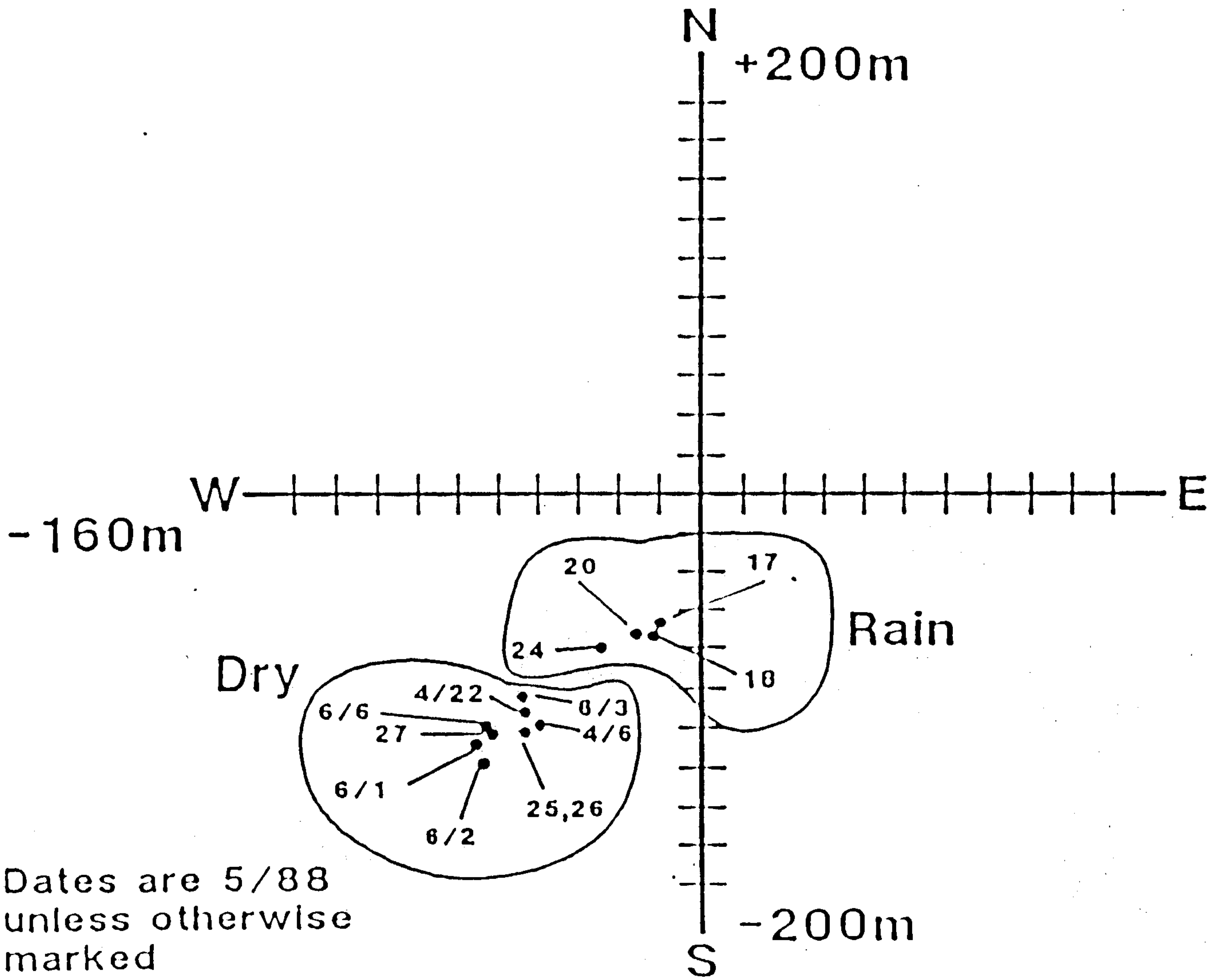
- **National Notification**
  (The Integrity Channel / GIC)

- **Receiver Autonomous Integrity Monitoring**
  (RAIM)



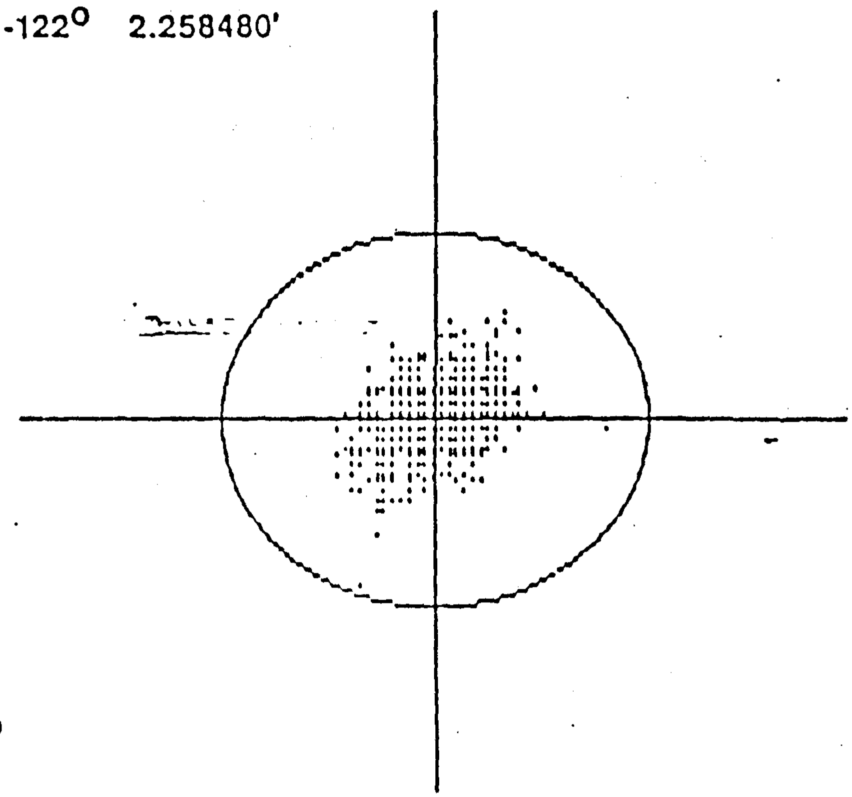
SYSTEM CONCEPT #1

ASF Corrections over 1 month



Dates are 5/88 unless otherwise marked

Center at: Latitude 37° 23.567986'
Longitude -122° 2.258480'



Datum: WGS 84

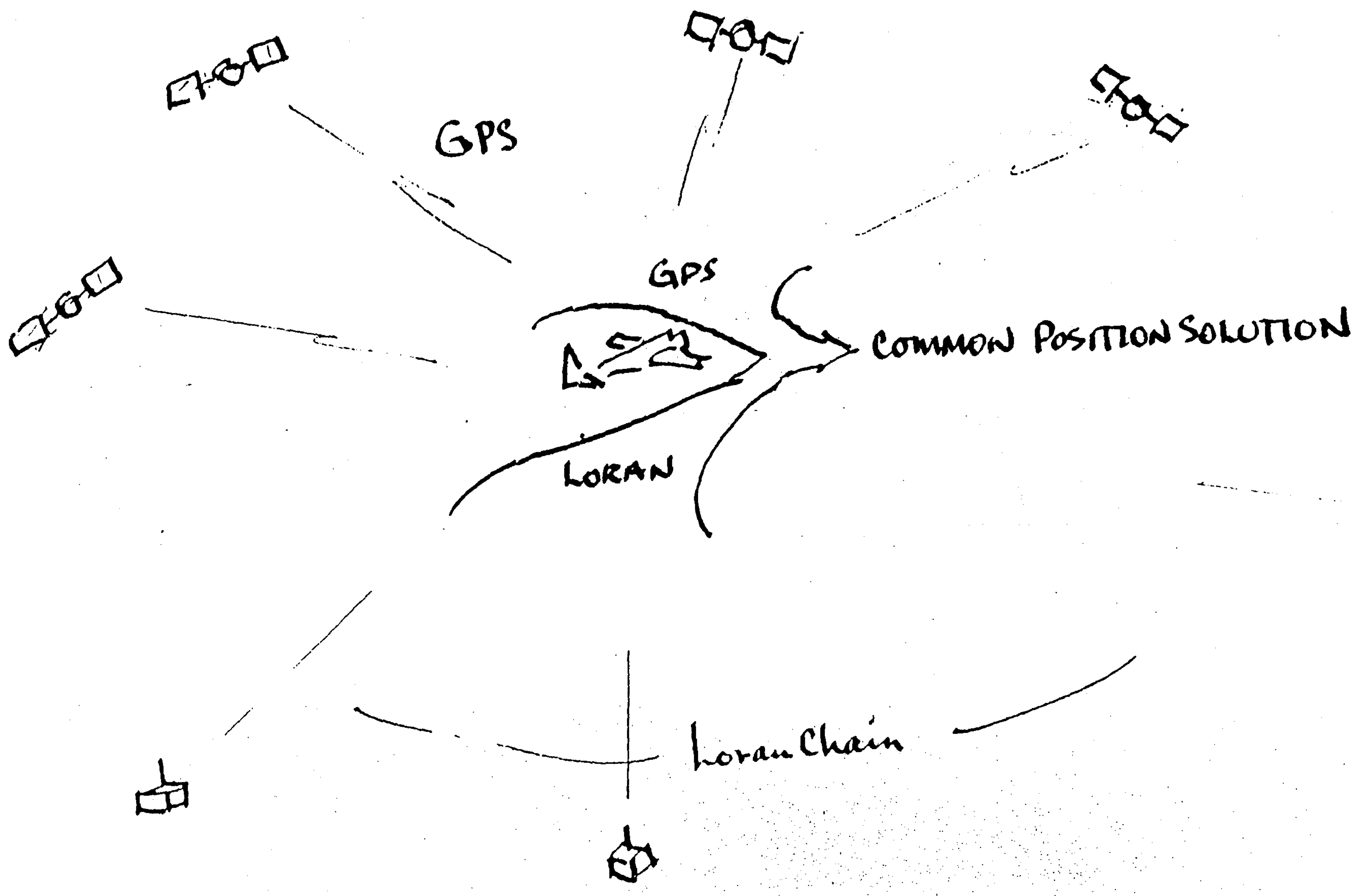
File: 0423gps.cap

RMS Distance: 7.15m

Center to Mean: 2.03m

Radius of Circle: 40.0m

Three Days of GPS and GPS Corrected Loran



SYSTEM CONCEPT #2

$$\begin{bmatrix} \bar{e}_{1S}^T \,\vdots\, 1 \,\vdots\, \phi \\ \bar{e}_{2S}^T \,\vdots\, 1 \,\vdots\, 0 \\ \vdots \\ \bar{e}_{1L}^T \,\vdots\, 0 \,\vdots\, 1 \\ \vdots \end{bmatrix} \begin{bmatrix} \bar{R}_u \\ B_{us} \\ B_{uL} \end{bmatrix} = \begin{bmatrix} \boxed{\bar{e}_{1S}^T \,\vdots\, 1} & & \phi \\ & \boxed{\bar{e}_{2S}^T \,\vdots\, 1} & \\ & \ddots & \\ \phi & & \boxed{\bar{e}_{1L}^T \,\vdots\, 1} \\ & & \ddots \end{bmatrix} \cdot \begin{bmatrix} \bar{R}_{1S} \\ B_{1S} \\ \bar{R}_{2S} \\ B_{2S} \\ \vdots \\ \bar{R}_{1L} \\ B_{1L} \\ \vdots \end{bmatrix} - \begin{bmatrix} \rho_{1S} \\ \rho_{2S} \\ \vdots \\ \rho_{1L} \\ \vdots \end{bmatrix} + \begin{bmatrix} \nu_{1S} \\ \nu_{2S} \\ \vdots \\ \nu_{1L} \end{bmatrix}$$

$$\bar{\bar{G}} \cdot \bar{X} = \bar{\bar{A}} \cdot \bar{S} - \bar{\rho} + \bar{\nu}$$

$$E\left[\bar{\nu}\bar{\nu}^T\right] \triangleq \mathrm{Cov}(\bar{\nu}) = \begin{bmatrix} E(\nu_{1S}\nu_{1S}) \ldots & & E(\nu_{1S}\nu_{jL}) \\ & E(\nu_{1L}\nu_{1L}) \ldots & \\ & & \end{bmatrix}$$

This is assumed to be:
$$= \begin{bmatrix} \underline{\underline{I}}\sigma_S^2 & \vdots & \underline{\underline{0}} \\ 0 & \vdots & \underline{\underline{I}}\sigma_L^2 \end{bmatrix}$$

The Combined Measurements

$$\hat{X} = \left[G^T \operatorname{cov}^{-1}(v)\, G \right]^{-1} G^T \operatorname{cov}^{-1}(v) \left[\bar{\bar{A}} s - \bar{\rho} \right]$$

The Combined Solution

Caveats / Comments:

-- *Front End Calibrations B_{us} / B_{ul}*

-- *Integrity by Looking at Residuals*

-- *Stability of Intersystem Biases*

CONCLUSIONS:

-- LORAN / GPS Interoperability Very Desirable

- Accuracy
- Coverage
- Integrity

-- Further Measurements are Needed

-- Costs Can Potentially Be Reduced

- Control Display Unit
- Oscillator
- Navigation Computer

INTEGRATION AND INTEROPERABILITY

of

OMEGA, G.P.S. and LORAN - C.

Abstract:

The three radio navigation systems: Omega, G.P.S. and Loran -C should be thought of as a combined set of three integratable and interoperable radio navigation systems (i.e. three parts of a whole) in the future and not as three competing systems. Each system has its advantages and disadvantages. By making use of the advantages, it is possible to build a superior navigation system.

This paper is intended to be a discussion of such a system and of some of the interesting related data.

The views expressed here are those of the author and not necessarily those of Canadian Marconi Company.

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Integration and Interoperability

of

Omega, G.P.S., and Loran - C

Introduction

The only wide range radio navigation systems available today are Loran - C, Omega and in the future: G.P.S. Other systems such as the DECCA network (analogous to Loran-C) are highly localized and outside this discussion. In fact, of these only Omega and G.P.S. provide true world coverage, and G.P.S. is not quite here yet. I should like to also point out here that the views expressed are mine and not necessarily those of Canadian Marconi Company.

There are a number of real or potential G.P.S. systems, including the U.S.S.R. GLONASS system, the proposed GEOSTAR navigation system which can only be made worldwide if GEOSTAR expands its coverage to the whole globe, and the recently proposed INMARSAT navigation addition to the international communications satellite system that has been around for many years mainly for the marine community. It is now also being developed for airline use. Finally, we have the NAVSTAR G.P.S. which is the system being implemented by the U.S. Armed Forces for their own use, but which will also provide a less accurate signal accessible by civilian users. More of this later. For purposes of todays discussion, we shall only consider the NAVSTAR system since it is the only system for which actual information is available and for which manufacturers are actively designing and building equipment.

At present, system integration has been persued by the avionics manufacturers for very practical reasons, but system interoperation is still a very new field and experimental in nature. Never-the-less, the combination of integration and interoperation can provide some surprising benefits.

Integration

The larger world of aircraft navigation equipment users has developed a real and growing demand for multisensor systems. An example of such a system is the Canadian Marconi Company CMA - 900 Navigation Management System (Fig. 1.). Here we have a number of separate sensors, each providing an estimate of the aircraft position to a central computer which accepts some, rejects others on the basis of the phase of flight and the quality of signals. Some signals, such as DME or Loran-C or, at present and for some time, G.P.S., are relatively localized. Never-the-less, they can provide a considerable improvement on flight path accuracy over such systems as INS or OMEGA, which are the only truly world-wide navigation systems operationally available today.

I do not intend to deal with INS (Inertial Navigation Systems) here, other than to say they are very expensive, and commercial versions have an accuracy drift rate of typically two miles per hour. DME (Distance Measuring Equipment) offers accuracies of better than a tenth of a mile, but signal coverage is not generally available outside the U.S.A., Europe and the most heavily populated areas of the rest of the world. It is not suitable for trans-oceanic flying, but is usefull for updating Omega and INS system positions where available.

Omega has its own weaknesses, such as less than desireable signal coverage in some areas, notably in the area around Winnipeg (the infamous Winnipeg hole) over to Chicago and partly down the Mississippi Valley. Advances in Omega signal receivers and signal processing software, coupled with the use of the U.S. Navy VLF signals, have largely eliminated this difficulty. Other signal anomaly areas have been discovered, but are being successfully dealt with on an on-going basis by the manufacturers. Canadian Marconi Company maintains a computerized signal processing laboratory and a set of airborne signal recorders for this purpose.

Loran - C provides good accuracy where signals are good, but like the little girl with the curl in the middle of her forehead, when it is bad, it is very very bad. Unfortunately, it is also relatively expensive and it may be impossible to try to blanket the world with stations. Despite this, Loran - C signals can and do permit excellent navigation in the U.S. east, west and southern coasts and parts of Europe. As the U.S. mid-continent gap is closed the entire nation will be covered. Great, but only of marginal value to Africa or South America or China, or even northern Canada.

G.P.S. is the critical factor that can tie the three radio based systems into a cohesive total which is greater than the sum of its individual parts.

Combining the calculated position outputs of a number of sensors in a Kalman, least-mean-squares, or similar filter, even with some intelligent data selection, is still only integration: i.e. each sub-system is still essentially independent. Interoperablity can remarkeably improve navigation reliability. You can have integration without interoperability, but you can't have interoperability without integration.

Interoperability

Interoperability makes use of signals available in one sub system to improve on the reliability or accuracy companion system.

Omega/G.P.S.

Canadian Marconi has designed a G.P.S. sensor that can be plugged inside the CMA - 771 system. (Fig. 2). Another unit can be mounted beside the Omega RPU as in Figure One. Once the GPS receiver is installed for position calculations, it is fairly easy to pick the timing signal off the GPS data stream (Fig. 3) and use it to stabilize the Omega system internal clock. This is like having an atomic clock on board. As a result, in the absence of three Omega stations, a rho-rho type of navigation for a period of time becomes possible. Alternately, with three or more Omega stations, position accuracy is enhanced for up to 30 minutes, even if all G.P.S. signals disappear. In the event that full NAVSTAR satellite coverage is not available, due to poor area coverage such at the artic latitudes, or a satellite fails (Yes, it will happen!), the Omega can act as an integrator to prevent drastic dislocations in the flight track.

Figure 4A shows a typical three station hyperbolic Omega position fix. A recent development now adds to the interesting possibilities. The Omega station timing clocks have been synchronized to each other and to the G.P.S. satellites via the G.P.S time signals. As a result, it will be possible to develop a line of position from a combination of one Omega and one G.P.S. station. (Fig. 4B) This is an obvious advantage in the event of a paucity of signals from one or both systems. This is not to be confused with the simpler but less effective approach in which complete lines-of-position (LOP's) from each sub-system or sensor is combined with the LOP's of another sub-system sensor. This latter technique is presently in use by CMC and has proven to provide very smooth transitions from one mode of flight to another (i.e. trans oceanic Omega to continental DME.)

Loran-C and G.P.S.

By synchronizing the G.P.S. and Loran-C time clocks, master and slave stations in a chain as well as other chains can be used in conjunction with each other for greatly expanded coverage and signal reliability. The interoperability of Loran-C and G.P.S. is simular to that described for Omega. Of course with all three systems synchronized, LOP's could be generated using mixes of all three types of transmitted signals. (Fig. 5)

I'm sure that the details of Loran-C and G.P.S. integration and interoperability are covered in much greater detail by some of the other speakers today.

CMA-900

As mentioned earlier, the CMA-900 represents an ideal system in which Omega, G.P.S. and Loran-C can be integrated and made interoperable. A brief overview of this system may be of interest to attendees at this conference. Please remember, this

equipment is aimed at the larger corporate aircraft, commercial carrier and military markets, not the smaller single engine users, therefore flexibility and reliability are more important than extreme small size, weight and cost.

The CMA-900 represents the company's latest approach to the design of an airborne navigation management system using the application of state-of-the-art technologies for a break-through in size, weight, flexibility and reliability (Fig. 6) for this class of equipment. But, first allow me to digress by describing what we mean by a Navigation Management System or N.M.S., since similar functions are also performed by what we call a Flight Management and Control System or FMCS. There appears to be considerable confusion on this point. Basically a full FMCS automaticaly controls all the flight functions of an aircraft in three dimensions. That is, it provides for lateral and vertical navigation from one place to another. Lateral navigation is parallel to the earth's surface. Vertical navigation often includes the appropriate cruising altitude for maximum fuel economy, shortest flight time or simply a pre-defined altitude. In addition, it also controls the thrust of the engines through an electro-mechanical connection referred to as auto-throttle to vary the speed of the aircraft through the air. It also provides display of the take-off speeds for the pilot for the specific aircraft, i.e. V1, VR, V2.

An N.M.S. basically navigates in only the lateral dimension. Tell the system where you are, where you want to go, and it will automatically plot a course to get you there in the most direct manner: unless the operator inserts special considerations, such as deviations from this direct or great circle path called waypoints or parallel offsets or airways, etc. The N.M.S. differs from a standard airborne Omega system in that it optimally combines the inputs at any given time from one or more navigation sensors to provide a more accurate and reliable position calculation. It also selects among these sensors for the most appropriate type for a particular phase of the flight. For normal cruise, Omega/VLF would be appropriate: for landing and take-off, MLS or ILS and DME are more appropriate; for terminal area operation, DME is usually most appropriate. An N.M.S. also frequently provides specific range computation, that is a calculation of estimated range based on fuel flow and operator inserted values of fuel quantity.

A navigation management system is not specific to a particular airframe and engine configuration whereas an FMCS invariably is closely tied to the specific engine, airframe and flight characteristics of the particular aircraft type.

The CMA-900 was designed to span the requirements of a basic navigation system with only two or three sensors and only horizontal navigation; through the capabilities of a full N.M.S. as described above and with the potential power to develop into an FMCS in the future. This great range of capability with a low economic overhead is possible only through the extensive application of recent developments, such as semi-rigid printed circuit boards, surface mount components (Figure 6), and special design integrated circuit gate arrays. It is a modular expansion approach to the use of multiple sensors (Figure 7) coupled to a control and display terminal carefully engineered designed to simplify the operator's work load and minimize "heads-down time" in the cockpit. It also minimizes the on-going training of pilots, a serious problem with some of the more sophisticated systems on the market. (Particularly Flight Management and Control Systems).

More specifically, these technical advances have enabled Canadian Marconi to design a system that, although it is extremely small and light, is able to provide

- an extensive internal data base capable of storing up to 35,000 waypoints, flight plans, VOR's, flight data, etc., plus a
- comprehensive interface capability including provision for both digital and analog interfaces to control the operation of and display the outputs from multiple aircraft systems, including cockpit instrumentation, maintenance functions and the various navigation systems such as Omega/VLF, GPS, MLS, DME, IRS, Loran-C, etc. These functions are controlled by an
- advanced color graphic and alpha/numeric display (Fig. 8) capability in the control terminal. This is combined with high display readability and easy to use single function alpha/numeric and control keys plus software programmed/display linked "soft" keys. This "smart" control terminal (Multi-Function Control and Display Unit-MFCDU) is also capable of handling a significant number of interfaces to systems other than the CMA-900 NMU.

This capability of the MFCDU to directly interface with other systems, while not specific to today's discussion, is of interest because it potentially allows the system to be applied in a very unique way. If a "Flight Critical" sub-system such as a Microwave Landing System (MLS) is to be incorporated into the overall NMS package, it can be accomplished without the complexities involved in declaring the entire system to be "Flight Critical". An MLS, because of the extra reliability required during the crucial landing and take-off phases of 10

flight, has extra reliability and redundancy conditions imposed on it. In the CMA-900, the MLS sensor can be connected to the control and display unit(s) through one of its multi-function interface ports. Thus, only the terminal and the MLS need be considered "critical" to the landing and take-off process, considerably simplifying the installation and its operation, lowering the cost and weight and improving overall reliability.

The CMA-900 Navigation Management System sets a new standard for smaller size and flexible expandability while remaining light in weight: under 20 pounds for the basic system. It is the flexibility which can enable implementation of interoperability as well as integration.

Before concluding this paper, I feel it is appropriate to raise a few thoughts on GPS NAVSTAR that need resolution before it can become a really useful international navigation signal source. I have no axes to bear in this since my company designs and manufactures both Military P code and commercial C/A code receivers.

The GPS NAVSTAR system cost is extremely high. While it is currently funded by the U.S. Congress through the USAF, the "user shall pay" concept is still very much alive. A comparison of signal coverage (transmitter) costs by the U.S. Coast Guard indicates that

- G.P.S. costs about \$30 per square mile

- Loran-C costs about \$2 to \$3 per square mile.

- Omega costs about 10 cents per square mile.

Who will eventually pay the bill? NAVSTAR satellites are also expected to be required replacement at a rate of three per year (at about \$16M each) when the full constellation is in place due to failures. These failures also impact signal availability while the replacement is being manouvered into place.

Area coverage of the satellites should be better now that they will be boosted in higher orbits. However, the polar regions will still be poorly served. Crucial for many airlines in transpolar routes.

International acceptance of a system under the control of the U.S. military establishment is being seriously questioned. Recent events have indicated that the civil applications of NAVSTAR fall far down the list of priorities of the Pentagon.

As a result, approval of the GPS NAVSTAR as a "sole means" of navigation system is a long way off, if it ever does happen. Therefore, combining the use of its signals with Omega or Loran-C is most appropriate. By integrating the three sensors, the size and weight of the resultant package can be reduced. By further developing the interoperability of these systems, a more reliable and accurate system can be derived, even though the full acceptability of the G.P.S. NAVSTAR system (or its alternates) may be in question.

<u>Side Issues</u> -

Following are four side issues that may also be of interest.

- <u>Omega station saving</u> -

GPS will save money through use of the G.P.S. timing signals via receivers at each station. The Coast Guard up to now had to transport a special calibrated atomic clock time standard across the world to recalibrate each station on a regular basis. At a rate of one station per month: very expensive!

- <u>G.P.S. Accuracy</u>

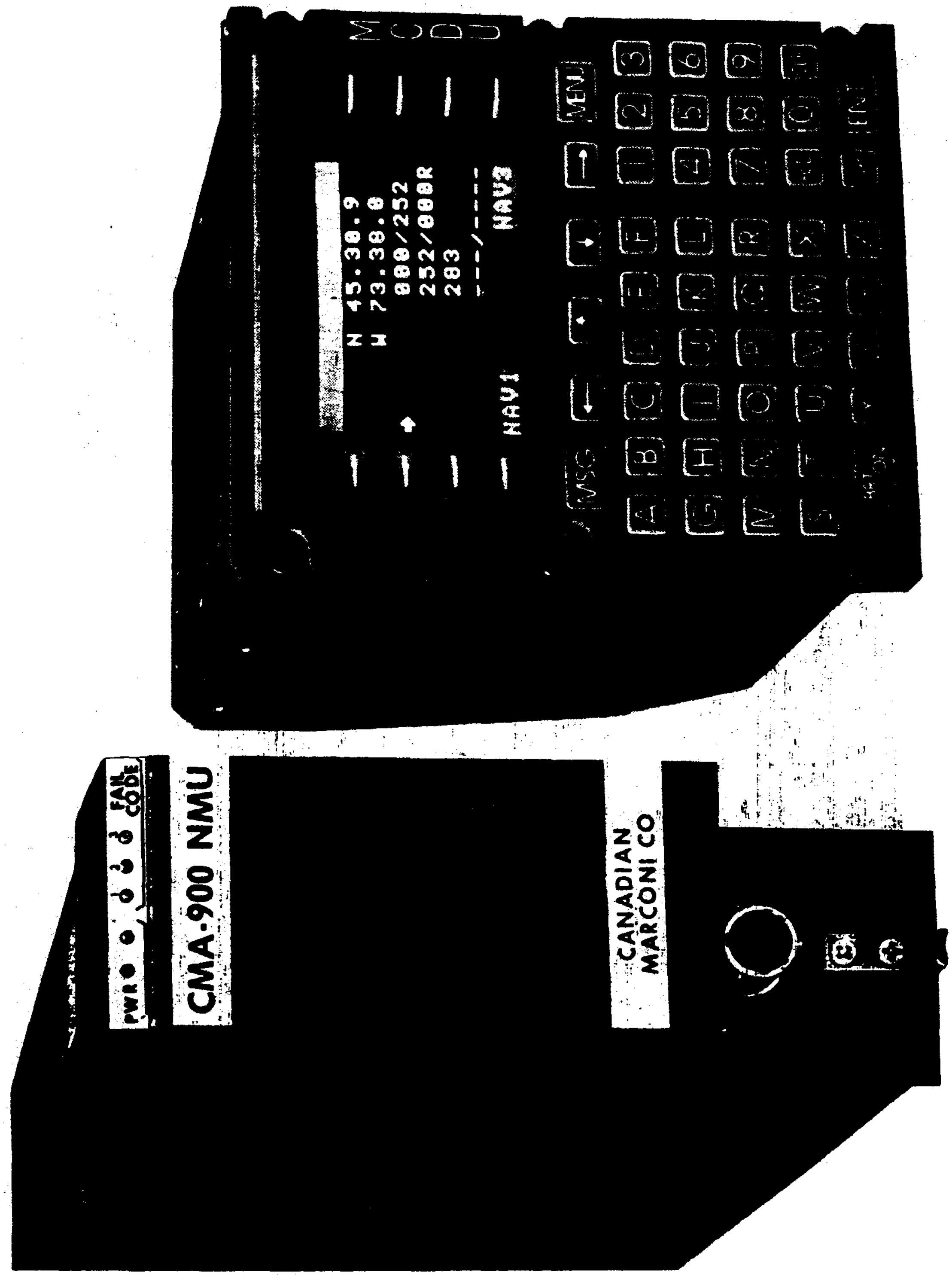
No doubt G.P.S.NAVSTAR is potentially a great navaid. C.M.C. experience shows 2D accuracy of <u>3 to 5</u> meters in a P-Code 5 channel receiver and 20-30 meters in a 2 channel C/A code signal receiver. The C\A code signal is to be degraded to allow only 100 meters accuracy when the full constellation is up-still very good!

- <u>Omega accuracy improvement</u> -

With G.P.S. timing signals to improve Omega Rx clock accuracy, navigation accuracy should be improved to 0.75 to 1.0 N. Miles instead of the present 1.5 to 2.0 N. Miles.

- <u>G.P.S. Military</u> -

G.P.S. signals are easy to block in times of conflict by relatively low power above user aircraft altitude levels. Omega is almost impossible to jam. (Ref. J. Saganowich, G. Litchford, Fort Monmouth).


MCDU
NAV1
NAV3
MENU
MSG
CMA-900 NMU
PWR
FAIL CODE
CANADIAN
MARCONI CO

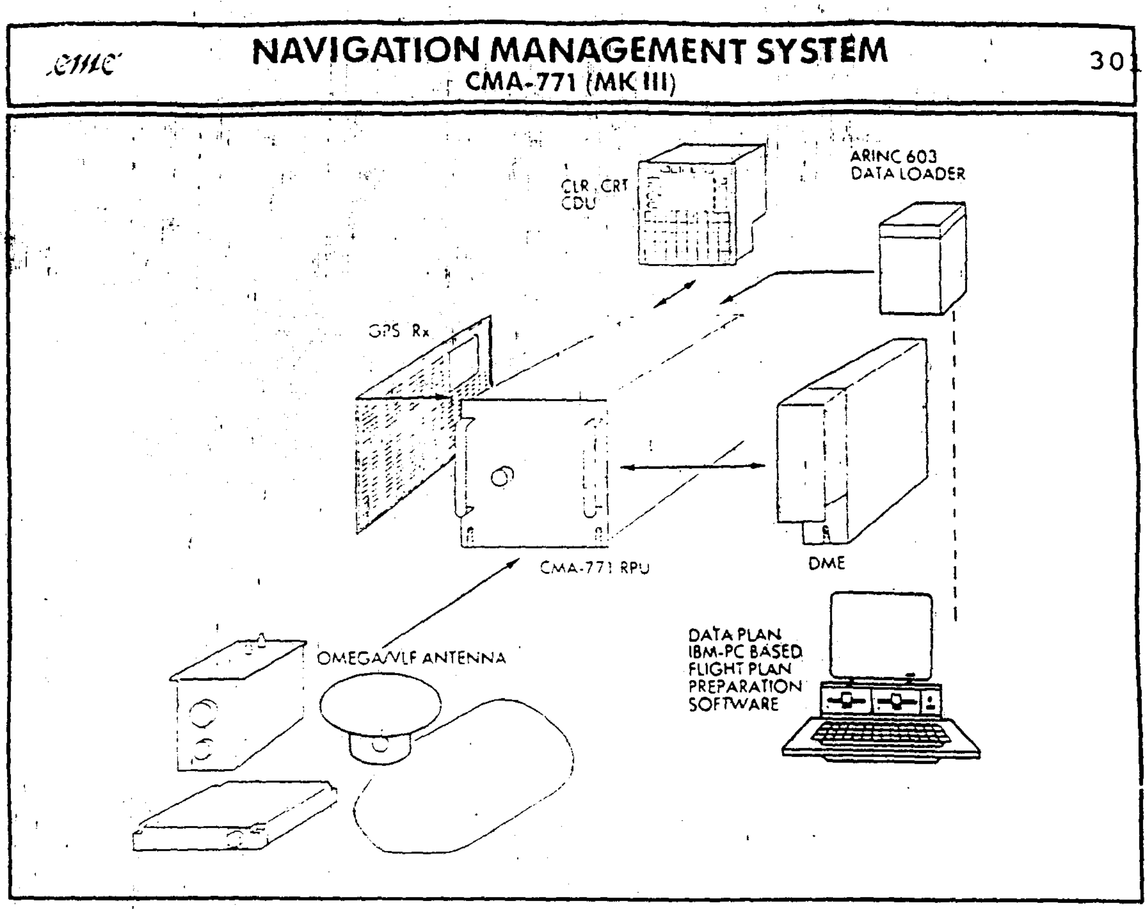


FIGURE 2

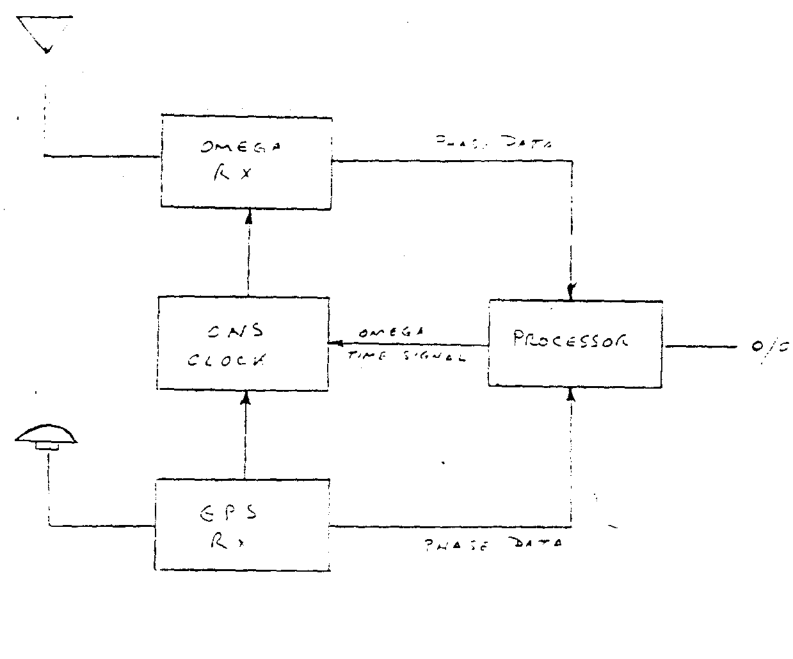
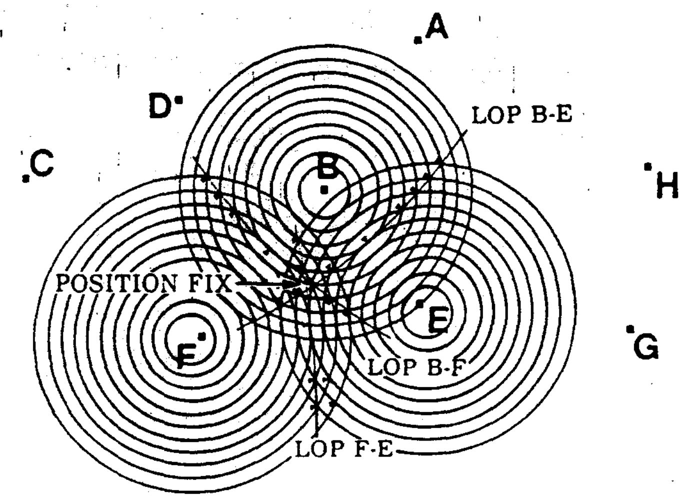


FIGURE 3

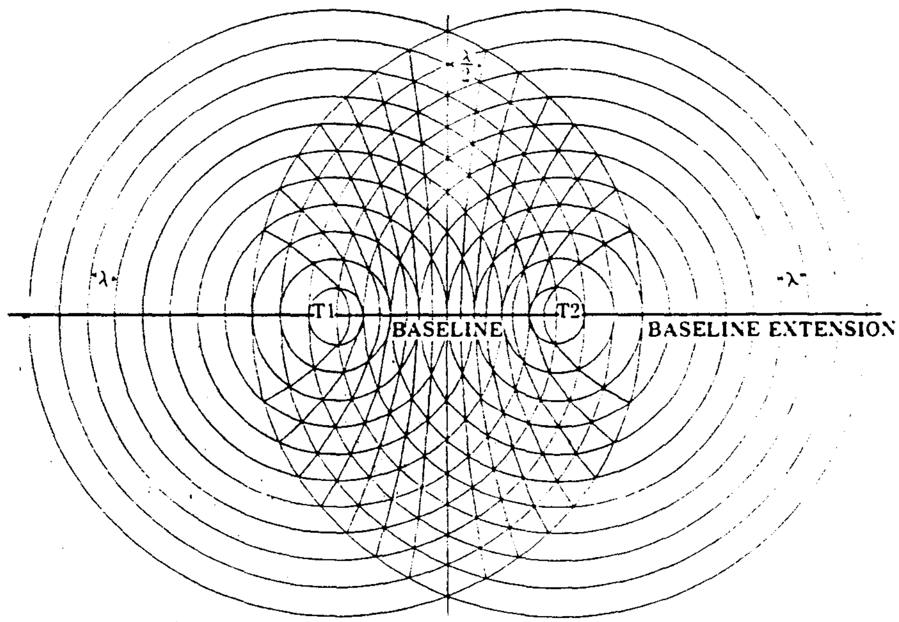


HYPERBOLIC NAVIGATION

NOTE: FOR CLARITY ONLY
THREE LOP'S ARE SHOWN.

CMC OMEGA RECEIVERS UTILIZE
ALL AVAILABLE LOP'S.

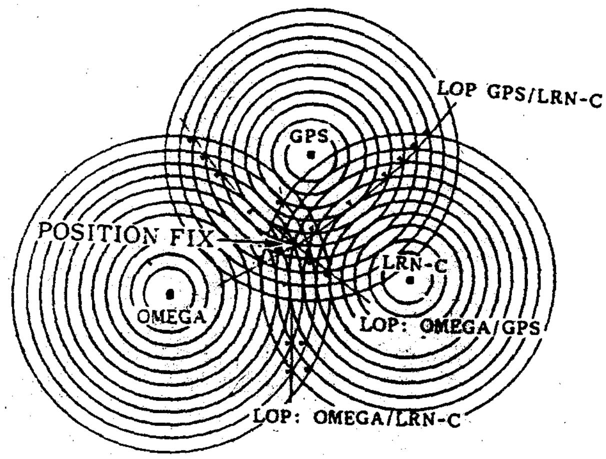
FIGURE 4A



T1 - OMEGA TRANSMITTER

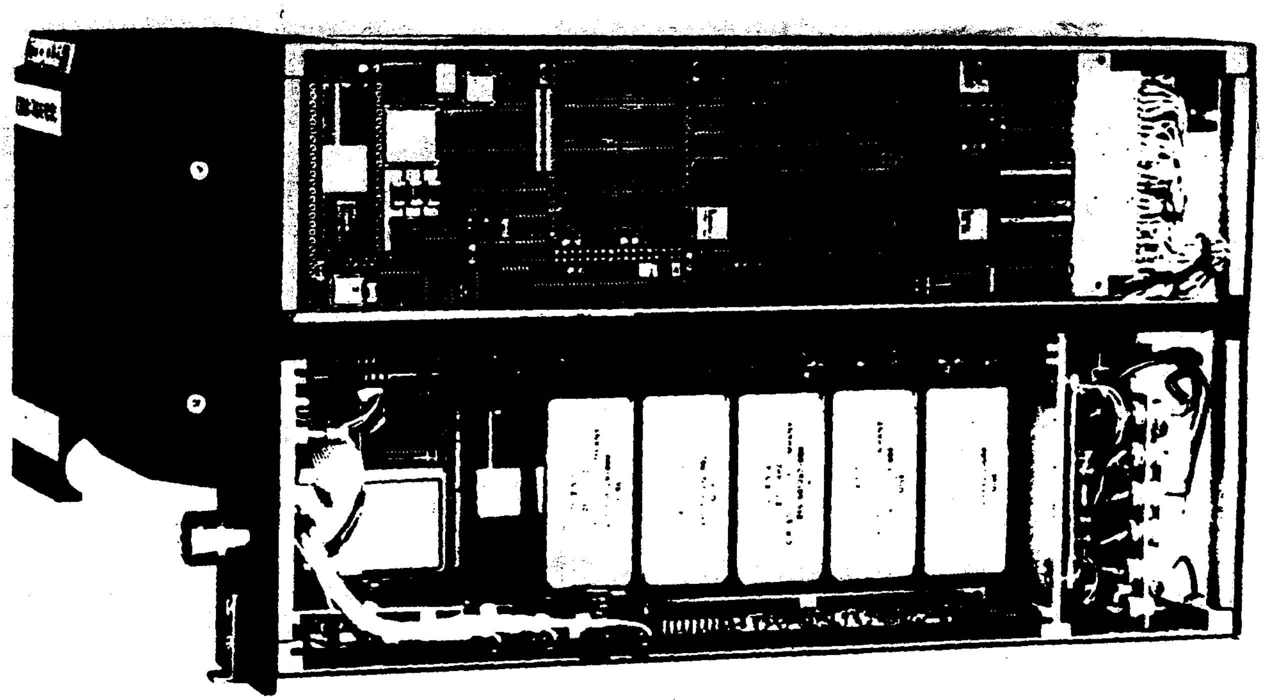
T2 - GPS SATELLITE TRANSMITTER

FIGURE 4B



HYPERBOLIC NAVIGATION

FIGURE 5



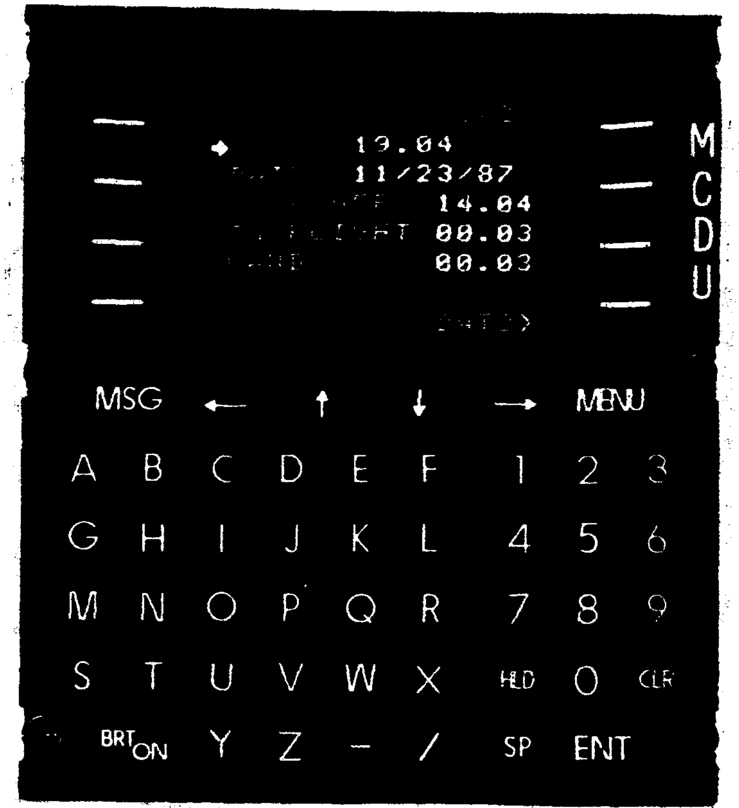


FIGURE 7

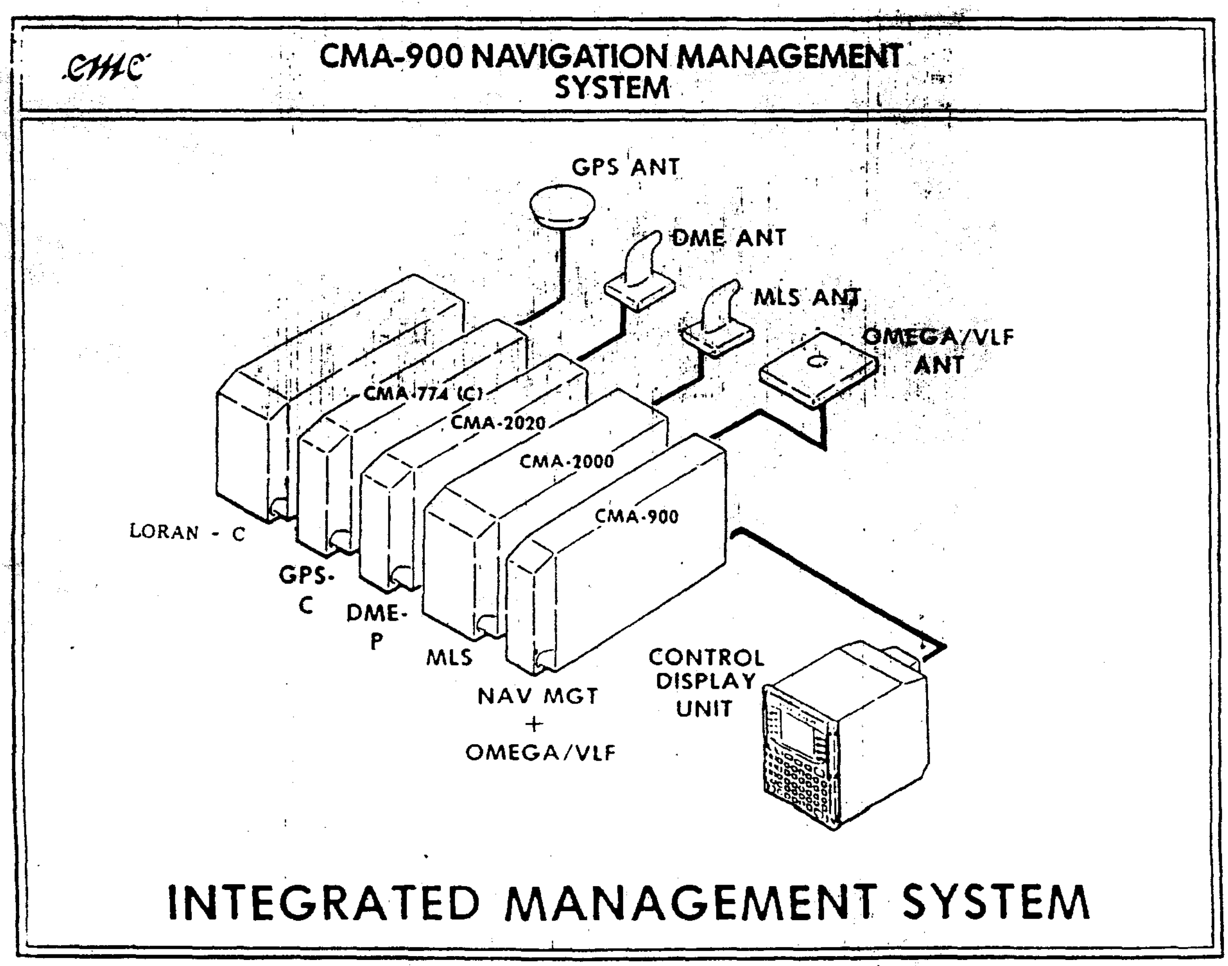


FIGURE 8

LORAN/GPS INTEROPERABILITY: PAST, PRESENT AND FUTURE

by

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and
Russ Gordon

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Sunnyvale,CA 94086

Abstract

During the past few years, the Radio Technical Commission for Aeronautics (RTCA) has been developing guidelines for GPS and LORAN equipment used in the National Airspace System (NAS). During this same period of time, Trimble Navigation has built a LORAN/GPS product called the 10X Navigator. In this paper we review our operational experiences with this equipment and analyze established and pending FAA regulations. Based on this survey of regulatory and technological considerations we make some predictions concerning the future of LORAN/GPS Interoperability.

OPERATIONAL EXPERIENCE WITH A LORAN/GPS RECEIVER

Figure 1 shows the block diagram of Trimble's 10X Navigator. The 10X has both a LORAN and a GPS sensor. Both sensors are independently powered and work from separate clocks. Their outputs may be combined together by a central processor called the input output processor (IOP) to provide position outputs. In addition to the radionavigational sensors, the 10X can also use speed and heading inputs derived from a number of external devices such as synchros, gyros, steppers and speed-logs to operate in a dead-reckoning (DR) mode.

The output from the 10X can be sent to one or two control/display units (CDUs), a number of different auto-pilots, and up to three other external devices.

The GPS portion of the 10X is a two channel, sequencing, C/A code, L1 receiver. It sequences at a 0.5 sec. rate and tracks all satellites in view.

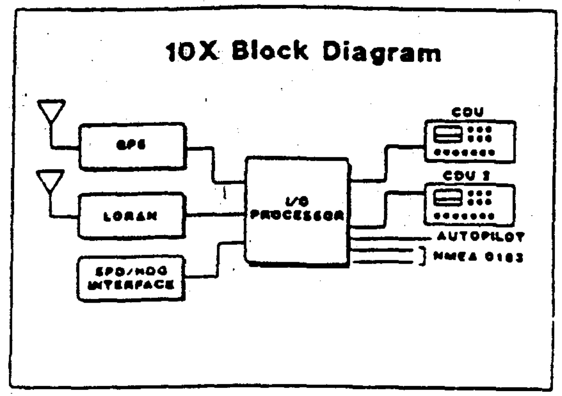

Figure 1

The LORAN portion of the 10X uses Trimble's all-digital LORAN technology. This receiver uses a signal processing chip rather than analog components to implement a high quality, linear LORAN receiver with extremely precise bandpass characteristics and variable, high-Q notches. A comparison of the standard analog LORAN and the Digital LORAN sensor block diagram can be seen in Figure 2.

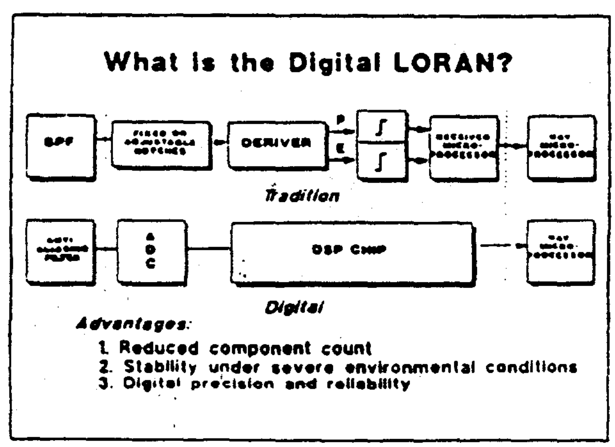

Figure 2

Purposes of the 10X

The 10X was designed three years ago for a marine environment-long before LORAN/GPS Interoperability was common terminology. The original goals of the Navigator had little to do with the reasons for LORAN/GPS interoperability currently receiving so much attention. Nevertheless, the features listed below are still valid in the environment that will exist for the next few years until the full constellation of GPS satellites is available.

Extended Range for LORAN-

The ability to obtain "oceanic" precision position fixes far from land and normal LORAN coverage areas was and is of importance. The 10X provides this extended range by augmenting the LORAN sensor with lines of position (LOP) obtained from the two GPS satellites hence requiring only one time difference (TD) and frequently improving the geometry.

Improved Precision for LORAN

Another important mode for the 10X is its ability to provide extremely precise LORAN position fixes. This mode is made possible by calibrating the LORAN receiver during periods of GPS coverage. The LORAN repeatability numbers then become its absolute accuracy specs. This will typically give a factor of 5 improvements in absolute accuracy.

Integrity Monitoring for LORAN

Because the 10X is frequently used in poor coverage areas, GPS (when available) is used as a means of "confirming" the integrity of the LORAN solution. If the actual LORAN TD measurement and the GPS predicted measurement agree, a TD is marked "confirmed" and cycle selection on the LORAN signal is discontinued. If the position fixes don't agree, the LORAN is allowed (and sometimes forced) to determine the correct cycle.

Extended Availability for GPS

The most important advantage of the 10X is it's ability to extend GPS availability. GPS IS A BETTER, MORE ACCURATE AND ROBUST NAVIGATION SYSTEM THAN LORAN. A primary goal of the 10X is to extend the periods of time that GPS can be used in the position solution.

Additional information on the exact specifications of the sensors and Kalman filter may be found in References 1-5.

Performance Characteristics

Figure 3 shows a comparison of LORAN and GPS data taken from the 10X over a three day period. The center of the figure is surveyed antenna location at Trimble Navigation in Sunnyvale, CA.

We can see that both GPS and LORAN data have roughly the same scatter characteristics, but the GPS data contains considerably less measurement bias. It should also be pointed out that the LORAN data has slightly smaller filter bandwidth than the GPS data. Nevertheless, it has been our experience that LORAN and GPS measurements can be considered as equals with the exception that LORAN measurements have biases that change (slowly) with position and time. This is an important observation, since it greatly influences the design of interoperable systems.

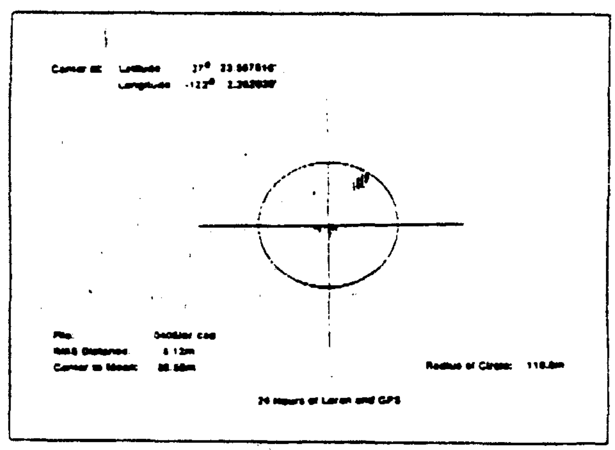

Figure 3

Figure 4 shows LORAN data after it has been corrected by measurements made during periods of GPS availability. The correc tions to the data collected in the LORAN only mode of operation are corrected in the state space of our filter. It is our intention to change this characteristic of our filter to make the bias corrections to the LORAN pseudoranges in measurement space.

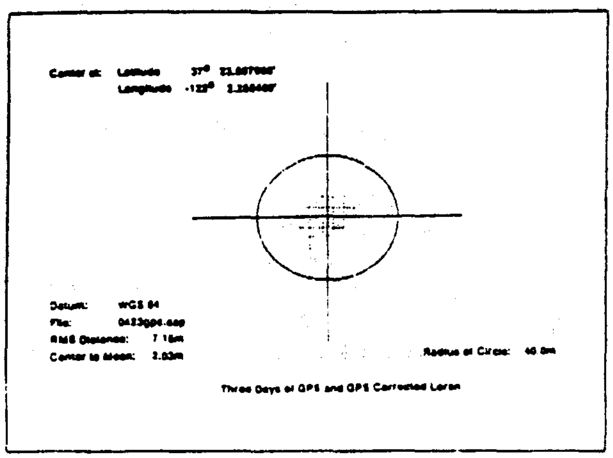

Figure 4

Our static tests, however, indicate that GPS derived LORAN bias estimation can be extremely effective over time. The quality of the bias estimate over space, i.e., when the receiver is moving, is more difficult to estimate and may cause some problems. Differences in the dynamic behavior of LORAN and GPS can be modeled in the filter. Rapid fluctuations of propagation anomalies in the LORAN measurements as a function of position, however, can't be eliminated.

Nevertheless, dynamic performance of the 10X shows excellent agreement between the LORAN and GPS positions obtained. Figures 5 and 6 show actual data obtained during operational testing of the 10X. Figure 5 shows the LORAN and GPS positions obtained during departure from San Jose Airport and Figure 6 shows the results of a standard rate turn.

THE PRESENT REGULATORY ENVIRONMENT

Given that brief review of the performance of a combined LORAN/GPS receiver, we'd like to review the regulatory environment before making a set of recommendations concerning future architectures for interoperable receivers.

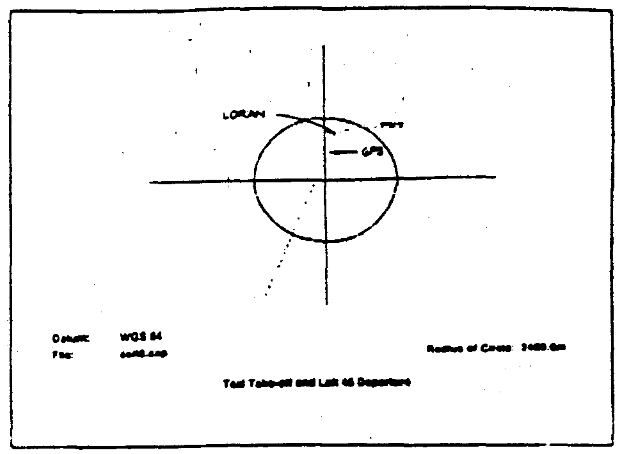

Figure 5

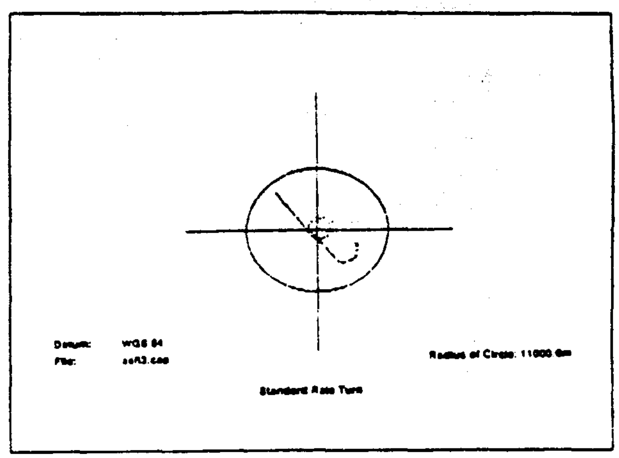

Figure 6

The 1984 Federal Radionavigation Plan[6] seems designed to accomplish two purposes. First, it calls for the phaseout of several obsolete and redundant navigation systems for the purpose of limiting the government's maintenance and operational expenses. Specifically, it recommends the VOR/DME system, currently used as a primary means of aircraft navigation, be phased out in 1997. Second, it specifies improved performance goals for systems used in the NAS.

Both of these goals seem logical, especially since the GPS system is scheduled for full deployment by 1992. It may, however, be later than 1997 before the old systems can be obsoleted.

The requirements for navigation equipment used in aircraft can be broken into two categories: supplemental navigation systems and sole-means navigation systems.

Regulations for Supplemental Navigation Systems

The FAA has released minimum performance requirements for LORAN equipment when the equipment is used as a supplemental means of navigation. The RTCA has also completed its recommendations on a minimum aviation performance standard for GPS.

We expect that manufacturers will increase production of equipment to meet these requirements since certification is a prerequisite to sales into high-end market segments. Once software and hardware have been designed which meet the requirements for high-end products, the same designs will be cost-reduced and sold at the low-end.

In order to comply with these requirements a complicated maze of regulations must first be understood. Environmental standards are contained in DO-160B[7]. This document outlines the categories and test standards for various types of avionics. Applicability of DO-160B varies with type of equipment and level of certification desired.

Software standards for all digital computer-based avionics equipment should conform to the requirements of DO-178A[8]. While compliance with this document is not the only means of FAA software approval, it is the most expedient[9].

LORAN as a Supplemental Navigation System

LORAN C units must meet the minimum performance performance standards prescribed in TSO C60B[10] to be IFR certifiable. Units not meeting TSO C60B standards may obtain field approval of installation through FAA Form 337, limiting their use to operation under VFR conditions.

In addition to TSO C60B approval, installed performance and accuracy standards in AC20-121A[11] must be met. Standards for IFR approval are stricter and more numerous than VFR approval standards.

Integrated navigation units using LORAN C in addition to or in conjunction with other navigation sources are addressed under multi-sensor navigation devices.

GPS as a Supplemental Navigation System

Currently there is no TSO outlining minimum performance standards for GPS receivers. Special Committee 159 of the RTCA has written a document[12] which combined with DO-160B and DO-178A, will likely form the basis of the GPS TSO.

Multi-Sensor Navigation Devices

Navigation devices using multiple sensors to derive position data are addressed under TSO C115[13]. Current navigation management and flight management systems fall into this category.

Examples of such systems include BENDIX/KING's KNS 660, Global-Wulfsberg's GNS X and Universal's UNS 1A. These units combine LORAN C and GPS with VLF OMEGA, VOR and DME. A hybrid LORAN/GPS system would be approved under the same TSO.

Installed accuracy and performance of multi-sensor navs must meet requirements established in AC 90-45A[14].

IFR Certification of LORAN/GPS Interoperable Systems

Compliance with TSO C115 is a prerequisite for IFR certification. Additionally, operational accuracy must conform to standards contained in AC 90-45A. IFR certification for a particular aircraft type may be acquired during the initial certification of type. In this instance the certified installation becomes a part of the Type Certificate. The more common form of approval is the Supplemental Type Certificate (STC), which is obtained subsequent to Type Certification.

After an STC is obtained, approval in other types of aircraft begins with installing the unit in a similar manner. Performance and accuracy in other aircraft must be proven to equal the performance documented in the STC. An aircraft flight manual supplement is written for each installation and submitted with a Form 337 to the FAA Flight Standards District Office having jurisdiction over the installing facility.

Navigation devices may be approved either on a sole-means or supplemental basis. A LORAN/GPS system cannot be approved as a sole-means navigation system under the current multi-sensor system specification (TSO C115), because neither system is approved as a sole-means system[15].

Regulations for Sole-Means Navigation Systems

While the requirements for LORAN or GPS Supplemental Navigation Systems seem clear and attainable, the requirements for sole-means navigation cannot be met by either system. This leaves the question, "What manner of system can meet the sole-means requirements and serve as the replacement for the VOR/DME network?".

The sole means requirements that cause problems are the requirements for integrity monitoring and time to alarm. As designed, the GPS system is capable of providing continuous, worldwide position fixes. It is, however, the recommendation of SC159 that the GPS system not only provide a position fix, but be capable of checking its integrity. The integrity and time to alarm requirements used by the committee were derived from VOR non-precision approach requirements. These requirements are shown in Table I below. Additionally, the FAA has taken the position that the GPS system must work even in the absence of one satellite.

The FAA's position is understandable. It is logical that any system, as important to the infra-structure of our society as the aviation system is, must be capable of fault detection. It must also be redundant enough to allow a single component failure. This should be true especially when the repair of the failure might involve a space launch. It would also seem logical that any new system installed in the NAS be as robust and capable as we can make it given certain technological and economic constraints.

When the GPS system is put to this test, it fails to provide adequate coverage. A sufficient condition to meet the FAA's criteria is that five satellites be in view, where all combinations of four satellites have a position dilution of precision (PDOP) of less than six[12].

Some of the earliest GPS integrity work was done under the assumption that only 18 satellites and 3 spares would be in the constellation. Recently, the Department of Defense has announced it's intention to return to the original 24 satellite constellation. While this increase in satellites greatly improves the number of satellites available at any given time, it still cannot prevent 5 percent lapses in the coverage necessary to do receiver autonomous integrity monitoring (RAIM)[12,16,17].

A SUMMARY OF THE TECHNICAL SOLUTIONS TO THE SOLE MEANS INTEGRITY PROBLEM

We have already noted only four satellites are necessary to obtain a three dimensional position fix, however, five are necessary to obtain an integrity check. It is also appropriate to mention that the periods of RAIM outage are predictable. Hence, what is required to solve the integrity problem is a means of supplying other measurements to the receiver to assure the integrity of the position solution during those predictable periods when GPS is not capable of determining its own integrity.

The proposed solutions to the GPS integrity issue can be divided into four categories:

Internal Aiding
External Integrity Monitoring
Constellation Changes
Requirements Changes

We would like to briefly summarize the technical feasibility of each of these solutions.

Integrity Criteria

Present Requirements

	En Route Ocean	En Route Domestic	Terminal Area	Nonprecision Approach
Alarm Limit*	12.6 nmi	1.5 nmi	1.1 nmi	0.3 nmi
Time to Alarm	120 sec	60 sec	15 sec	10 sec

Goals for Integrity Criteria

	En Route Ocean	En Route Domestic	Terminal Area	Nonprecision Approach
Alarm Limit*	5,000 m	1,000 m	500 m	100 m
Time to Alarm	30 sec	30 sec	10 sec	6 sec

* Radial horizontal position error

Table 1

Internal Aiding

GPS/LORAN

One of the most promising techniques for GPS aiding is to combine it with LORAN inputs. Several architectures for such a receiver have been proposed[18].

We feel the architecture shown in Figure 7 below, involving a common clock for both the LORAN and the GPS sensors, is the most powerful combination and technically feasible. In this type of receiver, both LORAN and GPS pseudoranges are used in the position solution. The advantages of this type of receiver are:

1) The common clock requires one less Line of Position (LOP) than designs with independent clocks for the two receivers.

2) The use of pseudoranges in the solution is a natural form for LORAN/GPS filters as well as Cross-Chain LORAN/LORAN filters. This is especially true once all LORAN master station emissions are synchronized to UTC.

3) The creation of fault detection heuristics is simplified by the homogeneous treatment of all signals.

4) The use of such a receiver wil provide the maximum coverage an availability prior to full deployment of the GPS system.

In a paper by Brown and McBurney[18], a system like the one we advocate was analyzed The analysis was primarily concerned wit the integrity monitoring capability of the interoperable system. While the system wa generally determined to work an obscur mode was identified which could cause detection failure. This failure mode mus be studied further but we feel most of th internal aiding methods can have obscure failure modes: the question becomes one of probability.

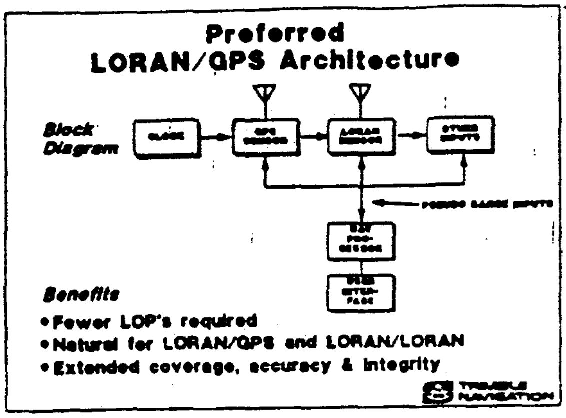

Figure 7

GPS/BAROMETRIC ALTIMETER

The barometric altimeter has been studied and has proven to be effective for enroute applications. The system analyzed kept barometric altitude calibrated to GPS altitude during periods of good coverage. Only during the predictable periods of RAIM outage was the altimeter used[19].

In another paper[20] on the same type of system, operational tests were performed by the Department of Transportation. Results indicated that altimeter aiding during periods of poor vertical dilution of position (VDOP) degraded GPS performance.

GPS/CLOCK

High quality clocks have also been considered as a means of aiding GPS[21].

One paper concludes that a clock with a short term stability of 10^{-10} can be used to perform RAIM aiding for periods of up to 15 minutes[22]. Such short term stability is relatively easy to achieve as long as the temperature remains constant during the 15 minute interval. A stability of 10^{-10} over temperature, however, could require prohibitively expensive clocks.

GPS/INS

In the studies that have been performed on combinations of GPS and INS, GPS has been used to provide a means of calibrating the inertial system. Results to date are inconclusive as far as the systems capabilities since the exact nature of selective availability (S/A)[23] must be considered before the results can be predicted. This is certainly one of the more expensive alternatives for the user of this equipment.

External Aiding

In addition to the techniques studied above, other alternatives for monitoring GPS integrity include means by which the navigation system is externally informed of a failure or externally supplied with the information require to make the integrity determination. Of the systems proposed, several not only provide the required integrity monitoring, but also improve the accuracy of the GPS system by providing differential measurements using the RTCM 104 protocols and eliminate the adverse effects of Selective Availability.

The solutions that improve the accuracy of the system as well as provide the integrity monitoring seem most desirable. It appears, however, that considerable time and study will have to go into the various proposals before funding can be obtained to implement the differential monitors or pseudolites necessary for such solutions. For this reason, the systems listed below are not considered in detail.

GPS Integrity Channel(GIC)[24]
Long-Baseline Differential GPS[25]
Local GPS Monitors[26]
Pseudolites[27]

External systems involving differential will solve the integrity problems, reduce the effects of selective availability, and increase the accuracy of GPS. Long term, such external solutions seem the most robust.

The Table below, reprinted from Appendix B of the SC159 Report, summarizes the different alternatives for receiver autonomous navigation systems and for certain external alternatives. In the case of each alternative listed below, the committee has studied its' characteristics and concluded whether or not the system meets the requirements dictated by the FRP.

SUMMARY OF WORKING GROUP ANALYSES

		En Route Ocean			En Route Domestic			Terminal			Nonprecision Approach		
		REQ	GOAL	COV	REQ	GOAL	COV	REQ	GOAL	COV	REQ	GOAL	COV
Stand-alone GPS System													
2.2.2	Self Contained GPS	Y	Y	N	Y	Y	N	Y	Y	N	Y	N	N
2.2.3	GPS Integrity Channel (GIC)	Y	Y	N	Y	Y	N	Y	Y	N	Y	N	N
2.2.3.2	GEO GPS/GIC	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	N	Y
GPS hybrid Systems													
2.2.4.2	GPS/Baro*	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	N	N
2.2.4.3	GPS/IRS	Y	Y	Y	Y	N	Y	N	N	N	N	N	N
2.2.4.4	GPS/LORAN-C	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	N	Y
GPS as a Supplemental System													
2.2.4.5	GPS/OMEGA	Y	N		N	N		N	N		N	N	
2.2.4.6	GPS/Multi-Sensor	Y	Y		Y	N		Y	N		Y	N	
2.2.4.7	GPS/VOR/DME-RNAV	N	N		Y	N		Y	N		Y	N	

REQ: Technique Meets GPS Integrity Requirements

GOAL: Technique Meets GPS Integrity Goals

COV: Technique Meets Coverage Requirements for GPS Sole Means

NOTE: The results shown for integrated GPS systems describe only the requirements that can be met without relying on information from redundant GPS satellites.

* Further study is required to confirm coverage is available for oceanic navigation.

Table 2

Constellation Changes

In addition to the internal and external aiding techniques mentioned above, changes to the constellation could be made. Several possibilities are described in the references. One obvious alternative is to increase the number of satellites. This seems unlikely since only recently the planned number of satellites had been decreased to reduce deployment costs. Another alternative that has been mentioned is to slightly modify the orbits to improve coverage in certain areas of the world[18].

Requirements Changes

The last possibility, is to change the requirements. Either the accuracy goals or the integrity goals could be changed if it were discovered that the costs of implementing the desired system where too high or that other, less expensive means where available.

CONCLUSIONS FROM REGULATORY AND TECHNICAL ANALYSIS

In the short term, LORAN and GPS systems meeting the requirements for Supplemental Navigation Systems will become common. These systems will use LORAN/GPS interoperability for the same purposes as those articulated for the 10X: to improve coverage and availability.

Within the next ten years, GPS/LORAN will become the domestic standard for Sole Means Navigation. It is likely that such systems may also include barometric altimeter aiding since such interfacing would be both easy and low cost. We feel that this will become the answer because:

It is one thing to read the FAA regulations to determine the minimum operational requirements, it is another to ask, as a matter of national policy, what is the best and safest. An interoperable LORAN/GPS solution will provide the most robust radio-navigation system alternative to the current VOR/DME approach.

The cost of a LORAN receiver is not a significant factor in the cost of equipment to the user. Already, the cost of the receiver in a Supplemental LORAN Navigation System is less than 15 percent of the system cost. The price of the package, power supplies, displays, keyboard, database and distribution dominate the user equipment costs.

By the time the FAA reaches a consensus on the exact requirements for certification of GPS based equipment for sole-means navigation systems, the LORAN/GPS solution will have been implemented by many manufactures as a means for providing Supplemental GPS navigation before the full constellation is deployed.

Long-Term, Differential GPS capabilities of some form will be added to the NAS and precision and non-precision approaches using the same equipment will become possible.

Ground based, rather than satellite based communications will prove more economical for integrity monitoring. Once the communication channel is established for integrity, the possibility of differential accuracy will be compelling. The accuracy obtained by differential systems will have profound effects on ATC procedures, collision avoidance, and NAS operations in general.

ACKNOWLEDGMENTS

The authors would like to acknowledge Ralph Eschenbach, Len Kruczynski and Anil Tiwari who worked on the 10X design and who have contributed many suggestions for this paper. We would also like to thank Chris Sieracki who prototyped the new receiver, and Kathy Porter and Laura Hurn for the graphics and layout of this paper.

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THE USE OF A GPS CALIBRATED LORAN-C NAVIGATION SYSTEM FOR OCEAN SURVEY

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Abstract

This paper presents the results of tests performed to validate the use of an ANI-7000 Loran-C receiver as a reference for ocean surveying. An aircraft was flown over a 60 mile square perimeter during GPS coverage time. Position measurements were recorded from the ANI-7000 as well as a Litton LTN-700 GPS receiver during the flight. The measurements were post-processed to determine the position differences; these differences were used to develop calibration constants for use by the Loran-C receiver in a calibrated mode of operation. Several test flights and survey flights were performed and the data analyzed in terms of accuracy, stability and grid warp characteristics.

1. INTRODUCTION

This paper results from a collection program performed in an area located 200 miles west of Seattle, Washington. Specifically, a section of the ocean was mapped repeatedly for several days. The track angles of the aircraft passes were based on known wind directions as determined by surface measurements. The INS position estimates used for navigation were not suffiiciently accurate for the test program. As a result, a GPS calibrated Loran-C receiver was used to augment the INS prior to each mapping pass. This paper describes the navigation system implemented to achieve this enhanced accuracy along with a description of the survey testing performed to calibrate the Loran-C receiver. Analysis to validate the navigation system performance is also described.

2. NAVIGATION SYSTEM DESCRIPTION

The aircraft navigation system as originally designed consisted simply of an LTN-51 Inertial Navigation System (INS) which was coupled to the aircraft's autopilot. Computer-generated waypoints which define aircraft pass lines were input to the INS before each pass. Staying on the given line (at the proper specified altitude), then, was paramount to making that pass a successful data collection pass. The success of the navigation method is determined by how closely the airplane followed these lines in earth coordinates.

In previous measurement programs, the INS position was updated before each pass by means of a position fix from a tracking radar or other reference source. In this program, such reference sources were not available in the test area and an alternate reference was needed. Loran-C, being designed for marine navigation, provided such a reference in the test area. However, Loran-C itself, while being stable, is not necessarily accurate in absolute position because of local biases due to RF propagation effects. The Global Positioning System (GPS) provides a very accurate (25 to 40 meter error) absolute position but, because the satellite constellation is incomplete, it is only available for several hours each day. In order to provide accurate navigation, a system using GPS to calibrate Loran-C, and using Loran-C in turn to update the INS before each pass, was developed. The system realization is shown in Figure 1.

2.1 EQUIPMENT DESCRIPTION

An ANI-7000 Loran-C system and an LTN-700 GPS system were installed along with a computer defined as the Navigation Computer. The INS sends data to the autopilot and the computer. Universal Coordinated Time is sent to the Navigation Computer from the Time Code Receiver (TCR). The GPS and Loran-C units send data to the Navigation Computer via RS-232 interfaces.

The Control and Display Units (CDUs) of the GPS and Loran-C systems were mounted near the INS CDU in the navigator's station to allow one person to operate all three systems. Each CDU is equipped with a "Position Hold" button which freezes the display while continuously calculating the current position internally. Upon release of the hold, the new position entered is automatically updated to the new current position. This makes in-flight position updates possible. The operator pushes the Loran-C and INS CDU hold buttons simultaneously and then transfers the Loran-C position to the INS. After the transfer is complete and verified for accuracy, the hold buttons are released.

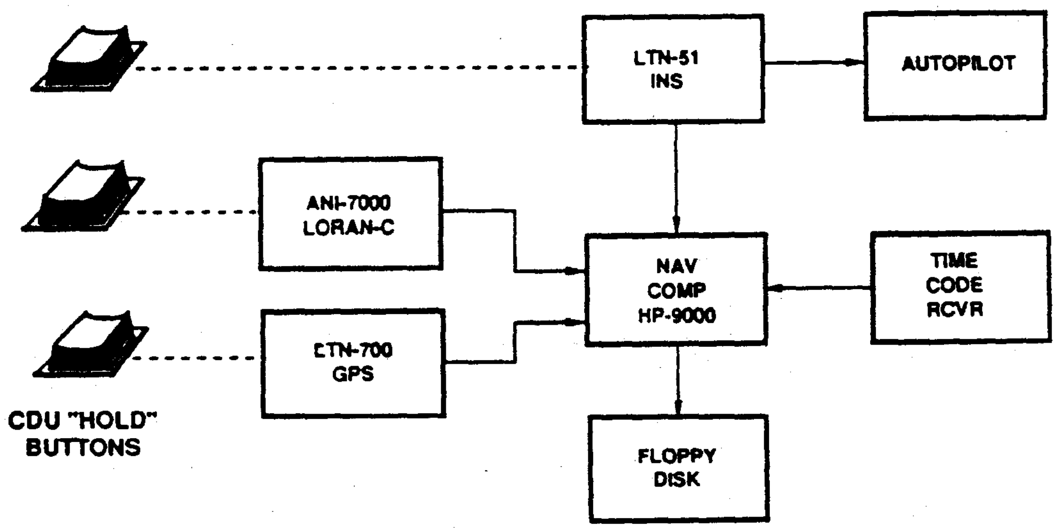

Figure 1 Navigation System Block Diagram

The Loran-C receiver was operated in three different modes during the test program. The modes are defined below.

Automatic - provides a position solution based on measurements from all available stations

Dedicated - provides a position solution based on measurements from three stations defined by the operator

Calibrate - provides a differential position solution relative to a location defined by the operator.

The GPS receiver was operated in the normal mode where four satellites were required to provide a three-dimensional position solution.

2.2 DATA LOGGING

In addition to the manual entry and display of the data at the CDU, the data is also available on a serial output port from each navigation device. A block of data is output from each port approximately once each second. The GPS and Loran data blocks along with the INS and TCR data blocks are sent to the Navigation Computer for transmission to the microdiskette. The four data blocks are read into the Navigation Computer on a priority encoded interrupt system. As each block is received by the Navigation Computer, it is stamped with a time of arrival.

Position (latitude and longitude), time of arrival, and error status are a few of the data words received in the data block from each source. The data block from GPS additionally includes altitude, HDOP (Horizontal Dilution of Precision), VDOP, Vertical Dilution of Precision) and satellite coverage and SNR. The Loran data block includes the current waypoints, aircraft groundspeed, and cross-track error. The four data blocks form a single 58-word data block within the Navigation Computer. Select values are displayed on the Navigation Computer screen and updated once each second. The entire block of data is transferred to a buffer every five seconds. The buffer, after accumulating one minute of data, stores the data on microdiskette. Each microdiskette can store 2 hours of data. The buffer is designed such that no data is lost when disks are exchanged, allowing continuous data to be collected over long periods of time.

To perform the Loran calibration, it is of major importance to keep track of the time of Loran and GPS positional validity. If positions are compared that were not recorded at the same time, or if this time skew is not accounted for, the resulting error will appear as grid warp. For example, if the aircraft speed is 250 knots, a one second error in the time of recording Loran position (perhaps due to a late time stamp) will result in up to 420 feet (depending on the aircraft heading) of apparent grid warp. Note that the absolute time of position validity is not needed. Only a relative time is required to allow the GPS and Loran position samples to be time synchronized.

Within the HP9000 Navigation Computer is a timer, accurate to 10 milliseconds, which is used to provide the time stamp. The time stamp is performed at the time the interrupt from the GPS or Loran unit is serviced. Assuming the position data is valid at the time it is output to the Navigation Computer, the time stamp is accurate to the resolution of the timer. Unfortunately, this assumption has not been validated. Therefore, steps were taken during the calibration analysis to minimize the effects of possible position validity errors.

3. ANALYSIS TOOLS AND METHOD

Calibration of Loran is performed post-flight using the data stored on microdiskette. Software tools are available to plot each data word in terms of samples, seconds, or mapping passes and to perform more elaborate analysis on the GPS and Loran position data. In addition to providing latitude versus longitude plots, the tools can perform time synchronization of the positions, calculate the GPS and Loran latitude and longitude differences, and perform statistic calculations on the differences (average, standard deviation, least square fit, and residual RMS error). The majority of this paper is based on these calculations.

Because of the possible unknown time of position validity, the time synchronization performed may not completely align the position samples. Two methods were used to bypass this potential problem. The first involved flying cardinal headings (i.e., East-West and North-South). By doing this, the time delay only affects one component of the position at a time. (This was done in the first two days of testing.) Box patterns were flown and the biases, or grid warp, were extracted one component at a time.

The second method exploits the fact that by flying the same line at opposite headings and compensating for groundspeed changes, any constant time delay effect in the biases can be cancelled out. This method was used on the third through tenth day of the test. Appendix A provides the details of the calculation. The equations provide a way of determining the overall navigation system time delay. The results of the time delay calculation show that a time delay is indeed present in the system, but the place where it is introduced has not yet been determined.

4. NAVIGATION SYSTEM PERFORMANCE VALIDATION

Navigation validation was performed by collecting GPS and Loran-C data during a series of measurement passes in the area in which mapping operations took place. Two types of passes were analyzed. First, several passes were made along the perimeter of a 60 mile square box encompassing the operations area. This phase of the testing is identified as survey testing. Next, data were collected during mapping passes; this phase is identified as mapping passes.

4.1 SURVEY TESTING OVERVIEW

Survey testing was performed over a period of four days. The first day the perimeter of a 60 nautical mile square was to be flown twice during the four-hour GPS window where both GPS and Loran-C measurements would be collected. The Loran measurements were taken with the receiver in the dedicated triad mode. The purposes of the tests were to:

- measure GPS and Loran position differences and,
- show an indication of hour-to-hour stability of the relative position measurements.

Unfortunately, only three legs of the first square were completed while collecting both the Loran and GPS measurements.

On the second day, two boxes were again scheduled and successfully completed. The first box was flown with the Loran receiver in the calibrate mode using calibration constants calculated from the first day measurements. This portion of the test indicated the accuracy of the Loran receiver when operated in the calibrate mode. The second box was flown using two different uncalibrated modes. One Lat/Long leg pair was flown in the dedicated triad mode to compare with flight conditions of the previous day. The results of the comparison indicate day-to-day GPS/Loran position stability. The other Lat/Long leg pair was flown with the Loran receiver in the automatic mode. This mode provides a position solution based on measurements from all available stations. The results of this portion of the test indicate the Loran navigation accuracy available from an uncalibrated "all-stations" mode of operation.

The third day, one longitude leg of the box was flown in the calibrate mode to validate the effect of a longitude correction change in the receiver. The fourth day survey measurements consisted of two passes; a constant latitude pass and a constant longitude pass were not performed due to procedural failure in collecting the navigation data.

The end result of the limited navigation survey testing is that calibration constants for use by the Loran receiver were obtained but were not well validated. However, the calibration constants determined during these survey tests were used throughout the mapping program, and resulted in acceptable navigation accuracy.

4.2 DETAILED SURVEY TESTING

A detailed discussion of each survey test day is presented in the following paragraphs.

Day One - During this test GPS and Loran-C measurements were collected while the aircraft flew the perimeter of a 60-mile square encompassing the radar mapping operations area. GPS coverage was intermittent during the test time. As a result, data were obtained from only three sides of the square. Figure 2 shows a Lat/Long plot of GPS and Loran. Note that GPS position is erroneous in the bottom leg and some data are missing for the right leg. The loops executed at each corner were used to align the aircraft along the correct flight path and stabilize the aircraft attitude two minutes prior to the start of collecting data. Figure 3 shows a plot of GPS and Loran longitude versus time along the vertical leg. The jumps in the Loran longitude are attributed to discontinuities in the propagation maps used in the Loran receiver. Similar jumps in position were noted in the other two legs of the box where survey data were analyzed. It should be noted that longitude is not constant as a function of time. The slope is due to the fact that the INS used by the aircraft autopilot has a drift resulting in an aircraft position defined by the position estimate of the INS. As a result, this plot can also be used to characterize INS drift characteristics. Figure 4 shows the average GPS/Loran differences for the three useful legs of the box. A comparison of the two longitude legs indicates a bias of 2000-3000 feet. Furthermore it appears that there is a grid warp gradient of 1000 feet across the 60-mile distance between the two legs.

Although no measurements were useful in the bottom leg in Figure 2, analysis of the latitude differences of the left and right legs of the box indicate that the latitude grid warp gradient is also approximately 1000 feet, resulting in an estimate of the GPS/Loran difference for the bottom leg of 5200 feet. Based on these survey conditions, corrections were selected as 2500 feet in longitude and 4600 feet in latitude, and were converted to calibration constants for use by the LORAN receiver.

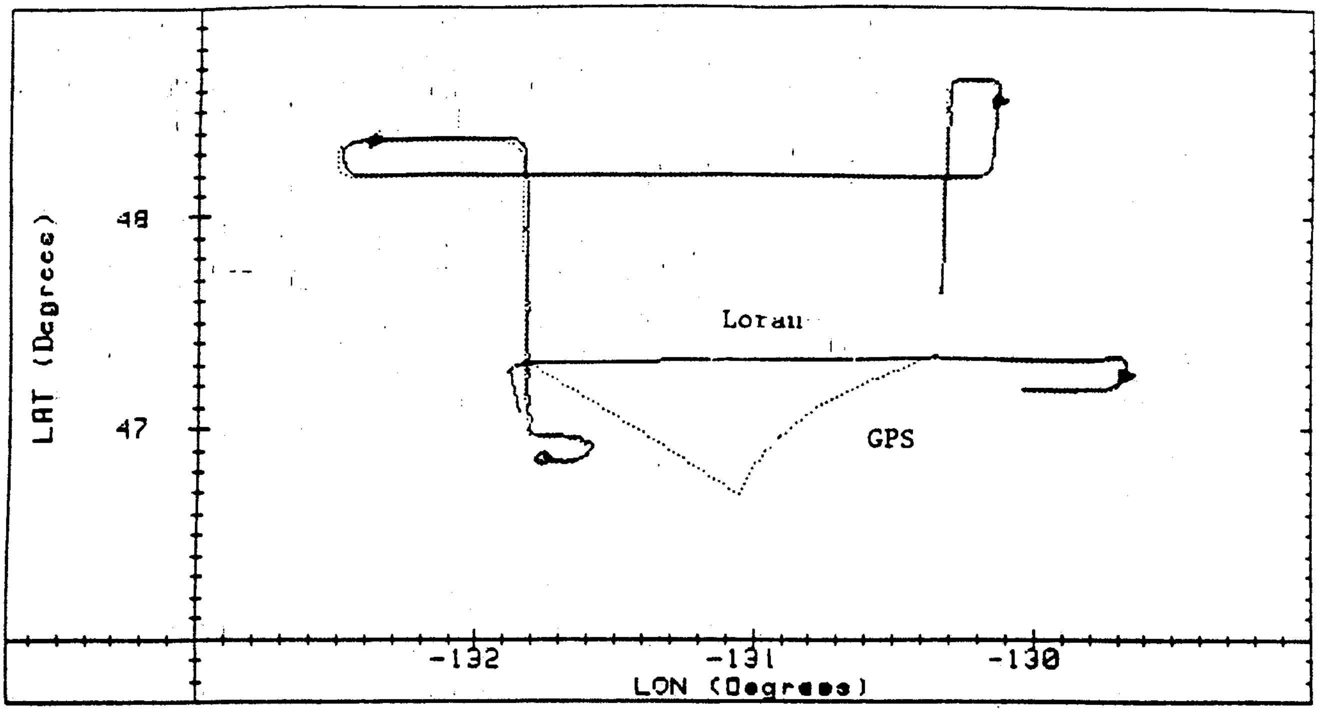

Figure 2 GPS/Loran Position Estimates
(Dedicated Triad Mode) - Day 1

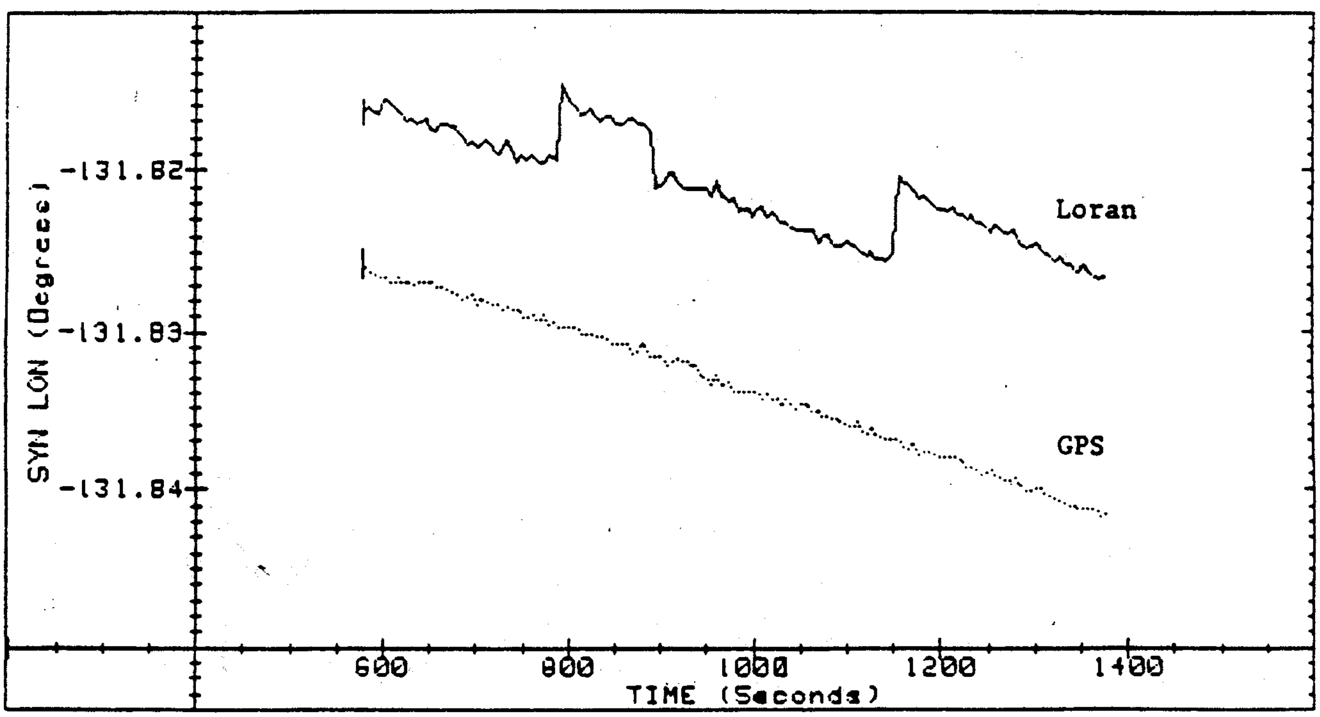

Figure 3 GPS/Loran Longitude Position Estimates
(Dedicated Triad Mode) - Day 1

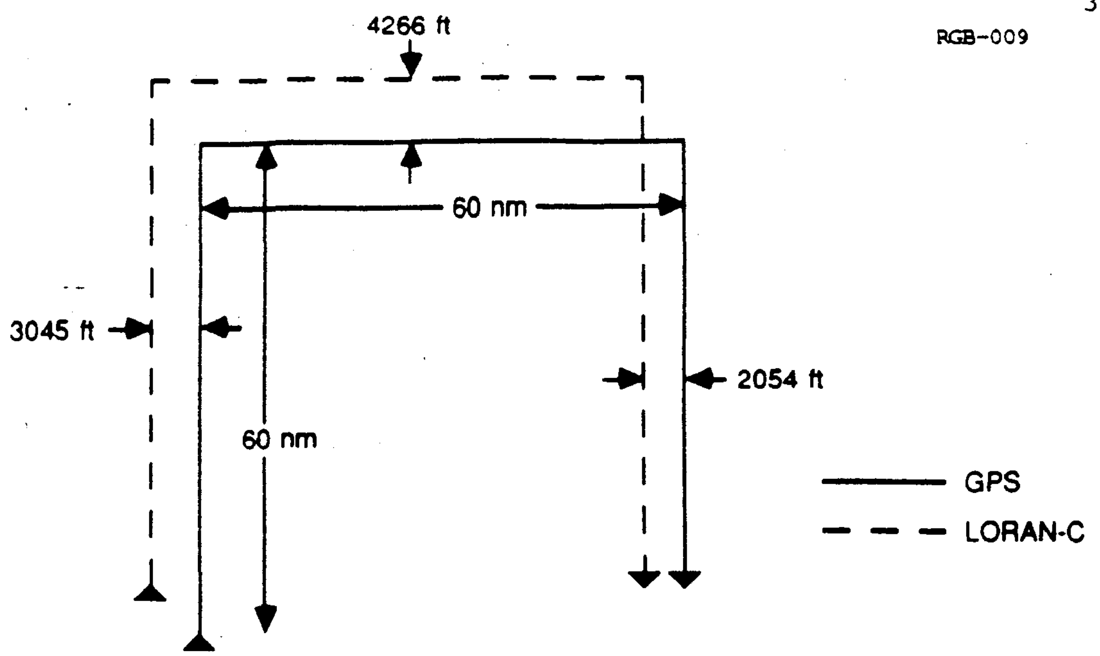

Figure 4 GPS/Loran Survey Results
(Dedicated Triad Mode) - Day 1

Day Two - This test consisted of flying two 60-mile square boxes. The first box was flown with calibration constants, obtained during the Day One flight, and inserted into the Loran receiver while operating in the calibrate mode. The second box was flown in an uncalibrated mode. Two legs were flown in the dedicated triad mode, to get an indication of position measurement stability when compared to the previous day test results. The other two legs were flown in the automatic mode, to determine the accuracy capability of the receiver when using all measurements available from the Canadian and U.S. West Coast Loran chains.

Figure 5 shows the GPS and Loran measurements of longitude vs time taken as the aircraft flew north in the calibrated mode. Note that with the receiver in the calibrated mode, the large discrete jumps in position shown in the uncalibrated mode (Fig. 3) are not apparent. This is because propagation maps internal to the Loran receiver are not used in the calibrated mode. The cyclic behavior in position at the start of the pass was due to an aircraft maneuver to get the aircraft aligned with the proper flight line. Figure 6 shows the longitude differences

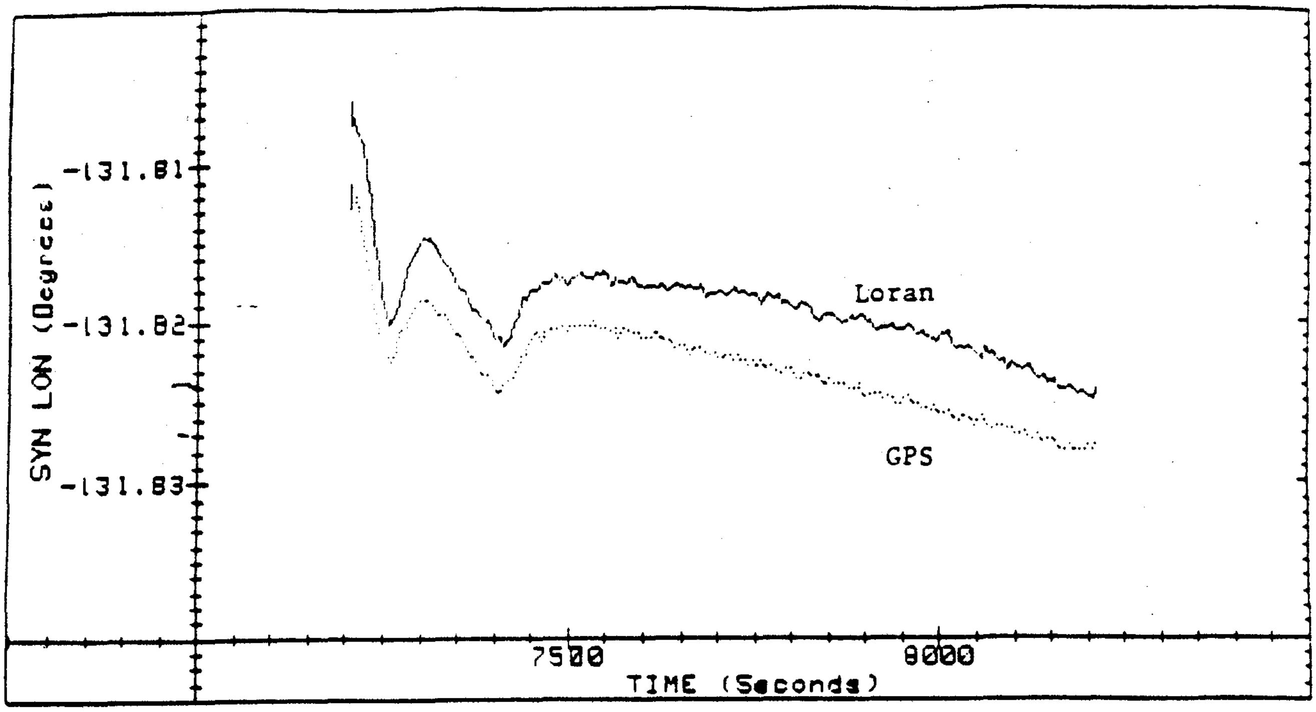

Figure 5 GPS/Loran Longitude Position Estimates
(Calibrated Mode) - Day 2

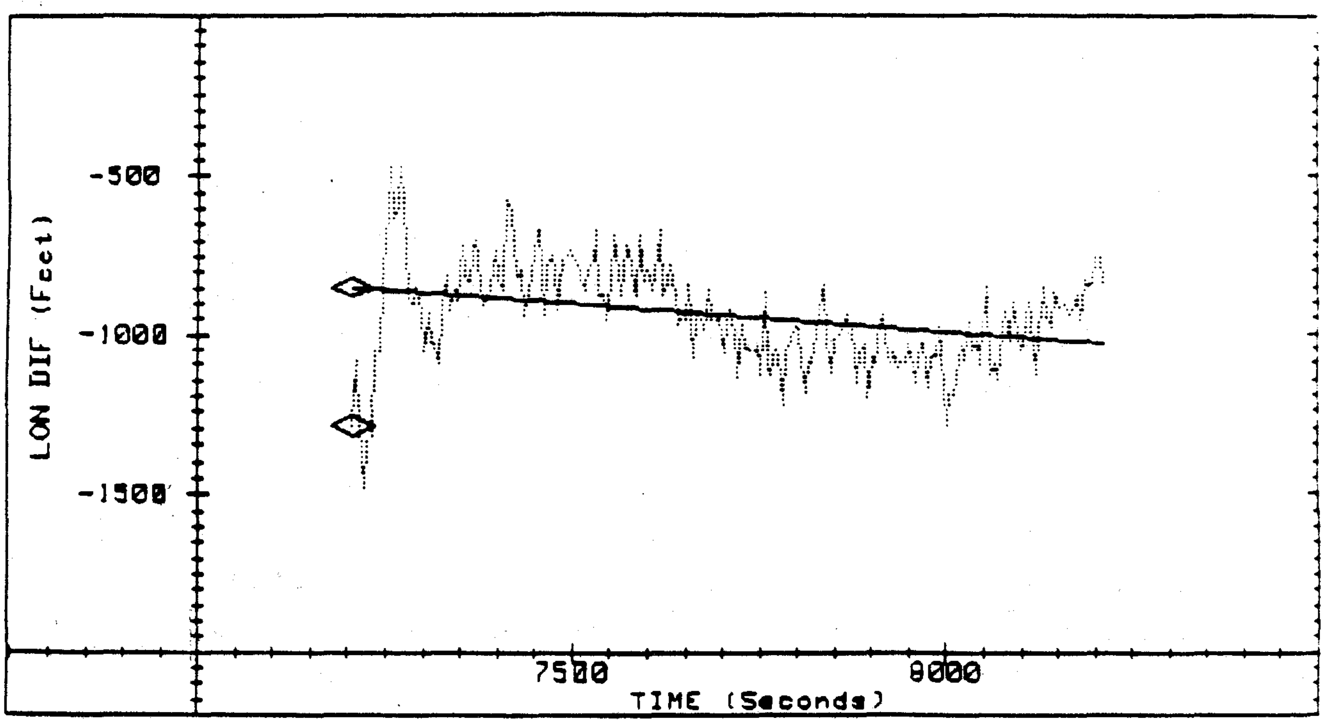

Figure 6 GPS/Loran Longitude Differences
(Calibrated Mode) - Day 2

as well as a linear least squares fit (LSF) to the data corresponding to Fig. 5. The mean longitude bias remaining in the calibrated mode is 941 feet. The noise characteristics are consistent with a measured GPS noise level of 50-65 feet and a Loran noise level of 70-90 feet. Note that the grid warp characteristic can be described as a 300-foot variation over the 60 mile length and a sinusoid with a 100-foot peak deviation. Figure 7 shows a comparison of the Loran measurements relative to the GPS measurements for all four legs.

The longitude measurements indicate a grid warp bias of 900 feet and a grid warp gradient of 80 feet over the 60 mile distance. The latitude measurements indicate an eight-foot grid warp bias with a grid warp gradient of 400 feet over a 60 mile distance. The 900-foot residual error is attributed to the influence of the 1000-foot jumps in Loran position estimates on the LSF used to determine the calibration constants.

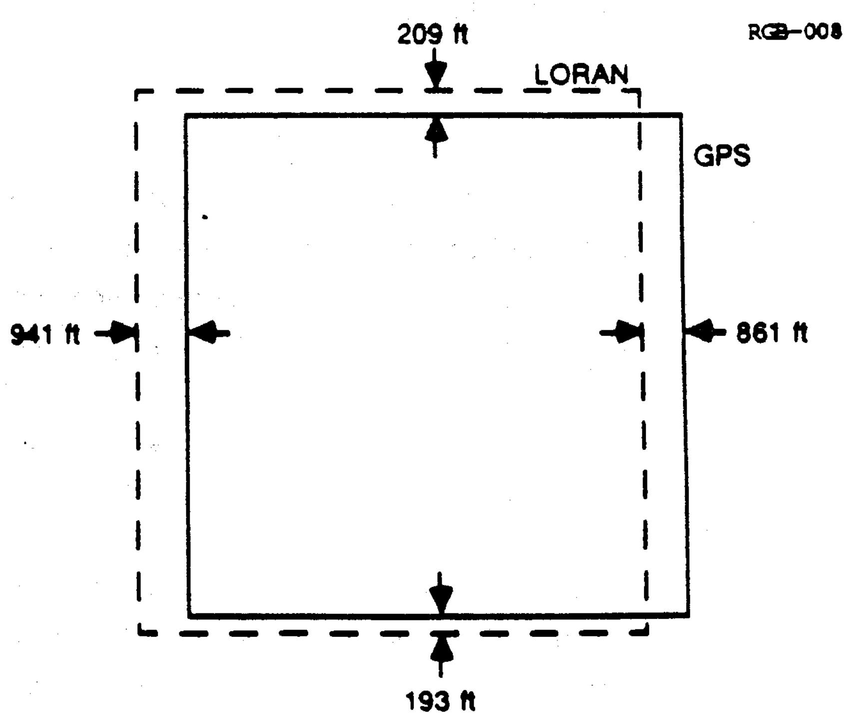

Figure 7 GPS/Loran Survey Results (Box 1) (Calibrated Mode) - Day 2

The second 60 mile square box was flown with two different receiver modes. The first and fourth legs were flown with the Loran-C receiver in the automatic mode, allowing an all-station solution of aircraft position. The second and third legs were flown in the dedicated triad mode. Figure 8 shows a longitude plot which is almost identical to a plot of the same leg flown a day earlier (Fig. 3). The average GPS/Loran difference is 50 feet greater than the previous day. This similarity indicates that the stability of both GPS and Loran-C measurements on a day-to-day basis is very good.

Figure 9 shows a plot of longitude position estimates obtained with the Loran-C receiver in the automatic mode. The longitude bias is reduced from approximately 3000 feet to 500 feet. Furthermore, the effect of the Loran receiver propagation-model-induced position jumps is reduced from 1000 feet to 400 feet. Although the reduction in error is significant, it is clear that operating the Loran-C receiver in the calibrated mode removes the large propagation-model-induced error as well as any bias errors, resulting in more accurate position estimates.

Day Three - For this test, one leg was run at constant longitude with the Loran-C receiver operating in the calibrate mode. (The position of the leg is near the center of the square shown in Fig. 2). An additional correction of 420 feet (0.1 min.) was added to the longitude calibration constant in the Loran-C receiver to compensate for the 900-foot bias error measured on day 2. The whole error was not removed because of the uncertainty associated with the 900-foot estimate.

Figure 10 shows a plot of the longitude position estimates of both the Loran-C and GPS receivers. Figure 11 shows a difference plot with a linear LSF. The average error for this pass is 488 feet with a variation of 150 feet over the 60-mile leg. This test again indicates the stability of the day-to-day GPS and Loran-C measurements, in that a 900 foot bias on one day was corrected by a 420-foot bias on the next day, resulting in a 488-foot residual

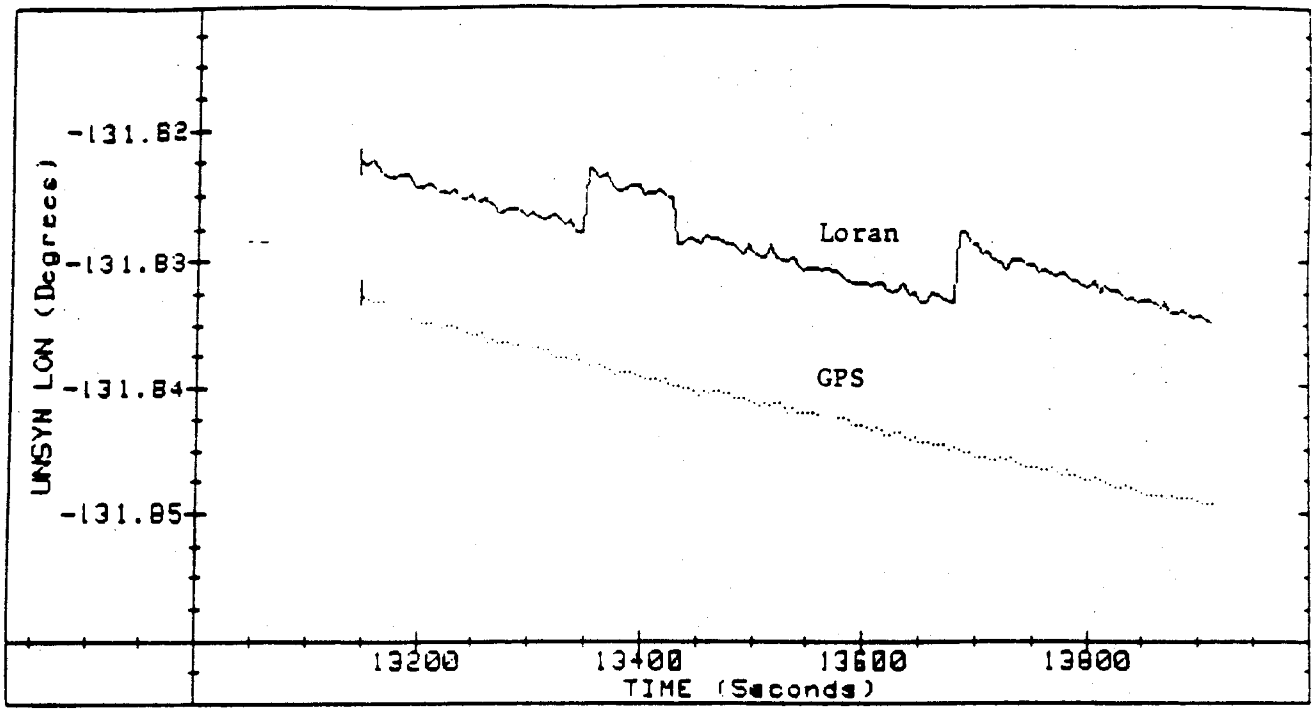

Figure 8 GPS/Loran Longitude Position Estimates (Dedicated Triad Mode) - Day 2

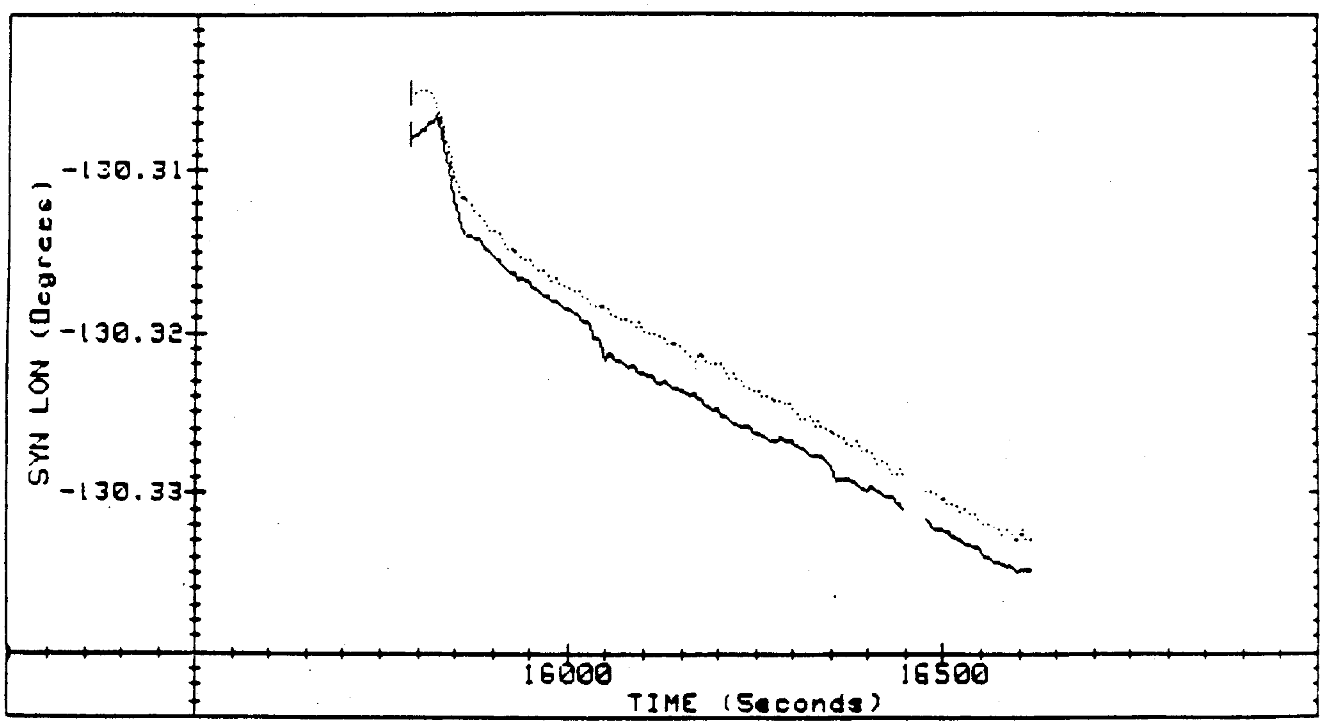

Figure 9 GPS/Loran Longitude Position Estimates (Automatic Mode) - Day 2

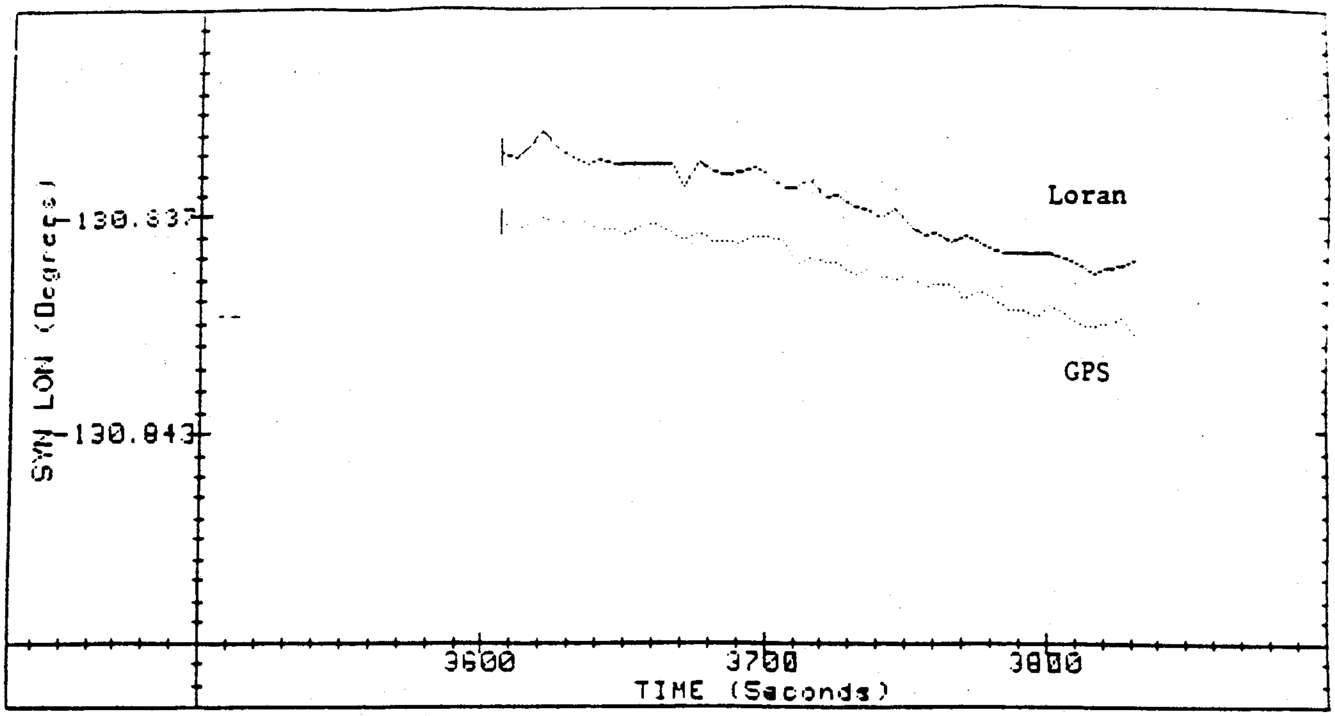

Figure 10 GPS/Loran Longitude Position Estimates (Calibrated Mode) - Day 3

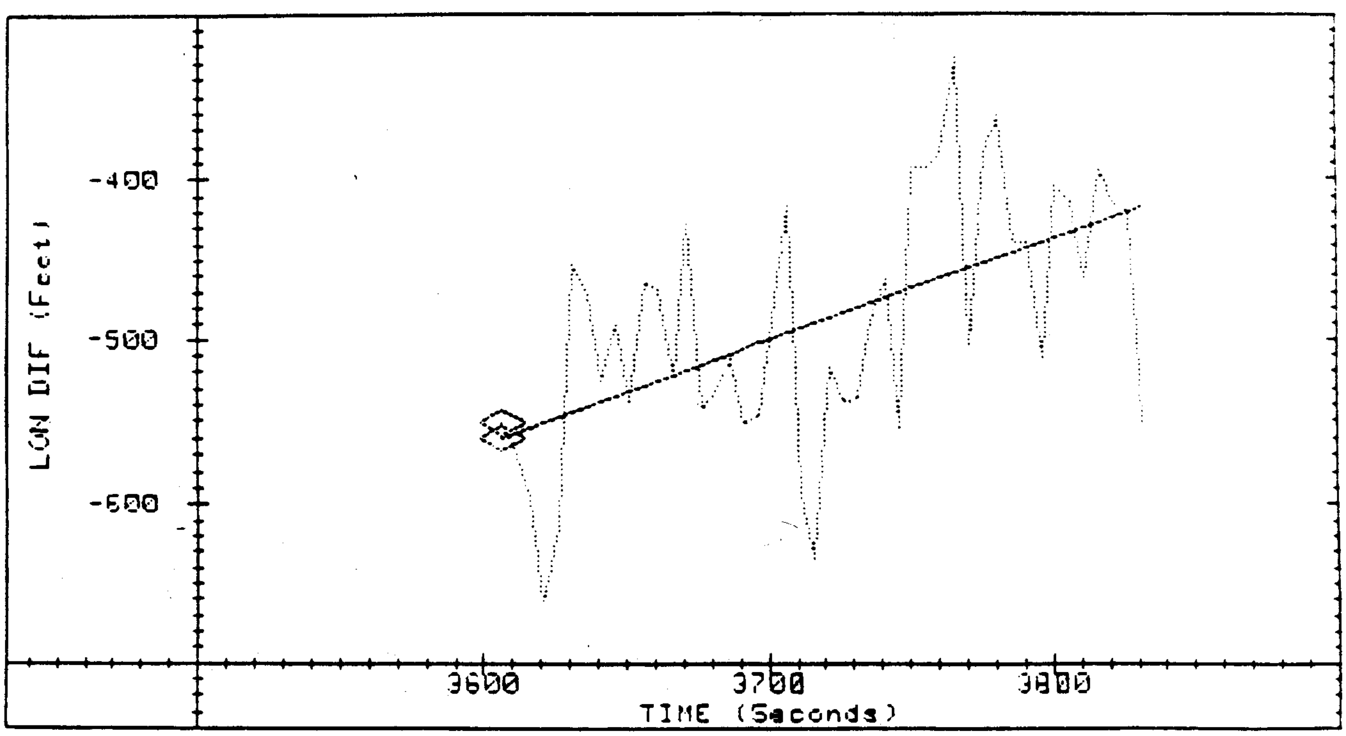

Figure 11 GPS/Loran Longitude Differences (Calibrate Mode) - Day 3

Day Four - On this day, both mapping passes and survey tests were performed. The survey tests were run to validate the calibration constants to be used throughout the mapping program. There were eight mapping passes run, during which navigation data were collected. The passes consisted of repetitive runs flown over a single defined line projected on the ocean at reciprocal track angles of 30° and 210°. The Loran receiver was operated in the calibrated mode with the constants the same as used on Day 3 (plus an additional 420 foot longitude correction). Since the GPS and Loran data are not synchronized during collection, legs of opposite track angles headings were combined so that the GPS/Loran Lat/Long differences were averaged over the two directions (as described in Section 3). This technique requires that the average pass speed be the same value in both directions. The Lat/Long GPS/Loran plots of the mapping runs are shown in Figure 12. (Note that a GPS position anomaly developed during

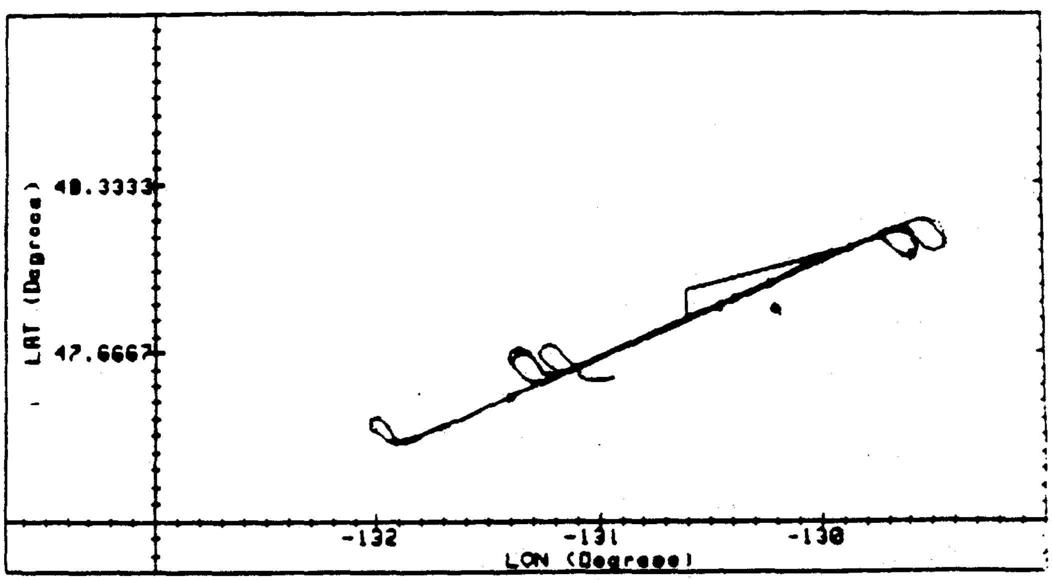

Figure 12 GPS/Loran Position Estimates (Calibrated Mode) - Day 4

one of the passes.) There is a considerable variation in the Lat/Long differences over the eight passes due to aircraft velocity effects mentioned above. The statistics (means and variances,) are shown in Table 1. The survey tests consisted of a constant longitude pass and a constant latitude pass. The South-North pass was run close to the third leg (Fig. 2) while the West-East pass was run 0.25 degrees above the second leg (Fig. 2). The mean longitude error was 17 feet, while the mean latitude error was was -320 feet.

It is clear that the longitude bias has been effectively removed as indicated by the small residual. Although the latitude error appears to be large, it is consistent with expectations due to the location of the West-East pass. Figure 13 shows a -200 foot latitude error along the top leg of the box. It is not unreasonable to expect a -320 foot error 0.25 degrees above the top leg.

The survey residual biases, along with the Lat/Long residual biases tabulated at the bottom of Table 1 (-82 ft and -110 ft), were deemed sufficiently low that no further corrections would be made throughout the mapping program unless the biases increased in size as a function of time. Figure 13 portrays the relationship of the calibrated Loran-C position estimates to the GPS estimates assuming all biases have been removed. The upper latitude has an average error of -200 feet while the lower latitude average error is +200 feet. A peak cyclic error of 100 feet is superimposed on each, and 0.66 feet per nautical mile longitude rate of the latitude error. The longitude error has a negligible bias and a latitude rate of 2.5 feet per nautical mile. Note that the latitude rate changes sign as a function of longitude. A peak cyclic error of 100 feet is also incorporated into the longitude error.

TABLE I

PASS STATISTICS (Day 4)

Pass #	Track Angle (°)	Latitude (Ft) Mean /σ	Longitude (Ft) Mean /σ
1	210	- 66/217	206/193
2	30	260/109	103/176
3	210	-204/88	159/134
4	30	- 32/90	112/83
5	210	-227/97	353/93
6	30	- 77/77	43/89
7	210	-196/*	273/*
8	30	-112/*	76/*
Summary		- 82/120	110/85

*data unavailable

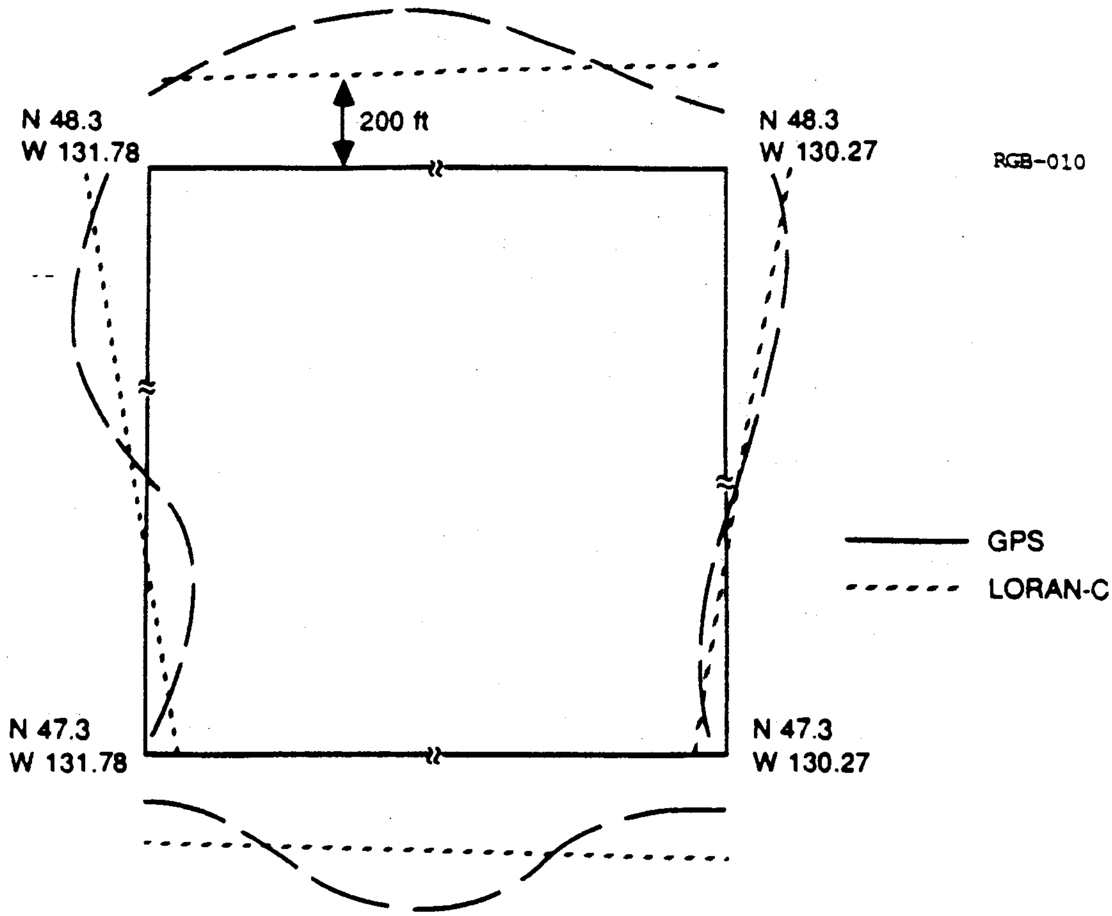

Figure 13   Grid Warp Characteristics for 60-nm Square

4.3 MAPPING PASSES

On all succeeding days, mapping passes were made. That is, a series of passes was run up and down a fixed 35-mile line whose track angle was selected daily based on wind directions. The Loran-C receiver was always operated in the calibrated mode with the same set of corrections used for all passes. As stated earlier, the GPS receiver always computed a four-satellite position solution. Figure 12 shows a typical day's passes at a 30^{o} track angle. The statistics are provided in Table II, obtained using the procedure described in Appendix A.

It is clear that the statistics appear to vary as a function of track angle. These variations result in part from the position within the grid where the pass line is situated. In addition, the 30^{o} and 90^{o} track angle data requires different adjustments for the effects of aircraft speed variation in the reciprocal heading passes. Although there is a track angle dependency to the data, it is clear that both GPS and Loran receivers provide stable measurements over a period of at least five days.

The "Reference" column in Table II defines the midpoint position for a set of passes. Longitude is not more precisely defined because of longitude variations that occurred within a given set of passes. If this midpoint is projected onto Figure 13, an "estimate" of Lat/Long errors from Figure 13 can be compared with measured Lat/Long errors in Table II. The comparison results in differences between the estimated position biases and the measurement biases of 100 feet or so. This prediction capability is important because the prediction can be used to modify the calibration constants for those mapping passes that use only a small portion of the surveyed 60 mile square.

TABLE II

SUMMARY STATISTICS

Day #	#Pass Pairs	Track Angle (^{o})	Lat (ft) Mean / σ	Long (ft) Mean / σ
4	4	30	-82/120	110/85
5	3	90	331/38	25/25
6	7	30	-52/54	194/11
7	7	90	288/67	29/81
8	7	30	-175/22	191/31
9	5	90	298/45	8/131
10	4	30	-70/159	245/95

4. CONCLUSIONS

The survey analysis illuminates several significant points. First, the differences between GPS and Loran are very stable. Considering only east/west runs which remove velocity as an error source in latitude measurements, it is clear (from Table II) that on three different days over a span of five days the data shows a maximum difference in the mean latitude of 43 feet. The corresponding maximum mean longitude error is only 42 feet.

Second, the grid warp characteristics are appropriately described as a bias, and a non-linear gradient function. The non-linear gradient is attributed to variations in the land/sea path between the stations and the aircraft as it transverses the perimeter of the survey square.

Finally, the absolute accuracy of Loran-C navigation cannot be quantified for three reasons. First, the GPS receiver measurements were never validated in flight over an instrumented range. Furthermore, there were times when position information was provided that was clearly in error. Second, the time tagging of the Loran data is not very precise, nor is it known to have a constant delay relative to the GPS data. As shown in Appendix A, changes in synchronization time and aircraft velocity introduce errors in the position accuracy. Third, the actual lat/long error contours within the 60 mile box are not verified. It is assumed that the errors within the surveyed box can be no larger than those on the perimeter (i.e., the warp characteristics are approximately linear).

Despite the potential error sources described above, a measure of the quality of the Loran-C accuracy relative to GPS was determined by comparing Table II biases to Fig. 13 estimates as described earlier. It is felt that the overall geodetic accuracy of the calibrated Loran-C is in the 100-200 foot area.

6. ACKNOWLEDGEMENTS

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APPENDIX A

VELOCITY COMPENSATION TO LAT/LONG DIFFERENCES FOR REVERSE HEADING PASSES

The GPS and Loran position measurements are collected at the time they appear at the interface port of the receiver. A problem exists in that the Loran data block does not have an absolute time at which the position data are valid, although it is valid at the time the data block appears at the interface port. The GPS does have absolute time at which its position is valid, but it appears at the output receiver sometime later. Since the data reduction software differences the values collected at a given time, Loran data are compared with delayed GPS data.

To overcome this problem, it was decided to take advantage of the fact that if the GPS data latency at the receiver port is constant, a procedure could be used which would compensate for velocity errors. This procedure consists of averaging the position biases from two passes over the same mapping line that have complementary bearings. The equations used are show below:

$$\Delta Long = \Delta Lo - V_B \sin B \Delta T \qquad (1)$$

$$\Delta Lat = \Delta L + V_B \cos B \Delta T \qquad (2)$$

where

Lat/ Long = computed mean of GPS-Loran Lat/Long difference measurements collected during a mapping pass and converted to units of feet

$\Delta L/\Delta Lo$ = actual Lat/Long position difference converted to units of feet

V_B = aircraft speed along the pass line in units of feet/sec.

B = bearing of the pass line in degrees

ΔT = data block latency of GPS relative to Loran data block in units of seconds

It is easily seen that for a North/South pass ($\sin B\Delta T = 0$) there is no speed compensation term required for determining longitude biases. Similarly, for East/West passes, no speed compensation term for determining latitude biases is needed. For all bearings, two passes of complementary bearing are averaged. To illustrate the procedure, an example of determining longitude bias from two complementary passes is provided.

$$\Delta \text{Long}\ (1) = \Delta \text{Lo} - V_B \sin B\Delta T \tag{3}$$

$$\Delta \text{Long}\ (2) = \Delta \text{Lo} - V_{-B} \sin (B + 180)\ \Delta T \tag{4}$$

For the case where the average velocity V_B is different from V_{-B}, V_{-B} can be defined as KV_B. Then

$$\Delta \text{Long}\ (1) = \Delta \text{Lo} - V_B \sin B\Delta T \tag{5}$$

$$\Delta \text{Long}\ (2) = \Delta \text{Lo} + KV_B \sin B\Delta T \tag{6}$$

multiplying Equ. 5 by K and solving for Lo,

$$\Delta \text{Lo} = \frac{K\ \Delta \text{Long}(1) + \Delta \text{Long}(2)}{K+1} \tag{7}$$

similarly

$$\Delta L = \frac{K\ \Delta \text{Lat}(1) + \Delta \text{Lat}(2)}{K+1} \tag{8}$$

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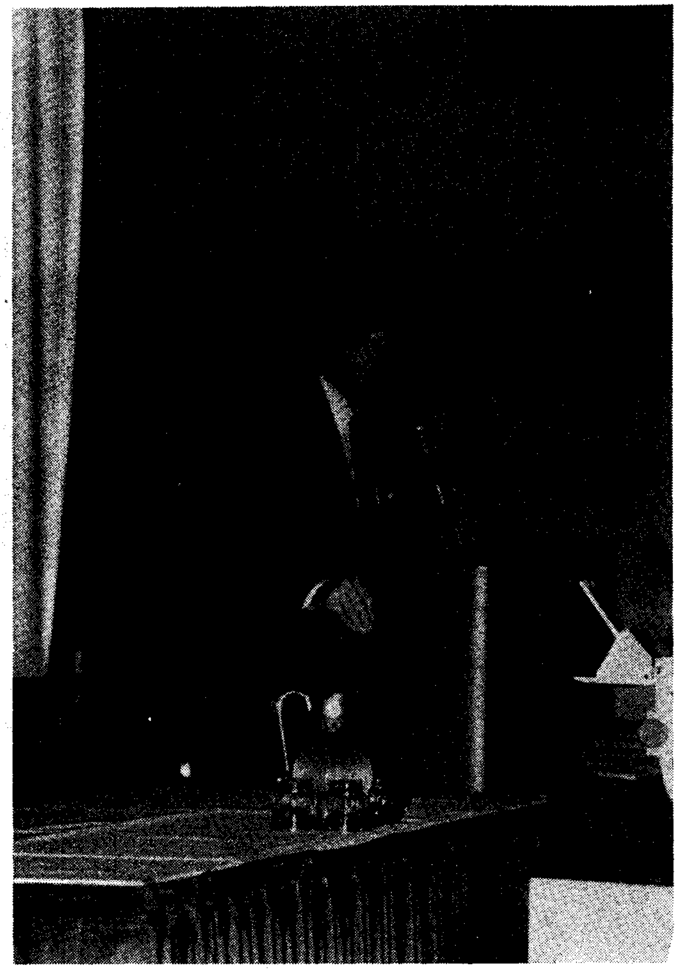

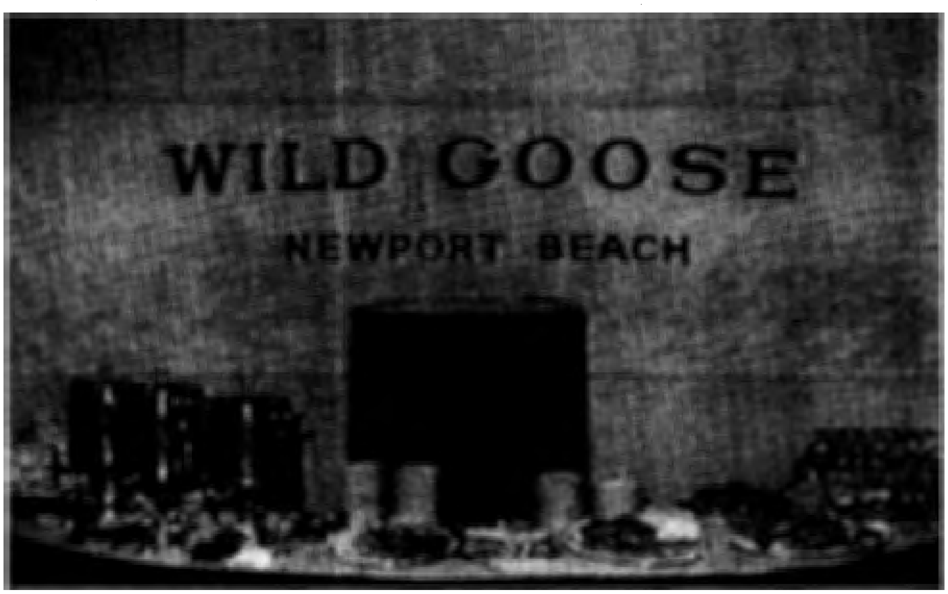
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