

THE WILD GOOSE ASSOCIATION

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*The International Loran
Radionavigation Forum*

Proceedings of the Twenty-Second Annual Technical Symposium

October 18 - October 21, 1993

Santa Barbara, California

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The Wild Goose Association
P.O. Box 556
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The Wild Goose Association

The Wild Goose Association is a professional society for individuals and organizations with an interest in loran navigation. Organized in 1972, the WGA was named after the majestic bird that navigates thousands of miles with unerring accuracy, the Canada Goose. The Association's membership of professional engineers, administrators, scientists, operational personnel and users come from all segments of government, industry, academic and research institutions and the loran user community throughout the world.

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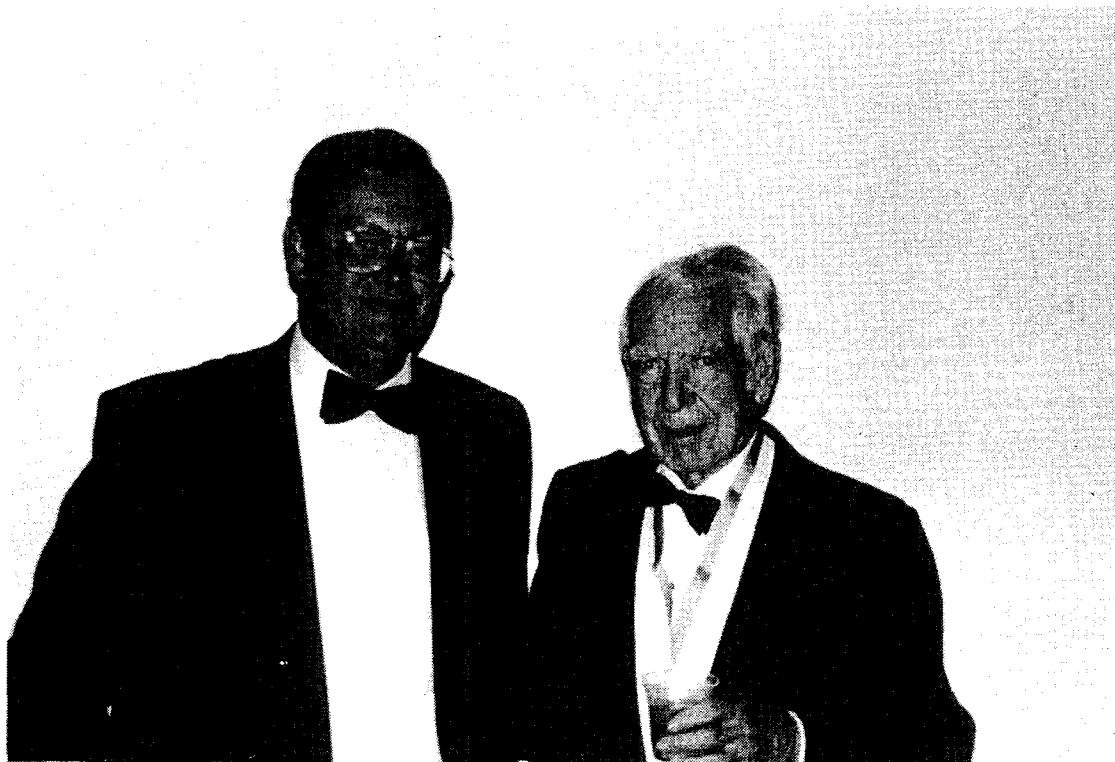
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WGA Corporate Office
P.O. Box 556
Bedford, MA 01730
United States of America

WGA Administrative Office
150 Plains Road
The Plains, OH 45780, U.S.A.
Phone: 614/797-2081
Fax: 614/797-2081



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Megapulse, Inc.

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¹Department of Geomatics Engineering, The University of Calgary, Alberta, Canada

²Canadian Hydrographic Service, Ottawa, Canada

³Canadian Hydrographic Service (Pacific Region), Sidney, British Columbia, Canada

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United States Air Force

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Policy and Technical Papers

SESSION 1

System Management and Policy

The Compelling Case for a NavSat (GNSS) Council and Secretariat

Should the IAIN be involved?

John M. Beukers
Beukers Technologies
Vero Beach, Florida

Preface: This paper was first presented at a special meeting of the International Association of the Institutes of Navigation on October 15, 1993. It was summarized, along with other international radionavigation news, at the WGA Convention four days later and provides an international perspective for a Global Navigation System consisting of terrestrial and space-borne systems.

BIOGRAPHY

Three years after graduating from London University in 1954, Mr. Beukers emigrated to the United States to continue a career in radionavigation working on the development of doppler radiodirection finders and the doppler VOR. In 1963 he formed Beukers Laboratories specializing in the implementation and use of Loran-C, Omega and VLF Communications, where he pioneered navaid retransmission technology now used worldwide to track balloon-borne meteorological weather probes.

Twice winner of the ION's Burka Award for the best paper of the year, he has authored numerous papers covering the radionavigation discipline. He is a Fellow of the Royal Institute of Navigation, a member of the IEEE, the ION and a Director of the International Navigation Association, and the Wild Goose Association.

Mr. Beukers is currently a consultant and writer on radionavigation matters devoting much of his time to finding a rational approach to realizing the potential of satellite navigation technology.

ABSTRACT

A proposal has been made to set up an office to look after world-wide civil interests in a Global Navigation Satellite System (GNSS), to be formed by and operated under the guidance of the European members of the International Association of Institutes of Navigation (IAIN). This paper addresses the proposal from the perspective of an inter-governmental structure and suggests a supportive role for the IAIN and its member institutes.

The opinions presented are those of the author and have not been submitted for endorsement by the U.S. Institute of Navigation of which the author is a member and a designated representative.

INTRODUCTION

The thoughts and suggestions contained in this paper are provided in response to a letter received from the Director of the Royal Institute of Navigation with an invitation to attend and speak at a special meeting of the International Association of Institutes of Navigation (IAIN). The meeting was called to discuss a proposed resolution for the IAIN to set up a Global Navigation Satellite System office in Europe with the view to developing a suitable institutional and operational organization for the GNSS under the guidance of the IAIN.

Precedent for initiating and setting up inter-governmental organizations suggests that this is a highly political activity that involves State foreign policy and inter-agency cooperation associated with memoranda of understanding. Further, the desire to participate is motivated and authorized from within State governments.

Having some doubt as to the influence that member institutes would have in persuading their respective governments to take appropriate and timely action, the writer first sets up a suitable structure for an international organization based upon a successful model and then addresses how IAIN can best assist in meeting the GNSS objectives.

PROPOSED RESOLUTION

The proposed resolution to come before the meeting states:

A GNSS is of vital importance for the proper development of a modern transport infrastructure and is demanded by international commitments. Operation and control by a civil agency is necessary for its correct implementation.

Because of the wide spectrum of potential users, a central coordinating office is required to develop a suitable institutional and operational organization and resolve the many questions surrounding existing satnav systems. Such an office has been recommended by ICAO and IMO.

Therefore, the meeting, convened by the International Association of Institutes of Navigation and acting in the best interests of navigation, recommends that:

- 1. A Civil GNSS Office charged with looking after world-wide civil interests in satnav systems be instituted.*
- 2. This office be formed by, and under the guidance of, the European members of the International Association of Institutes of Navigation.*
- 3. Assistance be sought from organizations already having first-hand experience and knowledge of the requirements for operating such an office.*

THE PROPOSAL IN PERSPECTIVE

To give the resolution the serious consideration it deserves we need to take a step back and put the proposal for an IAIN office into perspective with current activities and the future plans to implement global navigation satellite technology for civil use.

On the **PREMISE** that:

- (a) *navigation satellite technology* will provide substantial benefits to every State of the world;
- (b) *the technology* will be employed in many modes on land, at sea and in the air throughout the world;
- (c) consolidation and commonality of *the technology* throughout the world is both desirable and necessary;

it **FOLLOWS** that a Coordinating International Body to organize, oversee and manage global satellite technology is essential to avoid administrative fragmentation, duplication, and the generation of multiple, differing standards.

In the execution of its responsibilities, The Coordinating Body should:

RECOGNIZE that ownership and the responsibility for administration, control, funding, legality, safety, inspection, certification is now a State prerogative and that operation is currently decentralized with a multitude of systems working *independently*;

and **ACKNOWLEDGE** that the future GNSS is just one constituent part of a Global Navigation System consisting of an interrelated mix of complementary terrestrial and space-borne systems.

THE 21ST CENTURY

As we enter the 21st century and introduce global satellite technology into the inventory of navigation systems it will become necessary to part with tradition by centralizing much of the current administrative infrastructure and giving up our birthright to some of those systems that have taken decades to evolve. Treated on a global scale we are confronted by a monumental management challenge.

This is going to require all the skill and patience of those charged with the responsibility. To move forward, individual States are going to require the confidence that the new centralized structure is not going to collapse under the sheer weight of the task and associated responsibilities.

This point needs to be stressed. With the growing global awareness of satellite navigation for land, sea and air it is not surprising that virtually all the organizations having a vested interest in navigation and associated disciplines are involved. To these we must add new groups and individuals whose appearance has been stimulated by new applications of the technology and who have limited experience with traditional navigation techniques.

A partial listing that comes to the writer's mind falls into five categories:

1. Inter-governmental and Advisory Groups - Global and Regional

- International Civil Aviation Organization (ICAO) supported by Committees and Working Groups
- International Association of Lighthouse Authorities (IALA)
- International Maritime Organization (IMO) supported by IALA
- World Meteorological Organization (WMO)
- COSPAS/SARSAT Secretariat
- INMARSAT
- International Telecommunications Union (ITU)
- International Radio Consultative Committee (CCIR)
- International Omega Technical Committee (IOTC)
- European Civil Aviation Conference (ECAC)
- European Commission (EC)
- Eurocontrol
- Eurocae

2. National Governmental and Advisory Groups

- Departments of Transportation (CAAs, FAA, Coast Guards, Highway Authorities, etc.)
- Civil GPS Service Interface Committee (CGSIC)
- ARINC
- Maritime and Fishery Agencies
- Mapping and Charting Agencies
- Radionavigation Planning Agencies
- Radio Technical Commission for Aeronautics (now RTCA Inc.)
- Radio Technical Commission for Maritime Services (RTCM)
- Internavigation Committee (Russia)
- Russian Institute of Radionavigation and Time (RIRT)
- Intergovernmental Council of the CIS

3. National and International User Organizations

- International Aircraft Owners and Pilots Association (IAOPA)
- International Air Transport Association (IATA)
- National Association of State Aviation Officials (NASAO, U.S.)
- Recreational, Yachting, Boating, and Fishing Organizations
- International Federation of Airline Pilots Associations (IFALPA)
- Airport Council International (ACI)
- International Business Aviation Council (IBAC)
- Helicopter Association International (HAI)
- International Federation of Air Traffic Control Associations (IFATCA)

4. National and International Professional Organizations

- National Institutes of Navigation
- International Association of IONs
- American Institute of Aeronautics and Astronautics (AIAA)
- Institute of Electrical and Electronics Engineers (IEEE), Aerospace and Electronic Systems Section
- International Navigation Association (INA), formerly International Omega Association (IOA)
- Wild Goose Association (WGA)

5. National Trade Organizations

- Electronic Industry Association (EIA)
- General Aviation Manufacturers Association (GAMA)
- GPS Japan Industry Council
- GPS Industry Council (USGIC)
- National Marine Electronics Association (NEMA)

Add to this list numerous special interest groups, and it is not surprising that there is a wide range of opinions regarding the future role of navigation satellite technology. How best, and how fast, (if at all) to employ the new technology on a global basis has become a much debated and, at times, a controversial issue. Four examples specific to aviation serve to illustrate this lack of consensus:

- (a) The transition from ILS to MLS is a firm commitment of the member states of ICAO dating back to 1978 and the plan will not be revisited until 1995.⁽¹⁾⁽²⁾ In the meantime, some states are procuring and installing hardware; others are claiming that satellite technology has made the MLS requirement redundant. They are stalling or even abandoning the concept.
- (b) The European ATC Harmonization and Integration Plan (EATCHIP) as described by D. Martin in the September 1993 issue of the *Journal of Navigation* (U.K. RIN)⁽³⁾ calls for the use of DME/DME for area navigation while the U.S. FAA thrust is to

declare the U.S. Global Positioning System (GPS) as the sole-means navigation system and to plan for the decommissioning of the nation's VOR/DME network.

- (c) The RTCA Special Committee 159 in the U.S., charged by the FAA with the responsibility to generate Minimum Operational Performance Standards (MOPS), has concluded that GPS must remain supplemental unless augmented with some other navigation system⁽⁴⁾. The first MOPS to be published will be GPS/Loran-C with GPS in combination with GLONASS, Inertial, Omega, VOR/DME, and an integrity channel (GIC) to follow.

And lastly a personal example that illustrates the impatience and frustration of the U.S. airline industry:

- (d) At the July 28, 1993 Congressional Hearing on the *Future Use of Satellites in Aviation*, as a witness, the writer provided both written and oral testimony⁽⁵⁾ expressing the international community's concern over the adoption of GPS as it is now institutionally constituted and the need to enter into agreements for a satellite system that would be internationally acceptable and suitably structured for adoption by international organizations. Other witnesses submitted testimony indicating an impatience with the implementation schedule for GPS stating that the system is here today and it is not necessary to wait 10 years for ICAO to come up with its own system. A considerable amount of the testimony given at the hearing was directed towards the U.S. going it alone with satellite technology. Similar views were expressed at the Hearings of the National Commission to Ensure a Strong Competitive Airline Industry⁽⁶⁾⁽⁷⁾.

To get some semblance of administrative order into this confusion, it is imperative to structure an international organization that can move quickly and not be burdened by international bureaucracy or politics. In a paper presented at the European International Space Year Conference in Munich last year⁽⁸⁾⁽⁹⁾, the writer suggested that a new organization be created as a special agency of the United Nations. This idea was picked up by the ICAO Future Air Navigation System Committee (FANS)⁽¹⁰⁾⁽¹¹⁾⁽¹²⁾⁽¹³⁾ but flatly rejected on the basis that it would take too long to set up. The committee offered an alternative proposal suggesting that the charter and structure of INMARSAT was suited to operating the system but were silent as to who would take the initiative to get the project started. Also it must be remembered that the FANS committee represents aviation interests only whose user population will be in the minority. Users on land and at sea need to have a say.

Recently correspondence between IMO and ICAO has indicated agreement to cooperate on the use of satellite

technology for air and sea navigation. But these organizations are highly political and slow moving. The work that gets done is accomplished in relatively small groups of which the International Association of Lighthouse Authorities (IALA) is a prime mover for IMO and the All Weather Operations Panel (AWOP), along with other panels, guarantee forward movement for ICAO. However, these groups are sharply focused on specific issues that pertain to sea and air respectively.

Clearly a new structure is needed and it must be inter-governmental to be effective. In a paper presented to the Canadian Aeronautics and Space Institute in May 1993, concerning ICAO CNS/ATM Systems⁽¹⁴⁾, William Fromme, the Director of the Air Navigation Bureau of ICAO, suggested that the structure for international cooperation might be found in the COSPAS-SARSAT agreement that is now in successful operation⁽¹⁵⁾. A study of the administrative work that went into bringing this agreement into force, and the structure that finally materialized, reveals that there is much to recommend further investigation as to its relevance to satellite navigation.

CREATING THE COSPAS-SARSAT AGREEMENT

The paper by J.M. Anderson⁽¹⁶⁾ provides an excellent review of the process that led to the signing of the COSPAS-SARSAT agreement. In the introduction

Anderson stresses that *Simplicity became the primary objective in the design and implementation of appropriate institutional arrangements and that it was essential to ensure worldwide access to, and participation in, the system, and provide reasonable assurance of long term continuity, while at the same time avoiding the construction of a large complex, bureaucratic and expensive international agency.* This is confirmed in a paper by Levesque et al⁽¹⁷⁾ describing the development of the institutional structure for COSPAS-SARSAT.

Figure 1 depicts the evolution from a memorandum of understanding to the final agreement and the establishment of the Council and Secretariat. Since the U.S. Global Positioning System is a candidate component of a future GNSS, of importance is the Circular 175 authorization procedure that must be followed for the United States to become involved in an international agreement governed by international law. Figure 2 shows how this procedure works and its linkage to the U.S. Constitution and President. Details of this procedure were presented by the writer at the Annual Meeting of the U.S. Institute of Navigation in June 1993⁽¹⁸⁾.

OPERATION OF THE COSPAS-SARSAT AGREEMENT

Figure 3 illustrates how the COSPAS-SARSAT agreement operates. The four parties to the agreement are

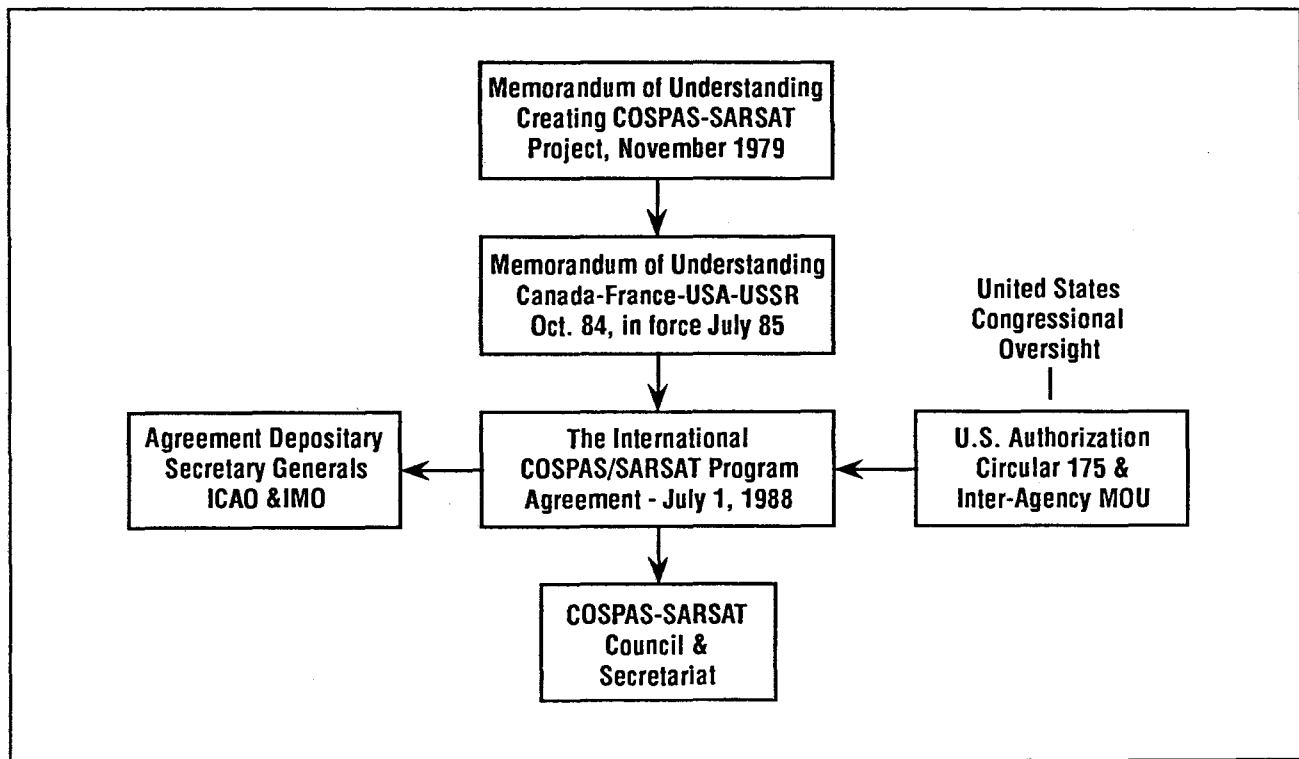


Figure 1. Creating the COSPAS-SARSAT Agreement

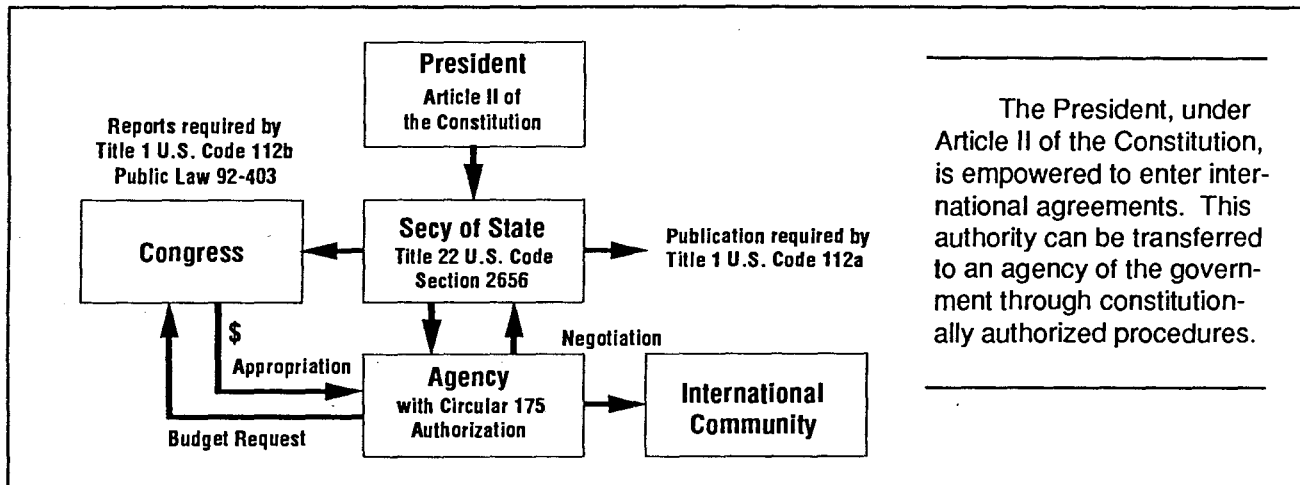


Figure 2. The Circular 175 Authorization Procedure

providers of the satellites constituting the space segment and form the Council. Each party has assigned a cooperating agency within its government for operational oversight of the space segment. Administration is handled by the Secretariat with administrative services being provided under contract by INMARSAT⁽¹⁹⁾. The Secretariat office is co-located at INMARSAT headquarters in London. Any State may become a ground segment provider and/or a user by submitting a Standard Letter of Notification to the Secretary General of either IMO or ICAO⁽²⁰⁾⁽²¹⁾⁽²²⁾⁽²³⁾. States that become involved appoint an internal agency for execution of the obligations as a participant in the system. Liaison with the agencies, international organizations and others are conducted through the

Secretariat. The Council can meet in closed session or provide a forum for all parties at open meetings⁽²⁴⁾. The structure is simple and, moreover, it works.

RELEVANCE TO NAVIGATION

Using the COSPAS-SARSAT agreement as a model, the parties to a NAVSAT agreement would be the space segment providers; the United States (GPS), Russia (GLONASS), INMARSAT (Geosynchronous Overlay), Japan (Geosynchronous Overlay) and others (the European Space Agency, for example). The system would be open to Ground Segment Providers and Users through a Standard Letter of Notification. This immediately opens the door for States to contribute to the system.

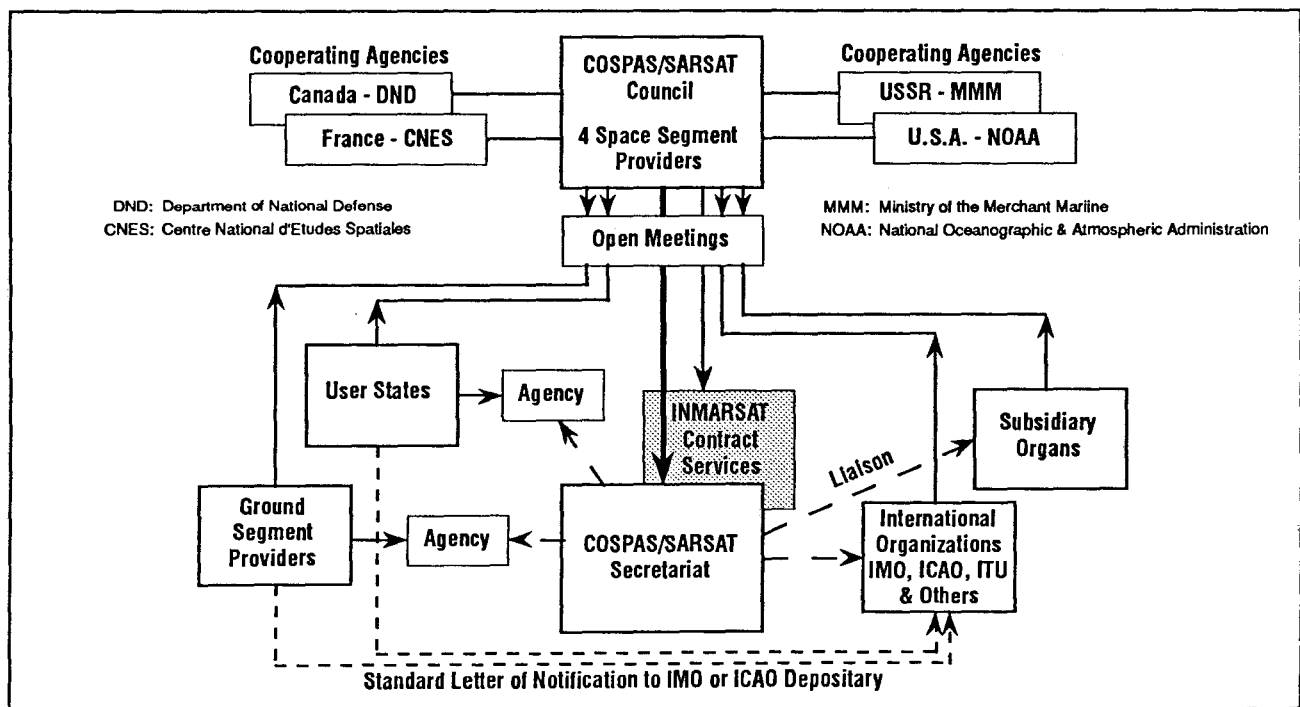


Figure 3. Operation of the COSPAS-SARSAT Agreement

The 21st century Global Navigation System will undoubtedly maintain terrestrial systems and these assets should be exploited to the fullest extent possible. In this regard, GNSS monitoring stations can be brought on line with minimal additional cost. The world-wide Omega and Loran-C stations are uniquely suited for this purpose as they are already equipped with multiple Cesium Standards tied to UTC, provide a communications capability and have a supportive administrative infrastructure. Gunther describes these stations in this role in a paper presented at the National Technical Meeting of the U.S. ION held in January 1993⁽²⁵⁾. Ground Segment Providers can also contribute to the GNSS, as recently described by Van Willigen⁽²⁶⁾, by providing wide area differential corrections to satellite transmissions using the communications capability of new and existing Loran-C transmitting stations.

Ground segment providers could also contribute tracking stations, communications and any other aspects of a worldwide network. User States, after payment of a nominal fee (as is now required by COSPAS-SARSAT), would have a voice in the system operation through participation in the open meetings. This fee would defray the costs of operating the Secretariat.

AGREEMENT MODIFICATIONS

The COSPAS-SARSAT agreement can be characterized as a voluntary cooperative venture driven by a common need for preservation of life in situations of distress, emergency and accident. Study of the agreement reveals that to cover the more stringent requirements of aviation and maritime and, to a lesser extent, surface transportation, modifications will be necessary to cover liability, longevity and safety. For example, Article 14.2 specifically rejects any liability towards users and third parties for injury, damages or financial loss that may arise from the use of the system. Article 17 allows for a Party (space segment provider) to withdraw at any time with just one-year notice and only that the Party *shall endeavour to ensure continuity of the existing contribution* - there is no legal requirement for continuity.

Safety to users and the mandatory requirements of availability and integrity of the system are not addressed. The article on safety, in addition to covering the space segment, would have to concern the ground segment control, operating procedures, personnel training, software quality assurance and fail-safe procedures in case of a catastrophic system failure.

THE FALL OUT

On the supposition that an agreement for GNSS based upon the COSPAS-SARSAT structure could be created, signed and entered into force, the possibility of the two agreements merging at a later date warrants consideration. There is a high probability that once an international

GNSS becomes operational, future emergency locator beacons will contain a GNSS retransmitter that will provide both position and identity. SARSAT and NAVSAT systems will be working together on a world-wide cooperative basis and duplication of the administrative offices may no longer be necessary.

FIRST ORDER OF BUSINESS

To formalize the institutional, technical and operational requirements for a land, sea, and air GNSS and to develop a total system specification (including communications for augmentation and user interface) will be the first order of business for the Secretariat. This will enable potential contributors to the Space Segment to negotiate an appropriate basis for becoming a party to the agreement. It will also be a signal to users throughout the world that an internationally acceptable civil satellite navigation system will be available at all times to meet the requirements of a terrestrial-satellite global navigation system mix. Ground Segment providers will be able to participate in accordance with the specified requirements.

ROLE OF THE IAIN

This presentation may have appeared to be a roundabout way to addressing the resolution regarding the GNSS office in Europe which, it is proposed, will be operated under the guidance of European members of the IAIN. Being of the opinion that the IAIN would unlikely succeed in creating an appropriate international organization, it was first necessary to set up the inter-governmental structure to see how the IAIN could contribute to a GNSS project. It must be recognized that the Institutes of Navigation are not political, they are not empowered to enter agreements, and some, if not all, have charters that do not permit them to take advocacy roles or lobby (in the U.S., tax laws covering non-profit status specifically preclude this sort of activity). In addition, institute constitutions require that dues be spent on membership activities that satisfy the wishes of the membership, suggesting referendums may be required to support a specific and perhaps contentious activity.

It follows that an IAIN-led European GNSS office cannot substitute for an inter-governmental body. However there would appear to be merit in pooling the technical and administrative resources of the IAIN member institutes to assist, in an advisory capacity, the international organization set up to oversee the GNSS. In addition, individual institutes might be effective, if permitted and accepted, to act as advisors to their own State governments. The development of system requirements and specifications would appear to be one area that the IAIN could be particularly helpful.

RECOMMENDATION

Pooling the technical resources and experience of the in-

dividual member Institutes of the IAIN to generate and present a unified approach for a land, sea, and air GNSS has merit and should be encouraged. An office specifically set up for this purpose as a point for coordinating the efforts of individual institutes would seem appropriate if it can be adequately funded and properly administered. Its location in Europe is one option that should receive consideration but only in the context of convenience and not merely for enhancing European influence and participation in a GNSS.

ACKNOWLEDGMENTS

The writer wishes to acknowledge the cooperation of colleagues in the navigation community for their input to this paper and for their assistance in reviewing its content for accuracy.

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Overseas Loran-C: Transfer or Closure?

LCDR Phil D'Agnese, ENS Mark Bouchard and Mr. Stewart Shoulta

Radionavigation Division

U. S. Coast Guard Headquarters

Washington, DC 20593

ABSTRACT

The United States Coast Guard operates overseas Loran-C for the Department of Defense (DOD). With the full deployment of the DOD's Global Positioning System (GPS), the DOD requirement for the Loran-C system will end 31 December 1994. As such, the U. S. Coast Guard authority to operate overseas Loran-C will end.

The time has come, and will soon pass, when nations of the world will need to assess their needs for a navigation system. Specifically, foreign nations must decide whether they want to operate their own national system or depend on another nation's military system for their civil use. They must also consider the endless possibilities of joint/cooperative efforts across national boundaries, which is an enticing first, albeit small, step in breaking down any potential barriers that may exist. Loran-C cooperation amongst nations will allow for the sharing of technical expertise, and more importantly, the development of a safe worldwide navigation system.

INTRODUCTION

Ever since man has decided to move from one place to another, over land, by water, or by air, he has had a need to navigate. Knowing position (where you are and where you need to go) is as important as how you get there. Today's debate, among nations of the world, whether to continue with Loran-C or some other form of navigation will take the same logic and skills of an astute navigator; however this time, traveling through political and budgetary obstacles. Governments of the world need to decide where they are today and where they want to be tomorrow. The question becomes -- do they want a national system dependent only on themselves and the close cooperation of neighboring countries with similar needs for a navigation system or do they want to be dependent on the military system of another country, in some cases, thousands of miles

away with very different application requirements and objectives.

BACKGROUND

Dating back to World War II, Coast Guard personnel have been staffing and operating Loran stations in Europe and East Asia. The Loran system was first developed in the early 1940's by the Radiation Laboratory of the Massachusetts Institute of Technology. The Coast Guard began operation of Loran in the U. S. and overseas to serve U. S. Department of Defense requirements for radionavigation service. The development of modern Loran-C for commercial and domestic use was introduced in the 1970's. After much research, study and discussion, the Secretary of Transportation publicly announced in May 1974 that Loran-C was to be the official radionavigation system for coastal waters of the United States. Loran-C clearly became the preferred navigation system for continental and coastal cruising particularly in North America. This happened because of two factors, cost reduction and a governmental commitment on the part of the United States. This commitment for a national system of radionavigation was put in the hands of the U. S. Coast Guard (USCG). The USCG was a logical choice because of its dual role within the Department of Transportation (civil use) and as an armed service of the U. S. (military use), as well as its maritime ties. Over the years, the system has served millions of satisfied users and has helped defend and strengthen the commerce of the United States.

In 1981 the United States announced its intention to terminate overseas Loran-C operations, upon full deployment of the Global Positioning System (GPS). Five years later, the Department of Defense (DOD) stated in the Federal Radionavigation Plan that it would phase out military use of overseas Loran-C by December 1994. Following DOD's statement, tentative discussions were initiated between the U. S. and foreign

governments to close overseas Loran-C operations. However, due to host nation interest in Loran-C, the intent of the discussions have since changed to focus on transfer of overseas Loran-C stations to those nations. In 1990, the discussions entered a more formal stage. Since the initiation of these formal discussions the Coast Guard has made significant progress in negotiating with Norway, Denmark, and Germany (Norwegian Sea and Icelandic Sea Chains); and Italy and Spain (Mediterranean Chain) and concluded agreements with Japan (Northwest Pacific Chain) and Turkey (Mediterranean Chain) to transfer control and operation of overseas Loran-C stations to the respective host nations. To emphasize the worldwide interest in Loran-C, in addition to the above mentioned chains, there have been Loran-C chains established in the countries of France, Egypt, Saudi Arabia, China, India and Korea. There is also a similar radionavigation system operated by the Russians called Chayka.

NEGOTIATIONS

On 12 February 1992, the U. S. Department of State (DOS) granted the Coast Guard authority (Circular-175) to terminate existing agreements and to negotiate

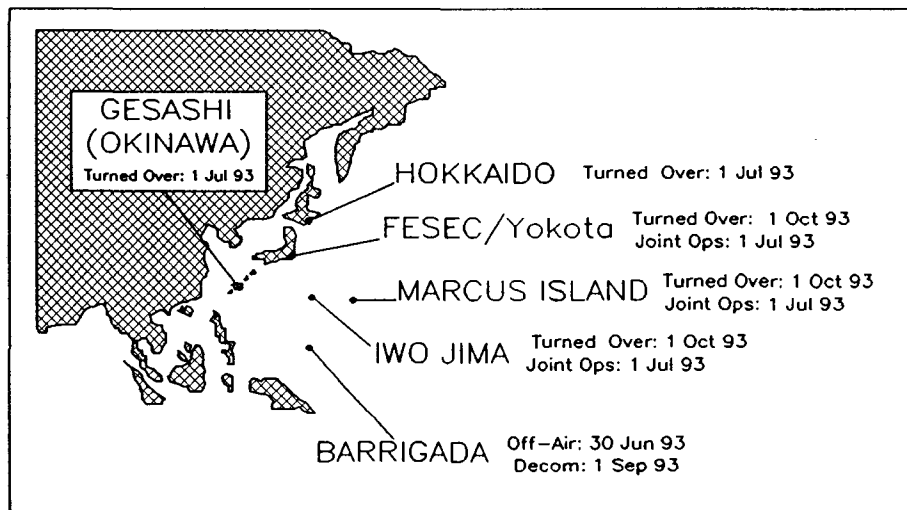


Figure 1 Northwest Pacific Loran-C Chain

new agreements to transfer overseas Loran stations. This task would involve the closure or transfer to host nations of sixteen Loran stations operated by or for the Coast Guard. The Loran stations involved are in the Far East, Northern Europe, and the Mediterranean Sea area.

FAR EAST

Since 1990, United States Forces Japan (USFJ) under the Status of Forces Agreement (SOFA) has led discussions with the Government of Japan (GOJ) concerning the termination of U. S. Government operation of the NWPAC Loran-C chain and the transfer of the system to the GOJ. United States Forces Japan worked closely with U. S. Coast Guard Far East Section Office, Japan Ministry of Foreign Affairs, Japan Defense Facilities Administration Agency and the Japanese Maritime Safety Agency to develop a transfer plan which would be acceptable to both governments. In 1991 the GOJ allocated funds and showed a commitment to reach a mutually satisfactory agreement. In 1992 USFJ negotiated, with USCG assistance, an agreement regarding return/joint use of the real property and structures at Iwo Jima, Marcus, Hokkaido, Gesashi, and Yokota, all under provisions of the Status of Forces Agreement. This agreement provided a vehicle for an agency-to-agency transfer of existing Loran equipment from the Coast Guard to the Japanese Maritime Safety Agency (JMSA).

As shown in Figure 1, transfer occurred at Hokkaido and Gesashi on 1 July 1993, and at Iwo Jima, Marcus, and Yokota on 1 October 1993. In addition, Loran station Barrigada ceased operation on 30 June 1993. The agreement specified return of Marcus and Hokkaido to Japan, long term joint use of Gesashi (essentially transfer of that part of the property needed for Loran, while USFJ retains a DOD communications facility) and short-term joint use of Iwo Jima and Yokota (by 31 December 1994, they revert to USFJ). JMSA has plans to replace the master station at Iwo Jima with a new station at Nii-Jima and the monitor/control facility at Yokota with a new facility. The Guam

Primary Monitor will be operated by the U. S. Coast Guard on a reimburseable basis with the GOJ until 30 September 1994.

NORTHERN EUROPE

Since the early 1980s, the nations of Northwest Europe have known that the Coast Guard would eventually leave, and they have been actively working toward taking over these stations and/or developing their own Loran chains. On 6 August 1992, six nations signed an

agreement to continue Loran in their area. These nations are Norway, which took the lead in the effort, Denmark, Germany, Netherlands, France, and Ireland. Several other nations showed interest, but dropped out of the Policy Group developing the agreement; these were Great Britain, Iceland, and Canada.

All Coast Guard Loran stations in the Northern European region are operated by the host nation. Host nation operation is defined as the U. S. Coast Guard retaining ownership of the stations while directly funding the host nations for staffing, operating and maintaining the stations. Figure 2 illustrates the relative location of each station in the Northern European region. There are two host nation operated stations in Norway, both north of the Arctic Circle, one isolated on the island of Jan Mayen, the other in a small community at Bo on the mainland. Denmark operates two stations, one at Ejde in the Faeroe Islands, the other at Angissoq, an extremely remote location on a southern island off the tip of Greenland. Germany operates the station at Sylt, a barrier island on their North Sea coast very near the Danish border. Iceland operates the station at Sandur, a somewhat remote location (three plus hour drive from Reykjavik), near a growing small community, and the control/monitor station on the base at NAS Keflavik. There is also an unmanned monitor site in the Shetland Islands, UK.

chain.

NORWAY: The Norwegian Defense Communications Administration (NODECA) is the designated negotiating agency for Norway. NODECA is the host nation agency currently operating Loran for the Coast Guard. The Chairman of the Northwest Europe Loran Steering Group and NODECA employees staff that group's Project Management Office (PMO). The Steering Group is comprised of members from the nations which signed the Policy Group agreement referred to above. Under the Steering Group, the PMO is developing plans for Loran operations in the region after the Coast Guard ceases operations. The PMO is planning to use the existing Loran stations Bo, Jan Mayen, Ejde, and Sylt, to upgrade the equipment at these stations, to build two new stations in Norway and one new station in Ireland, and to reconfigure these seven stations, along with the two French-owned stations into four new chains greatly enhancing coverage. The PMO has signed a contract with a U.S. company for the equipment required to upgrade and dual rate these stations.

Norway wishes to assume ownership of the Loran stations at Bo and Jan Mayen on 1 January 1995. They are also planning to upgrade the existing vacuum tube transmitters with new solid state transmitters and associated equipment before turnover.

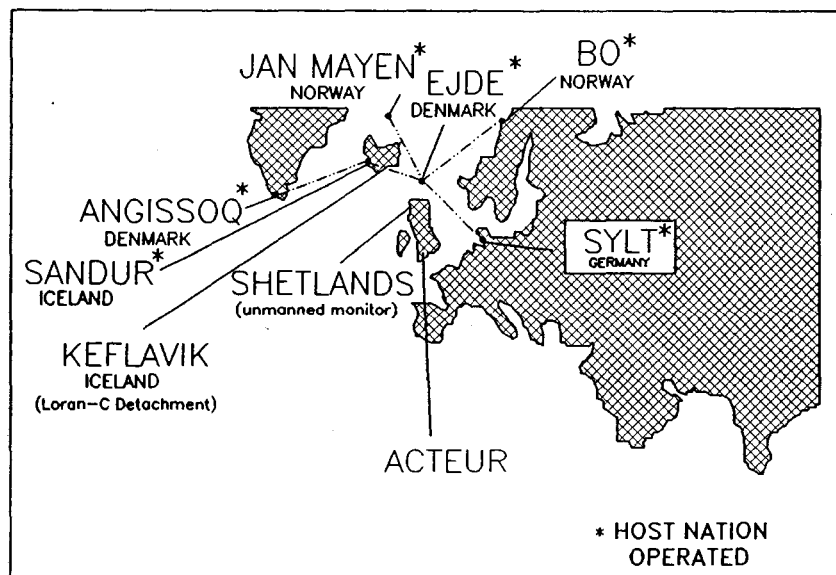


Figure 2 Northern European Loran-C Chain

Loran stations Sandur (master), Angissoq and Ejde (secondaries), and the monitor at Keflavik comprise the Icelandic Sea Chain. Loran stations Ejde (master), Bo, Jan Mayen, Sylt, and Sandur (secondaries), and the monitor at Keflavik and the unmanned monitor in the Shetland Islands, UK, comprise the Norwegian Sea

DENMARK: The Ministry of Defense (MOD) is the negotiating agency for Denmark. The Royal Danish Administration of Navigation and Hydrography (RDANH) is providing technical assistance. RDANH is the host nation agency currently operating Loran for the Coast Guard in Denmark.

Denmark wishes to assume ownership of Loran station Ejde on 1 January 1995, and like Norway, they would like to upgrade the equipment there as soon as possible.

Denmark has no wish to continue operations at Loran station Angissoq after the Coast Guard departs, and the station will close by 31 December 1994.

GERMANY: The Ministry of Transportation (MOT) is the negotiating agency for Germany. MOT is also the host nation agency operating Loran for the Coast Guard.

Germany wishes to assume ownership of Loran station Sylt on 1 January 1995, and like Norway and Denmark,

they would like to upgrade the equipment there; as soon as possible.

ICELAND: The Ministry of Defense (MOD) is the negotiating agency for Iceland. Icelandic Post and Telegraph Administration (IPTA) is providing technical advice. IPTA is also the host nation agency operating Loran for the Coast Guard.

As of this writing, Iceland has no wish to continue operating Loran after the Coast Guard leaves.

MEDITERRANEAN SEA

The four Loran stations in the Mediterranean Sea (MEDSEA) region, as illustrated in Figure 3, are staffed by Coast Guard personnel and come under the auspices of the existing SOFA in each country. Loran stations Sellia Marina, Italy, (master and control site); Lampedusa, Italy; Estartit, Spain; and Kargaburun, Turkey, (secondaries); and the unmanned monitor site at Crotone, Italy, comprise the chain. On 15 November 1992 negotiations opened with Italy on Sellia Marina, Lampedusa and Crotone, Italy. The Italians have been extremely receptive to taking over the stations and operating Loran-C in the MEDSEA well into the future. As a matter of fact, Italy has taken the lead in the MEDSEA area and has worked closely with the European Commission (EC) to facilitate the possibility of a Loran-C system linking, as a minimum, Italy, Turkey, and Spain.

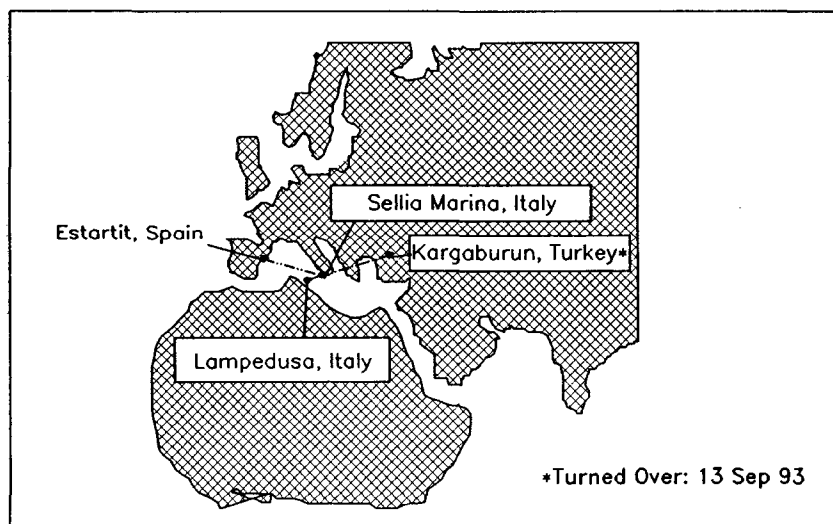


Figure 3 Mediterranean Sea Loran-C Stations

TURKEY: The Coast Guard operated Loran-C station located at Kargaburun, Turkey was turned over to the Turkish Government on 13 September 1993. The station had been operated by the Coast Guard

since 1960. The Turkish Government is expected to resume operations from the station as part of the Mediterranean Loran-C Chain as soon as they can procure and erect a new transmitting antenna.

EUROPEAN COMMISSION (EC) ROLE

The EC has expressed a desire to take an active role in facilitating chain coordination and operations after turnover. Their Transportation Directorate has played an active and commendable role as a facilitator for negotiations in the MEDSEA.

ADVANTAGES OF TRANSFER

There are a number of advantages to host nation take over of these stations from the U.S. Coast Guard.

First, transfer of existing facilities to the host nation has an obvious cost advantage. The U. S. transfer of existing operational Loran-C stations, facilitates a cost effective development of a European Loran-C Network. In addition, existing Loran-C charts and repeatability characteristics would continue to apply, thus lowering costs and interruption to mariners. Finally, Loran-C technology is at a mature development stage and transmitters/receivers are commercially available, thus accommodating lower unit costs as the Loran-C system is expanded.

Second, it provides a safe navigation system for civil users. Loran-C satisfies mariners accuracy needs and meets IMO Resolution A- 529 (13) requirements. The

Loran-C system accuracy is equal to and more encompassing than the existing DECCA system. In the future, combined Satellite/Loran-C coverage will offer a high degree of system verification and continuity of radionavigation coverage for the benefit of maritime safety and environmental protection.

Lastly, Loran-C allows for both autonomy and international cooperation. Each country can have its own national system, versus reliance on a military satellite system controlled by the United States. In addition, the chain configuration of Loran-C facilitates programmed network growth and cooperation between nations.

OUTLOOK

Despite all the progress in Loran-C international negotiations and developments, including the U. S. statement in the 1992 Federal Radionavigation Plan that Loran-C will remain part of the U. S.

radionavigation mix through the year 2015 and that the U. S. embarked on the Mid-Continent Expansion Project to expand Loran-C across the United States, there is a growing concern that the Global Positioning System (GPS) will eliminate the need for Loran-C altogether. Although the Global Positioning System offers several technical advantages over Loran-C, unfortunately it is a military controlled system and costly at that. Consequently and quite correctly, many countries have expressed reservations about adopting GPS as a worldwide civil navigation system. According to the 1992 Federal Radionavigation Plan, GPS has been designed primarily for military radionavigation needs, and will only be available on a very selective basis to U. S. and foreign private sector (non-governmental) civil organizations. For example, during a time of national emergency, it is highly unlikely that GPS service will be available for civil use. The recent conflict in the Persian Gulf proves that we still live in a very volatile world, and that gaps in GPS service to civil users may occur more frequently than we like to believe. Thus, total reliance on one type of radionavigation system (again, not a healthy consideration for the prudent navigator) by civil users would expose them to the risk of having no radionavigation aid. Loran-C provides a reliable alternative navigation system for civil radionavigation users because of reliability and low cost. But before Loran-C can become a viable low cost alternative to the "technically advantageous" GPS, nations must make a commitment to it much like the U. S. did many years ago, and in fact continues to do.

	DIRECT COSTS		
	PERSONNEL	O&M	BILLETTS
OVERSEAS	7928.8K	17464.7K	164
CONTINENTAL US	10764.0K	5848.6K	233
TOTAL	18692.8K	23313.3K	397
TOTAL FY93 BUDGET = 42 M			

Figure 4 FY 93 Budget: USCG Managed Loran Stations

This commitment also includes a monetary commitment. Since the inception of Loran, the U. S. has absorbed the development, personnel, and maintenance costs for stations both inside and outside its national borders. As Figure 4 shows, the annual recurring cost for its international stations has been

significantly greater than for its domestic system. The costs of operating an overseas system is much higher than a domestic/national system. Host nations operating costs should be much less than U. S. overseas operating costs.

CONCLUSION

The use of a military system as a civil navigation system should be viewed with reluctance by national authorities. A military system with full-time availability at an assumed accuracy should be questioned. One should also question how long such use will be at no cost to user nations.

Conversely, a low cost, highly reliable terrestrial based system such as Loran-C can be both a national system and an international system. This can happen simultaneously and effectively. A commitment to such a system by each nation is the first step.

The time to begin is now, the beginning is with cooperative talks on taking over existing stations from the United States and then a commitment to expand and cooperate with neighboring countries to effectively cover all areas of need.

DISCLAIMER

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

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THE NORTH WEST EUROPEAN LORAN-C SYSTEM - STATUS REPORT

Andreas Stenseth

Norwegian Defence Communications and Data Services Administration
(NODECA)
(Chairman LORAN-C Steering Committee)

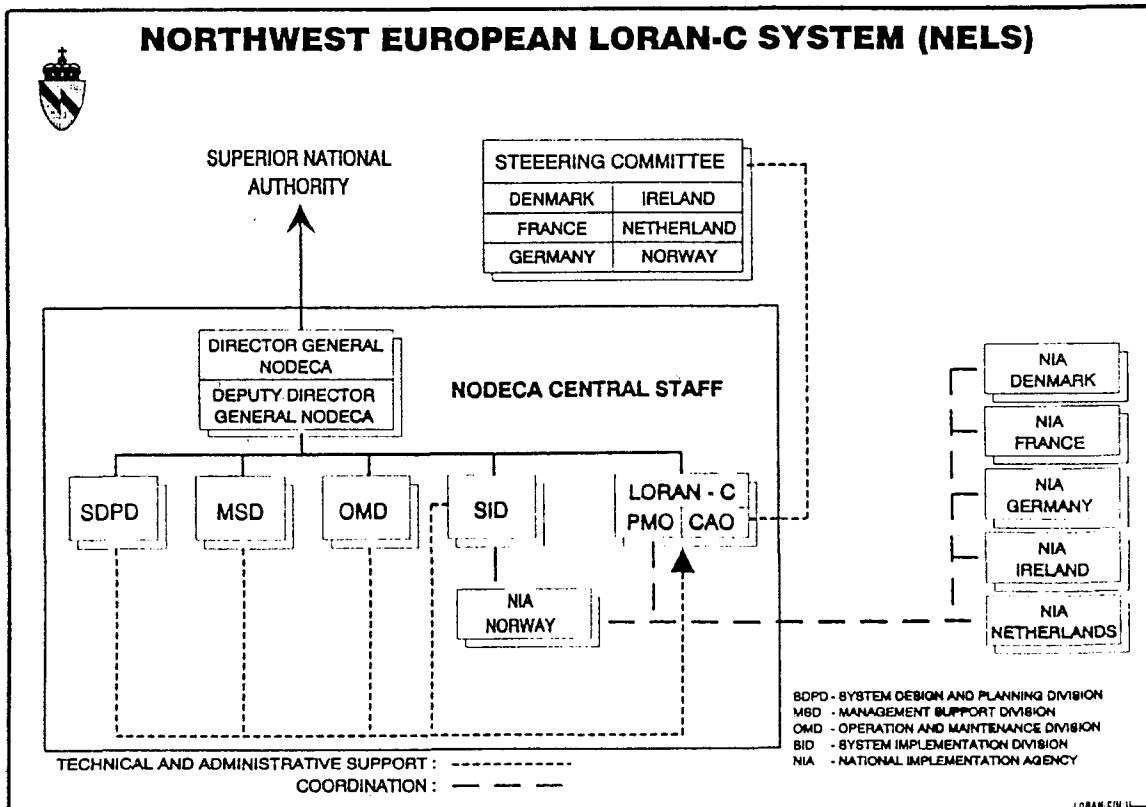
For many years now I have been given the opportunity to address the WGA Annual Technical Symposium on the developments towards a multinational LORAN-C system in North West Europe (NELS). My reports so far have been concentrated on the work of the LORAN-C Policy Group established in 1987 to investigate the feasibility of having such system established. However, at your symposium in Birmingham last year, I was finally in the position to inform the group that an international agreement concerning the establishment and operation of a LORAN-C system in North West Europe was signed in August 1992, resulting in the dissolution of the Policy Group and foundation of a Steering Committee as prescribed in the agreement.

The international agreement implied that a legal basis for translating plans into action was created and an up to then provisional Coordinating Agency was formally established to coordinate the activities involved. Norway was asked to take on the task as Coordinating Agency and the Norwegian Defence Communications and Data Services Administration -

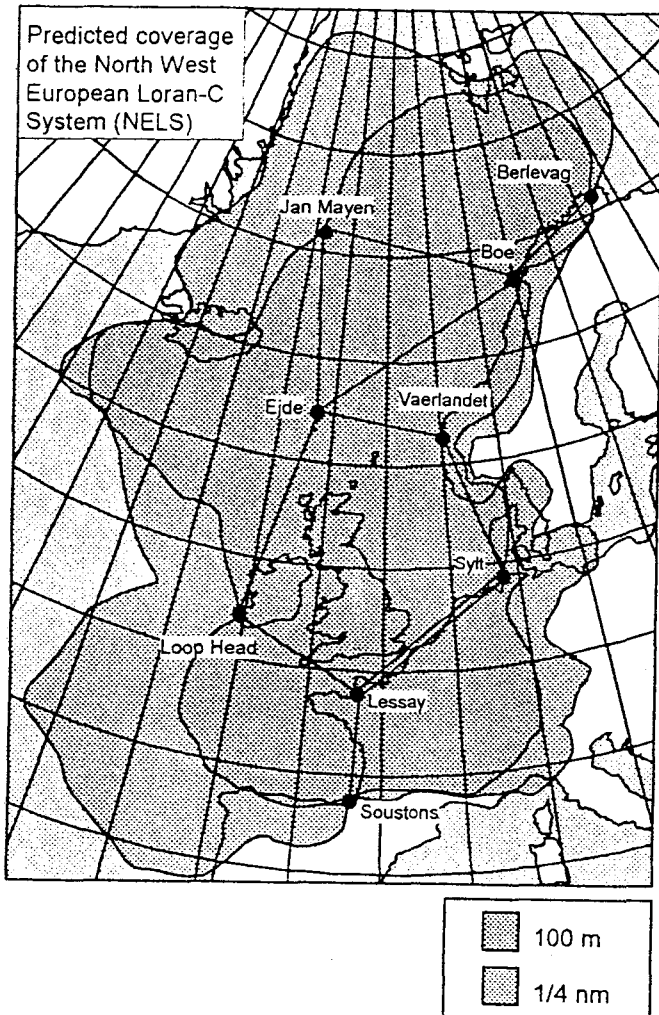
to some of you better known as NODECA - was tasked to undertake the executive part of it. Within NODECA Headquarters, staff units were established in support of this activity - a Project Management Office (PMO) responsible for the implementation of the system and a Coordinating Agency Office (CAO) preparing for the coordination of the operation of the system and acting as secretariate for the Steering Committee.

National activities are taken care of by so called National Implementing Agencies or NIA's as far as implementation of system elements in each member country are concerned - corresponding arrangements will be made for operation of the different national installations.

My first foil depicts this organizational structure (Foil no 1). As you will see, both activities of the Coordinating Agency and the national implementation and operation of the Norwegian part of the system are vested in NODECA and under jurisdiction of the Deputy Director General NODECA.



My next foil (Foil no 2) give you the final configuration and predicted coverage for the system. It is slightly different from the one that was presented in Birmingham in as much as two virgin sites in Norway had to be moved further to the north and east because of conflicts with environmental protection regulations at the original sites.



The main equipment contract was entered into by MEGAPULSE and NODECA on the 7th of September 1992 with due consideration for national regulations in some member countries. The contract covers the delivery of seven new transmitters type ACCUFIX 6500 and the necessary monitor-receivers and accessory. Four of these will replace old tube transmitters at present USCG sites in the German island Sylt, Ejde in the Faeroes and Jan Mayen and Boe in Norway. The other three will be installed in new virgin sites at Loop-Head in Ireland and Vaerlandet and Berlevag in Norway. In addition to this, two existing French stations, Lessay and Soustons, will be integrated in the system.

At the early planning stage it was decided to go for Time of Emission Control (TOE) - in some papers referred to as Time of Transmsion Control (TOT) -. This implies that the

emission time of all emitters will be controlled to occur in a fixed relationship to a system master clock which in the case of NELLS, will be synchronized to UTC. The reason for use of TOE is basically that TOE would offer evenly distributed errors within the whole area of coverage, new possibilities for a more effective utilization of advanced receiver technology like cross chain fixing, and coordination with other UTC related systems like GPS. Under TOE control the system can be controlled from one centre only and this mode of operation was the basis for the budget approved as part of the agreement. Location of this centre was planned to be at Brest in Northern France. However, the agreement also opens for a second control centre in Norway and this option will most probably be realized as an added function at the Boe transmitter station in North-Norway.

TOE control of a system of 9 LORAN-C transmitters organized in 4 chains has never been tried before and France has taken the lead in the development of the hardware and software necessary to realize this concept of operation. A development contract with MEGAPULSE is part of the French engagement.

As I have allready indicated, four of the NELLS stations are today USCG installations in full operational use. This use of USCG stations as part of NELLS has been made possible by the US offer to transfer these stations to present host nations when no longer needed by the US. The legal basis for this transfer is about to be established in negotiations between the US and the host nations concerned aiming at transfer of ownership the night between 31 December 1994 and 1 January 1995. The implication of this is that negotiations also are necessary to elucidate the terms on which intallation of new equipment can take place prior to take over of ownership. These negotiations are not believed to cause any delay or indeed any other difficulty for the project and I like to use this opportunity to underline the cooperation and good will demonstrated by the USCG throughout the whole transfer process.

A logistics Support Concept for NELLS has been adopted identifying activites and prerequisites for the overall support of the system. This includes organizational and administrative arrangements required to coordinate, manage and monitor the various activities involved and of course a maintenance organization to implement the maintenance policy in consonance with the operational organization. The maintenance policy is primarily based on the technical characteristics of the ACCUFIX 6500 transmitter, continoues monitoring and failure detection of each transmitter by the parent Control Centre and a required system availability of 99.7%. The characteristics of the transmitter are particularly important in this respect since it include high reliability and near 100% redundancy making the likelihood of an uncontrolled outage extremely low even if restoration of a faulty assembly is deferred say 48 or even 72 hours. On this basis the following three levels of maintenance have been established:

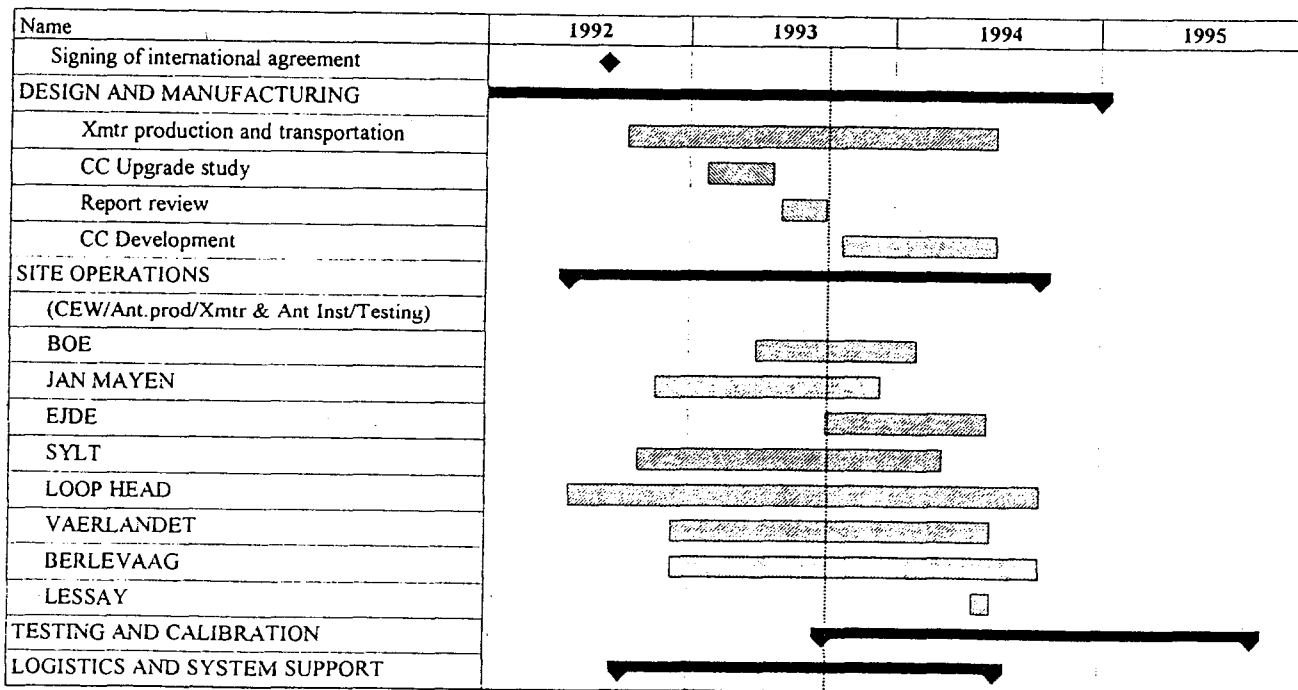
- Caretaker at the station to carry out limited corrective and preventive maintenance on request by the parent Control Centre or as directed by the Local or Regional Teams.
- Local Teams responsible for one station or Regional Teams covering several stations, to carry out corrective action on request of the parent Control Centre and preventive maintenance according to established procedures.
- Maintenance Centre for repair of defective modules or assemblies - if necessary in cooperation with the Manufacturer.

As already indicated defective modules or assemblies will be shipped to the Maintenance Centre in Brest for repair and functional verification. Since it is agreed to have only one spare unit of each kind at the station, supply stores with a common pool of "exchange spares", will be required. In NELS such stores will be established at Brest and Boe, however, administratively they will be considered as one and for instance exchange parts between them as necessary to maintain a balanced probability of meeting their respective demands.

Another area in preparation is NELS information service which is presently under development in two different directions - one to ensure that potential users are aware of the fact that a LORAN-C system will be available in North West Europe in the mid ninetieth and another to integrate LORAN-C into present arrangements for national and international system status reporting when in operational use. Assistance from WGA through Mr John Beukers in working out a NELS information and awareness program, has been of great value in this regard and is very much appreciated.

In my brief in Birmingham last year, I presented an overall Project Implementation Schedule. In my last foil (Foil no 3) an updated version of this schedule is depicted. As you will see the development of the control system has become a more timeconsuming job than originally anticipated with the result that date of completion is brought far into 1994 and has become a critical item together with testing and calibration. The result of this is that date for operational use of the complete system has moved into 1995 even if all the transmitters are on the air before the end of 1994.

North West Europe and North Atlantic Loran-C System System Implementation Schedule



DEVELOPMENT OF THE CHINA LONG-RANGE NAVIGATION SYSTEM (CHINA LORAN-C)

Lui Qing-Miao Kong Ling-Hu

Authority of China Long-Range Navigation Systems

ABSTRACT

This paper introduces the outlook of China Loran-C systems, with the following main points:

1. Location of China Loran-C systems and their stations.
2. Working area of China systems.
3. Developing procedures of China Loran-C.
4. Main technical features and their history.
5. Schedule to open China Loran-C to the world.

INTRODUCTION

The construction of the China Long Range Navigation System (China Loran-C) began in the 1980's and is used for developing China's economy. After this system was established, it achieved extensive application in various areas, and has a good reputation from its vast users.

TRANSMITTING STATIONS

The China Loran-C system consists of three chains (Southern, Eastern, and Northern Chains) with six transmitters and three monitor stations. The three transmitter stations of the Southern Chain are located in Chongzuo, Hexian in Guangxi province and Raoping in Guangdong province, and the monitor station is set in Shangchuan in Guang-

dong province. As to the Eastern and Northern chains, four transmitter stations are located in Raoping of Guangdong province (dual rate, also for the Southern Chain), Xuancheng of Anhui province (dual rate for both), Rongcheng of Shandong province (dual rate for both), and Helong of Jilin province, and two monitor stations are temporarily set in Nanhui of Shanghai and Chengshantou of Shandong province. The navigation range of these systems is 1000 to 1300 miles. The signals cover an extensive ocean area to the north of the Nansha Islands, the west of the Ogasawaro-Gunto, the south and west of the Tsugaru Strait (see picture). The system positioning accuracy is about 50M to 2200M, and could supply the navigating and positioning service for transportation, ocean, investigation, oil and gas exploration, and fishing boats in the above areas.

The construction work of the Southern Chain started in 1983. In 1988, the system successfully finished its test work. In 1989, this system was put into primary operation and in 1990 was formally put into operation in China. During the operation, all technical specifications reached the expected requirement. As to the Eastern and Northern Chains, they were started in 1989. At the end of 1992, all the stations successfully transmitted their signals. These

two chains will finish their test work in 1993.

China Long Range Radio Navigation System uses the same technical format as American Loran-C in the 1950s. But system performance and equipment technology have gotten development synchronized with the progress of science and technology in the world. The system is equipped with the newest technology and advanced equipment of Loran-C system. For example, all our stations use either Megapulse solid-state transmitters or Megapulse technology.

TECHNICAL DIFFICULTIES

Also, our radio navigation system is successfully established in accordance with the special conditions in China and has overcome the following series of difficulties.

The first one is the arrangement of system stations. As our coast line is a protruding curve outward, in order to meet the requirement of navigation positioning on the above areas, the transmitter stations must be located deeply inland. After repeatedly discussing and proving many times of reconnaissance and designing work at the sites, we finally designed our system arrangement with short baseline, big outward obtuse angle, and high radiated powers. The system operation and measured data show that the specifications and performance have reached all design requirements; navigation positioning on extensive ocean area of the South Sea has been ensured.

The second is that we use a single tower transmitting antenna with high efficiency, in order to reduce the construc-

tion scale of transmitter stations and save cost. Through many discussions with some famous antenna specialists in China, we finally gave up a scheme with four tower antenna and decided using a single tower antenna with top umbrella and insulated bottom. The measurement and operation show that these antennas have higher efficiency than the same types of antenna inside and outside of China. Also, these antennas have undergone strong thunder and violent typhoons. They are very safe and reliable.

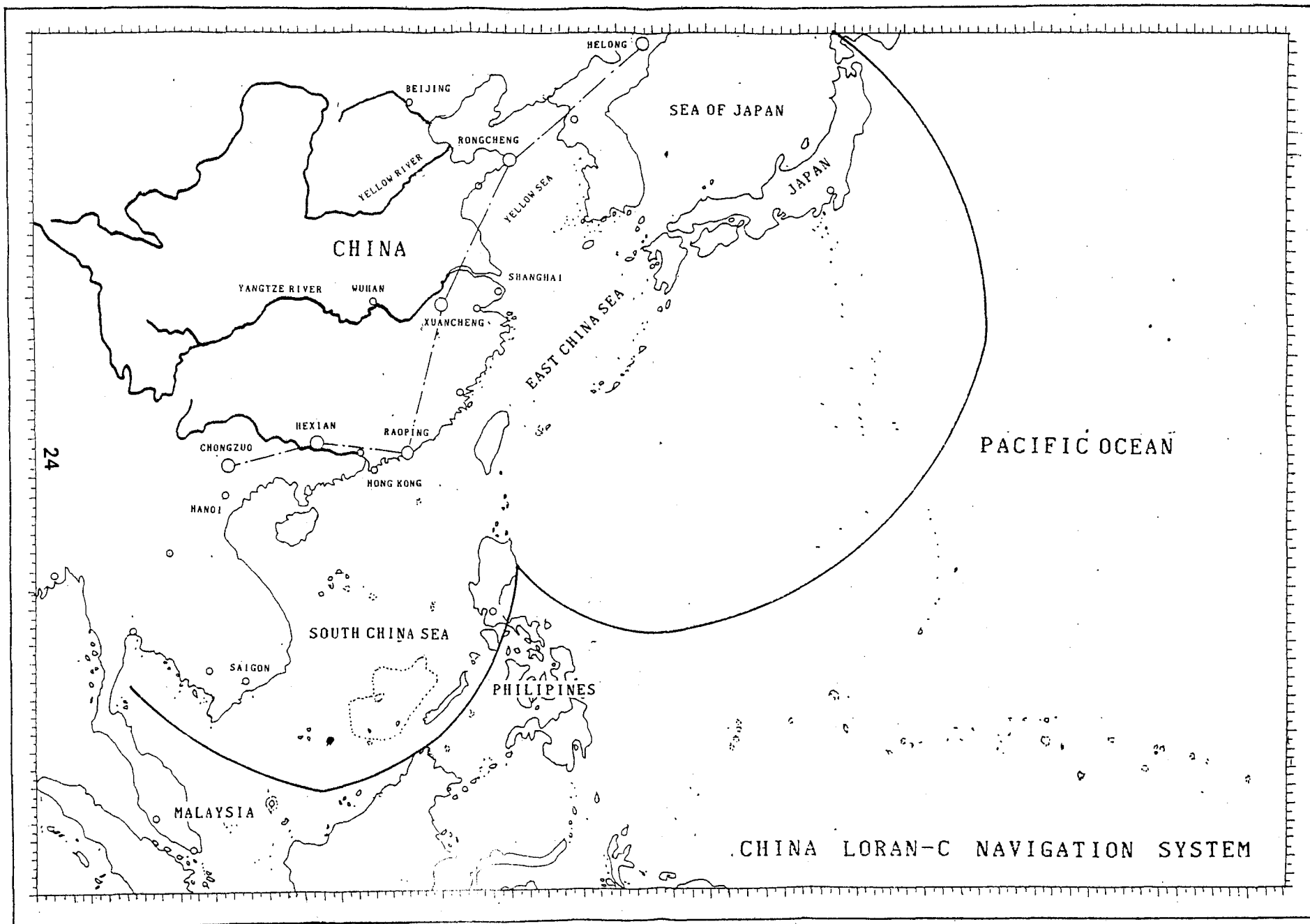
The third one is the locations. All Transmitter stations are located in hilly areas. This is contradictory of the requirements of navigation stations for high electricity. We seriously and scientifically investigated and analyzed this situation. Even without large-scale work of smoothing the sites, through reasonable requirement, correct design work, and strict construction, we finally made once designing work, once construction work, once testing work, and once to get success. All these assure sound technical performance on these navigation stations.

Besides, on system timing with cesium standards, remote measurement and control of the chains, resisting skywave interference, radiowave propagation corrections, and so on, there are various distinctive features, which are well received by domestic and foreign specialists.

INTERNATIONAL COOPERATION

These years, our proper authorities sent representatives to attend the fourth meeting of the Far-East Loran-C and Chayka Technical Working Group,

which was convened by IALA. The representatives of four countries, China, Russia, Japan, and South Korea, at the meeting finally signed an agreement, which was named "Comments on the agreement on an international program for the establishment of a joint radionavigation service in the Far-Eastern waters using Loran-C and Chayka stations." We are now actively making everything ready, according to the requirement of this agreement, and plan formally to open our China long-range radio navigation system (China Loran-C) to the world. At that time, we shall, in accordance with international practice, publish all our system's parameters to the world.



STATUS ON THE CONTROL METHODS FOR THE RUSSIAN/AMERICAN CHAIN

CDR Doug Taggart, CWO Jim Robinson,
LTJG T. Thomson and ENS J. Thompson

U.S. Coast Guard G-NRN-1
Washington, D.C. 20593

ABSTRACT

The Russian/American Chain provides Loran-C/Chayka coverage in the Northern Pacific/Bering Sea area. The chain is formed by a master Chayka station at Petropavlovsk on the Kamchatka peninsula, a secondary Loran-C station on the island of Attu, Alaska and a secondary Chayka station at Alexandrovsk, Sakhalin. This chain is the first radionavigation aid developed through a mixture of the Loran-C and Chayka navigational systems. This fact alone makes this joint chain unique in many ways; one of which is the method of chain control. This paper presents background on the chain's formation, an update on the chain's operational status, a discussion of control methods, and a forecast of when the chain will be declared operational.

BACKGROUND

The U. S. Coast Guard (USCG) and the agencies of the former Soviet Union began discussions on radionavigation in 1980. Most of the efforts up to 1987 focused on standardization of signal characteristics and avoidance of mutual interference, both from other Loran-C/Chayka chains and from third party radio sources. In August 1987, in Washington D.C., the Soviets proposed that both countries join in the operation of radionavigation systems. They specifically suggested combining Loran-C and Chayka chains by dual-rating existing stations. The USCG agreed to consider joint operations with Loran-C stations in Alaska.

In April 1988, the USCG and the former Soviet Union negotiated a proposal to set up a Loran-C/Chayka chain in the North Pacific.

In May of 1988, an Agreement was signed at the Moscow Summit between Secretary of State Schultz and Soviet Foreign Minister Shevardnadze on the

creation of a joint Soviet-American Network (SAN) of Chayka and Loran-C radionavigation systems. In November 1989, a Memorandum of Understanding (MOU) between the Russian Internavigation Committee and the USCG was signed to implement the 1988 agreement. This MOU established a Russian/American Coordination Council, established technical working groups, developed milestones to meet deadlines, and agreed upon a phased development approach to the Russian/American Chain (RAC). Reference (1) contains a number of chain configurations to join the Loran-C system with Chayka stations. For the purposes of this paper, we will set aside an explanation of the discussions and compromises which took place to reach the chain configuration currently being developed. The interested reader may obtain more information on the various proposals by reviewing references (1) and (2). With this stated, we will simply proceed to the agreed configuration. The joint chain was to be made up of four Chayka stations and a single Loran-C station. The chain was to be developed in stages. The first stage would be made up of a master Chayka station at Petropavlovsk (on the Kamchatka peninsula), a secondary Loran-C station at Attu, Alaska, and a secondary Chayka Station located at Alexandrovsk in Sakhalin. Stage two was to include the addition of a low powered secondary Chayka station in the Kuril Islands. Stage three was to have included the addition of a third Chayka secondary (again a low powered station) in the Okhotsk area. Figure 1 shows the chain configuration as proposed in 1989.

Since April 1988, there have been five formal meetings of the RAC Coordination Council. The most recent meeting was held in Alexandria, Virginia in August 1993. In addition to these formal Coordination Council meetings, there have been a number of technical meetings. These meetings have focused on resolving various technical issues associated with the development of this joint

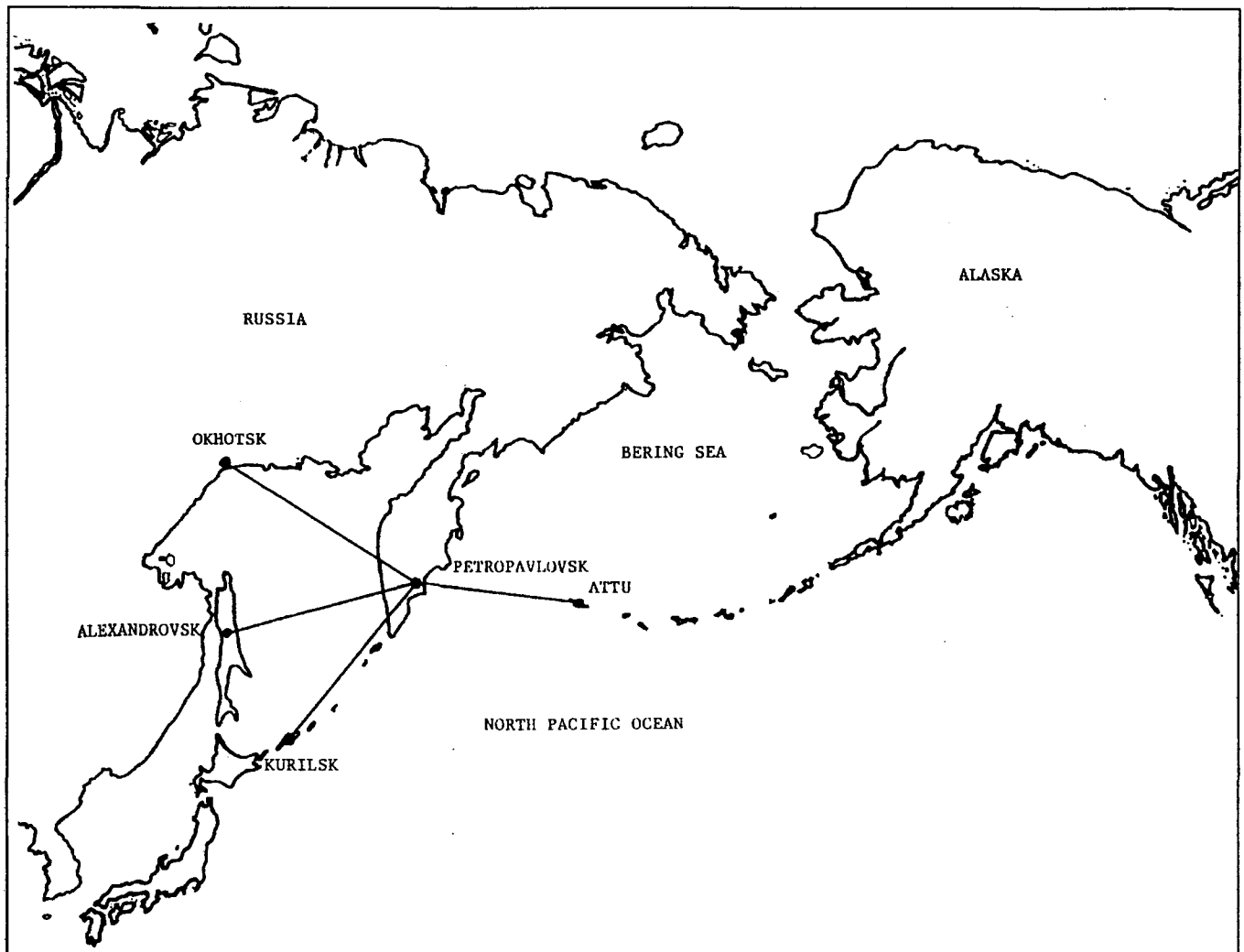


Figure 1 1989 Proposed Chain Configuration

chain. Examples of these technical matters include: development of communications methods, determination of the Group Repetition Interval, operational guidelines, user receiver tests, calibration tests, and the development of control and monitoring procedures.

USCG UPGRADES AT ATTU

In February of 1991, the USCG dual-rated the Attu, Alaska station and began Loran-C transmissions on Group Repetition Interval (GRI) 9070. This GRI was chosen by the USCG because it provided for the least amount of mutual interference between the numerous GRIs existing in the area of the RAC, and also was large enough to allow for expansion of the chain through each of the three phases. In the

summer of 1991, following a Coordination Council meeting held at the USCG's Electronic Engineering Center in Wildwood, New Jersey, the GRI for the developing RAC was agreed to be 5980. Selecting this rate was a combination of compromises. 9070 is somewhat more desirable than rate 5980 for the rejection of cross-rate interference, but is not compatible with existing Russian user equipment (both aviation and marine receivers). Shifting to rate 5980 was achievable for the USCG's transmitting equipment at Attu, but it did require that the output power be lowered until the AN/FPN-42 transmitter could be replaced with the more powerful AN/FPN-44B transmitter (a project that was being pursued concurrently, independent of the RAC project). In June 1991, the GRI of the Attu station was changed from 9070 to 5980 and the output power was

adjusted to a level of approximately 150KW peak radiated power on the RAC rate. The upgrade of the ATTU transmitter was completed in April 1993. At that time, the transmitting power of the Attu signal (on rate 5980) was raised to the same level as the 9990 Northern Pacific Chain (approximately 400 KW peak radiated power). The Attu station has been transmitting as a dual-rated station continuously since the spring of 1991.

CHAIN CONFIGURATION

As mentioned, the RAC was to have been developed in phases. The first phase consisted of dual-rating the Petropavlovsk station to be configured as the master station, dual-rating and upgrading the Attu, Alaska Loran-C station, and dual-rating the Alexandrovsk Chayka station. Both

the Petropavlovsk and Alexandrovsk stations are part of the Russian, Chayka Eastern Chain (GRI-7950). During the Coordination Council meeting of 1992, held in Moscow, it was agreed that phases II and III of the 1989 MOU would be deleted and that the addition of the Okhotsk and Kuril Island Chayka stations would therefore not occur. Deleting phases II and III made it unnecessary to consider choosing an alternative to the GRI of 5980. The resulting chain configuration and the estimated coverage is as shown in Figure 2.

INTERIM CHAIN PARAMETERS

The chain parameters for the chain are shown in Table 1.

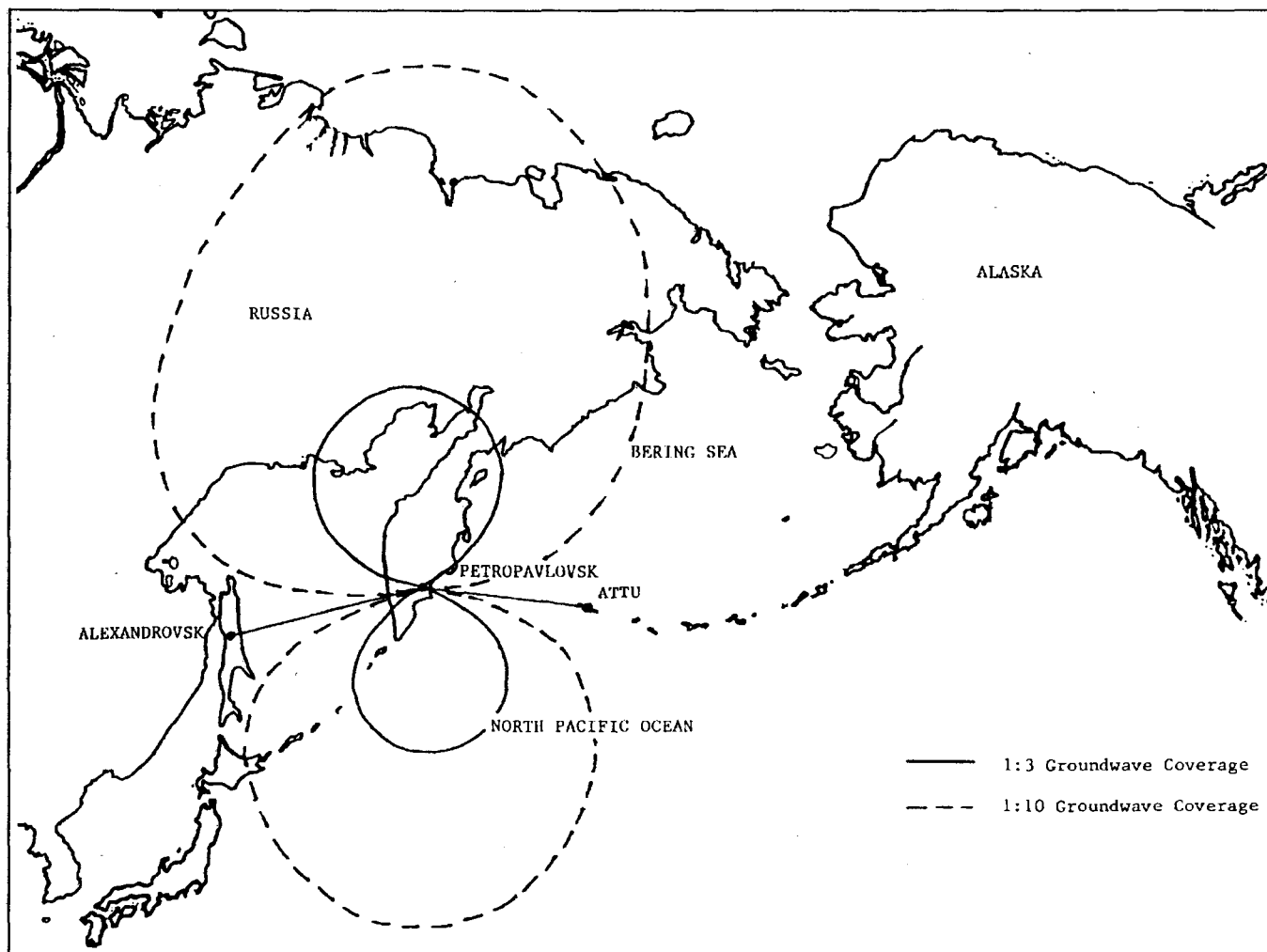


Figure 2 Russian/American Chain Configuration

Station Name and Lat/Long (WGS-84 equivalent)	Designation/ Transmitted Power	Coding Delay	Emission Delay (seawater path)	Transmitted ECD
Petropavlovsk 53-07-47.584 N 157-41-42.900 E	Master/700KW	N/A	N/A	(note 1)
Attu, Alaska 52-49-44.1 N 173-10-49.5 E	Xray/400KW	11000	14467.56 (interim)	0.0 usec
Alexandrovsk 51-04-42.8 N 142-42-04.9 E	Yankee/700KW	28000	31506.50 (interim)	(note 1)

Table 1
RAC Interim Chain Parameters (GRI-5980)

Note 1: The Chayka signal shape is not identical to the Loran-C Signal Specification. Defining the transmitted ECD using USCG convention has no meaning. For further details on the Chayka signal shape see Reference 3.

The values expressed for the Emission delay are the calculated values based on an all seawater path between the respective sites. The propagation velocity used is 299530 Km/sec.

CHAIN COMMUNICATIONS

To coordinate operations, a means of communication is required. In addition to the language barrier, choosing a means of real-time (or near real-time) communications is essential for successful operations. Although USCG chain operational procedures contain contingency plans for operating a chain in the absence of communications for short periods of time, it is unrealistic to assume that operations could be conducted without having a dedicated communications scheme in place. Developing the communications method directly relates to the concept of control. Early on, the Russians expressed a strong desire to be in total control of the signal from the Attu station. Many technical discussions focused on the methods and technical aspects of USCG control procedure. From the USCG perspective, the subject of developing communications means not only focusing on the issue of real-time control of the baseline, but also on the administrative nature of operating and managing the baseline. Questions such as: How would routine maintenance be coordinated?, How would the stations respond to equipment breakdowns?, Who would initiate blink?, How would synchronization of the time base be accomplished?,

etc... were all part of the discussions. Each of these issues needed to be addressed in the communications plan. The Russians suggested that communications could be conducted through HF between Petropavlovsk and Attu. Although HF capabilities exist at Attu, using HF would require a full-time manned watch at Attu and would likely require an HF communications/frequency plan that was different than that used between Attu and Kodiak control site (Kodiak is the chain control for the NORPAC 9990 chain). The USCG preferred to establish a dedicated teletype link through commercially available satellite and line hops between Petropavlovsk and Kodiak and rely on existing communications links between Kodiak and Attu. Payment for these circuits would be based upon costs incurred within the borders of each of the respective countries. This approach was not desired by the Russians due to the remoteness of the Petropavlovsk station and the difficulty in routing such circuits through Russia.

In addition to conventional two-way communications, the Russians have a means of communicating information from the master station to the secondary stations through the modulation of the master's ninth pulse, referred to as the "radionavigation

communication channel". Russian user receivers are capable of decoding these modulations and thereby receiving direct information from the master station. The Russians requested that one of these receivers be installed at Attu. They suggested that a "code" book be used to cut down on the length of messages (thereby increasing the information rate and also overcoming the language problem). They further suggested that a scheme be developed where the receiver could be connected directly to the Attu timing equipment so that control information could be directly introduced.

It should be pointed out that the USCG Loran-C system provides for the passing of information via the Loran-C signal through a modulation scheme of time shifting pulses 7 and 8 of the master and secondary stations (referred to as "Two-Pulse Communications"). The Russians were aware of this technique and suggested that the USCG consider the installation of the "Two-Pulse Communications" equipment at Petropavlovsk. This would provide a direct means of communications between Petropavlovsk and Attu. The USCG determined this proposal was too complicated because of the design of the equipment and its dependency on the transmitting site timing-and-control equipment. In other words, introducing "Two-Pulse Communications" receiving equipment at Petropavlovsk would have required a significant amount of ancillary equipment. This, combined with the aspect of powering the equipment and maintaining it, let alone the training of its use, far exceeded any benefit from the perspective of establishing useful communications.

The USCG suggested that Inmarsat-C communications between Petropavlovsk and Kodiak be used for the primary communications link. This approach was adopted and equipment has been located in recent months at Petropavlovsk, Kodiak and Attu (Inmarsat-C use at ATTU was a temporary installation used during a recent chain calibration phase). As of the writing of this paper, communications between Kodiak and Petropavlovsk have been established and administrative messages directly related to the operation of the current configuration are being transmitted on a routine basis.

RUSSIAN CONTROL TECHNIQUES

Reference (4) provides a summary of the

procedures used to control a Russian Chayka chain. The Chayka control technique is based on maintaining a constant time interval between the transmission times of the master signal and the secondary signal. The "transmission delay" (t_t) of the secondary is the sum of the propagation time along the baseline t_b and the coding delay t_{cd} . Therefore, the transmission delay is expressed as; $t_t = t_b + t_{cd}$. Figure 3 depicts this simple baseline.

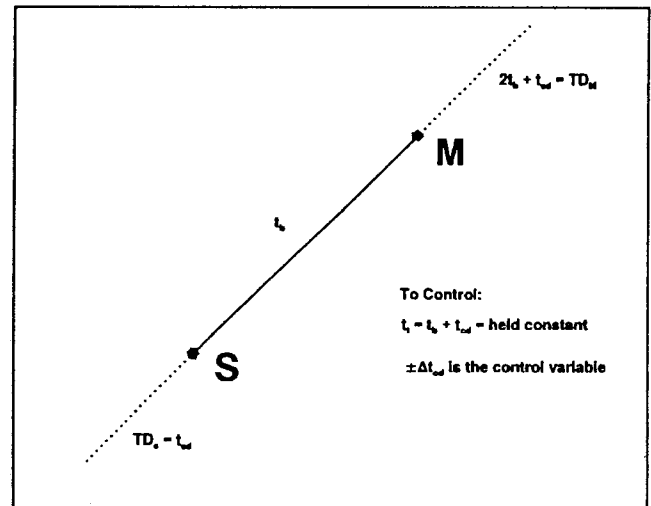


Figure 3 Chayka Control Diagram

The Chayka method of collecting data to measure these times is based on receiving equipment connected directly to the transmitting antennas as well as a procedure of doing baseline extension measurements during the execution of chain calibration. The time difference for the master baseline extension is: $TD_M = (2t_b + t_{cd})$ and the time difference on the secondary baseline extension is $TD_S = t_{cd}$. During the calibration of a Chayka baseline, the measurements at each end of the baselines are made and averaged over time. These calibration values are assigned the values TD_M^C and TD_S^C for the master and the secondary, respectively. The half-sum of these two average calibration measurements can be shown as:

$$(TD_M^C + TD_S^C)/2 = (2t_b + t_{cd} + t_{cd})/2 = t_b^C + t_{cd}^C = t_t^C$$

(equation 1)

Chayka timing control following calibration is executed by the master station. At some time (t) following the calibration, should the TD at the master (TD_M^t) change by ± 0.2 microseconds of the most current value, the master station requests the

secondary to forward its value of TD_S^t . Using these two measurements, the half-sum and half-difference of each are calculated as;

$$(TD_M^t + TD_S^t)/2 = (2t_b^t + t_{cd}^t + t_{cd}^t)/2 = t_b^t + t_{cd}^t = t_t^t \quad (\text{equation 2})$$

$$(TD_M^t - TD_S^t)/2 = (2t_b^t + t_{cd}^t - t_{cd}^t)/2 = t_b^t \quad (\text{equation 3})$$

Timing changes are made if the difference between $t_t^t - t_t^c$ and the difference $t_b^t - t_b^c$ are approximately equal and of the same sign. When this occurs, the coding delay is adjusted by the calculated amount in order to maintain the transmission delay, t_t^c . If these measurements do not agree, variations are attributed to changes between the reference clocks at either end of the baseline and appropriate actions are taken to resolve these differences. This method of control tends to null out changes in the propagation paths at the mid-point of the baselines. This is exactly the case if it is assumed that the propagation velocity is uniform throughout the coverage area and that any changes in this propagation velocity are equal throughout. Before moving on to a short explanation of the USCG's control method, it is also worth noting that in the Chayka system, corrections from the master to the secondary are accomplished with the "radionavigation communication channel", i.e. modulation of the master's ninth pulse.

REVIEW OF USCG LORAN-C CONTROL TECHNIQUES

The USCG's control method is based on the concept of maintaining a constant time difference at a single point in the user area. This point is referred to as the System Area Monitor (SAM). For a single baseline, the time difference at the SAM is expressed in terms of the time to transit each of the paths is:

$$TD_{SAM} = t_b + t_{cd} + t_{S-SAM} - t_{M-SAM} \quad (\text{equation 4})$$

Referring back to the discussion of the Chayka control technique, the term $t_b + t_{cd}$ is called the transmission delay; for the Loran-C system, this term is called the Emission Delay (ED). Substituting this into equation (4) and expressing the ED as a function of the other values yields;

$$t_b + t_{cd} = ED = TD_{SAM} - t_{S-SAM} + t_{M-SAM} \quad (\text{equation 5})$$

For later use, it will also be stated that the time difference at any point P is represented by the expression:

$$TD_P = t_b + t_{cd} + t_{S-P} - t_{M-P} \quad (\text{equation 6})$$

and substituting equation 5 yields:

$$TD_P = TD_{SAM} - t_{S-SAM} + t_{M-SAM} + t_{S-P} - t_{M-P} \quad (\text{equation 7})$$

Figure 4 depicts this simple baseline in terms of the various paths.

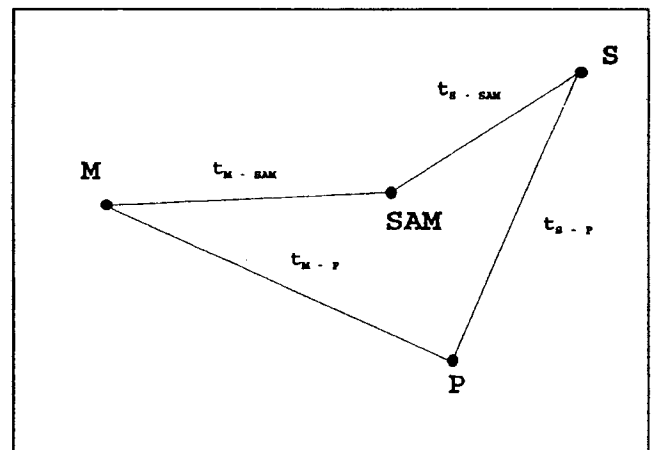


Figure 4 Loran-C TD Control through a System Area Monitor

In the Loran-C system, the ED is determined at the time of the baseline calibration. The respective TD_{SAM} is established and there-after referred to as the Controlling Standard Time Difference (CSTD). Chain control procedures ensure that this time difference is maintained within a strict tolerance at all times. Results of numerous studies conducted by the USCG's Research and Development Center in the early 1980's and a review of volumes of records maintained by the USCG's Loran-C Program Office, show that variations of this TD_{SAM} are maintained within ± 12 nanoseconds (1 sigma). Maintaining the TD_{SAM} (or the CSTD) is accomplished by making small changes (typically ± 20 nanosecond) to the secondary's time of emission. The need to make adjustments to maintain the

CSTD can be related to propagation path changes and/or cesium clock drift at either the master and/or the secondary. Administrative procedures within the USCG's Loran-C Program set guidelines to maintain the relative drift between the cesium clocks at the master and the secondary. Based on these maintenance guidelines, a significant portion of the changes required to maintain the CSTD can be attributed to changes in the propagation paths along the paths shown in Figure 4. Relating the Loran-C control procedures to the Chayka procedures, it can be stated that the two methods could be considered equal if the SAM were exactly located on the midpoint of the baseline between the master and the secondary. If the assumption that propagation velocity throughout the coverage area were equal, and that any changes in this velocity occurred in a homogeneous fashion, then it could also be said that the two methods would still achieve the same control results if the SAM were located at any point on the perpendicular bisector of the baseline.

Although not directly related to an understanding or an explanation of the USCG's control technique, it is worth taking a moment to briefly explain the results of some studies conducted by the USCG's Research and Development Center in the early 1980's. These studies focus on a method to quantify the repeatability of Loran-C. These studies relied on a uniform propagation model called the Double Range Difference (DRD) model. The DRD model was used to quantify changes of time difference values over an annual period in order to determine the degree of repeatable accuracy that could be anticipated at any particular point in the coverage area. Referring back to equation 7, assuming a uniform propagation velocity (v) and expressing time as a function of velocity and distance reveals the term:

$$\frac{(-t_{S-SAM} + t_{M-SAM} + t_{S-P} - t_{M-P})}{(-R_{S-SAM} + R_{M-SAM} + R_{S-P} - R_{M-P})/v} =$$

where the Double Range Difference (DRD) is defined as:

$$DRD_P = (-R_{S-SAM} + R_{M-SAM} + R_{S-P} - R_{M-P})$$

Also realize that $-R_{S-SAM} + R_{M-SAM}$ is a constant. The term $(R_{S-P} - R_{M-P})$ varies as P moves throughout the coverage area. Using these results, the TD at any point P can be expressed as:

$$TD_P = TD_{SAM} + DRD_P/v$$

(equation 8)

As shown by equation 8, and continuing to rely on the R&D studies, it can be seen that as the DRD magnitude increases, i.e. point P moves further away from the SAM (in the DRD sense) and looking at the time derivative of equation 8 with respect to V , the maximum TD variation will occur at the maximum value of DRD.

As one might expect, locating the SAM at the midpoint of a Loran-C baseline is directly related to the availability of land. In addition, choosing a location for a SAM must also factor in such things as: power to operate the site, communications capabilities to and from the site, and the availability of personnel near, or at the site to conduct routine and corrective maintenance.

In the case of the baseline between Petropavlovsk and Attu, it is readily obvious that locating a SAM near the midpoint of the baseline was not possible. As far as the USCG was concerned, the only site available for monitoring of the Petropavlovsk/Attu baseline was on the island of Attu. In the spring of 1991, an Austron 5000A receiver was installed just outside of the transmitting antenna's ground plane at the Attu transmitting site (approximately 1000 feet away from the antenna base). Data from the site is sent back to the control site on Kodiak Island through communication channels which are in place to support the Northern Pacific Loran-C (GRI 9990) chain.

Locating the SAM at this point presents an interesting situation if one examines equation 4. As the SAM approaches the secondary:

$$TD_S = t_b + t_{cd} + t_{S-S} - t_{M-S} = t_{cd}$$

$$\text{where } t_{M-S} = t_b \text{ and } t_{S-S} = 0$$

Although, in the case of Attu, the monitor receiver's antenna position is not the same as that of the transmitting antenna (as it is with the Chayka system), any changes along the small path length between the secondary and the SAM (i.e., 1000 feet) can be considered insignificant. In other words, with the receiver site at Attu, the coding delay of the secondary signal can be assumed constant. Given this "end of the baseline" control situation, and relying on the findings presented in

reference (5), it can be stated that the effect of maintaining a constant time difference at the secondary end of the baseline will create a seasonal component at the master end similar to that shown in Figure 5.

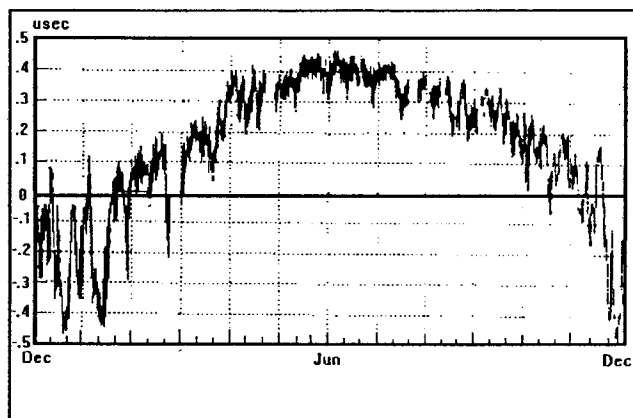


Figure 5 Typical Seasonal Pattern

As shown, the sinusoidal pattern will repeat itself on an annual basis. This pattern is a result of the signal traveling faster in the winter months, slower in the summer. The magnitude of the variation will be directly related to the variation in propagation velocity and the distance away from the SAM. Relating this to the R&D studies, the Double Range Difference will achieve its maximum positive value at the master station and its maximum negative value at the secondary. Extending this to the Petropavlovsk/Attu baseline (with the SAM at Attu) means that throughout the course of a year, the greatest change will occur at the master station and less and less seasonal variation will be observed as the secondary at Attu is approached. The R&D studies provide a method to quantify the peak to peak deviation and the maximum DRD distance at a rate of .5 to 1.0 microseconds. Referring back to the chain coverage diagram of Figure 2, it can be seen that this "TD grid" stability is unfortunately at the wrong end of the baseline.

DATA TO DATE

Over the past 18 months, three separate periods of joint on-air operations have existed between Petropavlovsk and Attu on rate 5980. Data presented in Figures 6, 7 and 8 were collected from: 28 June to 19 July 1992, 8 October to 27 December 1992, and 16 June to 26 July 1993, respectively.

During these periods, the Attu station was controlled through the use of the USCG's control equipment at Kodiak. Data presented in Figures 6a, 7a and 8a shows the number of daily timing adjustments required to keep the CSTD constant at Attu. These numbers were recorded by the Calculator Assisted Loran-C Control (CALOC) equipment at Kodiak. Figures 6b, 7b and 8b represent the daily cumulative totals (in units of nanoseconds) required to keep the Attu CSTD constant.

These data plots provide information on clock drifts at the transmitting stations and propagation path changes along the baseline. The trick is to be able to reach any meaningful conclusions about any one particular variable.

With regard to Attu's cesium standard, its drift is controlled by synchronizing it to the Master 9990 signal from the Loran-C Station at Saint Paul, Alaska. Through U.S. Naval Observatory data, the entire 9990 chain is synchronized back to Coordinated Universal Time (UTC). This synchronization approach eliminates Attu's cesium as a major contributor to these timing variations.

Propagation variations along the baseline can account for some of the changes depicted in the data. However, data collected over years of 9990 chain operations indicate that propagation changes of the magnitude shown in the figures are not traditionally experienced with this degree of daily variations. Therefore, the majority of the variations must be attributed to the time base of the Petropavlovsk master clock. Discussions with the Russians have indicated that they are actively taking steps to more closely synchronize their time base at Petropavlovsk to UTC. Referencing the statistics shown on these figures, it can be seen that there has been progressive improvement made to better control the long term drift. What does continue to remain present is a high degree of short term drift. As an example, typical USCG operating procedures require the Coordinator of Chain Operations to maintain synchronization between the clocks of the master and secondary stations so that the number of adjustments per day is on the order of 10 to 12. With regard to the cumulative offset, the goal is to keep daily averages in the range of 50 to 100 nanoseconds. Typical values of standard deviation when comparing a master clock to a secondary clock can be expected to be in the range of tens of nanoseconds. Accurate control of the time base

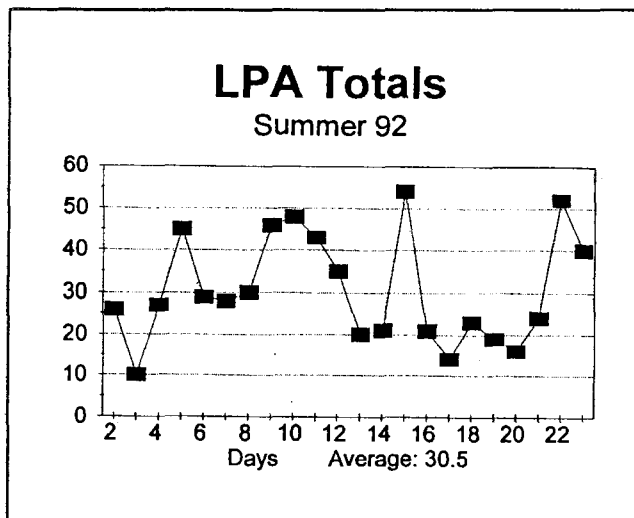


Figure 6a

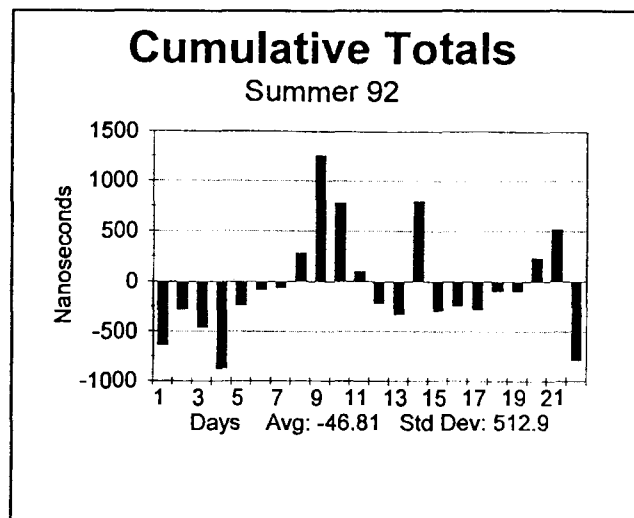


Figure 6b

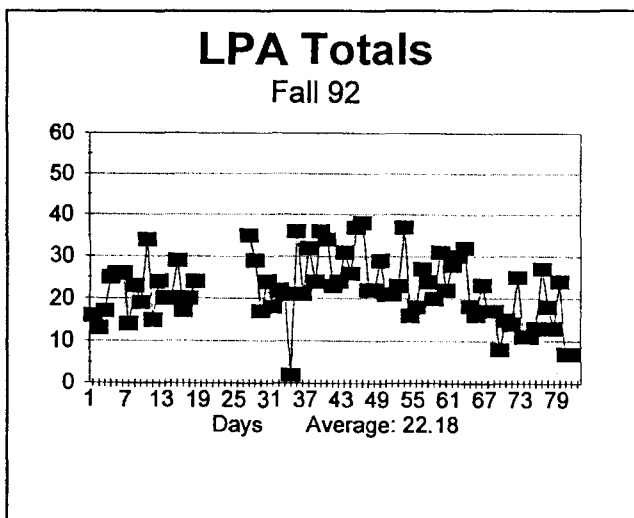


Figure 7a

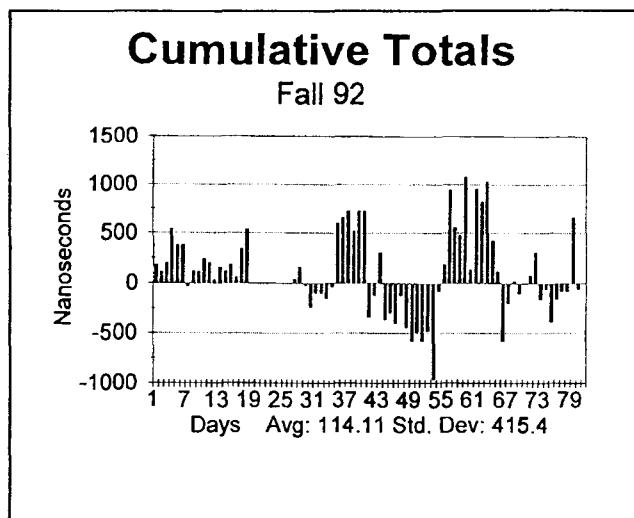


Figure 7b

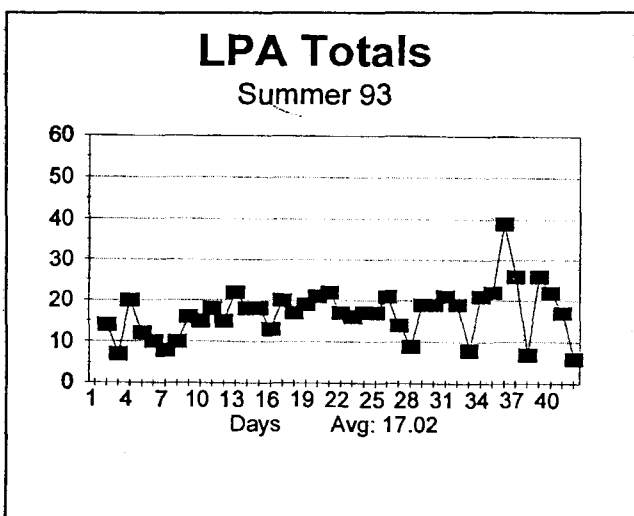


Figure 8a

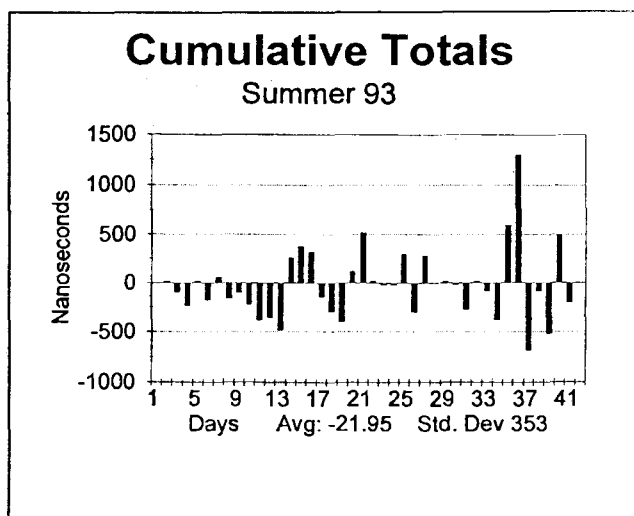


Figure 8b

between the two systems is a critical requirement which, although improving, still has room for improvement.

AGREED UPON RAC CONTROL PROCEDURES

Control of the Petropavlovsk/Attu baseline is a unique mixture of the Chayka and Loran-C control techniques. It has been agreed that short term control of Attu will be handled by Kodiak control equipment using the Attu monitor receiver. As discussed, the effect will be to hold continuously a constant Coding Delay. This control will compensate for clock drift between the two stations and will also mask, or compensate for, changes along the propagation path (in the direction of the master to the secondary). At the Petropavlovsk end of the baseline, the arrival of the secondary signal at the transmitting antenna (or baseline extension) will be a function of the baseline propagation variations in one direction (t_b from equation 1). If any change is observed at the master which exceeds the tolerance for variation (agreed to be no less than 50 nanoseconds), then Petropavlovsk will direct the Control station at Kodiak to adjust the CSTD at the Attu monitor by the amount necessary to reestablish the calibrated value of t_b^c in equation 1. The effect will be identical to the Chayka control procedure, i.e., changes near the center of the baseline will be minimized. Inmarsat-C will be used to coordinate these adjustments. Changes will be no less than 50 nanoseconds in magnitude. Adjustments will be announced to users before the change is made so that they can be informed that the grid will be slightly skewed or jumped. Viewed from the USCG control procedure, this control practice means that the CSTD value will not be a fixed constant but rather, the CSTD will annually vary around a "nominal value" on an annual basis.

FORECAST OF OPERATIONAL DECLARATION

Serious activity on the development of the RAC has been underway since the signing of the Memorandum of Understanding in 1989. Since the summer of 1991, there have been three completed periods of joint operations. In July 1993, the USCG conducted a joint "calibration" with Russian engineers of the Petropavlovsk/Attu baseline. The calibration consisted of a traditional "hot-clock" trip using established USCG methods of measuring and documenting emission delays. A portable cesium beam oscillator calibrated by the U.S. Naval

Observatory before and after the trip was used to make the independent time measurements at the master and secondary stations. The mathematical difference of the two observations is adjusted to account for reference clock drift and any other system adjustments that may have occurred in the interval between the two measurements.

As of the date of this paper, a fourth period of joint operations underway. The stations began an anticipated two month period of testing on 20 September 1993. During this test period, the Russians will be conducting calibration tests of the baselines using their own technique.

Once the Russian tests are completed, the results analyzed and compared, they will be distributed and the Interim Chain Parameters shown in Table 1 will be finalized and distributed. It is anticipated that this will occur before the end of 1993. This is in agreement with the timetable established in the MOU of 1989.

CONCLUSIONS

The development of the Russian/American Chain is a significant event in the history of the Loran-C and Chayka systems. It is the first example of the two systems being joined. The work conducted represents a significant engineering and technical achievement accomplished through a relatively simple exchange of information between the two countries. The mutually agreed control method stands as a good engineering compromise, a technically achievable compromise and an administrative compromise fully acceptable to both the USCG and the operators of the Russian Chayka System.

ACKNOWLEDGEMENTS

The authors would like to thank the USCG personnel stationed at Loran-C Station Attu, Loran Control Station Kodiak, Alaska, the Pacific Area Loran-C Staff, and the Electronics Engineering Center's Loran-C Branch in Wildwood, New Jersey for their numerous contributions to this paper and the subject in general. Without these dedicated Coast Guard military and civilian personnel, this entire project, let alone this paper, could not have been realized.

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SESSION 2

Loran-C/GNSS Interoperability

**A PROPOSED RADIONAVIGATION SYSTEM MIX
OFFERING A HIGH DEGREE OF INTEGRATION
BOTH IN SIGNALS PROVIDED TO MULTI-MODAL USERS
AND IN THE FACILITIES AS OPERATED BY THE SERVICE
PROVIDERS**

Edward McGann

ABSTRACT and SUMMARY

A variety of radionavigation systems are candidates for roles in the Global Navigation System (GNS) of the future. In arriving at the final system mix selections, the fundamental criteria will be that:

- the total signals in space satisfy the greatest number of Required Navigational Performance (RNP) criteria, as needed by the full range of multi-modal users—land, sea and air;
- the selections be acceptable to the large majority of countries and be in accord with the performance specifications set by international navigation authorities;
- the user equipment be designed to meet the RNP using the signals provided by the selected system mix and be effective, safe and economical; and
- the systems of the selected mix be operated by the service providers as safely, efficiently and economically as possible.

This paper describes an elegant candidate selection mix wherein the elements of a future Global Navigation Satellite System (GNSS), such as the successors to today's Global Positioning System (GPS) and the Global Navigation Satellite System (GLONASS), are combined with the elements of the terrestrially-based system—such as the long-range navigation (Loran-C) system and its CIS equivalent, Chayka. Further, the Loran-C/Chayka signals are used as a mechanism for

distributing service messages to the multi-modal user community. These service messages may include integrity information and differential correction messages for both satellite and terrestrially-based elements. In addition, the timing of the terrestrial transmitting stations and of the satellites are held with respect to a common reference clock, thereby offering an “all-in-view” signal processing capability. Also, the transmitting stations of the terrestrially-based system are used as monitor locations for the GNSS, taking advantage of all of their available capabilities ranging from precise clocks to facilities and operating personnel.

The advantages for the users are that they will have access to either the terrestrially-based or satellite signals independently or all signals may be used in combined modes. The same user equipment will also extract the service messages imposed on the signals from the terrestrial-based system and utilize them as required to meet the particular user RNPs. Therefore, there is no need for separate communication receivers and antennas to augment or validate the navigation signals.

For the service providers, this proposed system mix with its unique configuration—specifically, the co-location of as many elements as possible—offers an effective, economic implementation with low installation and operating costs, minimal intersite communication costs and increased overall system integrity due to a minimized infrastructure network. Using the proposed configuration, there will be no need, for instance, for one set of beacons to serve the maritime community and another separate set to serve aviation. Nor will there be a requirement for an expensive communications satellite system to distribute GNSS integrity messages and/or differential corrections.

Removing the need for separate beacons and communications satellites also removes the requirements for the radio spectrum allocations that are necessary to provide these capabilities. Finally, placing operational control of the terrestrially-based segment of the proposed system mix, along with its integrity and differential correction messaging capability, in the hands of national or regional authorities overcomes many legal and political issues associated with the establishment of a GNS.

LORAN COVERAGE DIAGRAM

Mercator Projection
Scale 1:40,557,982 at Equator

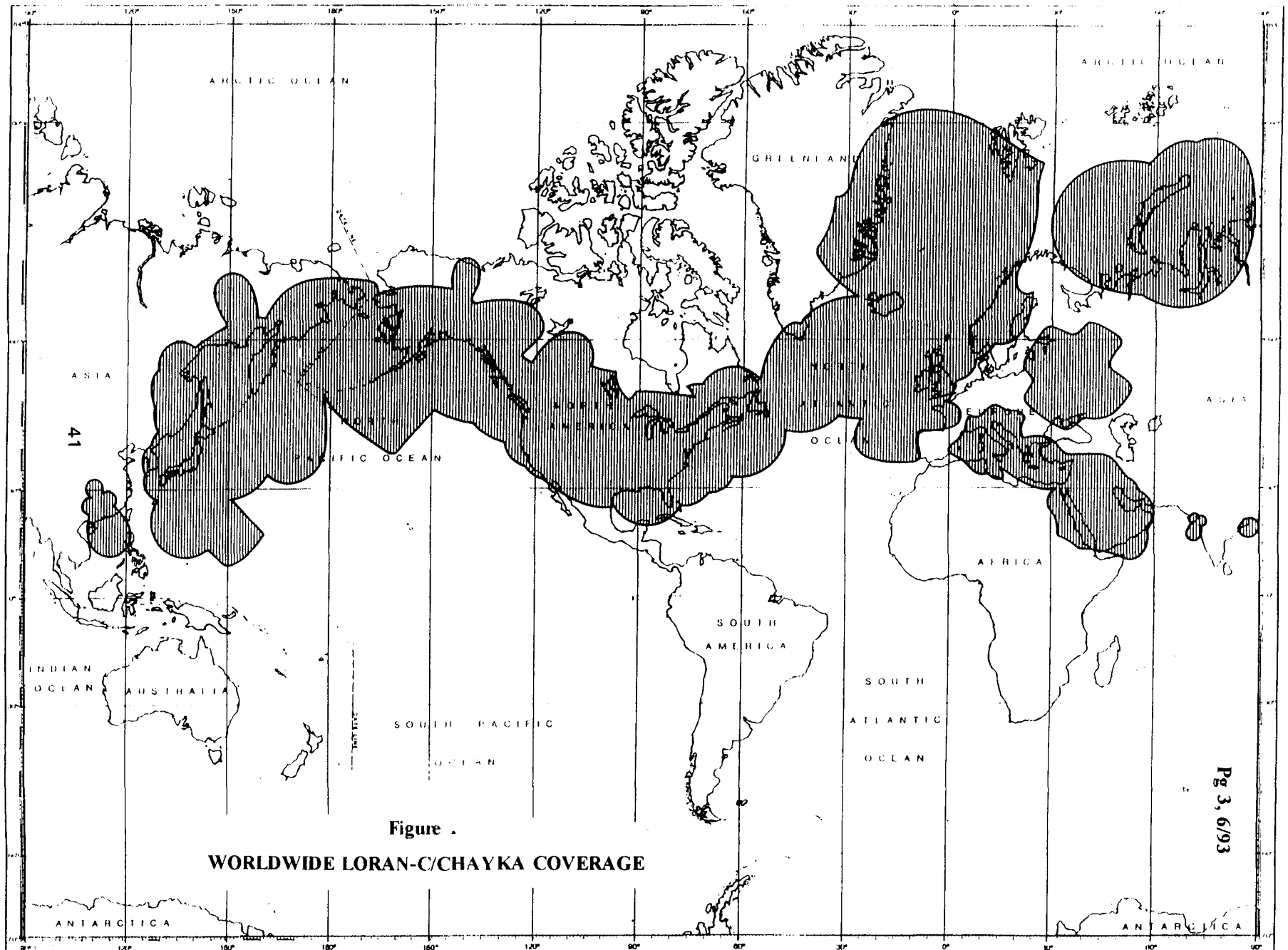


Figure .

WORLDWIDE LORAN-C/CHAYKA COVERAGE

DISCUSSION

In considering the GNS of the foreseeable future, one can really only realistically project the use of two systems simply because they exist—the satellite-based Global Positioning System and the terrestrially-based Loran-C/Chayka configurations. The CIS-sponsored Global Navigation Satellite System, GLONASS, is a potential candidate but is not currently in a position of assured availability, nor have either its satellites or its user equipment reached the stage of operational availability or confidence. Clearly, the GPS provides extensive worldwide coverage—the polar latitudes excluded. Loran-C and Chayka coverages are more limited, as shown in Figure 1 but these coverages exist over much of the more heavily traveled areas of the world and are currently being improved and expanded. Significant activities are underway in the Far East, Middle East, Northwest Europe, in the European Community and the Mediterranean Sea and Iberian Peninsula areas. Plans for linkages are underway in eastern Europe and western Russia for a number of Chayka/Loran-C interoperable configurations similar to the U.S./Russia configuration which recently became operational in the northern Pacific Ocean.

The 1992, Federal Radionavigation Plan (FRP) edition presents U.S. (and Canadian) intentions to support Loran-C in North America until the year 2015, while the newest Russian radionavigation plan sets out the intent to provide country-wide Chayka coverage specifically to replace all existing short-range aviation nav-aids which are reported to be obsolete and not in conformance with accepted worldwide standards. The satellite technology of the GPS, the transmitting stations' equipment of Loran-C/Chayka and a wide range of user equipment for both Loran-C and the GPS has already been developed, tested and extensively used for each system. (Note: Since Loran-C and Chayka are so similar, Loran-C user equipment can be readily used with Chayka and, with over 1.5 million Loran-C sets produced over the past two decades, this capability is well established.)

**EXAMINING HOW THE PROPOSED LORAN/CHAYKA-GPS
SYSTEM MIX MIGHT MEET THE DESIRED CRITERIA OF A GNS**

In the abstract section of this paper, four general fundamental criteria were presented as guidelines of acceptability for candidate systems seeking roles in a future GNS. Let us examine these criteria a little more deeply considering a Loran/Chayka-GPS system mix.

- (1) With regard to having the "signals in space satisfy the greatest number of RNP criteria, as needed by a full range of multi-modal users," each of the individual systems—Loran-C, GPS and Chayka—in the proposed mix can provide within their defined service areas most of the routine, nominal technical performance needed in most non-critical navigation applications—good accuracy (especially repeatable accuracy) and acceptable availability. Loran-C and Chayka system designs also provide assured signal correctness—termed signal integrity. The GPS has some limitations in this area, most directly related to satellite constellation health and completeness. However, the GPS simply by being an overlay on Loran-C or Chayka, of course, provides what all “prudent navigators” hope for—redundant, dissimilar systems providing the ability to crosscheck position-fixing information. If we are now to explore the higher order capabilities of the proposed system mix, perhaps we ought to examine how it might satisfy some of the more stringent RNPs of some representative user communities. For example:

- *“Primary” Instrument Flight Rules (IFR) enroute and terminal area services for the aviation community.*

These services are presently being provided by a network of terrestrially-based, short-range installations, primarily Very High Frequency Omni Directional Ranging (VOR) and Distance Measuring Equipment (DME) systems complimented by some radio beacons.

Signal coverage from these systems is limited by "line-of-sight" conditions. Aircraft at higher altitudes—at least in Europe and the United States—have access to a number of these nav aids. The CIS has a similar situation although its short-range nav-aids do not comply with international standards. Users at lower altitudes, in valleys or remote areas may not have consistent access to these services. Certainly developing countries lack these aviation navigation services and, also, in most cases, also lack the funding necessary to deploy and support such a system in the future. What would be most desirable would be to have a global capability wherein aviation users could accurately determine their three dimensional position from the ground up to maximum operational altitude in all topographic environments.

In the U.S., however, a replacement for the VOR/DME and radar-tracking-based Air Traffic Control (ATC) system is required to have 99.9999 (colloquially known as "six nines") signal availability. This is not to say that individual VOR/DME installations have that level of availability but rather that the considerable number of independent installations provides a "soft fail" capability that allows rerouting with safety a very large percentage of the time in the case of individual installation failures. Also, each installation monitors the correctness of its own signals and turns off if they are out of tolerance, thus assuring the integrity of the signals in space. A considerable number of investigations have unanimously shown that neither the GPS nor Loran-C alone can meet these required availability figures and that for this application the GPS falls far short of the necessary signal integrity assurance levels. However, recent work by Special Committee 159 (SC-159) of RTCA Inc. (formerly the Radio Technical Committee for Aeronautics) has shown that an integrated package embodying the GPS, Loran-C and a baro-altimeter may well satisfy the "primary

means” IFR enroute and terminal aviation requirements. Note that these SC-159 efforts have not taken into account the potential that GPS integrity and differential corrections messages could be supplied to the users on the Loran-C signals as is proposed herein—which capability would significantly improve the projected performance.

If the stringent requirements of IFR enroute and terminal operations were to be met by the GPS/Loran-C/Baro-altimeter configuration, then less stringent Visual Flight Rule (VFR) nav-aid considerations would be met by the use of the Loran-C/GPS/altimeter configurations in less regulated and, therefore, less expensive configurations for such users as general aviation. The GPS and Loran-C signals would be available for other multi-modal users. The VOR/DME network could be phased out with the resultant budgetary savings and the recovery of radio frequency spectrum. Further, no satellite communications network would be required to augment the GPS for these applications. A GPS/Loran-C system mix may well meet this requirement.

A political statement is in order here regarding the operational benefits that some GPS proponents have projected once the GPS is available to the airlines. Sometimes this projection is couched in terms of the GPS providing “position information” in a “dependent surveillance” environment wherein the aircraft determines its position by means of the GPS and then communicates this information, along with its identification code, to Air Traffic Control (ATC) ostensibly, thus obviating the need for the radars now used for airspace surveillance and control. Very simply put...the airline will get no operational benefits from the availability of the GPS or of any dependent surveillance system until ATC procedures, policies, training and culture

are changed. In the airspace today, we know where everyone is, where they want to go, what time they want to be there and all the qualifications of the aircraft and crew. Adding GPS or Loran-C-derived position information will gain NOTHING.

- *"Non-precision" approaches and Category I precision approach capabilities for the aviation community.*

For the past decade it has been popularly held and promoted that Loran-C could open an additional 5000-10,000 landing areas in the U.S. to what is termed Non-Precision Approaches (NPAs), nominally defined as the capability of bringing the aircraft to a position 2500 feet from the touchdown point at an altitude of 250 feet. If the pilot does not visually sight the runway at that point, a standard missed approach procedure must be executed. Some procedural issues and equipment upgrades for Loran-C operations—primarily related to its less stringently controlled maritime history—were recently addressed to bring the availability of this capability to the 99.9% region. Recently, similar NPA claims have been made for GPS operations but these would appear to be inappropriate since integrity and failed satellite identification, Receiver Autonomous Integrity Monitoring (RAIM), issues drop the resultant availability to less than 70% in some cases. Ironically, despite the claims of both Loran-C and GPS proponents, recent studies have shown that it would not be cost beneficial, even if desirable, to do more than 2000 or so approaches even though it is technically possible. So both proponent camps would appear to stretch the "truth". However, using the proposed system mix of Loran-C, GPS and differential GPS (dGPS) and integrity messages on the Loran-C signals, the availability of NPAs (either Loran-C or GPS/dGPS) is

raised to better than 99.9 wherever such approaches are justified. The key issue is that the requirement for performing RAIM on the GPS signals is removed in the proposed system mix environment since the dGPS and integrity messages carried on the Loran-C signals serve this function. Thus, the proposed GPS/Loran-C mix appears justified as it meets this stringent NPA requirement. Logically, aircraft that would need such an IFR capability would be carrying GPS/Loran-C/altimeter equipment to meet the enroute and terminal IFR requirements as suggested by RTCA SC159 studies. GPS and Loran-C NPA procedures are identical and transparent to the pilots. For the service provider—like the FAA—deriving and certifying an NPA procedure for either system does it for the other (except for slight signal quality monitoring aspects). No augmenting on-site capital equipment is required in either case.

Moving on now to the more critical issues of Category I precision landings generally defined as the capability to bring an aircraft to a point 2500 feet from the touchdown point at an altitude of 250 feet with less than ± 100 foot cross track error and ± 25 foot altitude error. It is universally conceded that the GPS without augmentation cannot meet the Category I requirements and Loran-C certainly cannot having no altitude information. However, the “GPS/Loran-C/dGPS on the Loran signals” approach appears to come close to meeting all the requirements of this critical RNP application, such the resultant augmented/corrected GPS position as will be shown later will be better than ± 10 meters horizontally and ± 20 meters vertically. Satisfying this Category I RNP requirement, if possible, would meet the needs of 98% of all commercial aircraft instrument approaches in the U.S. The discussion as to how to meet the

remaining 2% by ILS, MIS or locally-enhanced GPS would then remain a separate issue.

If indeed, the proposed Loran-C/GPS/dGPS capability met the stringent aviation requirements for NPAs and Category I precision approaches, it would certainly represent a highly desirable step toward a GNS. Before proceeding, another political comment is in order here regarding what appears to be a misguided, single-minded effort to establish national and international navigation policies and practices for the broad, multimodal user community based only on the transoceanic flight requirements of major air carriers. We need to get back to reality—only 200-300 U.S. registered aircraft fly international routes and perhaps twice that number operate internationally. If the U.S. donated \$1.0 Million USD per aircraft to equip each one of its domestic aircraft with the best flight management system (INS, Omega MLS/ILS) money can buy the \$200 Million USD spent would be less than the cost of one GPS satellite put into orbit and, more importantly, the RNP for intercontinental flights could be met. Sure it would be nice to have the GPS and Loran-C/Chayka but if they are not necessary to meet intercontinental flight RNP's then such applications do not provide any justification for their existence. In the approach areas, very few of the U.S. terminals need Category II or III approaches. In Europe, Category II and III approaches are required much more often but the legal and regulatory authorities there may well lean toward ILS/MLS rather than dGPS installations. In the developing world, the temptations to utilize Category II and III landings should be discouraged in the authors opinion due to the lack of regulatory control.

- *Harbor and harbor entrance services for the maritime community.*

The U.S. Federal Radionavigation Plan sets the criteria for the RNP for marine movements in the harbor-harbor entrance regions as having the ability to provide ± 8 to 20 meter horizontal repeatable accuracy. It will be shown in the data presented in later sections of this paper that based on recent work at the University of Delft in The Netherlands that the GPS/Loran-C/dGPS on Loran-C system mix can meet this requirement. Since there are no more stringent RNP requirements in any maritime operation, including maritime dependent surveillance operations and Vessel Traffic Systems (VTS), the GPS/Loran-C/dGPS on Loran-C system mix can meet all other local and regional maritime RNP requirements, while the GPS can meet any open ocean requirements just as it can satisfy (in combination with Omega or Inertial Navigation Systems (INS)) transoceanic aviation applications in regions where no complementary Loran-C signals are available. Stepping back for a minute here it should be clearly understood that the vast majority of U.S. marine users—recreational and commercial are satisfied by the performance of Loran-C alone. Its repeatable accuracy of 10-30 meters allow them to operate far more adequately than with raw GPS. The coastal marine beacon dGPS system only brings the repeatable accuracy of the so-augmented GPS back to slightly better than that which can be obtained with unaugmented Loran-C and requires a new network of shore stations, radio spectrum allocation and higher cost marine user equipment.

- *Position-fixing to part of an urban street block length for vehicular users.*

Again, we must begin our assessment by asking how might the GPS or the Loran-C system perform individually in this environment. For Loran-C, its position-fixing capability (or grid pattern) is distorted in urban environments but these deformations are consistent and repeatable to part of an urban block length from day to day. A "mapping" of each street in an urban region will generally be required so as to allow for geographical correlation with Loran-C-based position reports. Certainly there will be some areas of the urban environment wherein Loran-C will not function but these would appear from experiences to date to be a small percentage of the densest structural areas and particularly areas of extremely high ambient radio frequency noise. The operation of the GPS in urban areas is less stable and repeatable since it depends on the relative positioning of the constantly moving satellite configuration and the buildings and other obstacles that prevent satellite signal reception. Local areas of signal interference are also to be expected. The effects of Selective Availability (SA) (deliberate positional accuracy distortion) are a little more complex. Certainly with full Selective Availability imposed positional errors of ± 100 to ± 300 meters make "maps-in-the-car" systems inoperable without augmentation (some form of dGPS) to remove these errors otherwise no affirmed street locations would be possible. This distortion of position is only further complicated by the unavailability of direct GPS signals due to obstruction and the distortions introduced by multipath. All of the aforementioned difficulties for any positioning system must then face the fact that most maps, charts etc. are simply either wrong or in a different coordinate/reference system than the position fixing device. A Loran-C/GPS/dGPS or Loran-C system will give more capability - certainly enough for a stolen vehicle recovery system but perhaps not enough for

an emergency vehicle dispatch system. A high degree of performance and availability are required of dispatch services and public transport tracking. A stolen vehicle system will necessarily accept lower, "best effort" performance. In most urban vehicle location applications, the same levels of safety concern do not apply as they do in ATC or VTS environments.

Considering all of the above the Loran-C/GPS/"dGPS or Loran-C" System mix proposed herein appears to be a superb candidate for at least the initial steps toward a GNS.

Continuing now the discussion of fundamental criteria for acceptance into a future GNS mix—How does the proposed Loran-C/GPS/dGPS-on-Loran-C configuration meet international criteria?

- (2) This discussion is worth a full week of disclosure! However, one might begin by noting that traditionally many national and international organizations have addressed their own specific issues as they saw them—ICAO (and specifically its FANS sub-committee) focused on international commercial aviation; IMO and IALA primarily address commercial marine applications, local and international; the U.S. F.A.A. focused on aviation activity in the U.S. and its international aviation accords; and The Department of Lighthouses and Lightships in India addressed local and international maritime standardization. And, well they all should have focused on their specific missions! Now we all need to look at global, multi-modal services, including non-traditional users such as surveyors, land users and time transfer supplications. The Loran-C/GPS/dGPS-on-Loran-C GNS system mix proposed herein is suggested as a currently available role model to meet many of these multi-modal requirements. It is not suggested that

lighthouses and visual aids, or local airport aids, or even urban signpost-based positioning systems be discarded. It is simply suggested that this proposed configuration can do a lot effectively and inexpensively. The International Association of Lighthouse Authorities (IALA) has suggested such a system mix in its recommendations to the International Maritime Organization (IMO). Perhaps, that represents a first step toward wider acceptance.

- (3) Considering that the end user equipment not only must be designed to meet the RNP of the various user communities, it is suggested that the core user equipment suite be based on the proposed Loran-C/GPS/dGPS-on-Loran-C system element. This certainly does not preclude the addition of Omega and ILS/MLS or INS in-flight management systems, nor does it ignore the possibility of providing dependent surveillance positions information over appropriate communication links in ATC, VTS and vehicle tracking environments. This proposal simply suggests a core capability which, if adopted, would involve large scale market applications which would in turn reduce the costs to each individual user and to the service provider organizations.
- (4) It is beyond the scope of this survey paper to explore the detailed safety and cost benefit assessments which will be necessary for all major user community RNPs; but some things are certain—Loran-C is serving over a million users today, almost all of their own choice and without mandatory requirements, so it must be doing something right.

The GPS has had the most extensively funded and supported development in navigation history, which efforts have led to tremendous technological advances. No two systems are more developed or tested. The proposed system mix of Loran-C/GPS/dGPS-on-Loran-C recognizes this current posture in the evolution to an eventual GNS. It also acknowledges the performance shortcomings of each sub-system and uses the strengths of the others to overcome these issues. Finally, the proposed design makes maximum use of existing or easily extended capabilities, minimizing operational costs, developmental programs, and radio spectrum allocations. For instance, doing away with separate beacons for marine and aviation industry and the need for providing complementary communications satellite augmentatives can save billions of dollars for the service providers. At the user end, the proposed configuration provides redundant cross-checked nav-aids capable of confirming and assisting one another at a minimal cost, since the origin of most of the information derived from the processing of the signals in space is transparent to the user. Certainly for a few explicit examples examined herein it would be far more efficient and economical to use the proposed Loran-C/GPS/dGPS-on-Loran-C configuration as compared to other alternatives. For example, it would be more economical and efficient to:

- a) Establish a network of GPS monitors located at the existing, well supported Loran-C transmitter sites than to implement and support a whole new independent set of monitors;

- b) Dispense dGPS and signal integrity information over an existing Loran-C network than over a new communications satellite and ground station supporting structure. (The latter estimated recently by the Japanese at \$1.0 billion U.S.D.);
- c) Do away with the costs and spectrum use requirements of separate marine, urban and aviation beacons as a means of distributing dGPS and do it on existing Loran-C capabilities.
- d) Emphasize commonality such that user equipment costs will be reduced as the cross use for various RNP increases. Therefore, encourage the widest multi-modal applications for the simplest candidate navigation system mix.

PROPOSED SYSTEM CONFIGURATION DESCRIPTION

This paper proposes an elegant candidate system mix for inclusion in the near-term GNS which utilizes two existing navigation systems—the GPS and Loran-C/Chayka configurations—with differential GPS corrections (also being de-facto signal-in-space integrity messages) provided to the users as messages modulated onto the Loran-C signals. Also, it is proposed that the Loran-C transmitting stations be used as the sites for the GPS signal monitoring equipment. Finally, it is proposed that the GPS satellites' time reference and the Loran-C transmitting station time references be the same such that user equipment can process all received signals, not as either GPS or Loran-C, but as common all-in-view pseudo range messages and thereby optimize position determination accuracy, overall system availability and integrity. Alternatively to having Loran-C station timing coincident with that of the GPS, the offset from the reference standard

timing of each Loran-C transmitter timing can be also sent out to the users as part of the message modulated onto the Loran-C signals in addition to the differential GPS corrections. As proposed, the mix minimizes the cost to the user while providing to him redundant navigation capabilities. It removes the necessity for new GPS signal monitoring sites and makes use of existing capabilities—from physical structures to inter-site communications networks, support personnel, conditioned prime power and precise frequency and time reference standards. It removes the requirement for separate beacons or networks/communication satellites for providing dGPS services to aviation users (except for on-airport capabilities for Category II and III approaches if proven to be acceptable) and marine users and by so doing removes the requirements for radio frequency spectrum allocations as would be required for these services.

Let us be very clear. What is being presented here is not a wholly new idea. Over the past decade or more various aspects of this concept have ruminated around in the Loran-C professional community and a number of the concepts have actually been brought into practice. Communications messages on Loran-C signals were operationally implemented in the 1970's by USCG and USN under the project title of Clarinet Pilgrim wherein the same Loran-C signals used to position nuclear submarines and their support vessels were used to transmit operational messages from command authorities to these users. Per Enge and Ed Bregstone presented ideas for coding the dGPS message format^[1] onto Loran-C signals and Dirk van Willigen set forth much of this concept entitled "Eurofix"^[2]. The Racal Survey Group in the late 1980's provided real-time dGPS corrections to their users via their PULSE/8[®] positioning system signals. PULSE/8[®] is the Racal tradename for privately coded Loran-C signals. And, Tom Gunther (with significant cooperation from Jim Nagle of INMARSAT) proposed the use of Loran-C (and Omega) stations as monitor locations for a GPS/GNSS network^[3]. However, the nagging question always remained as to how to provide to the users all the necessary dGPS data using only the 20-25 bits/second minimum data rate which Loran-C transmitters could provide. Conservative estimates had to be made, of course, as to what the characteristics would be of the final, normal Selective Availability (deliberate distortion) effects as will be imposed on the GPS signals in terms of maximum deviation and especially as to rate of change. This final step has now been

taken as a result of very recent investigations conducted at the University of Delft in The Netherlands by Lambert Beekhuis and Dirk van Willigen ^{[4][5]} supplemented by that of WGA et al ^[6] from the same university group. The results of these efforts which specifically make the implementation described herein practical and possible will be summarized in later sections of this report.

USER EQUIPMENT DESCRIPTION

Figure 2 provides a generalized illustration of user equipment for the proposed Loran-C/GPS/dGPS-on-the-Loran-C signals GNS mix. Remembering that one of the most attractive features of this proposed system mix is that it is intended to serve a multi-modal user community, this configuration would be complemented as required by ancillary capabilities (such as altimeters) peculiar to the specific user applications and/or this configuration would be embedded in a more all-encompassing suite of equipment such as a flight management or ship's integrated bridge system. It is also recognized, of course, that this functional diagram will be realized as a GPS antenna/coupler, a Loran antenna/coupler and follow by an "engine" to process all signals digitally for use with appropriate displays, control interfaces, etc.

It should be noted that in addition to the Loran-C subsystem providing dGPS corrections and integrity by demodulating the messages imposed on the navigation signal, the corrected GPS information is used to continuously calibrate the absolute Loran-C position. Thus, if either system goes down, the other would start off very well calibrated. Loran-C errors would then build up slowly both in time and distance dependent mostly on changing climatic and ground conductivity effects. The GPS errors would revert to being driven primarily by the SA characteristics.

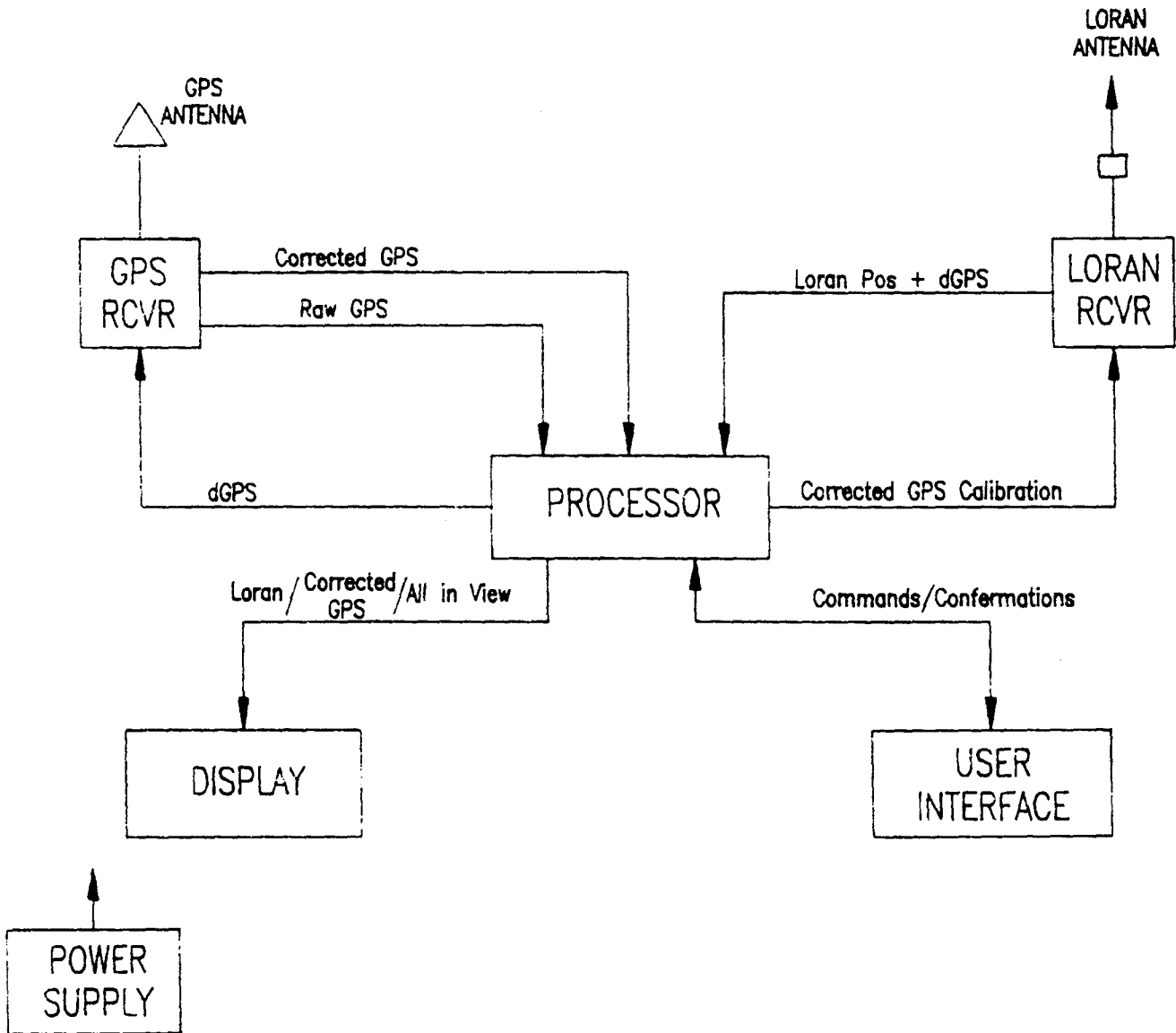


Figure 2
LORAN/GPS/dGPS-ON-THE-LORAN SIGNALS —USER EQUIPMENT
FUNCTIONAL BLOCK DIAGRAM

Figure 3 illustrates a Loran-C/Chayka transmitting station augmented by redundant GPS receivers and processors used to derive and format the dGPS messages. The ability to provide differential Loran-C is shown by the dashed line from the Loran-C signal monitors/processors to the modulator capability of the Loran timing equipment. These signal monitors can also be used to process the Loran signals from other nearby Loran transmitters, not only as to received signal quality, but also as a means of comparing the dGPS values being generated by adjacent installations. This information, along with all relevant site status and signal quality information, is made available to the overall Chain Control (COCO) Center via the Remote Operating system (ROS) or Remote Control Unit (RCU) and existing inter-system communications channels. The use of existing capabilities to implement the dGPS function is clearly shown. The Station Autonomous Integrity function, which automatically puts the transmitting station into the "blink" warning mode, is colloquially known as "aviation blink" and is designed to meet the rapid alarm integrity requirements of aviation operations, such as Non-Precision and Category I approaches.

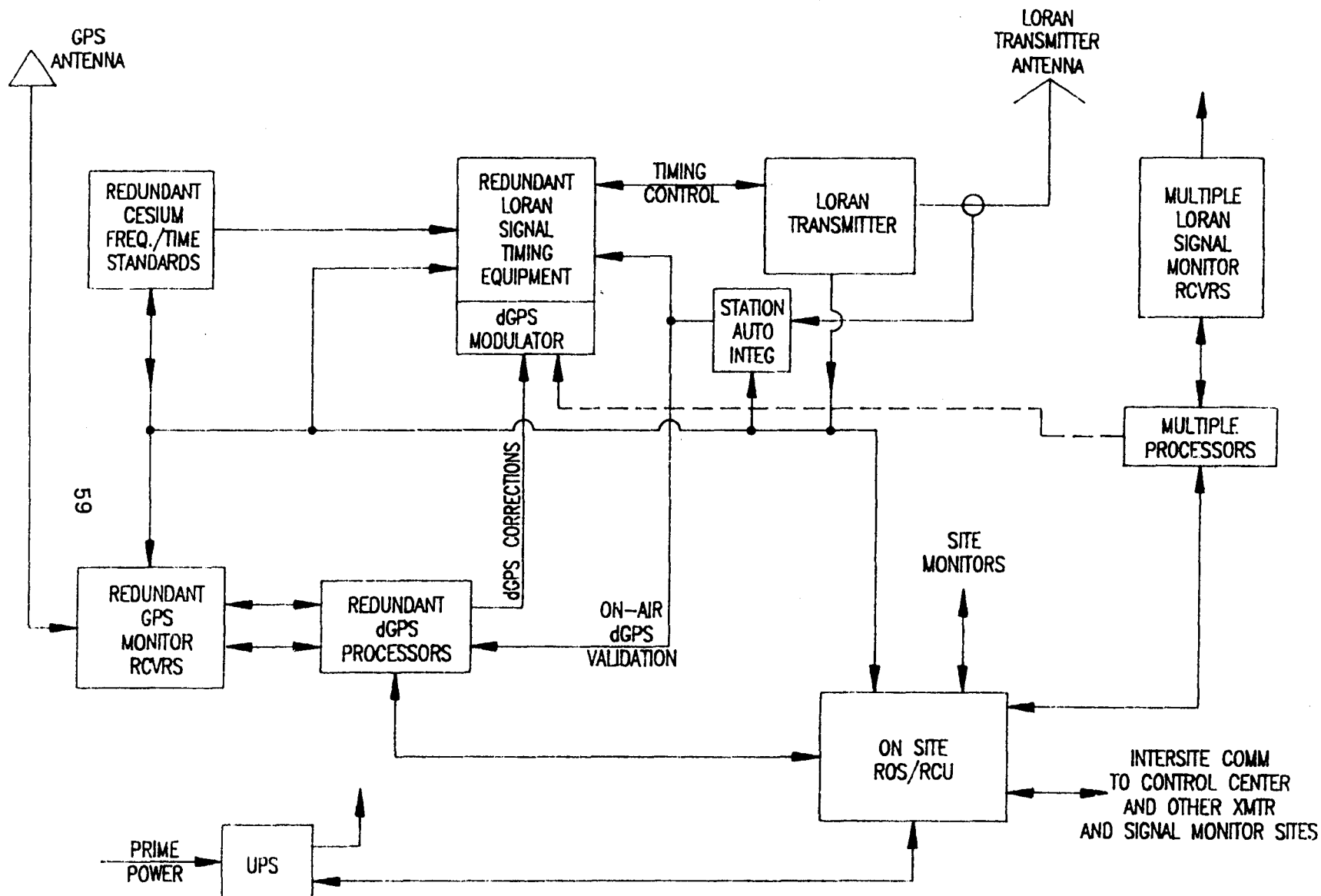


Figure 3

LORAN TRANSMITTER SITE WITH CO-LOCATED dGPS MONITORING
CAPABILITY FUNCTIONAL BLOCK DIAGRAM

**“EUROFIX RESULTS” — CONFIRMATION OF THE CAPABILITY TO ACHIEVE
PRECISE DGPS POSITIONING USING LOW DATA RATE (LORAN-C) TRANSMISSIONS.**

The following comments summarize the results of the Delft University Eurofix efforts as presented in references [3], [4] and [5]. The details are presented in those papers. The goals of the Eurofix efforts were:

- 1) Provide dGPS services throughout all existing and planned Loran-C and Chayka signal coverage areas.
- 2) Achieve baseline dGPS corrected horizontal accuracies in the order of ± 3 meters.
- 3) Limit the data rate of the modulation imposed on the Loran-C signals to 20-25 bits/sec, even servicing up to nine satellites.
- 4) Do not adversely affect the Loran-C navigation function.

Figures 4 and 5 illustrate the dGPS coverage that can be achieved in the area shown using existing and planned Loran-C transmitting sites. A conservative range of 600km from each site was chosen. At that range, the Loran signals are large and the resultant S/N, even in worst case noise conditions, will result in a bit error rate of less than 1%—to be reduced further by “rationale testing” in the user equipment.

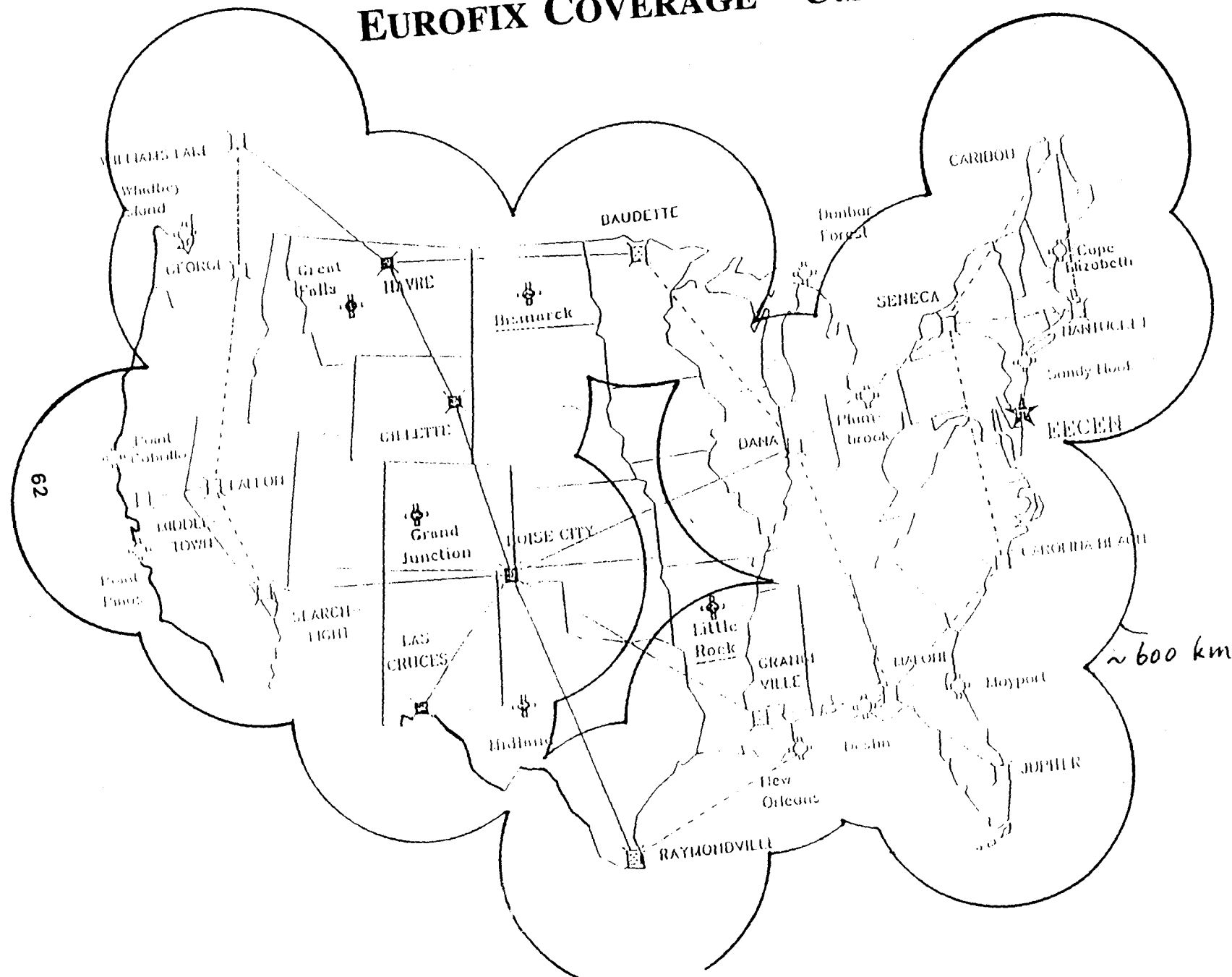
Figure 6 illustrates the resultant position errors after dGPS corrections to nine satellites at 20 bits/sec using the Eurofix “smart” data format and compares that to the errors obtained on the same data if the RTCM 104 Type 9 format is used at the higher rate of 50 bits/sec.

Finally, assessments have shown that correct selection of the extent and type of the modulation will not noticeably degrade Loran-C navigation performance and that the signal strength will be reduced by only slightly more than one decibel (- an insignificant amount considering noise in the Loran spectrum may vary 15-20 db over one day).

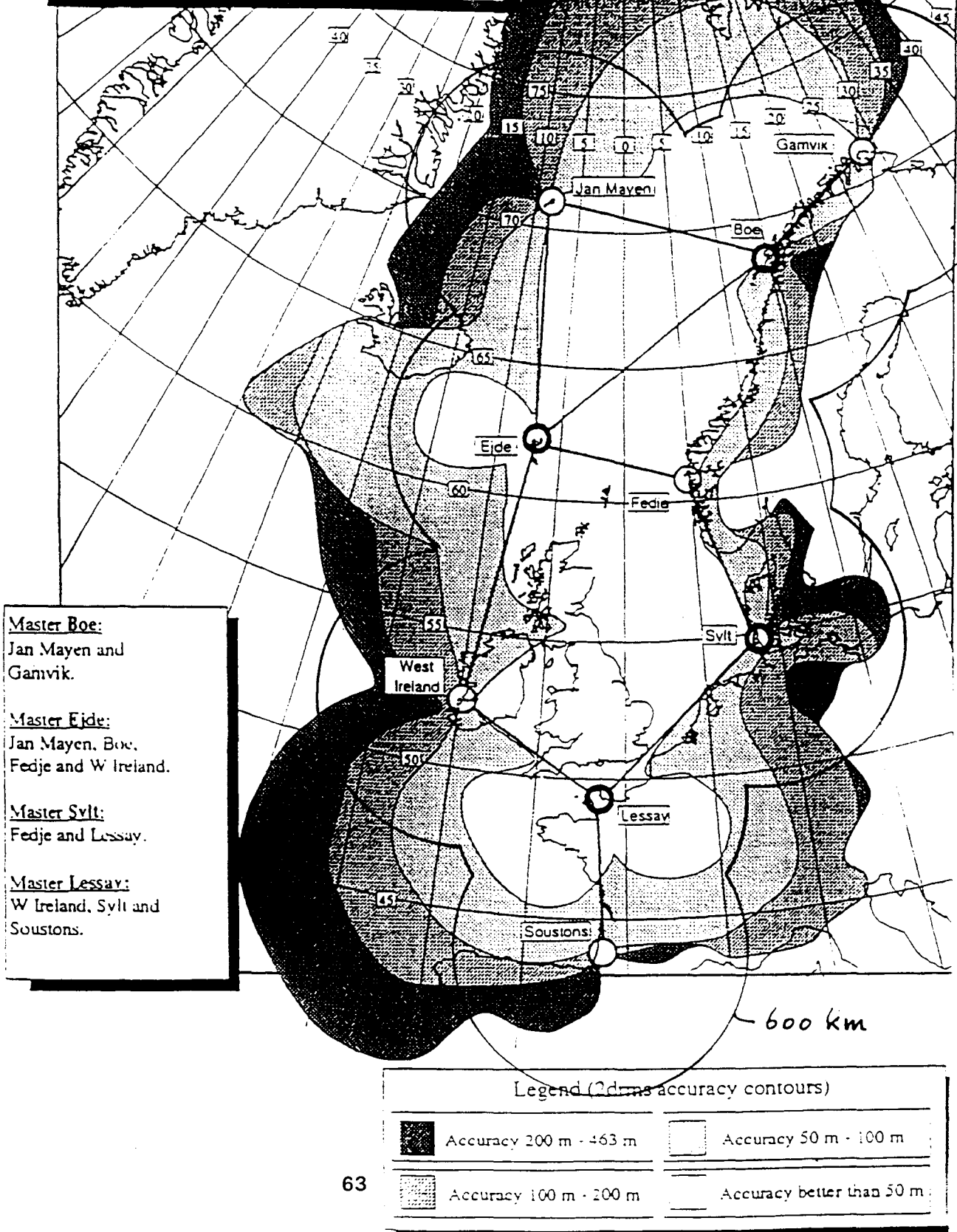
Thus, a marriage of the Loran-C/Chayka and GPS capabilities would appear to be a beneficial and quickly achievable step toward an eventual full GNS capability.

End

Figure 4



Predicted coverage of the
North West European and
North Atlantic
Loran-C System



dGPS CORRECTED DATA

RTCA Type 9
50 bits/sec

Eurofix Smart
20 bits/sec

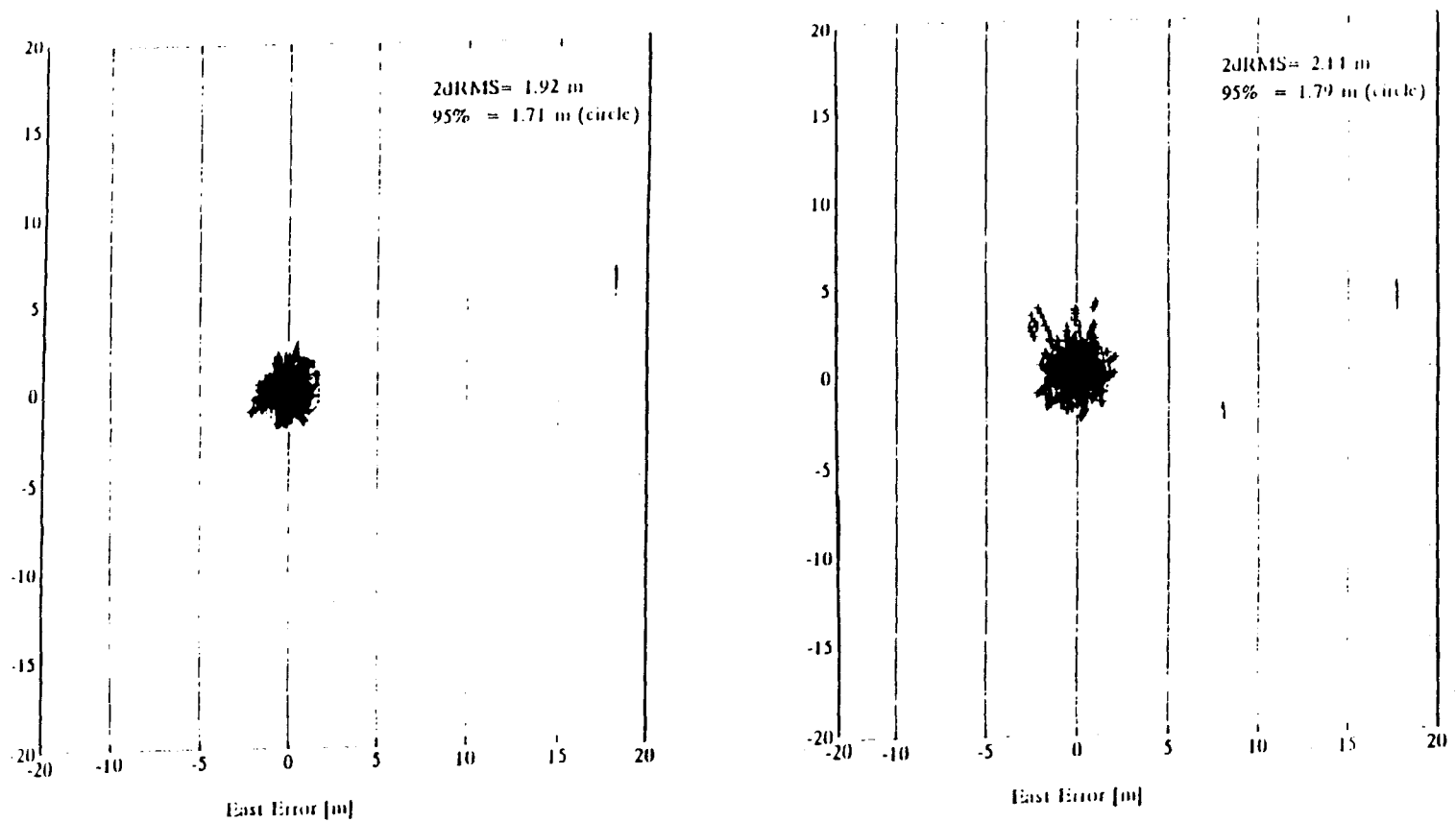


Figure 6
COMPARATIVE dGPS CORRECTED POSITION

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GPS AND LORAN-C IN DIXON ENTRANCE: AVAILABILITY, RELIABILITY, ACCURACY AND CALIBRATION

G. Lachapelle¹, D. Gray², B. Townsend¹, R. Hare³, and K. Lyngberg³

1 Department of Geomatics Engineering, The University of Calgary, Alberta, T2N 1N4

2 Canadian Hydrographic Service, 615 Booth Street, Ottawa, K1A 0E6

3 Canadian Hydrographic Service (Pacific Region), Sidney, British Columbia, V8L 4B2

ABSTRACT

The availability of GPS and Loran-C in Dixon Entrance, located between the Alaska panhandle and Queen Charlotte Islands, British Columbia, is analysed using shipborne field measurements collected in September 1992. DGPS corrections were provided by Marine Radio Beacons operated by the Canadian Coast Guard to assess the availability of DGPS. The procedure used to calibrate Loran-C along continuous profiles using LORCAL², a GPS-based Loran-C calibration system, is described. The use of two digital multi-chain Loran-C receivers resulted in the observation of SNR, FS, and TD data on the two chains available in the area, namely the Canadian West Coast Chain (GRI 5990) and the Gulf of Alaska Chain (GRI 7960). The analysis confirms an earlier conclusion by CHS that the 5990X and Z TDs are the most reliable in Dixon Entrance. The use of GPS resulted in accurate Loran-C TD distortion data along the observed profiles. A comparison of the distortions measured during the survey with those obtained during previous surveys reveals an excellent long term repeatability of Loran-C. An analysis of the accuracy of latticed Canadian and American nautical charts is presented. The calibrated lattices on current CHS charts of the area were found to be well within specifications. The observed ASFs were compared to theoretical models based on various ground conductivity values. Resulting position errors based on the use of theoretical models exceed 1 n.m. in some areas, confirming the necessity of using ASFs based on calibration measurements for safety of navigation and fishing near the Canada-U.S. border. The use of such ASFs results in absolute Loran-C position accuracies of 100 - 200 m.

INTRODUCTION

The major objectives of the project described herein were to assess the availability of GPS and of differential GPS corrections from Marine Radio

Beacons, the Loran-C availability, reliability and accuracy in Dixon Entrance, and to calibrate the Loran-C signals using GPS. As a by-product, the accuracy of the Loran-C lattices on the charts currently available in the area were assessed. Dixon Entrance, shown in Figure 1, is a rich fishing area and contains a contested boundary section between Canada and the United States. The A-B line shown in the Figure identifies the boundary between the two countries, as recognized by Canada. The project was initiated in Summer 1992 in response to public and government concerns about accurate navigation for fisheries management and other sovereignty issues. Loran-C is a regulatory system for marine navigation in Canadian waters and Loran-C lattices are printed on charts where Loran-C is available. The Loran-C transmitters available along B.C.'s and Alaska's Coasts are shown in Figure 2 and consist of two chains, namely the Canadian West Coast Chain (Group Repetition Interval 5990) and the Gulf of Alaska Chain (GRI 7960) [US DoT 1992].

The characteristics of GPS and Loran-C are well documented in the literature [e.g., Samaddar 1979, Frank 1983, Lachapelle & Townsend 1991]. GPS is limited by line-of-sight between satellites and the receiver. Its 2-D, 95%, single-point mode horizontal accuracy of 100 m, under Selective Availability (S.A.), can be improved to a few metres in differential mode. Loran-C does not require line-of-sight but is affected by strong signal attenuation due to nearby mountains [e.g., Lachapelle et al. 1992b, Lachapelle & Townsend 1993]. In addition, permanent wavefront distortions caused by conductivity variations and topography along the transmission paths can result in relative position distortions of up to 500 m over distances of a few kilometres [e.g., Lachapelle et al. 1992a]. These distortions may render Loran-C unreliable from an accuracy point of view in a critical area such as Dixon Entrance, unless carefully calibrated. Once calibrated, however, Loran-C can deliver an

accuracy close to 100 m. The Loran-C surface wave phase delays or lags are conveniently split into three parts, namely a primary phase lag due to the effect of the troposphere, a secondary phase lag due to an all-sea path propagation assumption, as opposed to free-space propagation, and an additional secondary phase lag due to propagation over terrain [Johler et al. 1956]. The corresponding corrections are called the primary factor (PF), Secondary Factor (SF), and Additional Secondary Factor (ASF), respectively.

METHODOLOGY AND FIELD OBSERVATIONS

Equipment

The GPS and Loran-C observations were gathered with The University of Calgary's LORCAL² system and with a single chain analog Internav 404 Loran-C receiver. The LORCAL² (Loran-C Calibration at The University of Calgary) system has been used extensively during the past few years for a variety of Loran-C calibration tasks across the country [e.g., Lachapelle et al. 1992b, c, 1993]. The configuration used herein consisted of two multi-chain digital Jet 7201 Loran-C receivers used in parallel to provide redundant measurements, one Magnavox 4200D GPS receiver and a PC laptop to time-tag the Loran-C measurements to GPS time and record the Loran-C and GPS data. The Jet 7201 Loran-C receiver can track up to eight transmitters on four different chains simultaneously. All Loran-C transmitters available in Dixon Entrance could therefore be tracked simultaneously. The error budget of the LORCAL² system is as follows: (a) internal Loran-C receiver noise, ≤ 10 m, (b) dynamic effects, due to receiver motion, ≤ 50 m, (c) effect of GPS time synchronization error, ≤ 5 m, and (d) GPS, 20 - 30 m (S.A. off), GPS, 100 m (S.A. on), DGPS, 3 - 10 m, with a GPS HDOP (Horizontal Dilution Of Precision) ≤ 5 , drms. The overall accuracy of the system is the quadratic sum of these errors, namely about 52 m or $0.17\mu\text{s}$ (1σ) [Lachapelle & Townsend 1993].

Field Observations

The field observations, which included a segment from Dixon Entrance to Sidney, B.C., were conducted over a 17-day period, from 11 September to 2 October. The ship tracks observed in the Dixon Entrance during the period 11-22 September are shown in Figure 1. The daily tracks are described in Table 1. The reference numbers (#) in the first column refer to the numbers shown on Figure 1. DGPS

corrections broadcasted by the Triple and Langara Marine Radio Beacons, which provide coverage to the Dixon Entrance and the Hecate Strait areas, were used. During the period 23 September - 2 October, the ship travelled back from Prince Rupert to Sidney. No DGPS was available for this voyage.

Data Recording and Reduction

The following Loran-C measurements were recorded every 5 s: Time Differences (TDs) and Envelope-to-Cycle Differences (ECDs) in μs , Signal to Noise Ratios (SNR) and Field Strengths (FS) in dB (referred to $1\mu\text{V}\text{m}^{-1}$). The GPS raw pseudorange and carrier phase observations were also recorded every 5 s, together with the received differential corrections. Since the GPS and Loran-C measurements were generally made at different epochs, the GPS positions were linearly interpolated to the Loran-C measurement epochs. This was done when the interval between the Loran-C measurement and the GPS measurement was ≤ 10 s; otherwise, the Loran-C measurements were not used.

GPS or DGPS positions were accepted when the GPS HDOP was ≤ 5 , either with the height component fixed or floating. Otherwise, GPS was considered unavailable and no Loran-C DTDs were calculated. In addition to the above GPS conditions, the following Loran-C conditions had to be met to calculate the distortions in the Loran-C TDs (DTDs): $\text{SNR} > -12$ dB, $\text{FS} > 30$ dB, and $-5\mu\text{s} < \text{ECD} < 5\mu\text{s}$. The presence of signal interference on the ship did result in loss of Loran-C data in some cases, as will be described later. The Loran-C TD distortion, DTD, is defined as

$$\text{DTD} = \text{TD}_{\text{Loran-C}} - \text{TD}_{\text{GPS}}$$

$\text{TD}_{\text{Loran-C}}$ is the TD measured by the Loran-C receiver and corrected for the emission delays, and TD_{GPS} is the corresponding TD calculated using DGPS positions. The primary (PF), secondary (SF) and additional secondary factor (ASF), due to tropospheric refractivity, sea conductivity and land conductivity, respectively, can be optionally removed from the TD_{GPS} s. The effects of the PF, SF and ASF on Loran-C positions are analysed later in this paper.

ANALYSIS OF MEASUREMENTS

Intercomparison of Loran-C Receivers

The two Jet 7201 receivers were intercompared to assess their performance in the marine environment. The results are summarized in Table 2. All measurements were first averaged at one-km intervals. Only the DTDs for which DGPS positions were available were used in this comparison. This is why the number of DTDs intercompared is low relative to the number of SNR, FS and ECD intercompared. The mean and rms DTD differences are $\leq |0.1\mu\text{s}|$. The largest single DTD difference of $-9.77\mu\text{s}$, measured on 7960Y, is due to a Loran-C cycle slip. This is also why the rms difference reaches $0.62\mu\text{s}$ in this case. The mean SNR and FS differences are ≤ 2 dB. The large SNR and FS maxima and minima are likely caused by spurious measurements due to signal interference on the ship and/or skywave interference. Likewise, the large ECD maxima and minima, which reach $|18.6\mu\text{s}|$, are caused by cycle slips. Overall, the agreement is satisfactory and superior to that achieved with analog and other digital receivers [e.g., Lachapelle et al. 1993]. The results presented in Table 2 show that there are no significant differences between the two Jet 7201 units used. The DTDs obtained from either unit can therefore be used indiscriminately for calibration purpose. This is a significant advantage in this case because it was found that signals from one or more Loran-C transmitters were often unavailable at either one of the two Jet receivers due to intermittent signal interference from the ship and the relative positions of the two Loran-C antenna with respect to the interference sources.

Analysis of Loran-C Measurements

The DTDs obtained by merging the measurements from the two Jet 7201 receivers are shown in Figure 3 to 7 for 5990X, Y, Z, 7960X and Y, respectively. They were obtained using single point GPS because the availability of DGPS corrections was relatively low and would have resulted in the rejection of too much Loran-C data (see Table 4). Selective Availability was minimal during the survey period and the single point GPS accuracy is estimated at 20-30 m. Summary statistics are presented in Table 3. Again, these results are based on 1-km averages. The effect of PF, SF and ASF is not removed from the DTDs. The data can be correlated to the map shown in Figure 1 using Table 2. The sharp variations in

the DTDs on 5990X, 5990Z and 7960Y are due to the varying ASF effect as the land/sea propagation path (transmitters/ship) ratios vary.

The most reliable TDs in the Dixon Entrance area are 5990X and 5990Z, due to a relatively high availability (Figures 3 and 5) as compared to 5990Y (Figure 4), which was available for only some 60% of the time; non-availability in this case is likely due to skywave interference. The SNR, FS and ECD measurements on 5990Y for 13 September are shown in Figure 8. The strong SNR and FS measurements during the first part of the day are caused by skywave tracking. The Internav receiver also tracked the skywave on 5990Y for the majority of the survey. The periods during which the skywave was tracked are however different for the Jet and Internav receivers. The poor performance of 5990Y in Dixon Entrance and as far south as Browning Entrance substantiates the decision taken in 1988 to remove the 5990Y lattice from CHS Chart #3802 (Dixon Entrance) and the caution note about the 5990Y performance that appears on CHS Charts #3000 and #3002 that was first issued in 1977, namely:

"Caution is to be exercised when using Loran-C from the approaches to Dixon Entrance through Hecate Strait to Browning Entrance due to weak signal strength from 5990-Y secondary."

The HDOP using only 5990X and Z varies from about 1.6 in the eastern part of Dixon Entrance to about 3.0 in the western part.

The rejection of 5990X observations recorded by the Jet receivers requires further comments. Only the 5990X TDs are affected and the problem is caused by Shoal Cove. The propagation path from this transmitter is not only mostly overland but crosses mountainous areas along the Alaska panhandle. This affects the ECD adversely. Indeed the ECDs measured by the Jet receivers on 5990X are of the order of 4 - 5 μs , while the minimum performance specification for marine receivers is $\pm 2.4\mu\text{s}$. This large ECD resulted in a cycle slip to the crossing point that is nominally 20 μs from the front of the pulse, instead of the 30 μs crossing point normally used. CHS has observed other instances when receivers slip ahead one cycle, i.e., 10 μs , on the stronger signal in areas where there is too great a relative difference in signal strengths, as would be the case in Dixon Entrance with the 5990X TD where the signal from Shoal Cove is much stronger than the signal from Williams Lake (5990M). The

average FS of 5990X is 84.3dB as compared to 59.4dB for 5990M, as can be seen in Table 3. This type of ECD problem is usually dealt with by applying a nominal ECD (NECD) at the transmitter to offset the ECD in the coverage area, since the ECD changes in a negative direction from the transmitter. This is often done for transmitters located in-land, e.g., Williams Lake which has a NECD value of 1 μ s. Shoal Cove is relatively close to the shore however and the application of such a NECD value would cause ECD problems in a much larger area farther from the shore. The NECD of Shoal Cove is therefore 0.

Of the 8880 points observed with the Internav receiver, no 5990X or 5990Z observations had to be rejected. However, the 5990Y data for all of Julian day 255 (skywave), day 257 from 0800 to 0921 (skywave), day 259 from 0649 to 1202 (1 cycle slip) and day 264 from 0836 to 0846 (1 cycle slip) had to be rejected. There are several other occasions where there are suspect 5990Y data that have not yet been resolved. Evidence comes from the comparison of observed ASFs on different days or from other years.

The multi-chain Jet 7201 receivers provided CHS with its first opportunity to sample data from the Gulf of Alaska Chain (7960). Given the long distances to Narrow Cape and the mountainous terrain towards Tok Junction, it is not too surprising that the number of 1-km averaged DTDs observed on this chain is relatively low as can be seen from Table 3. Only 210 1-km DTDs were obtained on 7960X. The conclusion is that the ground wave signals from 7960X (Narrow Cape, Kodiak Island) and from 7960M (Tok Junction) are very difficult to receive. Barring future data collections to the contrary, CHS is justified to exclude the 7960 Chain lattices from the charts of Dixon Entrance.

During the Prince Rupert to Sidney portion of the survey, all three TDs from the 5990 Chain showed a relatively high percentage of availability. The signals from 5990Y rapidly became more stable as the ship headed south. The signals from Shoal Cove were more stable during that portion of the survey as the measured ECD fell within the expected tolerance of $\pm 2.4\mu$ s; no cycle slips were detected.

GPS and Loran-C Availability Analysis

The percentages of GPS and Loran-C availability for each day of the survey are given in Table 4. Single point GPS was defined as available when

HDOP ≤ 5 with height constrained. Single point GPS availability is $>97\%$ for all days, except for 15 September when the availability was lower due to equipment problems. Differential GPS was defined as available when the differential corrections were received. The daily percentages range from 54 to 97%. Single-chain Loran-C was defined as available when at least two TDs were available on 5990. Availability for all Loran-C receivers should in principle be the same. The difference is caused by signal interferences from the ship as discussed earlier. This is also why Loran-C availability is lower than single point GPS. During the Prince Rupert - IOS part of the survey, when no DGPS corrections were received, Loran-C availability increased to $\geq 97\%$ during six days out of seven with the Jet receivers. Loran-C availability with the Internav 404 receiver was 100%, presumably due to better performance in the presence of interference. Multi-chain availability is defined when at least two TDs from 5990 and one TD from 7960 were available. The differences between single and multi-chain availability are only significant when two of the three 5990 TDs were unavailable. Since either single point GPS or Loran-C (Internav receiver) was generally available over 97% of the time, analysis of combined GPS/Loran-C availability is no longer relevant in this case. Still relevant, however, is the question as to whether the reliability of combined GPS/Loran-C, as opposed to that of either system in standalone mode, would be significantly higher. A detailed analysis of this question is beyond the scope of this paper. However, the application of internal and external reliability criteria to assess the ability of each configuration to detect blunders is straightforward and would provide answers to this question.

Long-Term Repeatability of Loran-C

One of the advantages of Loran-C is its repeatability, which is the capability of returning to the same location given the same observables. To show the repeatability of Loran-C in Dixon Entrance, Table 5 gives averaged ASF values for 11 test areas using surveys conducted during the period 1982-92. The ASF values are based on 5' x 5' grids and the averaged latitude and longitude components are given for each set of averaged ASFs. Table 5 shows that the ASFs for 5990X and 5990Z are consistent within 0.4 μ s. The larger differences obtained with 5990Y reflect the fact that this data is not completely free of spurious effects and corroborate the problems described earlier. Since the calculation of the ASFs takes into account the

absolute accuracy of the various positioning systems used for calibration and since different Loran-C receivers were used over the years, the results vindicate the claim that Loran-C is a highly repeatable system.

Coordinate Distortions Using Modelled PF, SF and ASF

The DTDs shown in Figures 3 to 8 reach several μ s but contain the effects of PF, SF and ASF. The Loran-C coordinate distortions which remain after applying theoretical models for PF, SF and ASF effects, were estimated using the 5990X and Z TDs and the following two scenarios. In the first scenario, a PF of 320 ppm and a SF corresponding to a sea conductivity of 5 S m^{-1} were used; no ASF correction was applied. A PF of 320 ppm corresponds to an index of refraction of 1.000320 for the troposphere, which is the average near the ground. The resulting latitude and longitude distortions are shown in Figure 9. The latitude error reaches some 300 m in Dixon Entrance and 700 m in Principe Channel. The latitude error along the A-B line, which is the most critical as far as navigation along the boundary is concerned, reaches 200 m. The corresponding longitude error varies between 1000 m and 2700 m. In the second scenario, the above values were retained except for 5990M where an ASF corresponding to a land propagation of 0.005 S m^{-1} was used. The resulting distortions are shown in Figure 10. The latitude error reaches 400 m along the A-B line. The corresponding longitude error ranges from 300 m near the coast where the above propagation assumption is the most accurate to 1100 m at the western extremity of the line. These results show the sensitivity of Loran-C absolute positions on the choice of ground conductivity models. In Dixon Entrance, the sea/land propagation paths vary rapidly as a function of position, resulting in large and rapidly changing position distortions. A better agreement would have been obtained using a mixed path conductivity model, such as Millington-Plessey's. The effective use of such a model however would require the use of a digital terrain model between Dixon Entrance and the Loran-C transmitters.

Many receivers, equipped with a coordinate converter, compute directly geodetic coordinates, eliminating the need to use the calibrated lattices on charts. However, the theoretical PF, SF and ASF models used in these receivers are usually the same or similar to the above simplified models and can therefore result in large absolute position errors,

a problem which is serious indeed for coastal navigation and for fishing along the A-B line as will be discussed later. The use of coordinate correction diagrams as the ones shown in Figures 9 and 10 would improve the absolute Loran-C coordinates significantly in such a case. The actual accuracy improvement would be a function of several parameters such as the accuracy of the calibration survey, the rate of change of the coordinate distortions, etc. In the best of case, it could be as good as 100 m.

CHART LATTICE VERIFICATION

How it is measured

Lattices are hyperbolic lines of constant TDs. In the case of Dixon Entrance, the lattices on CHS charts are based on calibration measurements to take the actual ASFs into account. The CHS method for measuring quality of printed lattices is done by calculating the distance $\{[\Delta\phi^2 + \Delta\lambda^2]^{1/2}\}$ at chart scale between the Loran-C fix (using the TDs and the lattices) and the surveyed position (for the 1992 survey, it is the GPS fix) on the same geodetic datum. These distances are then ranked and the quantitative assessment is taken at the 95% level (i.e., 95% of the fixes are better than a stated level). The CHS standard for acceptance of lattice parameters is 2.5 mm at chart scale for the pair of TDs that give the best repeatability.

CHS Chart #3802

CHS chart #3802 covers Dixon Entrance at a scale of 1:200,000. For the chart in general, two sets of analyses were done: one with the existing lattice specifications and the other with new lattice specifications. The mathematical polynomials used to model the ASFs in these new specifications were computed by a least-squares regression of the ASFs observed during all calibration surveys, including the 1992 survey. This procedure has been used by CHS since 1978 and is described in [Gray 1980]. The results are shown in Table 6. Also shown is the quality of the lattices in the immediate vicinity of the A-B line, which is shown in Figure 1, was examined, as described below. The immediate vicinity is considered here to be between latitude $54^\circ 36'N$ and $54^\circ 45'N$. Since the CHS standard for acceptance of lattices is an accuracy of 2.5 mm for 95% of the fixes, the existing lattices are not only acceptable but, in fact, cannot be significantly improved upon.

Chatham Sound

With the possibility that the next Edition of CHS chart #3802 might be expanded eastwards to include Chatham Sound and Prince Rupert, the accuracy of the lattices in that area was also examined. Here, lattice specifications were developed specifically for the Chatham Sound area. Some 2415 observations made over several years were used. The estimated accuracy with respect to the existing specifications was 2.1 mm, that with respect to the new specifications was also 1.4 mm, and that with respect to Chatham Sound specifications was 1.4 mm.

The above results show that the existing lattice specifications can be used to lattice an expanded version of chart #3802. They also show that the largest scale chart that could be latticed with these Chatham Sound specifications is approximately 1:120,000. It is known that the polynomial approach to ASF modelling is not as good as a grid of ASF data (as used by CHS Scotia/Fundy Region); nevertheless, it is not conceivable that CHS could lattice the existing 1:40,000 charts of the Chatham Sound area since the repeatability is no better than ± 100 metres, which would account for 2.5 mm at chart scale.

CHS Chart #3902

CHS chart #3902 covers the area of Hecate Strait at a scale of 1:250,000. The accuracy of the lattices on this chart was also examined since there were new data in Browning Entrance and the approaches to Caamaño Sound. The results are presented in Table 7. Again, the existing lattices are well within the standards. The 1600 data points taken in Principe and Grenville Channels during the September 1992 survey confirm that these waters should not be latticed - not that there was ever any intention to do so! It is good to know the quality of the lattices at the approaches to Caamaño Sound because there is the occasional discussion of laden tanker traffic using that channel.

U.S. National Ocean Survey Charts

Two N.O.S. charts are of interest here, namely #17400 and #17420. Modelled lattices for 5990X, Y, Z and 7960X and Y are printed on these charts. In order to analyse the accuracy of these lattices, it was necessary to obtain an estimate of the ASFs used. These were obtained by subtracting computed TDs based on an all sea-water model from the TDs measured from the charts on a 10' grid. The ASF

values were then modelled using the same least-squares regression technique as that used by CHS to fit surveyed ASFs. The standard deviations of the mathematical fits for the lattices are given in Table 8.

The analysis of N.O.S. Chart #17400 and #17420 is summarized in Table 9. The same technique as that used with the CHS charts is used.

N.O.S. Chart #17400 covers the west half of Dixon Entrance at a scale of 1:229,376 and contains 5990X, Y and Z and 7960X and Y lattices. N.O.S. Chart #17420 covers the east half of Dixon Entrance at the same scale and with the same lattices. Since the east part of the latter chart is in the baseline extension area of the 7960X pattern, the analysis of the 7960X and Y combination only extends as far east as $131^{\circ} 40'W$ longitude, or roughly to the line from Rose Point to West Devil Rock.

The 5990X and Z combination on these charts produces results which would be acceptable or marginally acceptable by CHS standards.

It also appears from the analysis that there are systematic differences between the observed TDs and TDs generated from the N.O.S. chart lattices based on the surveyed positions. These systematic differences can be interpreted as corrections to be used by mariners to obtain better positions. These estimated corrections are given in Table 10.

N.O.S. has been advised of these lattice errors and both CHS and N.O.S. are cooperating to improve the quality of the lattices in Dixon Entrance on N.O.S. Charts #17400 and 17420.

Improvement of ASF Chartlets

In order to assist users equipped with Loran-C coordinate converters which have the capability to input ASF corrections, CHS has published in Radio Aids to Marine Navigation (RAMN) [e.g., CCG 1992] maps or chartlets showing contours of ASFs for each TD. These corrections are derived from the survey data when available, and from predicted models when no observations are available. In the United States, the Defense Mapping Agency has published tables of predicted ASF corrections on a 5' x 5' grid. The 1992 survey will make it possible to improve the ASFs published in RAMN, particularly in Dixon Entrance, but also along the east side of Hecate Strait because of the data measured off Caamaño Sound. However, the area

from Banks Island to Cape Calvert will require additional Loran-C data in order to model the ASFs confidently.

Effect of ASF on Coordinate Conversion Calculations

Many Loran-C coordinate converters compute the geographic position based solely on the two best TDs from a single chain and without any consideration for ASFs. The effect of neglecting or taking the ASFs into account for various combinations of TDs was analysed using four data points in Dixon Entrance where all Loran-C TDs and GPS positions were available. The results are summarized in Table 11. The analysis was done using program HYPGEO which is a general least-squares approach to hyperbolic-to-geographic conversion that can use any two or more TDs and produce the computed position and its error ellipse [Gray 1989a, b].

Table 11 shows that systematic errors of up to 1.35 n.m. occur when the ASFs are not taken into account. Since this is a systematic effect unmodelled in the least-squares solution, the estimated error ellipses do not reflect this effect. When the ASFs, as determined by the GPS/Loran-C calibration survey, are taken into account, the absolute accuracy is consistently better than 0.08 n.m., i.e., 144 m. This demonstrates again the high performance of Loran-C, not only in terms of repeatable accuracy, but also in terms of absolute accuracy.

It is worth pointing out a typical hazard that occurs with coordinate converters when ASFs are assumed to be zero. For both the 5990XZ and the 5990X-7960X position solutions, the position computed without ASFs is farther offshore. This position gives the mariner the impression that he is farther from the coastal hazards than he really is. Not only does the coordinate converter yield a systematic error, the systematic error is in a potentially dangerous direction!

Canada and the United States claim different maritime boundaries in Dixon Entrance, and there is an agreement to disagree and to have flag-state enforcement in the disputed zone. However, there are occasions when the US Coast Guard apprehends a Canadian vessel for transgressing the northern limit of the disputed zone. This northern limit is called the A-B line from its source in the 1903 Arbitration decision. Point A is at Cape Muzon on the south tip of Dall Island, and Point B is between Dundas and Wales Island, as shown in Figure 1. The question arises as to whether the fisher crossed the

line knowingly, as an oversight, as an error in the Loran-C coordinate converter used, or as an error in the Loran-C lattices used. The earlier section of this paper attested to the fact that the lattices on CHS Chart #3802 (Dixon Entrance) and #3902 (Hecate Strait) more than meet the CHS accuracy standards for Loran-C positioning. There are now over 2300 data points along the A-B line (one point every 56 metres on average) and positioning capability is better than 1.3 mm at chart scale or 260 metres on the water. This error is partly random in nature since the repeatability of calibrated Loran-C is of the order of 100 to 200 m as shown above.

Many mariners use the coordinate converter facilities that are now an integral part of most Loran-C receivers. Although all receivers will measure substantially the same TDs, they will calculate different geographic positions because they use different mathematical algorithms. The minimum performance standards for coordinate converters are vague. The standards, no more than guidelines, are that the converter will calculate a position within 0.25 n.m. of the true geodetic position if the overland propagation corrections are automatically entered. But most coordinate converters do not take into account the overland propagation errors, and therefore compute a position that is systematically wrong. Assuming that coordinate converters will be using the 5990X and 5990Z TDs shown on CHS Chart #3802 in the A-B line area, the total position error caused by neglecting the ASFs varies from 1.5 n.m. near A to almost zero near 132°W, and to 0.5 n.m. at B. However, the error vectors are far more westerly than they are north-south. The error at right angles to the A-B line caused by neglecting the ASFs is 0.25 n.m. north of the A-B line at A and 1/8 n.m. south of the A-B line at B. The perpendicular distance off the line is less than 0.1 n.m. from 132° 20' W to 130° 45'W, which includes most of the line. Nevertheless, the errors exhibited by any particular model of receiver may be different than these figures because of the mathematical algorithms used.

CONCLUSIONS

The GPS/Loran-C survey described herein proved effective in demonstrating a high percentage of availability for both GPS and Loran-C in Dixon Entrance and to confirm the high accuracy of the calibrated 5990X and Z Loran-C lattices printed on CHS charts #3802 and #3902. The availability of DGPS corrections broadcast by the Marine Radio

Beacons varied between 54 and 97%. For an operational DGPS correction system, a level of availability approaching 100% should be expected. The 5990Y, 7960X and Y TDs were shown to be available for only parts of the time and in certain areas, due to skywave interference and ECDs outside the recommended minimal specification for marine Loran-C receivers; the TDs recommended for positioning in Dixon Entrance are therefore 5990X and Z. A comparison of the calibration results obtained herein with values measured with navigation systems other than GPS showed a level of repeatability better than a few tenths of one μ s in the TDs. The analysis showed the shortcomings of using ASFs based on theoretical models. In such an area of mixed sea/land propagation paths, neglecting ASFs based on calibration surveys can lead to Loran-C absolute position errors in excess of one n.m. However, the use of calibrated ASFs was shown to result in absolute Loran-C position accuracies of 100 to 200 m. Neglecting the ASFs can result in north-south Loran-C position errors of up to some 0.25 nm, i.e., 460 m, in limited parts of the A-B line. The use of calibrated ASFs was shown to be extremely important in this coastal area for safe navigation.

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Table 1: Description of Ship Track Segments Surveyed

#	Inter Dist km	Tot. Dist km	Date Sep 92	Start ¹ sec	End ¹ sec	N. Samp.	RT ² DGPS	Remarks
1	58	58	11	505186	515282	10096	ON	Chatham Sound
2	218	276	13	52412	90336	37924	ON	A - B Line (B->A) - Dixon Entrance
3	186	462	14	150931	184835	33904	ON	A - B Line (A->B) - Dixon Entrance
4	181	643	15	223193	254816	31623	ON	54-34 N Lat. (E-W Line) - Dix. Ent.
5	197	840	17	392991	428286	35295	ON	54-18 & 54-10 N Lat. - Dix. Ent.
6	186	1026	18	501901	534163	32262	ON	54-26 N Lat. - Dix. Ent.
7	155	1181	19	578813	4756	30743	ON	Grenville Channel
8	239	1420	20	56100	100183	44083	ON	Caamano Sound/Principe Channel
9	173	1593	21	136376	164594	282218	ON	Hecate Strait & Chatham Sound
10	70	1663	22	242372	258990	16618	OFF	Chatham Sound/Prince Rupert

1. GPS time of week.

2. Real Time Differential GPS

Table 2
Comparison of Jet 7201 Loran-C Receiver Performance¹

Transmitter	Nbr Samples	Mean	RMS	Max	Min
δDTD					
5990X	999	0.02μs	0.04μs	0.17μs	-0.45μs
5990Y	720	0.07	0.08	0.27	-0.13
5990Z	1606	0.09	0.09	0.18	-0.13
7960Y	518	-0.01	0.62	0.21	-9.77
δSNR					
5990M	2465	0.0dB	1.3dB	9.7dB	-13.1dB
5990X	2421	0.6	5.7	34.2	-19.8
5990Y	2448	0.5	4.4	30.9	-18.3
5990Z	2465	0.0	2.1	14.1	-14.8
7960M	1896	0.3	3.6	25.7	-17.9
7960X	2169	0.1	1.2	10.7	-8.7
7960Y	2146	0.0	4.0	34.0	-19.9
δECD					
5990M	2465	-0.1μs	0.9μs	10.0μs	-9.9μs
5990X	2457	0.1	2.4	14.3	-15.2
5990Y	2465	0.0	2.0	11.5	-12.0
5990Z	2465	-0.1	0.8	9.4	-9.0
7960M	1910	-0.1	3.0	18.6	-15.7
7960X	2169	-0.1	1.4	11.5	-12.9
7960Y	2168	-0.2	2.3	14.7	-14.8

¹ Based on 1-km Averages

Table 3
Loran-C Measurement Statistics - Dixon Entrance¹

Transmitter	Nbr Samples	Mean	Max	Min
5990X (DTD)	959	-3.84 μ s	-0.77 μ s	-5.61 μ s
5990Y	722	3.30	3.93	2.47
5990Z	1534	-2.55	-0.73	-3.71
7960X	210	-2.73	-2.21	-2.96
7960Y	625	-7.53	2.52	-8.90
5990M (SNR)	1562	13.7dB	18.8dB	-9.9dB
5990X	1562	14.7	23.3	-7.3
5990Y	1562	5.1	20.7	-12.7
5990Z	1562	20.0	23.5	2.4
7960M	1562	2.6	19.9	-11.2
7960X	1562	7.9	16.3	-9.5
7960Y	1562	19.2	23.4	-10.9
5990M (FS)	1562	59.4dB	65.0dB	49.6dB
5990X	1562	84.3	104.9	42.1
5990Y	1562	51.0	77.8	28.7
5990Z	1562	76.2	85.7	64.4
7960M	1562	48.9	75.1	31.1
7960X	1562	55.5	61.9	38.8
7960Y	1562	88.3	104.4	41.2
5990M (ECD)	1562	0.4 μ s	3.0 μ s	-4.1 μ s
5990X	1562	2.1	7.7	-9.9
5990Y	1562	-0.3	7.8	-9.8
5990Z	1562	1.6	2.7	-2.8
7960M	1562	-1.0	7.4	-9.9
7960X	1562	1.2	3.2	-7.9
7960Y	1562	3.1	6.5	-9.9

¹ Based on 1-km Averages

Table 4: Percentages of GPS and Loran-C Availability

Date	GPS		Jet 7201 (#1)		Jet 7201 (#2)		Internav 404
	Single	Diff.	Single-Chain	Multi-Chain	Single-Chain	Multi-Chain	Single-Chain
11-Sep-92	99.3%	97.3%	98.9%	98.9%	86.8%	86.8%	100%
13-Sep-92	97.9%	80.3%	63.0%	93.6%	59.3%	91.7%	100%
14-Sep-92	97.8%	95.5%	59.2%	62.1%	56.1%	79.2%	100%
15-Sep-92*	83.3%	66.4%	66.7%	66.7%	69.5%	69.5%	100%
17-Sep-92	99.0%	68.9%	78.3%	81.4%	77.8%	80.9%	100%
18-Sep-92	99.6%	81.9%	50.1%	50.9%	50.2%	51.0%	100%
19-Sep-92	99.6%	62.9%	71.7%	72.4%	71.6%	72.2%	100%
20-Sep-92	98.8%	54.2%	91.4%	91.4%	91.4%	91.4%	100%
21-Sep-92	99.7%	73.6%	59.2%	59.7%	56.4%	56.4%	100%
22-Sep-92	97.3%	88.4%	100.0%	100.0%	100.0%	100.0%	100%

* Data recording problems

TABLE 5
Comparison of ASF's Computed for Various Grid squares
of 5' x 5' of latitude/longitude

Test Area	Year of Survey	Nbr of Obs	Additional Secondary Factor			Latitude	Longitude
			5990X	5990Y	5990Z		
1	1982	29	-3.83	1.04	-2.81	53° 53' 07."	130° 51' 36."
	1984	1	-3.76		-2.71	53° 53' 04."	130° 54' 57."
	1992 (Internav rx)	24	-3.63	1.03	-2.63	53° 50' 45."	130° 53' 41."
	1992 (Jet rx)	4	-3.49	1.81	-2.64	53° 50' 41."	130° 53' 32."
2	1982	12	-3.96		-2.89	53° 59' 10."	130° 56' 18."
	1984	3	-3.87		-2.86	53° 57' 47."	130° 57' 06."
	1992(Internav rx)	51	-3.69	.50	-2.77	53° 57' 30."	130° 59' 34."
	1992 (Jet rx)	9	-3.64	1.45	-2.77	53° 57' 39."	130° 59' 32."
3	1982	10	-4.02		-2.97	54° 00' 50."	130° 57' 59."
	1983	25	-4.20	1.29	-2.98	54° 02' 10."	130° 57' 32."
	1992 (Internav rx)	24	-3.84	.53	-2.88	54° 01' 10."	130° 59' 53."
	1992 (Jet rx)	5	-3.82	1.38	-2.84	54° 01' 25."	130° 59' 52."
4	1983	12	-3.72	2.84	-1.69	54° 14' 24."	130° 45' 56."
	1984	10	-3.78	2.66	-1.51	54° 13' 21."	130° 48' 32."
	1992 (Internav rx)	82	-3.67	2.46	-1.26	54° 13' 14."	130° 46' 18."
	1992 (Jet rx)	7			-1.43	54° 13' 39."	130° 46' 07."
5	1983	8	-3.82		-2.40	54° 14' 20."	131° 04' 41."
	1984	10	-3.75	2.23	-2.39	54° 10' 14."	131° 01' 10."
	1992 (Internav rx)	54	-3.73	-.30	-2.15	54° 12' 34."	131° 01' 52."
	1992 (Jet rx)	9	-3.51	1.49	-2.21	54° 12' 37."	131° 01' 53."
6	1983	14	-3.69	-.07	-2.81	54° 19' 25."	131° 33' 23."
	1984	2	-3.64	1.41	-2.83	54° 15' 03."	131° 30' 11."
	1992 (Internav rx)	26	-3.54	.86	-2.63	54° 17' 39."	131° 34' 09."
	1992 (Jet rx)	4	-3.34	1.50	-2.63	54° 17' 39."	131° 34' 05."
7	1985	27	-2.88		-2.02	54° 16' 07."	132° 32' 27."
	1992 (Internav rx)	33	-2.82	.32	-1.97	54° 17' 59."	132° 32' 29."
	1992 (Jet rx)	5		1.42	-1.89	54° 17' 58."	132° 32' 36."
8	1985	17	-2.82		-2.02	54° 16' 42."	132° 37' 08."
	1992 (Internav rx)	33	-2.86	.13	-1.91	54° 17' 59."	132° 37' 33."
	1992 (Jet rx)	6		1.52	-1.77	54° 17' 57."	132° 37' 42."
9	1985	20	-2.80		-1.95	54° 16' 40."	132° 41' 37."
	1992 (Internav rx)	35	-2.86	.36	-1.84	54° 17' 59."	132° 42' 32."
	1992 (Jet rx)	5		1.60	-1.75	54° 17' 58."	132° 42' 41."
10	1985	34	-2.90		-1.89	54° 16' 33."	132° 47' 22."
	1992 (Internav rx)	96	-2.89	1.54	-1.83	54° 17' 39."	132° 47' 39."
	1992 (Jet rx)	16		1.65	-1.80	54° 17' 36."	132° 47' 35."
11	1985	13	-2.90		-1.83	54° 15' 29."	132° 52' 08."
	1992 (Internav rx)	146	-2.86	1.10	-1.76	54° 17' 35."	132° 52' 51."
	1992 (Jet rx)	27	-2.64	1.69	-1.70	54° 17' 33."	132° 52' 57."

TABLE 6
ANALYSIS OF CHS CHART #3802 LATTICES

Year of Survey	Number of Observations	Accuracy w.r.t. Existing Spec.'s	Accuracy w.r.t. New Spec.'s
<u>Overall Chart</u>			
1982	403	1.0 mm	1.6 mm
1983	2166	1.4	1.5
1984	1024	1.1	1.7
1985	618	1.4	1.6
1992 (Internav rx)	6011	1.7	1.6
1992 (Jet rx)	488	1.3	
<u>Vicinity of A-B line</u>			
1983	568	0.9	1.4
1992 (Internav rx)	1791	1.3	1.1

TABLE 7: ANALYSIS OF CHS CHART #3902 LATTICES

Area of Survey	Number of Observations	Accuracy w.r.t. 5990XZ Spec.'s	Accuracy w.r.t. 5990XY Spec.'s
Browning Entrance	269	1.0 mm	2.1 mm (215 obs.)
Caamaño Sound	172	1.0	1.5

TABLE 8: ESTIMATED ASF_s USED ON N.O.S. CHARTS

Chart #17400		Chart #17420	
Lattice	Std. Dev.	Lattice	Std. Dev.
5990X	±0.23 μ s	5990X	±0.27 μ s
5990Y	±0.35	5990Y	±0.06
5990Z	±0.19	5990Z	±0.09
7960X	±0.16	7960X	±0.11
7960Y	±0.23	7960Y	±0.18

TABLE 9
ANALYSIS OF N.O.S. CHART LATTICES

CHART #17400				
5990X and Z Combination			5990X and Y Combination	
<u>Year of Survey</u>	<u>Number of Observations</u>	<u>Accuracy w.r.t. Polynomial</u>	<u>Number of Observations</u>	<u>Accuracy w.r.t. Polynomial</u>
1985	325	2.1 mm		
1992 (Internav rx)	2294	2.3		
1992 (Jet rx))	200	2.3	157	9.8 mm
7960X and Y Combination				
<u>Year of Survey</u>	<u>Number of Observations</u>	<u>Accuracy w.r.t. Polynomial</u>		
1992 (Jet rx))	62	6.0 mm		
CHART #17420				
5990X and Z Combination			5990X and Y Combination	
<u>Year of Survey</u>	<u>Number of Observations</u>	<u>Accuracy w.r.t. Polynomial</u>	<u>Number of Observations</u>	<u>Accuracy w.r.t. Polynomial</u>
1982	47	2.1 mm	31	8.0 mm
1983	2676	2.4	1522	7.0
1984	619	1.4	588	7.1
1985	521	3.0		
1992 (Internav rx)	5657	3.1		
1992 (Jet rx)	610	3.0	235	9.0
7960X and Y Combination				
<u>Year of Survey</u>	<u>Number of Observations</u>	<u>Accuracy w.r.t. Polynomial</u>		
1992 (UofC)	30	5.0 mm		

TABLE 10
ESTIMATED TD CORRECTIONS TO N.O.S. CHART LATTICES

Chart #17400		Chart #17420	
Rate	Correction	Rate	Correction
5990X	~ +0.7 μ s	5990X	0.0 to +1.0 μ s
5990Y	~ -1.3 μ s	5990Y	~ -1.3 μ s
5990Z	~ -0.7 μ s	5990Z	-1.0 to 0.0 μ s
7960X	~ +0.9 μ s	7960X	~ -0.7 μ s
7960Y	~ +2.7 μ s	7960Y	~ +2.8 μ s

TABLE 11
Effect of ASF on Computed Loran-C Positions

GPS Position	Time Differences ¹		Positions	Positions	Error Ellipses (a, b, azimuth of a) (39% confidence reg.)
	7960	5990	Without ASFs (ϕ , λ , Δ from GPS)	With Cal. ASFs (ϕ , λ , Δ from GPS)	
Test Point # 1 54° 29' 32.00"N, 130° 32' 07.46"W		X 11677.6 μ s	54° 29' 24.7"N, 130° 32' 59.8"W	54° 29' 29.9"N, 130° 32' 00.2"W	93m, 30m, 53°
		Z 41829.81	0.52 n.m. @ 256°	0.08 n.m. @ 117°	
	X 14429.23	X 11677.64	54° 29' 06.8"N, 130° 33' 31.1"W 0.92 n.m. @ 243°	54° 29' 30.1"N, 130° 31' 59.8"W 0.08 n.m. @ 112°	95m, 32m, 46°
	X 14429.23 Y 25998.82	X 11677.64 Y N/A Z 41829.81	54° 29' 28.0"N, 130° 32' 50.9"W 0.43 n.m. @ 261°	54° 29' 28.6"N, 130° 32' 03.2"W 0.07 n.m. @ 144°	62m, 30m, 55°
Test Point # 2 54° 41' 54.47"N, 131° 10' 22.27"W		X 11492.01	54° 41' 51.1"N, 131° 11' 33.7"W	54° 41' 57.1"N, 131° 10' 18.6"W	107m, 32m, 63°
		Z 41807.30	0.69 n.m. @ 265°	0.06 n.m. @ 39°	
	X 14408.45	X 11492.01	54° 41' 39.8"N, 131° 12' 02.4"W 1.00 n.m. @ 256°	54° 41' 54.7"N, 131° 10' 24.5"W 0.02 n.m. @ 281°	95m, 35m, 57°
	X 14408.45 Y 26025.05	X 11492.01 Y N/A Z 41807.30	54° 42' 05.0"N, 131° 10' 36.1"W 0.22 n.m. @ 323°	54° 41' 57.1"N, 131° 10' 17.8"W 0.06 n.m. @ 44°	56m, 31m, 67°
Test Point # 3 54° 39' 59.80"N, 132° 32' 35.49"W		X 12314.19	54° 40' 04.0"N, 132° 34' 54.5"W	54° 39' 57.4"N, 132° 32' 34.3"W	179m, 44, 87°
		Z 41676.39	1.35 n.m. @ 273°	0.04 n.m. @ 165°	
	Y 26007.00	X 12314.19	54° 40' 33.5"N, 132° 31' 19.5"W 0.93 n.m. @ 52°	54° 39' 56.5"N, 132° 32' 40.7"W 0.08 n.m. @ 222°	67m, 46m, 39°
	X 14303.34 Y 26007.00	X 12314.19 Y 30521.38 Z 41676.39	54° 40' 05.0"N, 132° 32' 16.9"W 0.20 n.m. @ 64°	54° 40' 00.1"N, 132° 32' 39.3"W 0.04 n.m. @ 278°	41m, 38m, -52°
Test Point # 4 54° 21' 36.91"N, 133° 00' 32.14"W		X 11355.99	54° 21' 42.6"N, 133° 02' 40.3"W	54° 21' 38.2" 133° 00' 29.8"W	194m, 46m, 85°
		Z 41623.07	1.25 n.m. @ 274°	0.03 n.m. @ 47°	
	Y 26372.77	X 11355.99	54° 22' 15.4"N, 132° 59' 18.4"W 0.96 n.m. @ 48°	54° 21' 37.8"N, 133° 00' 32.4"W 0.01 n.m. @ 348°	72m, 46m, 38°
	X 14163.81 Y 26372.77	X 11355.99 Y 30521.61 Z 41623.07	54° 21' 45.5"N, 133° 00' 16.9"W 0.21 n.m. @ 46°	54° 21' 38.3"N, 133° 00' 32.6"W 0.02 n.m. @ 347°	42m, 40m, -51°

¹ TDs contain Emission Delays

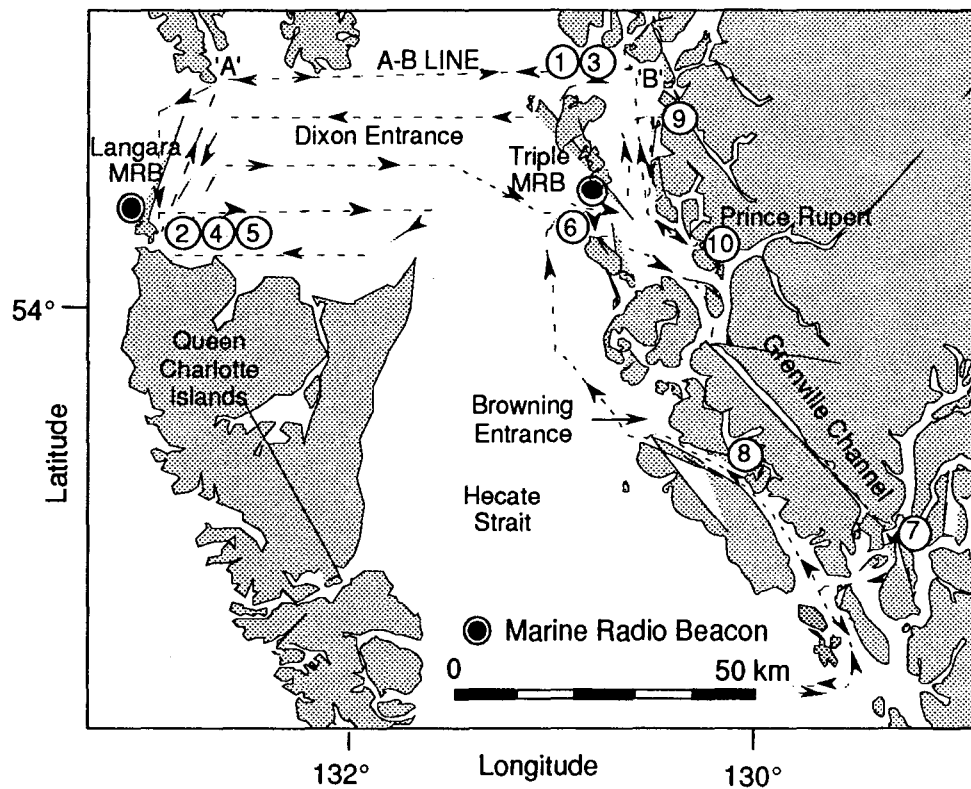


Figure 1: Dixon Entrance - Ship Tracks Observed in September 1992

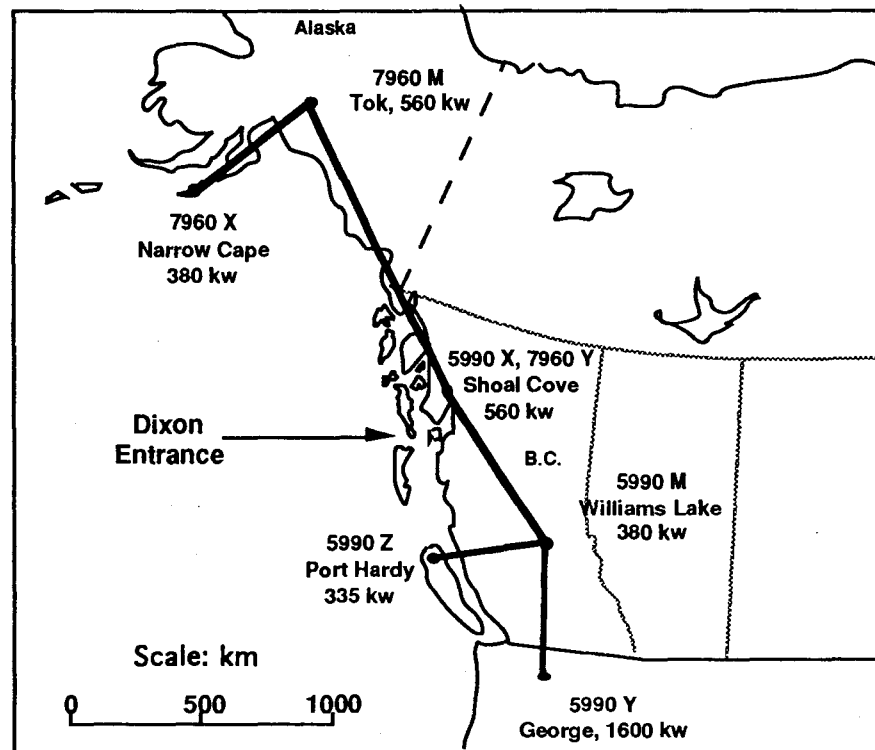


Figure 2: Loran-C Transmitters Available Along B.C.'s and Alaska's Coasts

Dixon Entrance, 5990X, Sept 92

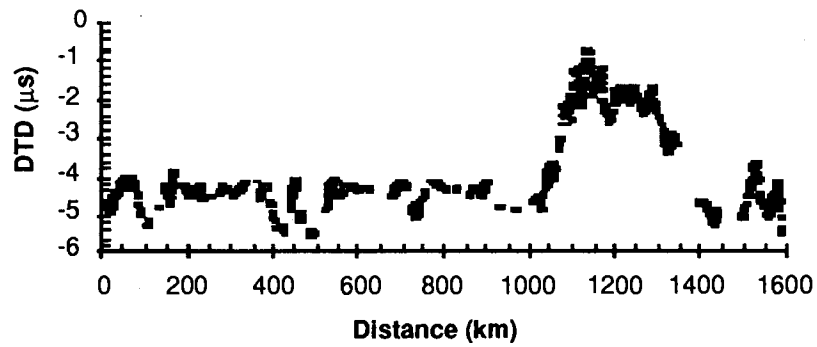


Figure 3: DTDs on 5990X, Dixon Entrance Area

Dixon Entrance, 5990Y, Sept 92

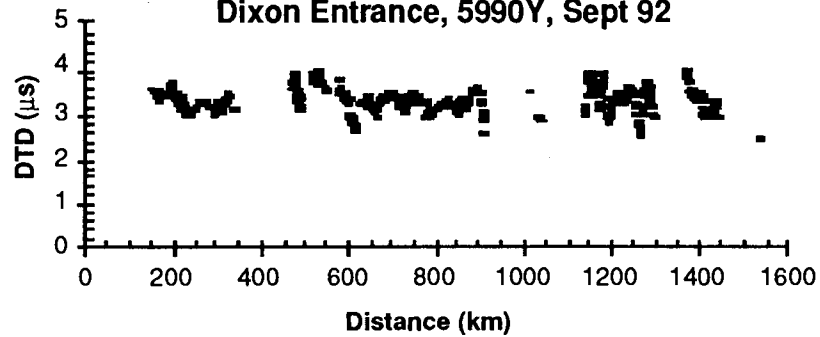


Figure 4: DTDs on 5990Y, Dixon Entrance Area

Dixon Entrance, 5990Z, Sept 92

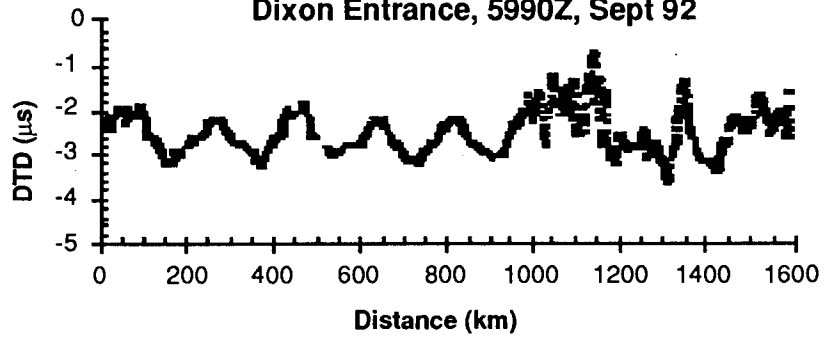


Figure 5: DTDs on 5990Z, Dixon Entrance Area

Dixon Entrance, 7960X, Sept 92

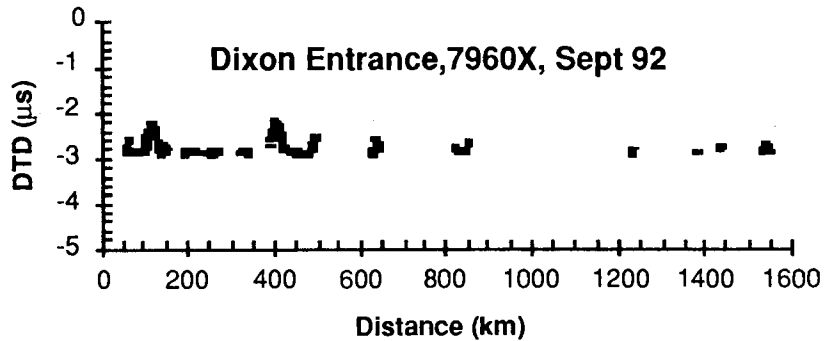


Figure 6: DTDs on 7960X, Dixon Entrance Area

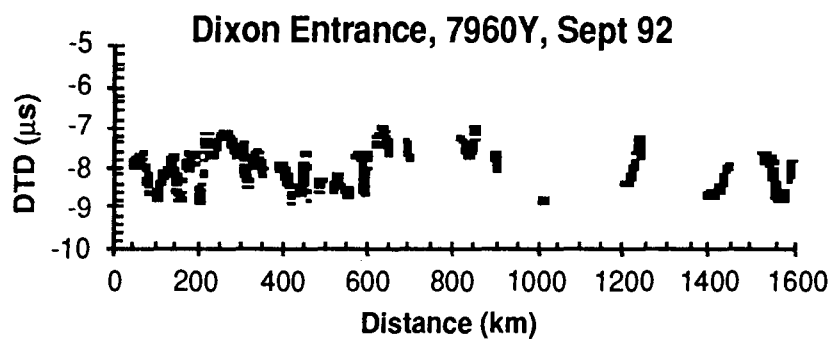


Figure 7: DTDs on 7960Y, Dixon Entrance Area

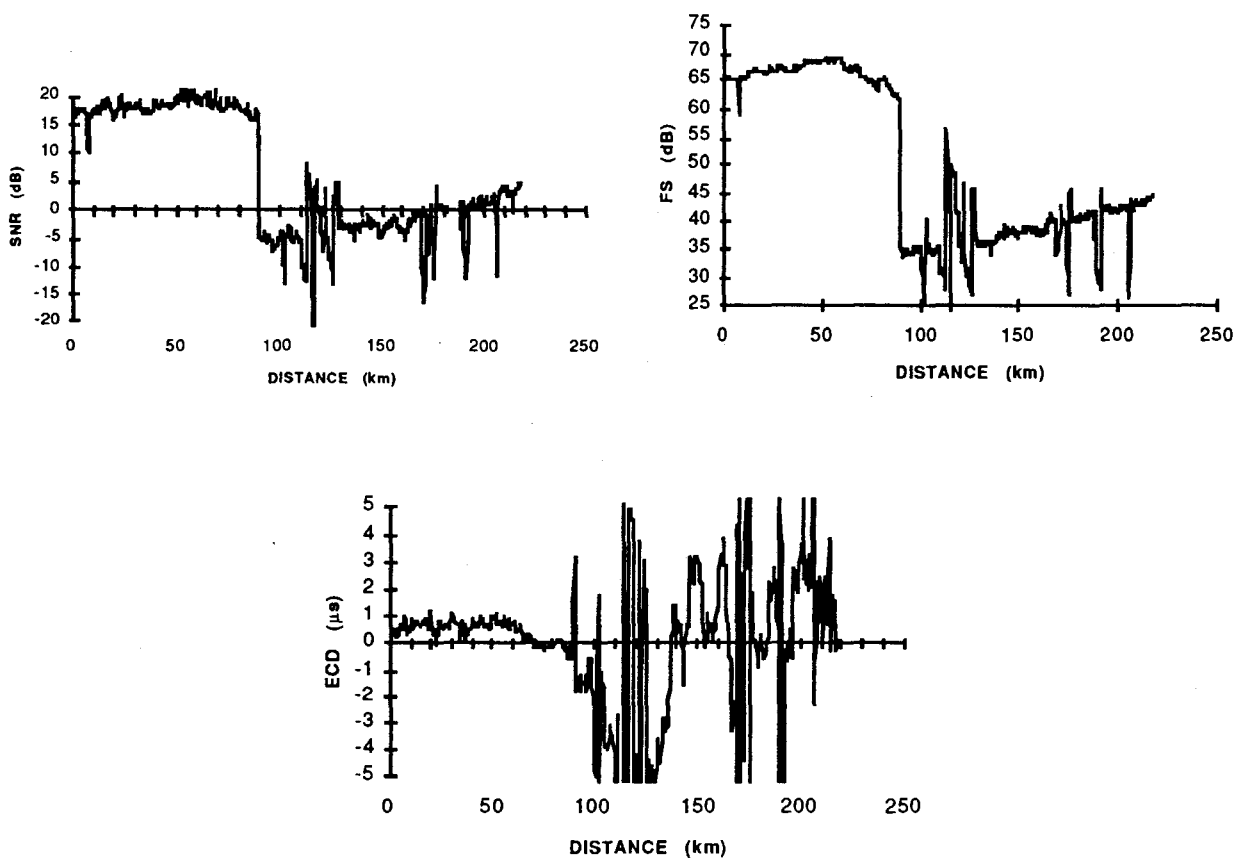


Figure 8: Jet 7201 Loran-C Receiver SNR, FS, and ECD in Dixon Entrance, 13 September 1992, 5990Y

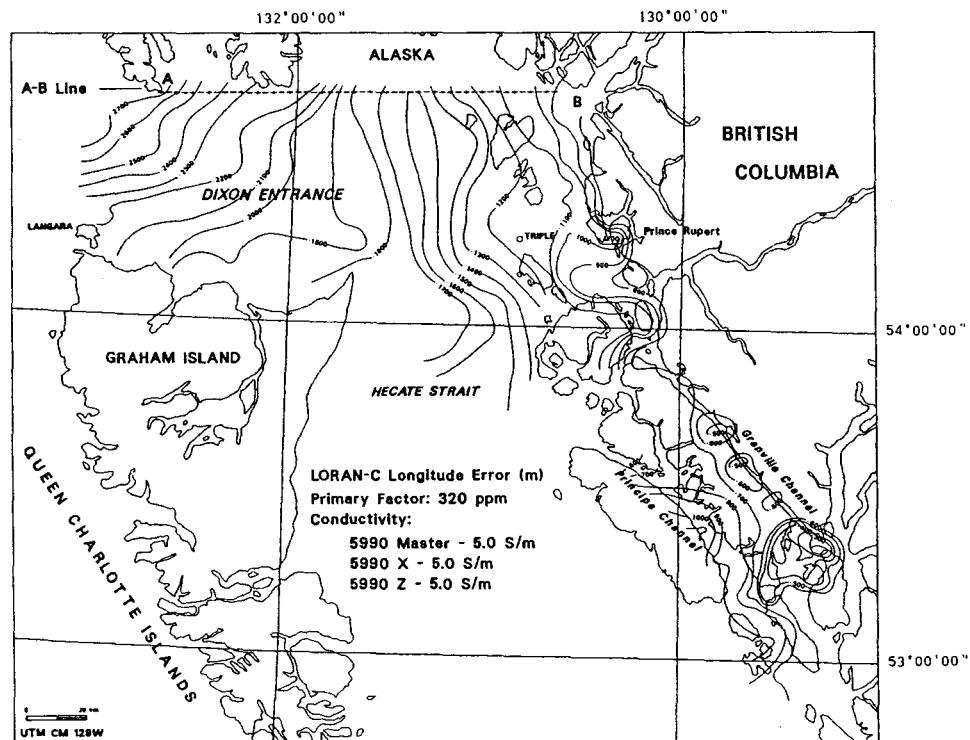
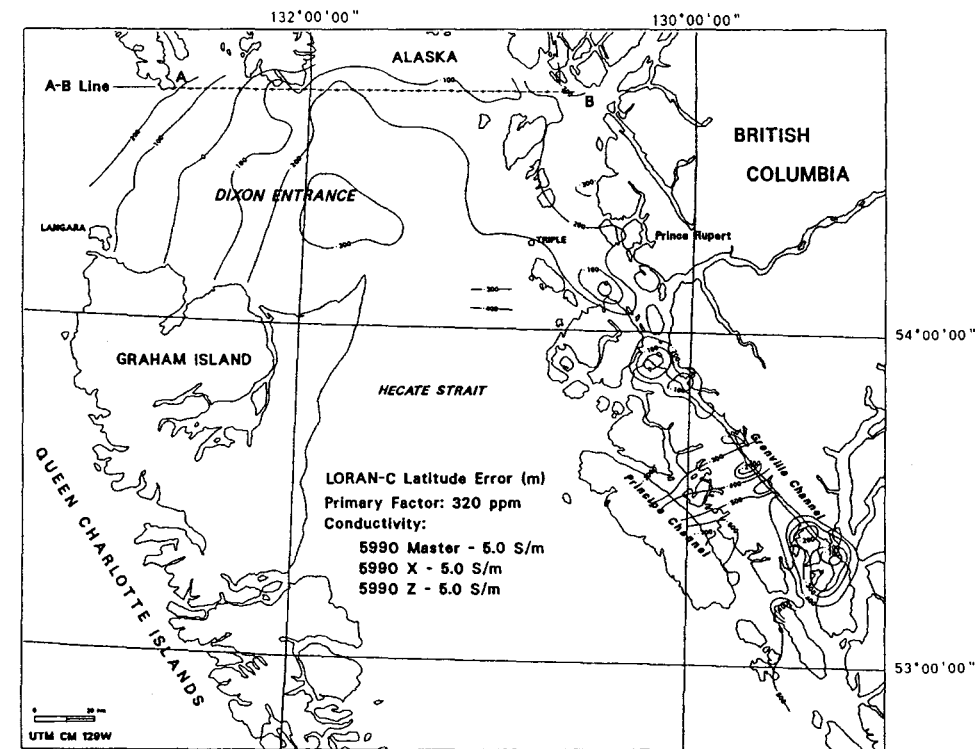


FIGURE 9: LORAN-C COORDINATE DISTORTIONS IN DIXON ENTRANCE USING AN ALL-SEA PROPAGATION PATH ASSUMPTION FOR THE 5990X AND Z TDs

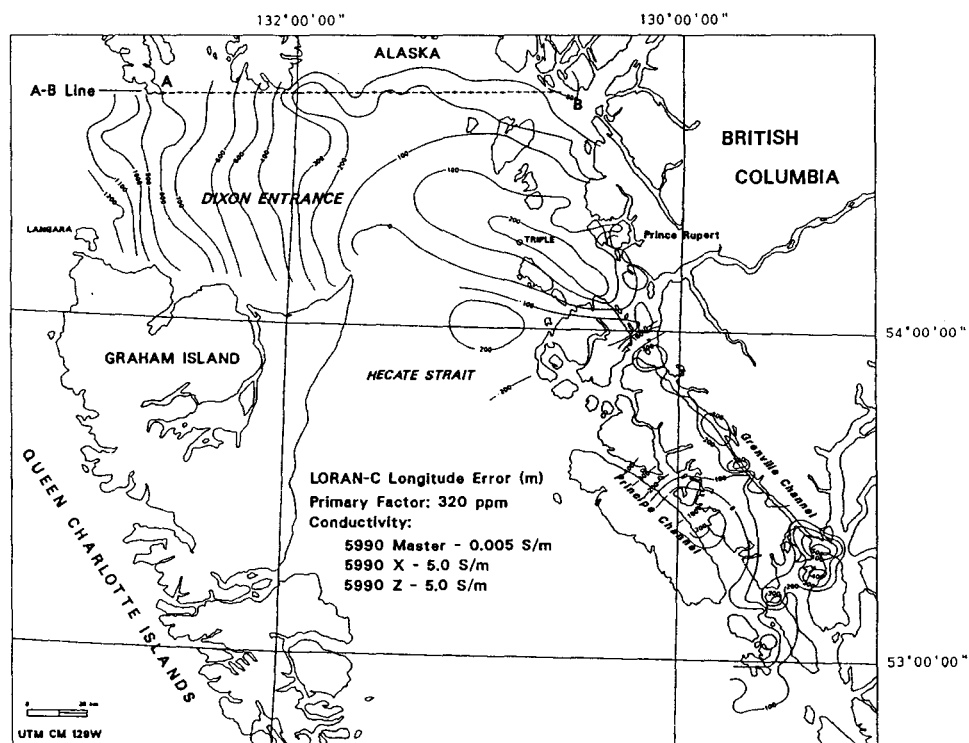
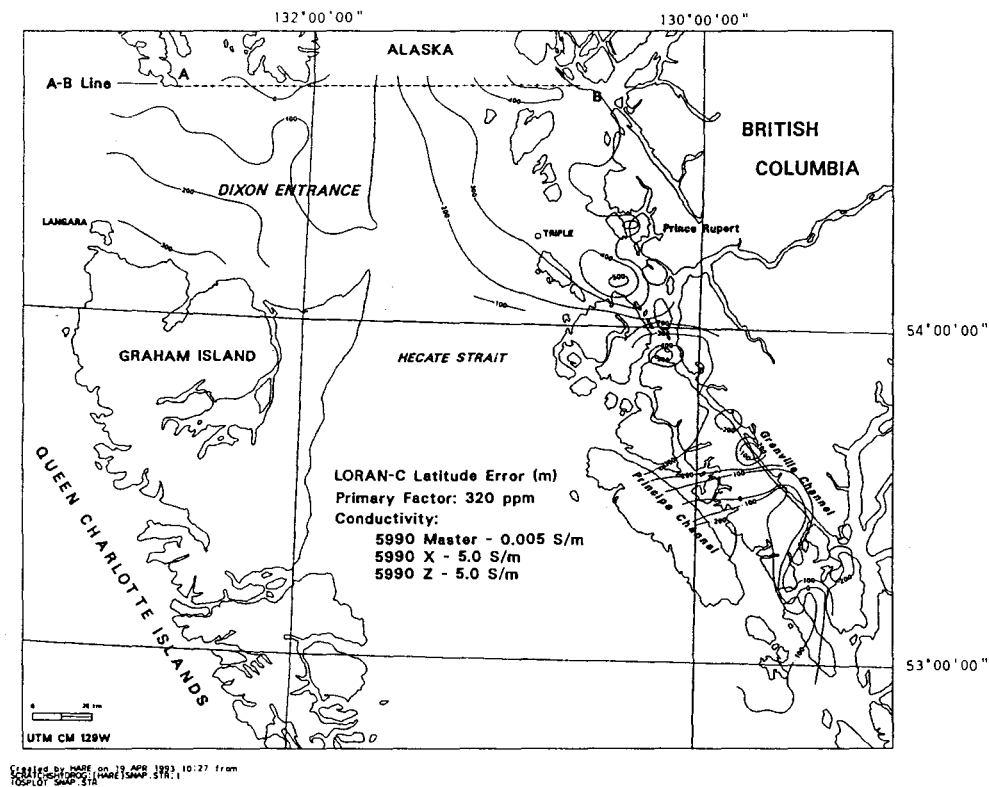


FIGURE 10 : LORAN-C COORDINATE DISTORTIONS USING AN ALL-SEA PROPAGATION PATH ASSUMPTION FOR 5990X AND Z AND A CONDUCTIVITY OF 0.005 S/m FOR 5990M

A SYNOPSIS OF SATELLITE TIME TRANSFER METHODS FOR SYNCHRONIZING LORAN-C MASTER STATIONS TO COORDINATED UNIVERSAL TIME (UTC)

Charles J. Justice and LT A. Norman Mason

USCG Headquarters
Office of Navigation Safety and Waterway Services
Radionavigation Division

ABSTRACT

Public Law 100-223 requires that all Loran-C master stations be synchronized to within approximately ± 100 nanoseconds of Coordinated Universal Time (UTC). The U.S. Coast Guard (USCG) has investigated several ways to meet this requirement. These include: (1) applying administrative techniques to control the Loran-C operate oscillators via U.S. Naval Observatory (USNO) far-field monitors; (2) comparing Loran-C Timing and Control Equipment (TCE) data to GPS-derived data; (3) comparing Two-Way Satellite Time Transfer (TWSTT) of Loran-C Time of Transmission (TOT) to the USNO master clock; and (4) using Common-View Time Transfer (CVTT) via the NAVSTAR Global Positioning System (GPS).

The USCG has contracted with the National Institute of Standards and Technology (NIST) to install a GPS receiver at Loran Station (LORSTA) Seneca (9960 master), New York. Data collected there from January through June 1993 indicate that the CVTT method may provide about 10-nanosecond time synchronization control at the one-sigma level.

These data also show a significant increase in the ability to measure TOT compared to the other methods. The USNO also receives these data from NIST and compares them to their far-field measurements of Seneca's signal.

This paper discusses the preliminary results of applying these methods at LORSTA Seneca and how they may affect future plans for using CVTT to measure

and control Loran-C master station oscillators.

BACKGROUND

In October 1987 the Airport and Airway Improvement Act Amendments extended the scope of the Airport and Airway Improvement Act of 1982[1]. That extension included the following stipulations which directly affected Loran-C operations. In summary, it stated that:

(a) Each master transmitter in the United States, or subject to United States Jurisdiction, shall be synchronized to within approximately ± 100 nanoseconds (ns) of Coordinated Universal Time (UTC).

(b) A study shall be made of the impact on Loran-C users of synchronizing the time of transmission among all secondary transmitters in the United States to within approximately ± 100 ns of UTC.

(c) Methods of coordinating the time references of the Loran-C transmitter system and the GPS to within approximately 30 ns shall be studied. The purpose is the possibility of exchanging positioning data between the two systems.

This paper concentrates on the USCG efforts to date to meet requirement (a). Efforts to meet requirements (b) and (c) are documented elsewhere [2],[3],[4]. The synchronization efforts documented herein are presented chronologically.

ADMINISTRATIVE METHODS TO SYNCHRONIZE LORAN-C MASTER STATIONS.

The so-called administrative methods were tested during 1988 and 1989 on four Loran-C chains in the continental United States[5]. These chains included the Great Lakes (GLKS), in which master station Dana, Indiana participated, the Northeast United States (NEUS), in which master station Seneca, New York participated, the Southeast United States (SEUS), represented by master station Malone, Florida and the U.S. West Coast (USWC), represented by master station Fallon, Nevada.

Time Step Control at LORSTA Dana

The method applied at LORSTA Dana primarily used small time steps to maintain synchronization. Occasional frequency adjustments were used to reduce the number and magnitude of the time steps.

The watchstander at the control station called an electronic bulletin board (EBB) established by the USNO and examined the report for the day's offset of the master station from UTC as measured by the USNO master clock, $[UTC_{USNO}, MC]$. If the offset exceeded ± 50 ns, it was "zeroed" using 40-ns time steps.

Time steps and offsets were then plotted and frequency adjustments were made, if necessary, after 30 days of observation and averaging.

From February 24, 1988 through August 17, 1989 LORSTA Dana was synchronized to $[UTC_{USNO}, MC]$ with a mean or average of -13 ns and a standard deviation or error (σ) of 99 ns.

Table 1 Compares the steering control at LORSTA Dana both before and after applying time step control.

Improved Synchronization at GLKS

From	To	Mean (μ S)	Sigma (μ S)
Jan 1, 1988	Feb 24, 1988	-0.08	0.64
Feb 24, 1988	Aug 17, 1989	-.013	0.099

Table 1 - The Synchronization Performance of Loran-C Station Dana

Improved Synchronization at NEUS

From	To	Mean (μ S)	Sigma (μ S)
Jan 1, 1988	May 25, 1988	-0.26	0.65
May 25, 1988	Oct 14, 1988	-0.045	0.139
Oct 14, 1988	Jan 17, 1989	-0.109	0.130
Jan 17, 1989	May 15, 1989	-0.023	0.160
May 15, 1989	Aug 17, 1989	-0.031	0.061

Table 2 - The Synchronization Performance of Loran-C Station Seneca

Using this method resulted in 76 percent of the data points being within ± 100 ns of $[UTC_{USNO}, MC]$.

Frequency Control at LORSTA Seneca

The USNO began frequency control of LORSTA Seneca by averaging offset data for four days and, based on the average, recommended a frequency correction if necessary. The averaging was gradually dropped to a single day to test the steering limits of this method. This correction was obtained from the EBB, as it was for LORSTA Dana.

After the control watchstander consulted the EBB for the correction, he entered it into the phase microstepper, which adjusts the offset of the operate cesium oscillator, and then confirmed the entry with the EBB.

From May 25, 1988 through August 17, 1989 LORSTA Seneca was synchronized to $[UTC_{USNO}, MC]$ with a mean of -4.5 ns and a standard deviation (σ) of 143 ns.

Table 2 Compares the steering control at LORSTA Seneca both before and after applying frequency control. Using this method resulted in 52 percent of the data points being within ± 100 ns of $[UTC_{USNO}, MC]$.

Accelerated Control at LORSTA Malone

This technique relied on offset data being collected for three days and then applying either a time step or a frequency adjustment, depending on the requirements. Prior to using this method, daily offset data were collected and analyzed for 30 days before making a

Improved Synchronization at SEUS

From	To	Mean (μS)	Sigma (μS)
Jan 1, 1988	Feb 24, 1988	-0.32	0.86
Oct 24, 1988	Apr 21, 1989	-0.029	0.188
Apr 21, 1989	Aug 17, 1989	-0.006	0.089

Table 3 - The Synchronization Performance of Loran-C Station Malone

steering adjustment.

From October 24, 1988 through August 17, 1989 LORSTA Malone was synchronized to [UTC_{USNO},MC] with a mean of -19.3 ns and a standard deviation (σ) of 166 ns.

Table 3 Compares steering control at LORSTA Malone both before and after applying this method. This technique resulted in 66 percent of the data points being within +/- 100 ns of [UTC_{USNO},MC].

Time Step Control at LORSTA Fallon

The same technique was applied at LORSTA Fallon, Nevada as was done at LORSTA Dana, Indiana. For the period of interest, February 24, 1988 through August 17, 1989, this station was synchronized to [UTC_{USNO},MC] with a mean of nearly 0 ns and a standard deviation (σ) of 160 ns.

Table 4 gives a before-and-after comparison of the data. This method resulted in 62 percent of the data points being within +/- 100 ns of [UTC_{USNO},MC].

SUMMARY OF ADMINISTRATIVE CONTROL METHODS

When the combined data from the administrative control methods for all four chains are analyzed, it is found that these methods reduce the average offset of these stations to within +/- 200 ns of [UTC_{USNO},MC] 84 percent of the time.

If Public Law 100-223 is interpreted to require +/- 100 ns synchronization at the plus-or-minus two-sigma level, as has been suggested[6], then other methods must obviously be used because these control methods did not attain that precision.

Improved Synchronization at USWC

From	To	Mean (μS)	Sigma (μS)
Jan 1, 1988	Feb 24, 1988	-0.151	0.61
Feb 24, 1988	Apr 27, 1989	-0.113	0.141
Apr 27, 1989	Aug 17, 1989	0.015	0.116

Table 4 - The Synchronization Performance of Loran-C Station Fallon

The administrative methods are even more deficient if the 30-ns standard deviation, as advocated in reference[2], is adopted as a goal. At this point, the USCG tested the feasibility of using the GPS system in the direct-view mode as another alternative. The preliminary results of this investigation follow.

UTC-OFFSET REPORTING EQUIPMENT SUITE

In September 1989, the Coast Guard Electronics Engineering Center (EECEN) installed the UTC-Offset Equipment Reporting Suite at LORSTA Seneca, New York[7]. This equipment was interfaced with the NEUS Loran-C Timer Set #2 and an Allen Osborne TTR-6 GPS receiver. One purpose of this test was to determine the affects of GPS Selective Availability (SA) on direct-view time transfer accuracy and precision.

In the experiment, two sets of data were derived[8]. The first, called the direct-view set, was obtained by observing several Block I satellites and one Block II satellite for 24 days. From these observations 835

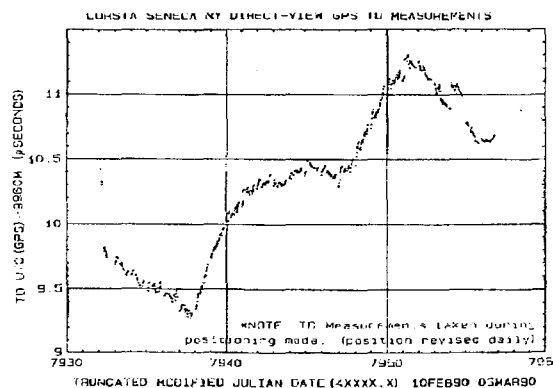


Figure 1 - LORSTA Seneca NY Direct-View GPS TD Measurements

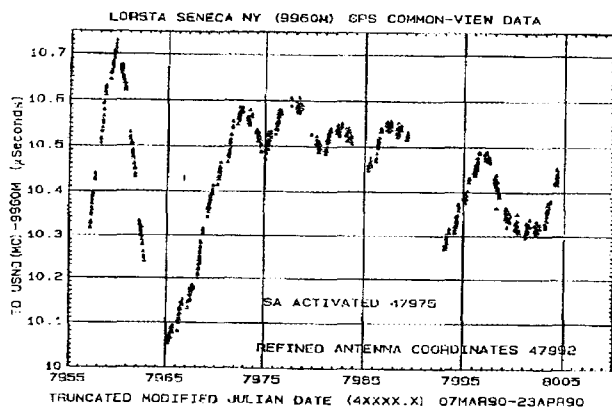


Figure 2 - LORSTA Seneca NY (9960M) GPS Common-View Data

data points were obtained from which the difference between LORSTA Seneca's oscillator and $[UTC_{GPS}]$ could be derived. Figure 1 is a plot of this data and shows a precision of about ± 2 microsecond.

The second, termed the common-view set, was obtained by observing all the block I satellites and one Block II satellite for 47 days. These observations yielded 1092 data points that were used to derive the difference between $[UTC_{USNO, MC}]$ and Seneca's operate oscillator. Figure 2 is a plot of this data and shows a precision of about ± 0.3 microseconds.

These two data sets can be combined to obtain, by

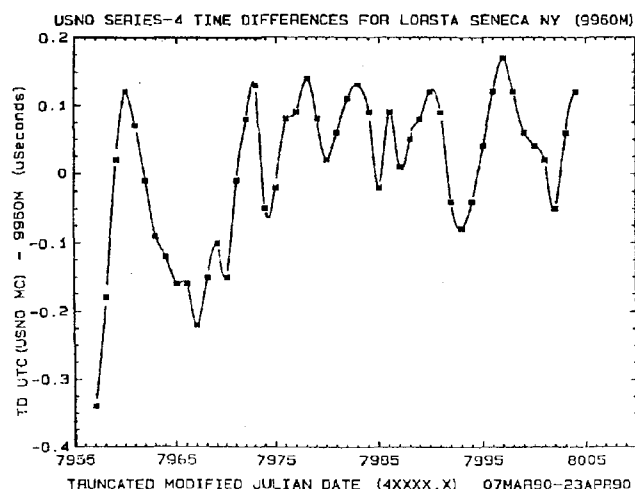


Figure 3 - USNO Series-4 Time Differences for LORSTA Seneca NY (9960M)



Figure 4 - TWSTT Van at LORSTA Seneca

direct subtraction, the time difference between Seneca's oscillator and $[UTC_{USNO, MC}]$. Figure 3 is a direct comparison of USNO series 4 steering data for Seneca and the direct-view results obtained under SA. While the results are promising from the consistency standpoint, the data indicate that direct-view mode may not provide the necessary synchronization.

The original hope was that, even with SA enabled, the loran system could use the GPS satellites to synchronize its stations to within ± 100 ns of $[UTC_{USNO, MC}]$ at an acceptable confidence level.

It must be noted that several factors existed that may have invalidated, or seriously compromised, the conclusion of this effort.

First, the time delay between Seneca's timing sample point at Timer set #2 and the third zero crossing of the first Loran pulse was not calibrated. Second, the antenna coordinates were not determined by a survey. They were obtained by using the GPS receiver in the positioning mode. Third, real-time access to data was not possible, since the USNO series 4 bulletin only provides one averaged point per day. Fourth, the adopted delay used by USNO to model propagation between Seneca and Washington, D.C. may contain enough error to invalidate the results. Last, there were no corrections for seasonal or weather variations in the data.

TWO-WAY SATELLITE TIME TRANSFER

After the techniques discussed above proved unable to attain 100 ns synchronization, the Coast Guard

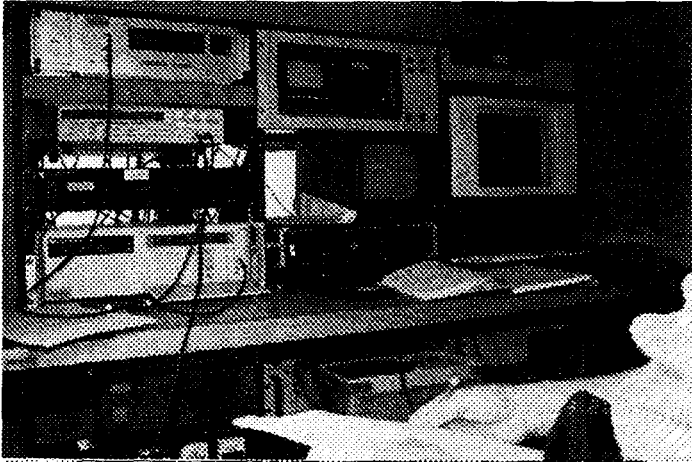


Figure 5 - USNO TWSTT equipment suite

consulted the USNO for an alternate method. The USNO occupies a unique position for understanding the function and requirements for UTC timing of the Loran system, because they have been monitoring Loran chains since 1961[9].

The USNO advised the Coast Guard that the Two-Way Satellite Time Transfer (TWSTT) method would probably guarantee synchronization to the 10 ns level (one sigma) or less. They also stressed that it was the most accurate and precise technology available. They have used it successfully in cooperation with the NIST since 1987 [10] for such transfers.

A TWSTT station was, therefore, established at LORSTA Seneca, and initial measurements using the

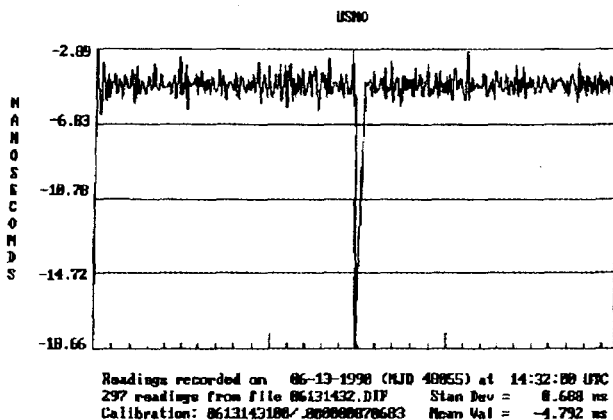


Figure 6 - USNO MC minus 9960M- GPS

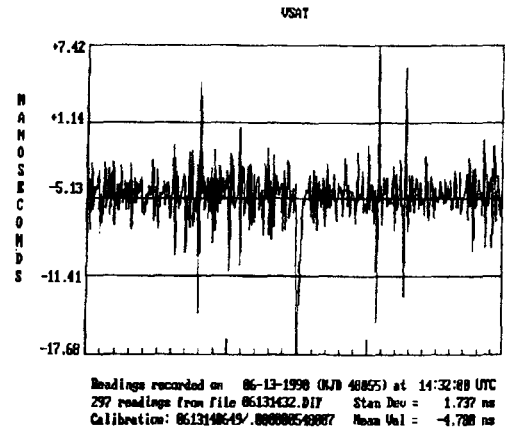


Figure 7 - VSAT readings for (9960M)

USNO TWSTT van [See Figures 4 and 5] were completed in June 1990[11]. Three sets of five-minute time transfers were made between the station and the USNO.

Figures 6 and 7 present the partial results of these measurements. In general, a mean time transfer of from 2-5 ns was attainable with a standard deviation of less than 1 ns.

A primary consideration was whether the TWSTT method might fail to perform properly in the high-intensity RF field of the Loran-C transmitting antenna. However, these data appear to alleviate that concern. The TWSTT van was in the parking lot adjacent to the transmitter building during these trials and functioned properly. This technique can apparently achieve 100 ns synchronization within the intent of Public Law 100-223.

The USCG originally thought that funding would be available to support a TWSTT approach to meeting the legal requirements for synchronization. However, due to budgeting constraints, this technique could not be supported at all master stations, and this necessitated a return to common-view considerations as the only remaining option.

RETURN TO COMMON-VIEW TIME TRANSFER

Theoretical considerations indicate that the common-view time transfer technique should eliminate most of the ephemeris error due to SA[12]. The remaining ionospheric, tropospheric, and receiver electronics errors can be suitably modeled and controlled. The

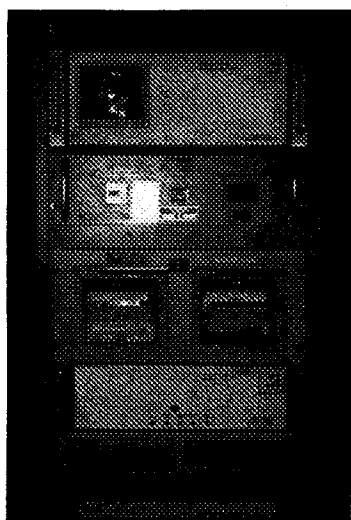


Figure 8 - Common-View equipment suite at LORSTA Seneca New York

final resultant estimate is that the common-view technique can control Loran synchronization to about 10 ns at the one-sigma level.

Based on this assumption, the USCG began work with both NIST and USNO to reevaluate the feasibility of using the common-view method to attain 100 ns synchronization while operating under SA. The first objective was to determine whether the cesium oscillator and the signal from the transmitting antenna could be monitored accurately enough and to verify that they were consistent with each other.

To meet this objective, NIST installed an experimental equipment suite at LORSTA Seneca in December 1992 [See Figure 8]. Figure 9 is a block diagram of this equipment setup. The suite consists of a Allen Osborne TTR-5 GPS receiver and a Allen Osborne TTR-5 microprocessor. An Austron 2000C receiver was connected through a current transformer to monitor the time of transmission (TOT) of the locally transmitted signal and to provide 1 PPS time of coincidence (TOC) to UTC_(USNO).

Starting on January 1, 1993, six months of common-view time transfer data were collected with this test suite. The data were collected in the TTR-5 microprocessor and then downloaded via modem by NIST for analysis. Upon request from USNO, NIST provided the same data to them for separate analysis to derive UTC_(USNO) using their "melting pot" algorithm. NIST also provided the USCG with the raw data so that they could run their own statistical tests as needed.

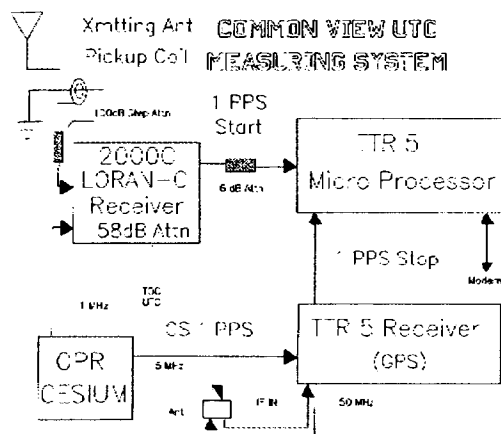


Figure 9 - Block diagram of the Common-View equipment suite

Figure 10 is a plot of the unsmoothed sidereal daily time differences between the Seneca operate cesium oscillator and UTC_(NIST) for January 1, 1993 through January 31, 1993. This figure shows that the Seneca cesium oscillator was offset about 4326 ns from UTC_(NIST) when data collection began and drifted to about 5077 ns difference by the end of January. This represents an average drift of about 24 ns per day during the month. Data for the other five months are omitted since they show the same trend. Table 5 gives a month-by-month summary of frequency drift of the Seneca operate oscillator.

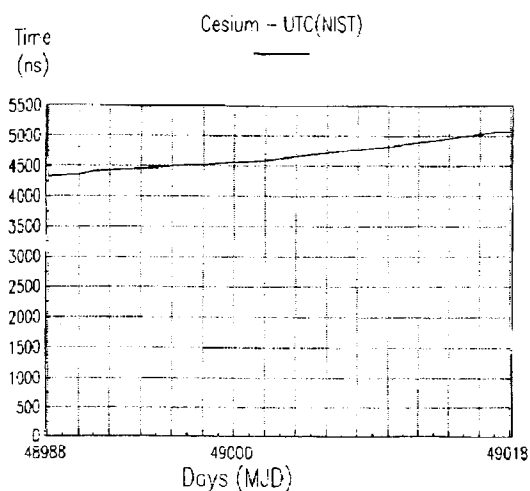


Figure 10 - The offset between the 1PPS from Seneca's Cesium and UTC_(NIST)

Monthly Comparison of the Drift of Seneca's Operate Cesium Oscillator

Month	Original Offset from UTC _(NIST) (ns)	Final Offset from UTC _(NIST) (μS)	Total Monthly Drift (μS)	Average Daily Drift (μS)
Jan	4326	5077	751	24.2
Feb	5095	5727	632	22.6
Mar	5759	6580	821	26.5
Apr	6610	7326	716	23.9
May	7345	8545	1200	38.7
Jun	8551	8740	189	6.3

Table 5 - Monthly Frequency Drift of Seneca's Operate Cesium Oscillator relative to UTC_(NIST)

Figures 11 and 12 show the relative drift of Seneca's signal, as monitored by the current clamp-on transformer on the antenna ground return, relative to UTC_(NIST) February and March 1993 respectively. During the six-month observation period, the station signal deviated from UTC_(NIST) through a range from 38 ns to 2840 ns.

Table 6 gives the correlation coefficient, r , relative to UTC_(NIST), between the signal from Seneca's antenna and Seneca's operate cesium oscillator.

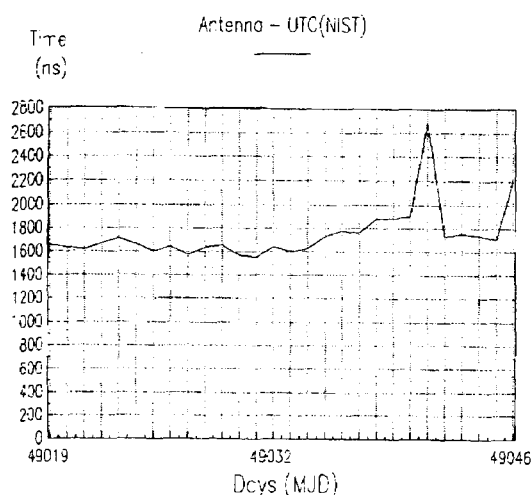


Figure 11 - The offset between the signal from Seneca's antenna and UTC_(NIST) during Feb. 1993

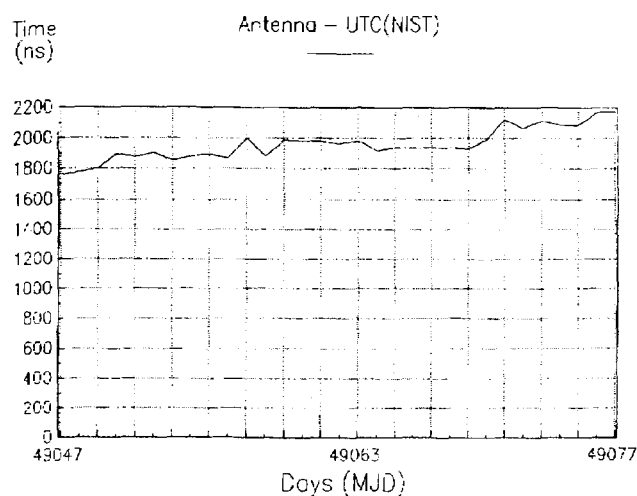


Figure 12 - The offset between the signal from Seneca's antenna and UTC_(NIST) during Mar 1993

The coefficient of determination r^2 , is also given. Although r is more often cited in statistical literature, r^2 is actually more meaningful. It tells the percentage of change in one variable that is actually explained by changes in a related variable.

The least significant of these values, that for January, is still significant at the 0.05 level, while the correlations for the remaining months are all significant at better than the 0.01 level.

These correlation values indicate, but do not prove, that the signal transmitted from the antenna is at least time-related to the cesium signal that ultimately initiates the transmission. Since we know that the two parameters must share a causal relationship, failure to indicate such relatedness would cast doubt on using the common-view technique to achieve synchronization.

CONCLUSION

Initial trial testing indicates that neither the administrative methods nor the direct-view satellite

Correlation Relative to UTC_(NIST) and Seneca's Antenna and Operate Cesium Oscillator

Month	Correlation Coefficient, r	Coefficient of Determination, r ²	Significance Level
Jan	0.411	0.169	>0.05 (0.355)
Feb	0.539	0.291	>0.01 (0.479)
Mar	0.881	0.777	>0.01 (0.456))
Apr	0.867	0.751	>0.01 (0.463)
May	0.754	0.569	>0.01 (0.456)
Jun	0.560	0.314	>0.01 (0.463)

Table 6 - The Correlation relative to UTC_(NIST), between the signal from Seneca's antenna and the output of the Operate Cesium

time transfer method achieved 100 nanosecond (+/- one-sigma) synchronization of Loran-C transmissions to UTC_(USNO).

The Two-Way Satellite Time Transfer method can achieve this synchronization, but it exceeded budgetary levels. Consequently, the only viable option remaining was Common-View Satellite Time Transfer method.

The data from the common-view trial measurements, taken from January 1, 1993 through June 30, 1993 at LORSTA Seneca, New York, seem to show that common-view satellite time transfer technique is capable of accurately monitoring Loran-C signals even in the presence of SA.

For instance, this technique disclosed an average monthly drift of 24 ns of the Seneca operate cesium oscillator relative to UTC_(NIST). It also allowed correlating the Seneca signal from the antenna with the operate cesium oscillator to better than the 0.01 significance level in five of the of the six months of trial data. This was accomplished despite the fact that the USNO simultaneously discovered some anomalies in the transmitted signal.

The next step is to find and eliminate the source(s) of these anomalies and then actually steer the phase microstepper which controls the operate oscillator. This will provide better evidence for whether synchronizing the transmitted signal to within 100 ns of UTC_(USNO) at the 95 percent confidence level or greater is possible using the common-view satellite time transfer method.

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DISCLAIMER

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

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Observations on the Loran-C Environment in Europe.

Dr. Jacqueline P. Bickerstaff.
Consultant. Daventry, England.

Abstract.

The paper presents a selection of data gathered at a number of locations in Europe during Loran-C receiver performance checking. The emphasis is on diagnostic measurements, and the variety, strengths, and variability of interference sources observed in particular, rather than detailed positioning accuracies or set performance comparisons; however some general comments on observed performances are included. Electrically the European Loran environment is proved to justify the description of 'hostile'. In conclusion some 'field derived' minimum requirements are suggested to compare with the industry performance standards, and some general comment offered on the implications for cost-effective receiver designs.

Introduction.

In an ideal Loran world transmitters would send out perfectly shaped pulses, ECD would remain within ± 1 μ S throughout the working area, skywave would not exceed groundwave amplitude, and interference sources would be few, narrowband, and known. In some places reality at least comes close. Figures 1 and 2 show the well defined pulse trains, and a spectrum dominated by Loran for an Asian chain, with solid state transmitters, and little interference.

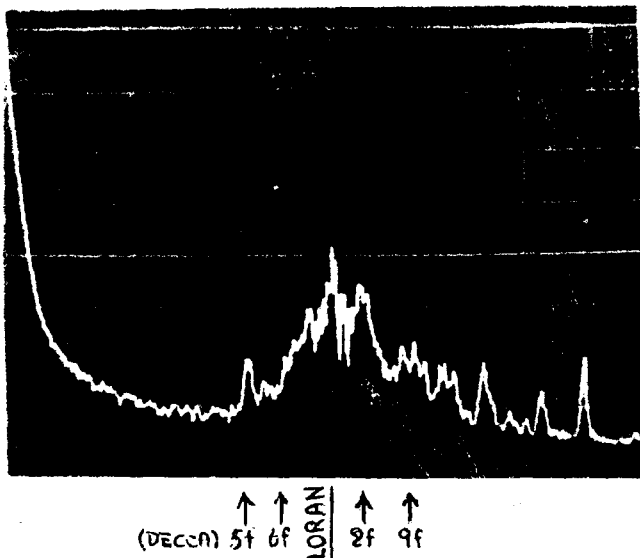


Figure 1. Clear Loran-C spectrum.

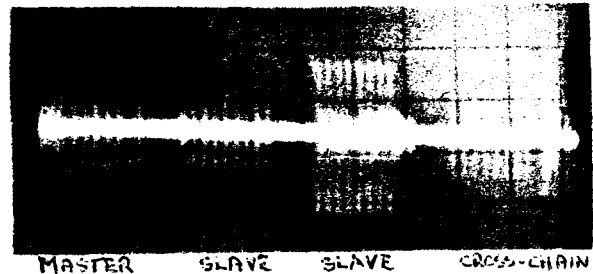


Figure 2. Clear Loran-C pulses.

Unfortunately Europe is not such a place! For example Figure 3 shows a daytime oscilloscope trace of the Loran-C pulse received from Sylt, after bandpass filtering, at a range of less than 100 miles. As the pulse on the lower trace aligns roughly with the 4th cycle the task of 3rd cycle detection can be imagined, and yet by European standards this is a clean signal. The corresponding Master station is approximately 700 miles away.

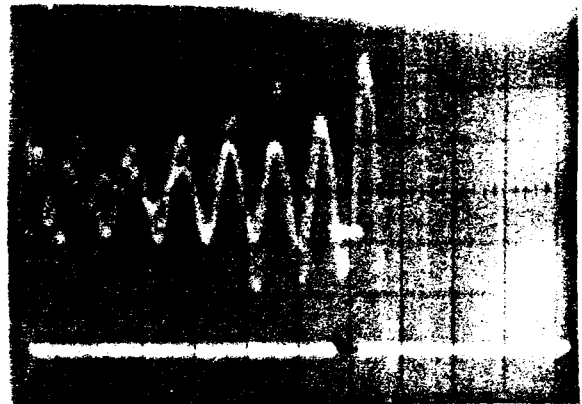


Figure 3. Sylt Loran-C pulse, at 100 miles

At this time NAVSTAR were offering a simple, fixed notch, Loran receiver and it became apparent that such designs suffer problems in the European coverage areas, which prompted my subsequent studies. This may be an appropriate place to apologise for the variety and limited quality of the data, which has had to be collected or copied by whatever means was available at the time.

Great Britain.

For any fixed notch set the objective is to identify the major interferers, and notch them out. Within the U.K. the expectation was that the Decca Navigator transmissions would be major problems (centred on 71, 85, 113, 125 kHz respectively). In practice this was rarely the case. Figure 4 shows a hand-traced spectrum

taken at Daventry. Although only a few miles from the Decca 5f transmitter this signal is 30 dB below the worst interferer! Large 16 and 60 kHz signals are visible, from the nearby Rugby standard frequency transmissions, and also the 198 kHz broadcast radio 4 signal from Droitwich. Land application engineers should be aware that major M1 and M5 motorway routes respectively pass by both of these transmitters, and in fact the A5 trunk road passes through the Rugby 'antenna farm'. Decca transmitters are also easily approached, the 5B Master is just off the A10 trunk road, so land and airborne usages are likely to impose greater stresses on filtering than the traditional marine environment.

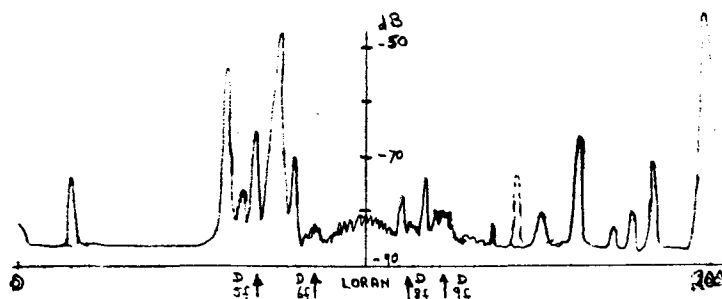


Figure 4. Loran-C band observed in Daventry

Medium wave transmissions, 1 - 2 MHz, were also observed at very high levels and whilst out of the Loran band they impose a significant requirement on the front end rejection required before any amplifying device. The total signal strength reached hundreds of millivolts per metre. Teams from Delft and Bangor Universities have found that spectra taken in Holland and Ireland are equally crowded with interference as evidenced by their published results (references. 1 & 2).

Further north in Scotland useful Loran-C reception is possible but a portable analyser found only those large interferers again, but was unable to resolve any Loran-C (figure 6). At one location there was some discrepancy between different sets on test and the data as to whether a 117 kHz interferer was present or not. What was however observed were very strong 50 and 68 kHz signals. Such inconsistencies have been observed on a number of occasions, leading to the conclusion that in some circumstances antenna front end filtering and linearity is insufficient, leading to the formation of in-band cross products of sufficient amplitude to be significant. For this reason it is considered that signal investigations should ideally cover considerably more than the nominal Loran-C band, up to the MW broadcast band.

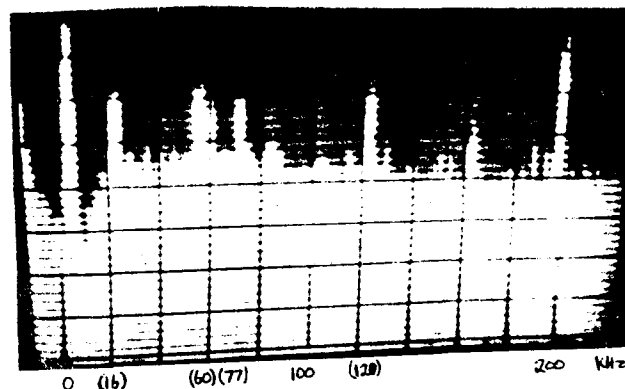


Figure 6. Loran-C band, Scotland

Mediterranean.

In the marine leisure market the Mediterranean Sea is a most major target, although the fall of the Kargaburun tower must impact the Eastern coverage. Many manufacturers have had cause to visit the area, and not always with the same conclusions. In general checks in the Western Mediterranean showed that interference levels are not high, Figures 6 & 7 show measurements taken at Cap d'Agde, France, about 100 miles from the Estartit slave transmitter, whose power is clearly visible with little sign of serious close-in interference nor even very large LF or MW signals.

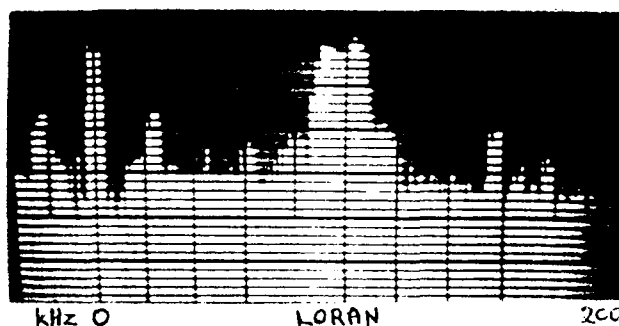


Figure 6. Cap d'Agde, 0 - 200 kHz

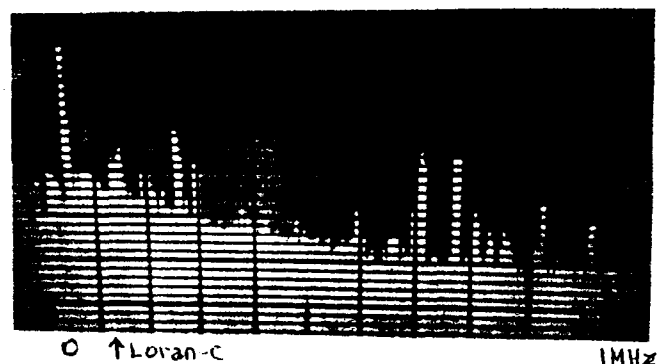


Figure 7. Cap d'Agde, 0 - 1 MHz

So what is the problem? No single problem, but signal strength is certainly a part of it! In the popular Golfe du Lion the Master is some 700 miles away, and these are old stations, listed at less than 200 kW. Thus in that region the local slave signal, shown in Figure 8, is of good quality but the Master is hard to identify at all - Figure 9 taken with higher gain shows what is probably mostly skywave.

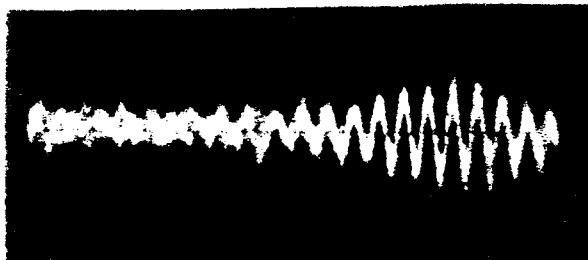


Figure 8. Estartit slave pulse, Golfe du Lion

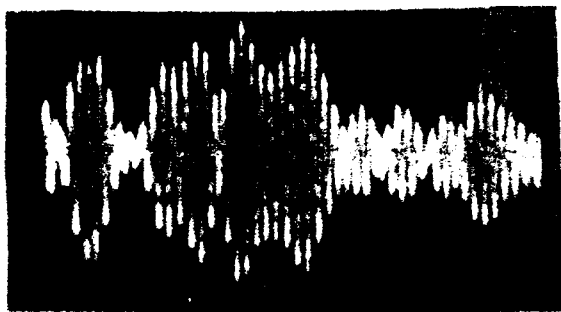


Figure 9. Master pulse, Golfe du Lion

A variety of checks leads the author to believe that 'shadowing' plays a significant part in the signal strengths observed. This can be local, such as is observed in Mallorca where reception is good on the East side, and the most modest receiver will obtain good fixes, but not in the harbour at Palma where the island shadow results in very poor signal strength on the Master, and thus poor performance from all but the best receivers. Equally the author believes that the more distant 'shadowing' effect of Sardinia leads to variations in performance along the French-Spanish coast even though the Master range hardly varies. Close to Estartit users report problems which are accepted as being 'overload' but which investigation showed to be skywave lock on the Master when the groundwave became undetectable. Alternative explanations are possible (local interference, perhaps from the slave equipment, or a reflection). An analysis based on ground conductivity according to the work of Bangor University would be interesting (ref. 3). A GRI trace taken from the vicinity of Estartit is shown in Figure 10 and indicates just how weak the master is. It is overshadowed by 7970 Norwegian chain skywave, and also by the strong 8940 French transmitters which

dominate the spectrum from the Mediterranean to Scotland, and yet which are not generally usable because there are only two and a single-chain triad cannot be made up with them! Figure 11 shows the pulse emitted from Estartit - no 'tailbiter' here! At least one set got into difficulty in the vicinity, with gross errors possibly consistent with locking on to a tail pulse.

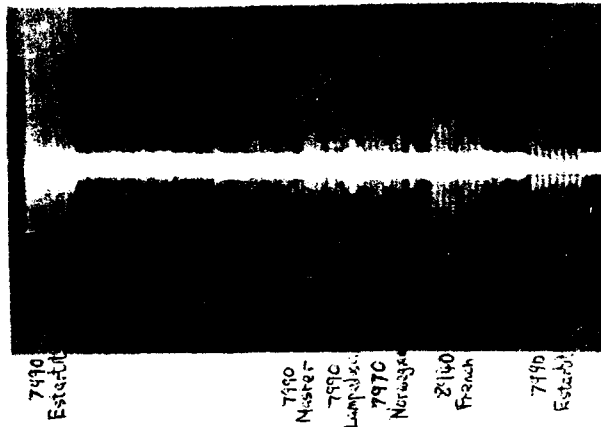


Figure 10. 7990 Mediterranean chain, observed near Estartit

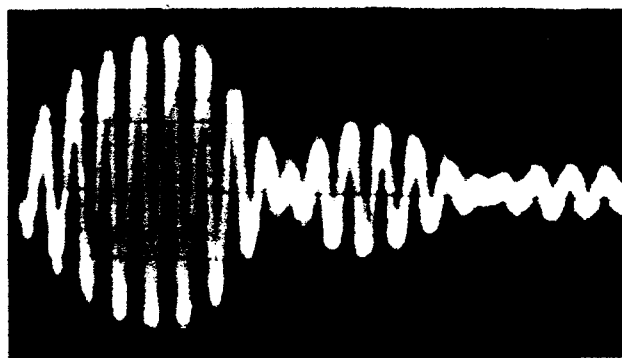


Figure 11. Estartit transmitted pulse

Just as it has been suggested that signal strength is 'shadowed' by the intervening land the author would suggest that ECD is similarly affected. The Golfe du Lion is known to have ECD problems and these were indeed observed. The results remained consistent over a return route and over a number of hours. Once again there are a variety of possible explanations which have been offered. Synchronous interference is one possibility - but such a frequency would have to be very well synchronised with the Loran-C (better than 1 part in 10^9 - achievable by time standard signals). Reflections from the adjacent coastline are another suggestion, this would be time-stable but might be expected to vary rapidly with position. The author therefore proposes a different explanation, arrived at to explain the observation that diagnostic data could not be replicated in a laboratory using any ECD adjustment. Land paths, with their lower conductivities compared

with seawater, significantly affect signal attenuation, but also the propagation speed. Loran-C is a relatively wideband signal format, and therefore potentially the propagation speed variation due to poor conductivity land could vary across the band (indeed a Decca Navigator database is characterised with different speeds for the four frequencies) - in other words the propagation medium is dispersive. Thus not only may there be envelope-to-cycle-deviation, but the envelope shape itself will vary. An ideal receiver will have significant envelope shape tolerance, but an ideal receiver will be wideband and therefore have poor noise and especially interference performance. In practice the author recommends, and it would seem most manufacturers adopt, fairly sharp and narrow filters which seriously compromise the pulse-shape internally. The internal 3rd cycle detector is easily adjusted to suit, but with what effect on pulse-shape tolerance? One effect will be that on the ideal pulse shape all receivers will recognise the same state as zero ECD, but with any deviation they may well no longer agree on zero ECD. Such disagreements have been observed by the USCG after station adjustments or maintenance, when the monitor receiver reports zero ECD but users in the field report serious problems. The author therefore suggests that the time has come to recognise that a single parameter 'ECD' is an inadequate characterisation, and that as a minimum a 2-parameter 'envelope-shift and maximum-slope' characterisation is required to explain and determine detailed performance.

It should not be assumed from the foregoing that interference sources are not a major problem in the Mediterranean region, as this is far from the truth. Installation induced interference was a major problem, which will be dealt with as a separate topic. During night-time significantly higher noise levels were observed, with skywave importing not only more Loran-C, but other sources too. The interference spectrum is thus dynamic, and always likely to outwit a fixed notch receiver. One such interference observed wiped out reception from all the receivers on test at the time, with only the best, variable notch set retaining any signals at all. Reception could be restored if the signal was double-notched out. It is believed that the frequency was 110.7 kHz, although a direct measurement at the time was not possible. Because of the low level of the distant Master and Slave signals even low level interferences can seriously affect performance. One such frequency identified was 93½ kHz. This observation is compatible with interference from a European 625 line 50 Hz television line-scan frequency harmonic: 93.75 kHz. Such interference has been recorded when operating with a TV set nearby (Figure 12), whilst on another occasion an on-board

plotter was found to virtually wipe out Loran-C reception due to its linescan frequency emissions.

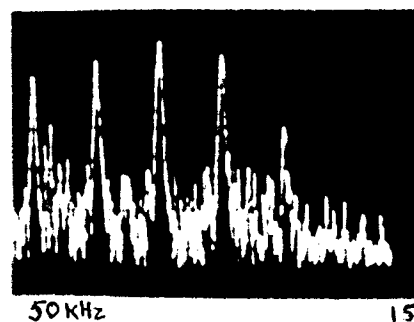


Figure 12. Television line-scan harmonic interference

The proliferation of portable TVs, electronic chart plotters, and PCs is bound to exacerbate this particular situation. The following table lists some potential interference frequencies, but the proliferation of computer screen scan rates and resolutions makes it far from comprehensive

Source	Fundamental freq.	Lower interferer	Upper interferer
U.S. NTSC (525 line 60Hz)	15.75 kHz	78.75 kHz 94.50	110.25 kHz 126.00
European PAL (625 line 50Hz)	15.625	78.125 93.75	109.375 125.00
MAC II	35.00	70.00	105.00
VGA	31.47	94.41	125.88
SVGA	35.16	70.32	105.48
VESA 640 x 480	37.86	75.72	113.58
VESA 800 x 600	48.08	96.16	-
VESA 1024x768	56.48	-	112.96

Table 1. T.V. and VDU interferers.

North Sea.

The oldest coverage diagrams would have one believe that Loran-C could be received across the U.K., Scandinavia, and even to the Baltic. The USCG handbook is more conservative, but still predicts coverage in England down to the author's own home area. Reality says otherwise. The Bangor University model of David Last and his team predict coverage into Scotland, and to the Norwegian West coast (not onto the land) in daylight hours, but under night-time conditions even the Highlands of Scotland are predicted as out of range (reference 3). This accords much more closely with reality. Norwegian mainland tests confirmed that although noise problems were not insuperable the Master reception was dominated by skywave, and groundwave signals were excessively attenuated by the land mass. Once again night and day spectra confirm that interference sources are a dynamic rather than fixed pattern, with skywave importing interference as well as Loran (Figures 13, 14 & 15).

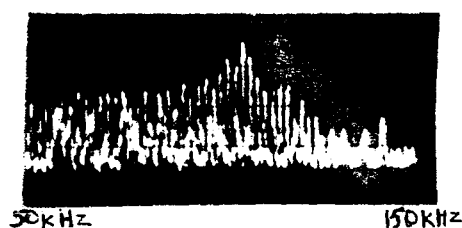


Figure 13. Daytime Loran-C, Norway

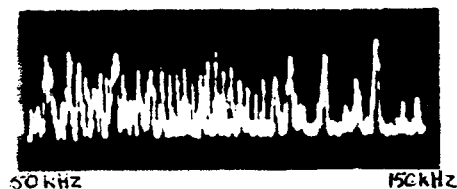


Figure 14. Night-time Loran-C, Norway

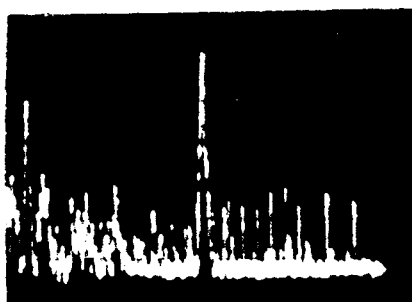


Figure 15. Night-time spectrum, 0 - 500 kHz

Iceland is host to the Sandur transmitter, which is Master for the 9980 Icelandic chain and Slave for the 7970 Norwegian chain. Considering its 'splendid isolation' it suffers a harsh and noisy Loran environment, with a spectrum as shown in figure 16.

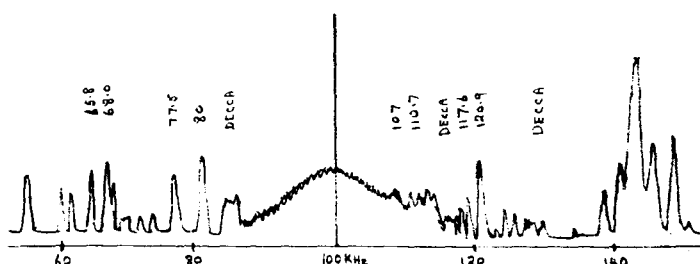


Figure 16. Loran-C and interference in Iceland

Dominating this is a local transmission at 142.25 kHz, sufficiently powerful that its sidebands may require separate attention. An R.F. trace taken after bandpass filtering shows that such a large out-of-band signal can still overwhelm the Loran-C signals (figure 17). It is worth noting that this frequency is outside the range of the variable notches in some receivers. The Angissoq signal, transmitted at reduced power from the spare tower since the fall of the large one, is very weak, not

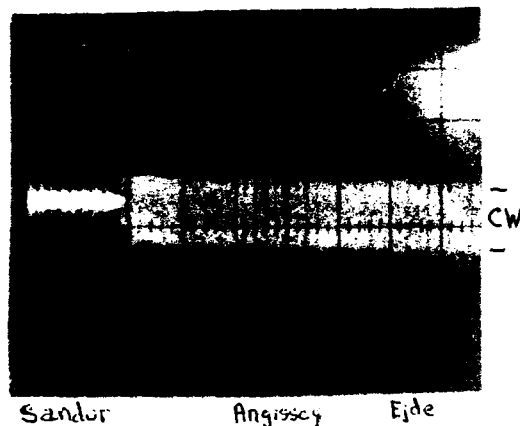


Figure 17. CW breakthrough of 142.25 kHz

only due to the long range but also to the ground in between. There may not be much of it along the propagation path, but what there is is composed of rock and ice which is about as bad as surfaces get. Another problem was detected in this vicinity when position finding using the Norwegian chain. Distinct instability in tracking was observed which correlated with the cross chain interference. 7970 'local' chain pulses and 7990 skywave Mediterranean pulses were observed at similar amplitudes, and with such similar GRIs they will interfere for seconds at a time, comparable with the receiver time-constant. Although the effect was not noticed in the Mediterranean tests the Norwegian signals there were observed at amplitudes above that of the Master Mediterranean station and thus must be presumed to have an equally serious cross-chain interference effect.

Earlier European Loran-C proposals would have left the Icelandic chain unaltered, and this may have coloured the Iclander's decision not to support the revised system, resulting in the later proposals which omit the chain (ref. 4). If so it is a pity, as it overlooks important points such as the work being done to optimise GRIs and reduce cross-chain interference for example. The European decision to adopt Time of Transmission standards also opens the way for multi-chain working, by which the Icelandic region could benefit from the additional Irish transmitter using a receiver capable of tracking two chains. Such techniques have already been used by MLR to extend European coverage with the existing transmitters - but with limited commercial success because of the calibration difficulties associated with unlocked chains.

Installation.

The paper has so far concentrated on the Loran-C environments imposed on users by their locations, but for many users this is not in fact the limiting factor in the Loran-C performance they observe. On EVERY occasion when a sea trial was undertaken noise sources

on board dominated the spectrum. For example the composite figure 18 shows an R.F. response in the Mediterranean, without and with the engine running. As the engine in question was a diesel the owner felt sure it could not be a problem, however even diesels have battery charging systems, which proved to be the main contributor in this case.

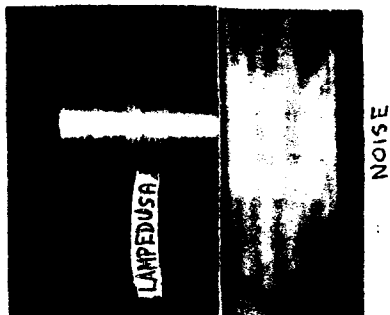


Figure 18. Diesel engine battery charging noise

On another occasion an excess of noise was observed when under sail, but it was still traced to the engine room; the prop-shaft freewheeling and generating static in its waterproof bearings. The resultant noise had a serious effect on a range of both low and medium cost Loran-C receivers, its wideband and variable nature outwitting any filters (note that earthing brush kits can be fitted to prop-shafts to overcome this problem). Such noise sources may have many routes into the receiver. Via the antenna is difficult to protect, and must be left to the installer (e.g. suppressing the noise, screening the source of noise, or maximising physical separation of source and antenna). However the noise may also find routes in through the power connection, or the long coaxial antenna cable and its somewhat indeterminate earth definition. The same problems have been experienced on land mobile installations, particularly when a minimal antenna size is desirable. In the modern world the end user expects a much easier fit-and-forget arrangement. GPS largely delivers this ease of installation so Loran-C design has some way to catch up, most especially if the theme of this Symposium - interoperability - is to be achieved (users will not want two antennas, most especially when one of them is a metre or two in length).

Receiver Design.

Antenna. These are subject to strong out-of-band signals. To prevent non-linear cross products appearing in-band a dynamic range of approximately 1 volt (per metre of antenna intended) is required in the active device, which should be preceded by a bandpass filter. As discussed above, current antenna arrangements do not please users and development to reduce size, and noise sensitivity, is badly needed.

Filters. Narrow bandpass filters are needed in Europe, notwithstanding the serious effect on pulse shape. In view of the observed amplitudes and frequencies of interference no fixed notch set can be widely effective, and in many areas cannot be tuned even to cope with the changing local conditions. The author believes that at least one variable notch either side of the band should be implemented in analogue form, in order to reduce the dynamic range requirements in any systems using A-D and DSP techniques. The popular choice of 6 notches is probably adequate, given the correct tuning algorithms. Interference signal strength may be adequate guide as to which frequencies to notch, although as pointed out by the Bangor team there are other factors to take into consideration - synchronous frequencies being the more serious ones.

Dynamic range. Interference sources and cross-chain pulses may be much larger than the signal of interest, 60-80 dB differential dynamic range should be accommodated by a receiver, with further range by AGC techniques of perhaps 30 dB to accommodate installation or chain variations. The commonly quoted requirement for 10 uV/metre is somewhat unrealistic, rarely if ever will external noise get within 10 dB of this figure.

Cross chain working. Receivers should have the capability of tracking at least two chains, if not more. This permits the traditional (but not very frequently used) Cross-chain working, Time of Transmission Multi-chain working, and a variety of other enhancements (including integration with GNSS systems).

ECD. The increasing power of microprocessor based receivers should permit adaptive ECD compensation, either using modelling predictions, or measured ECD deviations (figure 20 shows a low level signal reconstructed by the software of a simple hard-limiting receiver).

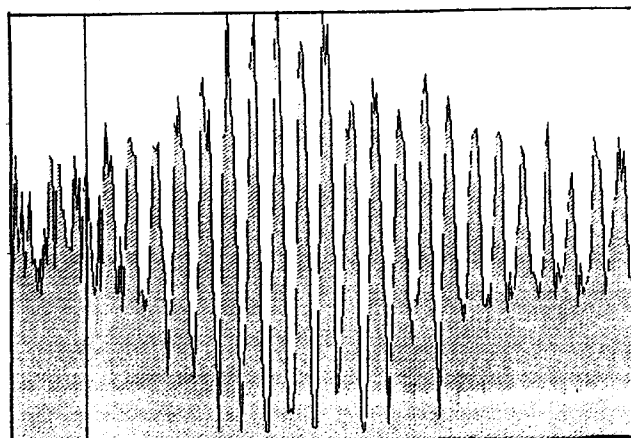


Figure 19. Loran pulse reconstructed in a simple hard-limiter receiver

Conclusions.

Europe has been shown to be a difficult Loran-C environment, very different from the USA as some manufacturers have found out the hard way. In addition to the graphical results a list of interferences is given in Table 2. Estimates of field strength are included, but have been measured very crudely and should not be given undue weight, and the source associations are taken from reference 2 (with acknowledgements to D. Last and N. Ward). This listing alone would justify the description 'hostile'. There is however little that is not amenable to research and engineering development, in chain specification, receiver hardware, and especially in receiver software.

The new North West European plans offer an opportunity for pushing Loran-C technology and application forward, as evidenced by the recent work on modelling, and GRI optimisation for the harsh environment undertaken at Bangor and Delft respectively. However Loran-C is also perceived as 'old technology' deserving of little investment. The two perspectives might be best reconciled by the close integration with the more fashionable GNSS, and GPS in particular. The combination might produce very good technical results, political security, and market acceptance.

Acknowledgement.

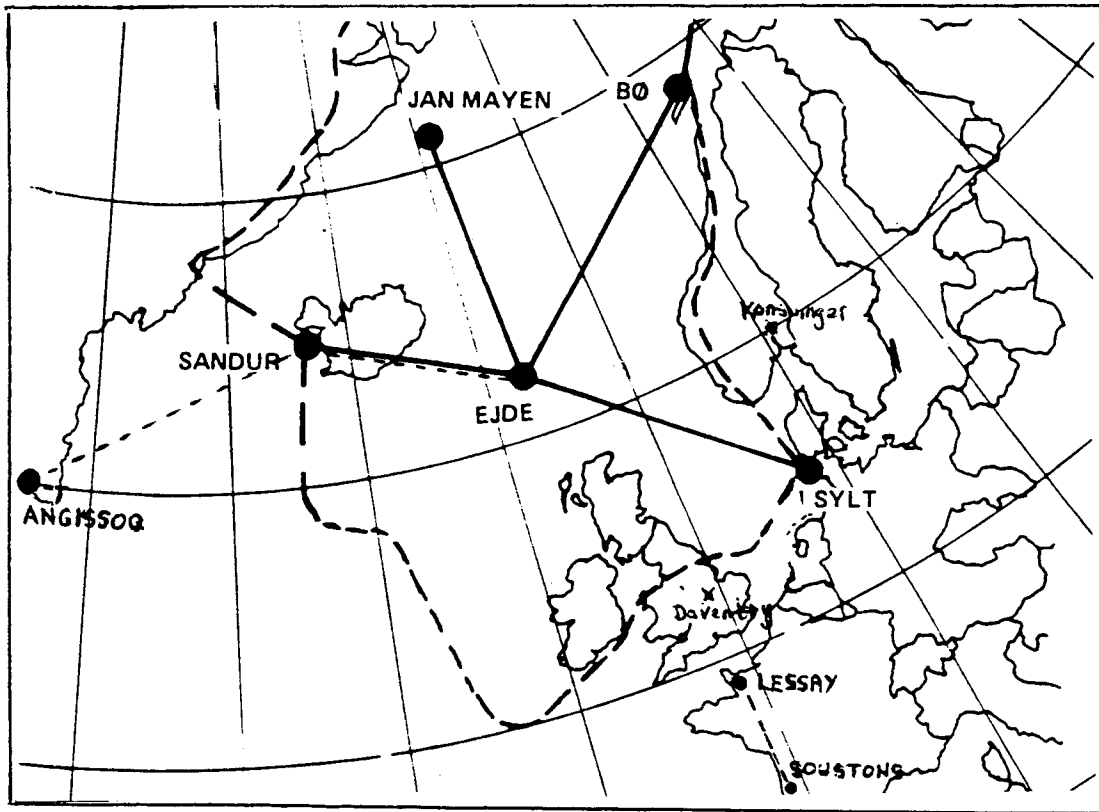
The author wishes to thank NAVSTAR Ltd., of Daventry, England for permission to use material gathered whilst employed by them in the preparation of this presentation.

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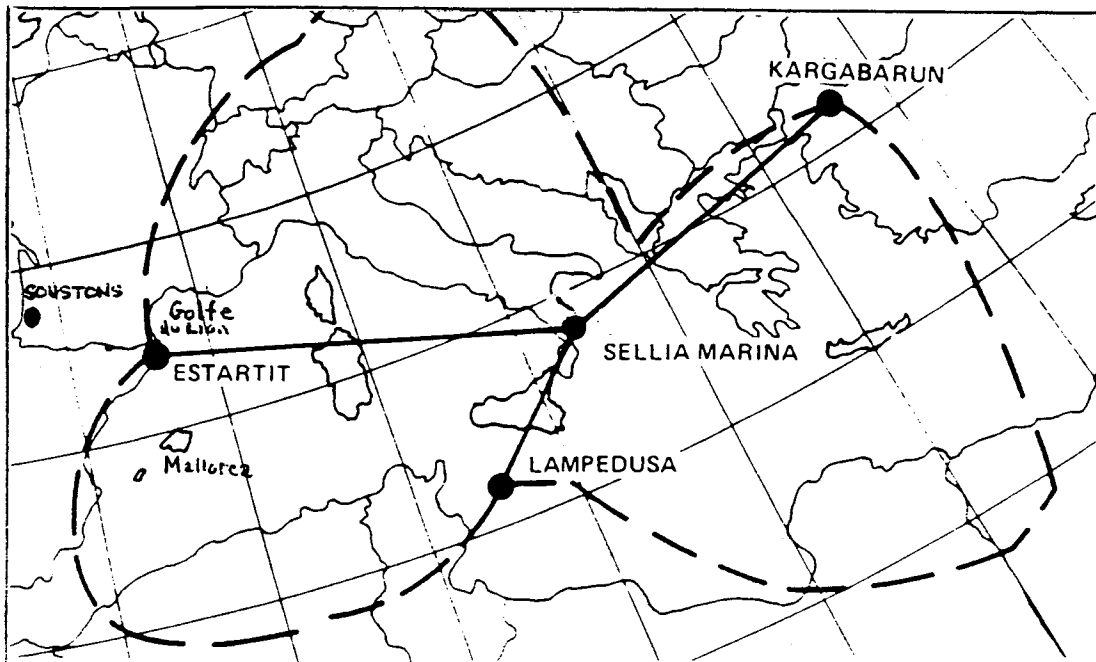
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4. 'The North West European Loran-C System, a New Update', Andreas Stenseth, Proc. WGA 20th Tech. Symposium 1991.

Table 2. Interference frequency listing (with acknowledgements to Bangor, ref. 2)

Frequency kHz	Type	Identity	Med. 1 mV	Med. 2 mV	Scotland mV	England mV
52.0	FSK				5	0.1
53	-				2	
54	-				1	
55.3	FSK	DCF55, Mainflingen, Germany			3	
59	FSK				3	
60	Time	MSF, Rugby	0.5		0.5	150
61	FSK				0.5	
61.8	FSK	GIZ, London	0.2	0.2		
62.6	FSK	FTA, Paris	1.5			
65.8	FSK	Kerlouan, France	0.5	2		3
68.0	FSK			0.2		2
68.9	FSK		0.3	0.3	3	2
70 - 71	CW	DECCA (5f)			1	5
72.5	-					0.5
73.4	FSK		0.2	0.2		1
75.0	Time	HBG, Nyon, Switzerland	0.5	0.5		1
77.5	Time	DCF77 Mainflingen, Germany	0.5	0.5	3	10
78.2	FSK	Crimond, GB			0.3	10
79.5	-					1
81.0	FSK	London	0.2	0.2	1	30
82.8	FSK	GYB, London		0.1	0.3	2
83.6	-					30
84 - 86	CW	DECCA (6f)				5
87.2	FSK	Bonn, Germany				10
91.6	CW					1
93.8	CW	TV linescan	detected			3
96.3	-				1	
97.6	-				1	
-----	-----	LORAN - C	-----	-----	-----	-----
105.3	-				1	
107.6	-					3
110.6	FSK	DCF30, Bad Vibel, Germany			0.2	4
111.3	FSK	SOA211, Warsaw, Poland			0.5	3
112 - 114	CW	DECCA (8f)			0.7	5
115 - 117	CW	DECCA (8.2f)			1	3
117.4	FAX	DCF37, Mainflingen	0.3	0.2		10
118.8	FSK	London			3	30
120.9	FSK	GYA, London	0.2	0.2		10
124.6	FAX	Olumouc, Czechoslovakia		0.1		
125	-		0.2		0.3	
125.8	-		0.3			
126 - 128	CW	DECCA (9f)			0.7	3
129.1	CW		0.2	0.2		5
131	-				0.5	
133.3	-					0.4
134.2	FAX	DCF54, Offenbach, Germany	0.3	0.2	0.5	3
138.0	FSK					1
138.5	CW		0.1			
139.0	FAX	DCF39, Frankfurt, Germany		0.3		0.1
140.3	FSK	DCF60, Frankfurt, Germany		0.1		0.05



**Norwegian chain, 7970, USCG coverage estimate.
(also shown Icelandic chain 9980 and French chain 8940)**



Mediterranean chain, 7990, USCG coverage estimate.

Tracking Strategies for Gollum's Loran-C Receiver

Andre Nieuwland

Delft University of Technology
Faculty of Electrical Engineering
P.O. Box 5031, 2600 GA Delft, The Netherlands
e-mail: koffie@donau.et.tudelft.nl

Abstract

This paper presents a brief overview of the *Gollum* integrated navigation system and the current status of some of the subsystems. This paper discusses in detail the automatic selection of Loran-C chains. Special attention will be paid to how the information available from the GPS (or other) subsystem(s) can be exploited to speedup the signal acquisition of the Loran-C receiver.

1 Introduction

Nowadays, reliability of navigation data is an important issue, especially in critical applications like aircraft navigation. An obvious solution is to combine several independent navigation systems. The respective systems are used to mutually complete insufficient information, hence increasing the total availability. Their redundancy is used to increase the integrity and accuracy of the final position estimation.

The “best” performance is obtained by using *complementary* navigation systems since the error sources for these systems may be regarded as independent. One of the approaches to come to such a system, is the *Gollum* integrated navigation system, described in [1, 2, 3]. The *Gollum* system combines the satellite based US Global Positioning System (GPS), the terrestrial long range systems OMEGA and Loran-C, and the Microwave Landing System (MLS) in a single receiver (see figure 1). This receiver is based on a an application specific processor, which is customized for this specific task [4, 5]. All of the navigation algorithms, and a large part of the signals processing are performed in software. Only those signal processing tasks which are too computationally intensive to run in software are implemented in hardware.

Integration into a single chip (or into a small chip set) increases the physical reliability by decreasing the number

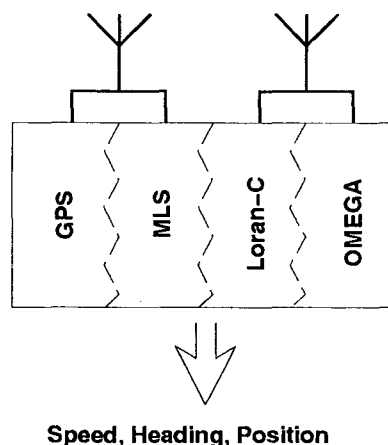


Figure 1: Schematic view of the *Gollum* navigation system

of components involved and by decreasing the amount of external interconnect. The disadvantage however is, that the total system might be more susceptible to common mode errors. Careful design and the use of redundant parts on a reasonable small scale (e.g. power supplies), relieve this problem without increasing the total system size and cost beyond unacceptable limits.

The next section gives a brief overview of the current status of the GPS and Loran-C subsystems, and of the *MOVE* processor which forms the core of the *Gollum* receiver. Section 3 discusses sharing of the available information for automatic selection of Loran-C chains, followed by an explanation of how this information increases the acquisition speed of Loran-C signals. Section 4 discusses the implementation of adaptive filtering techniques in the *Gollum* Loran-C receiver.

2 Current Status

The GPS subsystem, being designed by Eric Aardoom, is heading towards completion. Current activities are directed towards development of software for acquisition and tracking, and the development of GPS specific modules which will be implemented on the *Gollum* chip. One of the pieces of hardware currently being designed is a three level adaptive analog-to-digital (A/D) converter designed. This converter will be implemented on a 1.6μ Sea-of-Gates (SOG) chip (as is the *Gollum* system). To accommodate to the fixed transistor sizes, this design relies on the use of switched current technology [6, 7].

Furthermore, similar generality as exploited in the design of the multi-channel GPS subsystem is used in the design of a GLONASS subsystem [8]. In [8] is explained how GPS and GLONASS signals are down converted with a single RF/IF stage, and how GLONASS channels could be selected using only oscillators with low resolution.

Due to other activities, there is some backlog in the implementation of the Loran-C receiver. The main research items in this direction at this moment are filter design and pulse position estimation techniques.

To prevent this backlog from slowing down the realization of a *Gollum* prototype, it has been decided to keep preamplification, anti-alias filtering and A/D conversion of chip at first. Realization of these functions on a SOG chip moment would require more effort and (human) resources than is available at this very moment.

The samples obtained from the "conventional" front-end and A/D converter will be communicated to the *Gollum* chip by means of a serial data link. On chip, they are converted in to their parallel representation again before further processing takes place.

The nucleus of the *Gollum* system is formed by a powerful *MOVE* processor [5, 9]. A prototype called *Mini-MOVE* has been designed by Paul Stravers. Basic tests on supply voltages, currents and clock signals carried out recently did not reveal any sign of errors. Once the chip is properly packaged, more extensive tests can be carried out. Though the final *MOVE* is should run on 100 MHz, this first prototype is designed for a lower clock speed of 30 MHz to save design time. It uses only standard library cells, which are not optimized for speed an chip area consumption. The layout of this first prototype is not optimized either, since this prototype is primarily intended for testing and checking of the design concept. The prototype provides only the minimum required functionality, viz. 3 separate 16 bit busses, no cache and only a minimum amount of registers (hence its nickname *Mini-MOVE*). Following prototypes will have more registers for variable storage, and will be more optimized with respect to speed and area.

3 Fast initialization of Loran-C receiver

3.1 Sharing information

There are several navigation sources available in the *Gollum* system. Using each source independent of the other is not always very effective. During startup of the system, all subsystems are trying to find an initial position and to estimate the speed and heading. If this information can be provided to a subsystem beforehand, it may use this information to speedup the estimation of the initial fix, e.g. by presetting tracking filters.

Sharing the information of the subsystems already in lock among all the other subsystems, will provide these systems with the initial information they were lacking. Even though the information shared might not be completely accurate, in general it will be better than nothing at all.

Except for low-level support as for acquisition, the same information can be used to support high level decisions like chain selection. E.g. suppose the navigation information is provided by the GPS system solely, or by the GPS/OMEGA combination. Whenever an area with decent Loran-C coverage is entered, one would like to obtain the positioning information from the GPS/Loran-C combination, since this configuration results in a higher accuracy than the GPS/OMEGA combination. The main question is: How does the system know that there is Loran-C coverage, without trying to track all the Group Repetition Intervals (GRI's) in its database? Of course, it is possible to pass this problem on to the user, and request that he/she enters the GRI of the chain to use whenever a Loran-C coverage is entered. However, the *Gollum* system knows its position, and knows the positions and GRI's of all the Loran-C stations. If it has a rudimentary coverage map (or can estimate a coverage area in real time) of each chain as well, than the only thing the receiver should do to decide if there is Loran-C coverage and which stations should be used in that case, is to check if its current position is within the coverage of a certain chain. If the receiver is within such a coverage area, the GRI and desired stations can be selected automatically, without any interference of the user.

Though the system could operate fully autonomous, there must be a capability for the user to determine the mode of operation of *Gollum* system, viz. which combination of systems should be used. Furthermore, he/she should be capable of manually selecting the satellites, OMEGA stations and Loran-C chains to be tracked. This can be accomplished by providing an electronic interface to the user, to set the parameters he/she would like to change. In general however, the user should not be bothered with trivialities like satellite or chain selection if it can be done automatically.

During fully automatic operation, the user must be made aware of any change in the operational mode of the receiver, and must be able to overrule (or prevent) such changes whenever he/she wants to. Though interfacing is a very important topic for automated systems, especially in aviation [10], this subject will not be dealt with in this paper.

Though the Loran-C receiver can operate in multi-chain mode, there might be occasions that only one chain needs to/can be tracked. In such cases, a selection which chain to track has to be made. The optimal choice will be the one with the smallest circle of equivalent error probability (CEP). This does not necessarily need to be the chain with the highest signal-to-noise-ratio (SNR) at the receiver's position. Poor geometry at this position might lead to a larger CEP than would be the case with the chain with a smaller SNR. Since a receiver is aware of the signal to noise ratio, and of the transmitter positions as well, it is able to compute CEP's and select the chain offering the best CEP by itself, without any interference of the user.

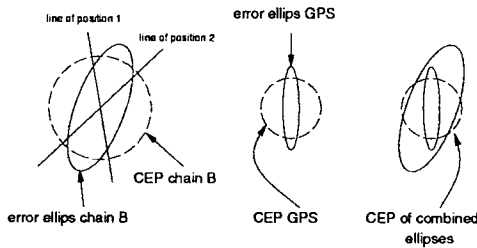


Figure 2: Bad combination of error ellipses

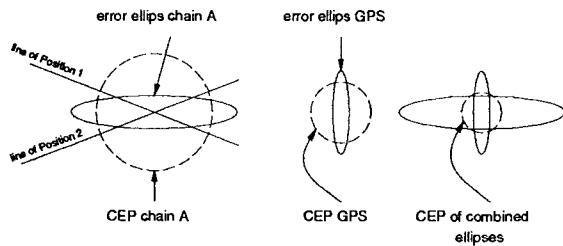


Figure 3: Good combination of error ellipses

In case the system is used in combination with GPS, it is not sufficient to base this decision only on the size of the CEP. The optimal chain for this combination is the one leading to the smallest overall error. The selection of the Loran-C chain now depends on the shape of the distribution of GPS position estimations, thus on the geometry of the GPS constellation. If position estimations of both systems result in an ellipse-shaped uncertainty area (see figures 2 and 3, then the optimal combination is the one in which the CEP of the intersection of the ellipses (not the combined CEP's) is the smallest.

3.2 Fast pulse detection

Once the system is locked on GPS and has a notion of position, the expected time differences (TD's) between Loran-C stations can be calculated beforehand. Therefore, the receiver can limit the search for master and secondary signals to small time frames spaced one expected TD apart. Whenever the pulses of one station is found, the signals of the other stations can be located easily in their respective time frames (see also figure 4).

Loran-C signals of the master station are synchronized within $\pm 5\mu s$ of universal time coordinated (UTC) [11]. Because GPS is synchronized to UTC as well, knowing an initial position and the GPS time allows the estimation of the actual time of arrival (TOA) of the Loran-C signal beforehand. Therefore, the search window can be reduced to small, fixed time frames at the estimated TOA's, providing much faster acquisition of Loran-C signals than a 'blind' search.

When the receiver is trying to lock on a specific GRI it is continuously sampling and searching for a set of samples that match the phase coding of the master/secondary signals. It will be clear that during this search process the amount of samples to be processed should be kept to a minimum, viz. the sample rate should be high enough to provide sufficient information but not much higher. The maximum useful sample rate is determined by the correlation between the samples caused by the band filter.

Whenever white Gaussian noise is filtered, the correlation between successive noise samples will increase when the time between the samples is decreasing. To estimate the time over which the correlation of the noise extends, one can regard the rise time of a filter. This is the time a filter needs to rise from 10% to 90% of its final value. If a noise spike is applied to a filter, it will take about the rise time of the filter before the output of the filter is returned to its original value. The rise time for a first order low-pass filter is given by formula 1 [12]. In our case, the input signal is band filtered with a 128 taps finite impulse response (FIR) filter of about 20 kHz width, thus B should be equal to 10 kHz.

$$T_{step} = \frac{0.35}{B} \quad (1)$$

In practice, the rise time will be slightly larger than the $35\mu s$ found with formula 1, because a high order band filter is used instead of a first order low-pass filter.

Since the correlation extends over a time span of $35\mu s$, there is no real need to sample at a rate much higher than once every $35\mu s$ (28.6 kHz).

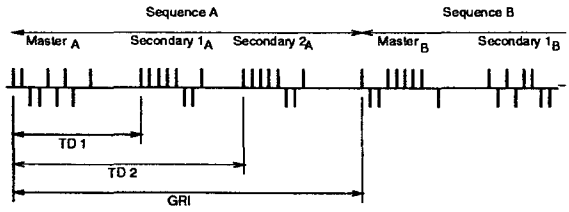


Figure 4: Spacing and phase-code of Loran-C pulses

Because the signal is sampled directly without prior down conversion, it is possible that the samples just coincide with the zero crossings of the incoming signal. To prevent this, samples are taken spaced $2.5\mu\text{s}$ apart. Since the input sample rate of the band filter is 400 kHz, these samples are obtained by computing the filtered output samples for two successive input samples. The lower sampling rate is obtained by decimating the output of the filter, viz. calculating the output samples on a lower rate than the input rate.

It will be useful when the sample rate produces samples at exactly 1 ms distance, since Loran-C pulses are spaced 1 ms apart. Sampling on multiples of 1 ms means that the sample rate must be an exact multiple of 1 kHz. For easy decimation, the final rate must also be integer factor of the input rate. Considering this, the sample rate could be either 40 kHz or 25 kHz, thus decimated by a factor of 10 and 16 respectively. The 25 kHz sample rate is chosen because it is the lowest rate and produces two samples every $40\mu\text{s}$. Taking into account that the second sample is taken $2.5\mu\text{s}$ later, the maximum distance between samples is only $37.5\mu\text{s}$, which is fairly close to the correlation time of $35\mu\text{s}$.

When sampling at 25 kHz, the data rate is 50 samples per millisecond. Because the correlation with the phase code is applied on a complete pulse group, at least 8 ms of data (400 samples) need to be stored. For efficiency, these samples are stored cyclicly (modulo 400) in the main memory. Every time a new pair of samples is taken, a new correlation value need to be determined. This "correlation" exists of an addition of the samples after multiplication with the four distinct phase codes: *Master_A*, *Master_B*, *secondary_A* and *secondary_B* (see figure 4).

Whenever the correlation value exceeds a positive (negative) threshold, a match with an in-phase (opposite phase) pulse group occurred. The match with pulse groups having opposite phase indicate a $5\mu\text{s}$ shift relative to the carrier. Note that the thresholds depend on the imbalance of the phase code, and on the noise level (see figure 4). E.g. the phase code of *secondary_B* is balanced, hence the thresholds lie symmetrically around zero, (un-

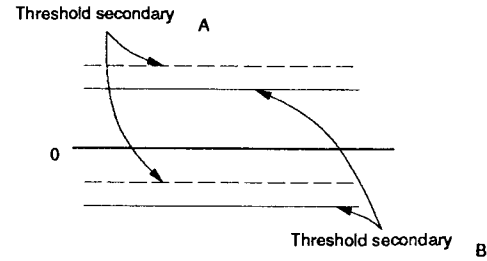


Figure 5: Correlation thresholds for *secondary_A* and *secondary_B*

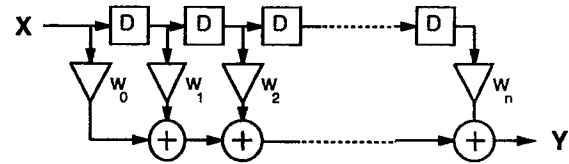


Figure 6: Direct form FIR filter

der the condition of no DC-offset). The phase code of *secondary_A* however, has an imbalance of 4 pulses, thus the threshold should have an offset with respect to zero to obtain the same detection reliability (see figure 5).

The obtained correlation curve can be integrated over multiples of 2 GRI whenever the noise level is too high for immediate detection of the Loran-C pulses. This implementation requires only 7 samples to be retrieved from memory and 4 values to be stored each time a correlation need to be performed.

4 Adaptive filtering

Adaptive filtering has the advantage of providing an optimum bandwidth with respect to signal-to-noise-ratio (SNR) and/or signal-to-interference-ratio (SIR) under varying conditions. The bandwidth of the filter decreases by increasing noise levels, and the bandwidth can be increased with decreasing noise levels.

In general, dynamically adjusting the bandwidth of analog filters is a complicated thing to do. One needs to take care of all kind of problems like instability, component drift etc. Secondly, changing the bandwidth of an analog filter will change the group delay of the filter, which causes a virtual shift in the arrival time of the Loran-C pulses. Tracking loops (and algorithms) should be able to cope with these changes, without losing lock.

Using a (digital) FIR filter (see figure 6), implemented in software allows simple bandwidth changes by modifica-

tion of filter coefficients. First of all, the filter coefficients will not suffer from component drift. Secondly, due to the direct form (no feedback), the filter is inherently stable. Furthermore, the delay remains fixed when the filter coefficients are changed.

Since the bandwidth of the FIR filter is known exactly, a prediction can be made of the straightening of the leading slope of the Loran-C pulse due to loss of frequency components. The increase in sensitivity for cycle-slip errors can be related to the probability of cycle-slips due to the poor SNR, to determine the optimum bandwidth of the FIR filter.

5 Conclusions

As has been discussed in this paper, sharing information among the navigation subsystems in an integrated environment is advantageous. It accelerates the initial signal acquisition, by decreasing the search-window, and it improves the speed of the first position fix by pre-setting (filter) coefficients for a reasonable estimation of initial position, heading and speed. This is especially useful in the combination GPS/Loran-C, since both systems are closely related to universal time coordinated (UTC). The same property however holds for combinations with OMEGA, though the dependency on propagation conditions over large distances introduce a larger uncertainty in the estimates.

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Biography

André Nieuwland received the Ingenieur (M.Sc.) degree in Electrical Engineering from Delft University of Technology, the Netherlands, in 1991. January 1992, he started a Ph.D. study at the same university. His research is mainly focussed on signal processing and low-frequency radionavigation systems, especially Loran-C. He is a member of the Electronic Engineering Group, where he is involved in the design of the Loran-C and Omega subsystems for the Gollum integrated navigation receiver.

Furthermore, he was actively involved in GRI-calculations for the new North-West European Loran-C chains as well as the Canadian East Coast Newfoundland Chain.

Currently, he is at the University of California, Berkeley, to research the use of formal verification in the design of the Gollum integrated navigation receiver.

Eurofix and the effect of Cross Rate Interference

*Lambert J. Beekhuis and Hein J. Andersen
Delft University of Technology*

Abstract

The proposed Eurofix system is a combination of Differential Global Positioning System (DGPS) and Loran-C, in which the DGPS information is transmitted by additional phase modulation of the Loran-C signal. Due to the availability of so many Loran-C transmitting stations in the US and Europe, the entire CONUS and Western Europe are within a 600 km range from a Loran-C transmitting station. Since the introduced Loran-C data link has a limited capacity of only 10-30 bps, an efficient DGPS technique is required to prevent temporal decorrelation. Fully asynchronous DGPS reduces the DGPS degradation due to the limited data capacity. The required high-quality time-reference for fully asynchronous DGPS is derived from the atomic references available in all Loran-C stations.

To use the Eurofix system, Loran-C receivers should be modified by sampling the signal at 50 μ s after the normal range tracking position. With the restriction of a maximum distance of 600 km, this close-to-the-peak sampling (high SNR) results in low susceptibility to continuous wave- and cross rate interference. Cross rate is expected to be the main limitation for the Eurofix data link. An analytical model is derived and measurements are performed to determine the Eurofix data link performance under cross rate interference. The Eurofix receiver DGPS output data is formatted according to the RTCM SC-104 standard. Finally, we emphasize the fact that the final zero-baseline DGPS performance is expected to meet the FRP-92 requirements for harbour approaches.

1 - Introduction

The Global Positioning System (GPS) offers positioning accuracies of 100 m. Many applications, like marine harbour approaches, require greater positioning accuracies. Differential GPS can improve the positioning accuracy to 2-10 meters. Currently, the US Coast Guard (USCG) is expanding the network of DGPS reference stations (64) employing radio beacon direction finders for transmission of differential corrections [1]. In this way, the US coastal areas are

covered with DGPS service.

In the concept of Eurofix, DGPS correction messages are transmitted to the users by additional phase modulation of the Loran-C signals. This modulation is simple and was, although for other purposes, already extensively tested by the USCG [2]. Besides the low costs due to using the existing infrastructure, Eurofix has two other main advantages [3, 10]:

1. Large coverage area: With a data link range of up to 600 km, almost the entire CONUS and Western Europe may be covered with DGPS data for improved accuracy and ground based integrity (fig. 1 and 2).
2. Improved continuity of service: Two completely dissimilar radio navigation system, like Loran-C and DGPS, improves the continuity of service.

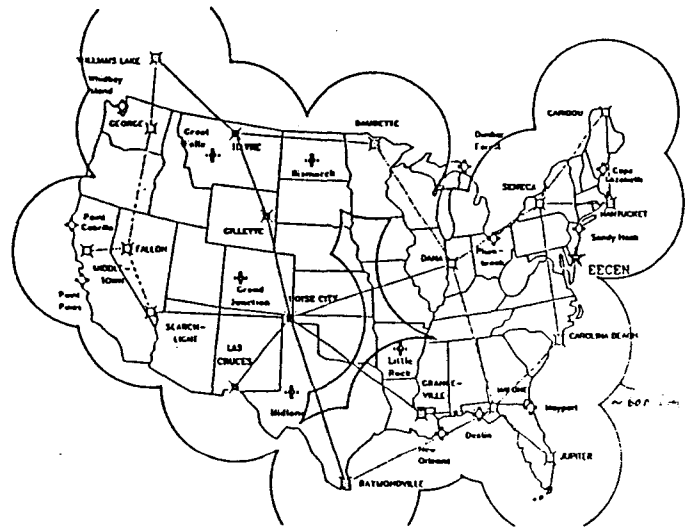


Figure 1. Estimated Eurofix DGPS coverage of US for a data link range of 600 km.

At the user's side, a simple modified Loran-C receiver provides DGPS corrections as well as Loran-C range tracking measurements. The DGPS corrections can be used in three different ways.

1. The Loran-C receiver only provides DGPS corrections, which are used by standard-type DGPS receivers to obtain accurate positions.
2. Loran-C and DGPS raw data are applied in a hybridized position solving algorithm.

3. DGPS position fixes continuously calibrate the unmodeled Loran-C propagation delays. In case of GPS outage or jamming, the Eurofix receiver continues with most current DGPS calibrated Loran-C [3].

Option 1) implicates the capability for low-cost (hard limiting) Loran-C receivers to demodulate and decode the DGPS correction data.

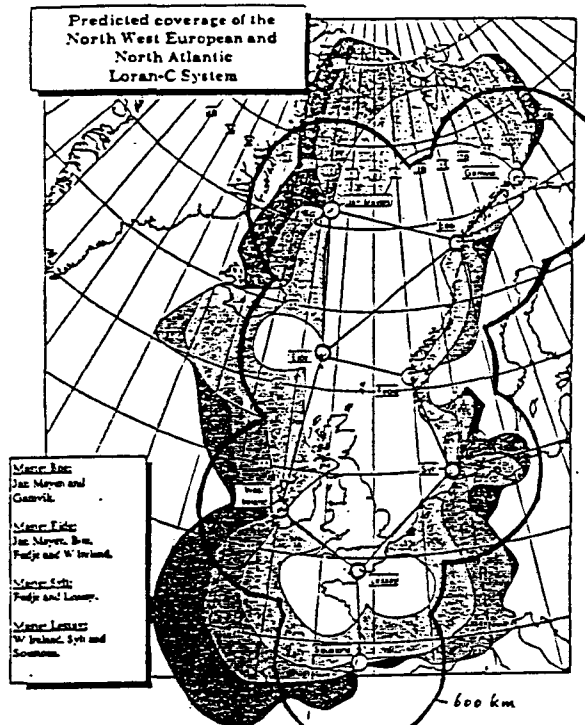


Figure 2. Estimated Eurofix DGPS coverage of Western Europe for a data link range of 600 km.

Section 2 of this paper covers the additional phase modulation of the Loran-C signal and its effect regular use of Loran-C. Section 3 treats the principle of fully asynchronous DGPS which is used to counteract degradation due to the low data rates of the Loran-C link. The demodulation in the Eurofix receiver should be simple to make wide-spread use of Eurofix feasible and to keep the production costs low. Section 4 deals with the demodulation using hard limiting receivers. Finally, Section 5 covers the effect of cross rate interference on the performance of the data demodulation using hard-limiting receivers.

2 - Eurofix data link: Loran-C phase modulation

The Eurofix DGPS data is transmitted by time-shifting the Loran-C bursts, both the 100 kHz carrier and envelope, by approximately 1 μ s (fig. 3). Only the

last six of a group of eight Loran-C bursts are modulated, as the first two are used for blinking. Furthermore, some 25% of the bursts should not be modulated to prevent bang-bang effects in hard-limiter type Loran-C receivers under high-SNR conditions. The additional Loran-C modulation (on top of the already existing phase modulation) is not harmful to the range tracking as long as the lowest modulation frequencies are higher than the tracking loop bandwidth. Moreover, the number of phase advances and delays must be equal to avoid a bias in the tracking loop. Both requirements are fulfilled by balancing the modulation pattern over 1 or 2 Group Repetition Intervals (GRI).

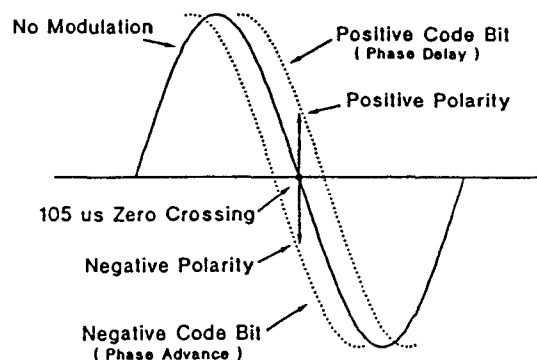


Figure 3. Eurofix additional phase modulation for data transmission.

The balanced modulation introduces a small bias which is counteracted by a slightly asymmetrical modulation for the phase advance and delay. Due to the phase modulation, conventional Loran-C receivers may notice a SNR-reduction of 1.3 dB. However, new designed Loran-C receivers, might reduce this SNR loss.

In the first proposals of Eurofix [3], a coding rate (CR) of 1/6 was proposed: 6 modulated burst represent one data bit. The data rate is increased by using a CR of 1/4 or 1/2 (Odd CR's are unbalanced and therefore excluded). However, this will result in higher data bit error rates. The Loran-C data rate R depends on the coding rate and the GRI,

$$R = 6 \cdot CR / GRI \quad (1)$$

The GRI may range from 40 to 100 ms. For GRI=100 ms, the data rate is 10, 15 or 30 bps for a CR of 1/6, 1/4 and 1/2 respectively. To obtain accurate

positioning for these low data rates, an efficient DGPS technique is required.

3 - DGPS in Eurofix

Besides the DGPS receiver dependent errors like receiver noise and multipath, the final DGPS accuracy of Eurofix is mainly limited by two mechanisms:

1. Spatial decorrelation: the distance to the reference station introduces a degradation of the final DGPS accuracy. For distances of up to 600 km this spatial decorrelation will limit the maximum accuracy to approximately 4-6 meters [4]. However, the user can model for the ionospheric- and tropospheric differences between the reference station and user receiver which reduces the spatial decorrelation by about 50% [5].
2. Temporal decorrelation: The low data rate of Eurofix DGPS, as compared to the 50 to 200 bps suggested by the Special Committee no. 104 of the Radio Technical Commission for Maritime Services (RTCM SC-104), results in significantly longer transmission delays of the DGPS correction messages.

For Eurofix it is not required to broadcast the DGPS corrections in the RTCM SC-104 data format. As long as the transmitted Eurofix messages are convertible to the standard SC-104 format, full compatibility with existing DGPS receivers will be maintained. The required performance of 8 to 20 meters for harbour approaches [6] can be met using a fully asynchronous data format.

3.1 - Comparison of three DGPS data formats

To illustrate the effect of temporal decorrelation as function of the data format, the physics of temporal pseudorange error growth is shortly reminded.

The error on the pseudorange correction grows with its age. The rms error growth is modeled as:

$$\sigma(t) = k + \frac{1}{2}at^2 \quad (2)$$

Where a is the acceleration of the Selective Availability ($a=3.7 \text{ mm/s}^2$ [8]), t is the age of the correction and k accounts for noise floor of the receiver. With current receiver technology the measurement noise is reduced below decimeter level. Multipath can be reduced by proper antenna placement and by use of receivers with anti-multipath properties. For the analysis in this paper we assume

$k=0.5 \text{ m}$ and $a=4\text{mm/s}^2$. Pseudorange corrections are used on a certain interval of application. The average error (rms) on the interval of application $[t_1 \ t_2]$ is given by:

$$\overline{\sigma(t)} = \sqrt{\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} \sigma^2(t) dt} \quad (3)$$

Three data format approaches are compared for possible application with low data rates of 15 bps [10] (CR=1/4, GRI=100 ms):

1. RTCM Type 1.
2. RTCM Type 9.
3. Fully asynchronous.

1) A RTCM Type 1 message [7] contains pseudorange corrections of all satellites in view of the reference station. The long messages result in large message transfer times (MTT) when applying low data rates. Therefore, the final DGPS accuracy is low. Figure 4 shows the principle of RTCM Type 1 messaging.

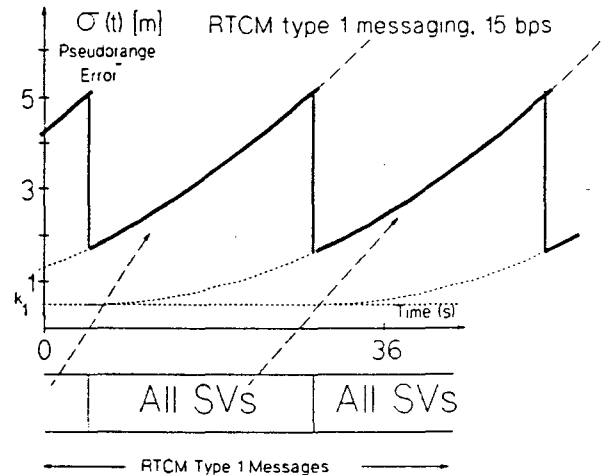


Figure 4. Illustration of RTCM type 1 messaging for a data rate of 15 bps (6 SVs)

2) The MTT is reduced when applying RTCM Type 9 messaging according to the US Coast Guard Broadcast Standard [13, 9]. Each Type 9 message will carry no more than three satellite corrections. If the total number of satellites is not divisible by three, an additional Type 9 message with one or two corrections will be transmitted. The reduced message length results in an improved accuracy in case of low data rates.

3) Fully asynchronous DGPS provides best

Data Types	RTCM Type 9 bits/SV	(Preliminary) Eurofix bits/SV	Comment
Preamble	8	-	Frame sync by parity bits [11]
Message type	6	2	Up to 4 Different messages
Station ID	10	-	Loran-C GRI & phase code
Modified Z-count	13	10	One-hour range, 3.6 sec resolution
Sequence #	3	-	Sequential frame sync by GRI
Length of frame	5	-	Fixed length
Station health	3	-	Replaced by UDRE
Scale factor	1	1	
UDRE	2	1	Station/SV health per SV
Satellite ID	5	5	32 SV's
PRC	16	14	Pseudorange correction
DRC	8	8	Range-rate correction
IOD	8	8	Issue Of Data
Fill bits	18	-	
Parity	24	12	25% of parity bits
Total # of bits	120	61	

Table I. Length of single-SV RTCM Type 9 and (preliminary) Eurofix Data Format

performance for low data rates [10]. Every satellite correction is transmitted in a single compressed message (fig. 5). Table I shows an example of the compressed data format for Eurofix, a 50%-reduction compared to single-SV Type 9 messaging. For fully asynchronous DGPS required high-stability time references are derived from the already available Loran-C atomic references.

Messaging Type	Interval of Application	Calculated 95%-accuracy (HDOP 1.5)	Measurement (HDOP 1.3)
RTCM Type 1	[34s 68s]	18 m	11.49 m
RTCM Type 9	[14s 56s]	10.8 m	7.76 m
Fully Asynchronous	[4s 40s]	5.8 m	3.94 m (smart 2.44 m)

Table II. Zero base line DGPS accuracies as calculated and measured for 9 SV's using different data formats at a data rate of 15 bps and no transmission errors

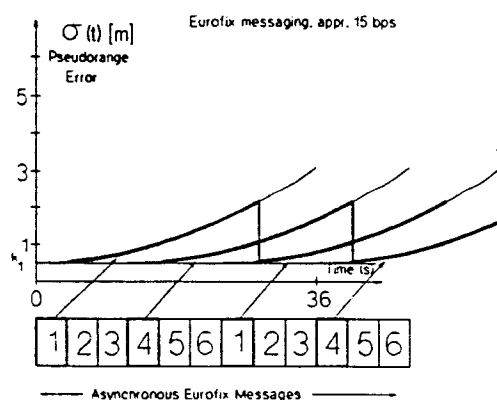


Figure 5. Fully Asynchronous Messaging, 1 satellite correction per 4s (15 bps, 6 SV's).

3.2 - Measurements result

A one hour GPS data set was used to test the various data formats for different data rates. The data set was collected on August 18th 1993 from 10.00 to 11.00 UTC using two Magnavox MX4200D receivers

connected to the same antenna (zero base line). These receivers can not track more than 6 SV's simultaneously. To simulate 9 satellites in view, 3 'dummy' satellites were added. For this data set, only Block II and IIA satellites (containing SA) were tracked. The average HDOP was 1.3 and least square methods were used to compute the final DGPS positions.

Figure 6 shows the zero baseline accuracy for the three message formats at a data rate of 15 bps. The fourth scatterplot of figure 6 shows the performance using Smart DGPS [12, 10]. In Smart DGPS, satellite are not corrected in a fixed order. However, satellites are corrected in an order that gives optimal performance. Figure 7 shows the performance when applying a 1/2 CR and additional parity bits to the message for error correction. For all measurements, no data transmission errors were taken into account.

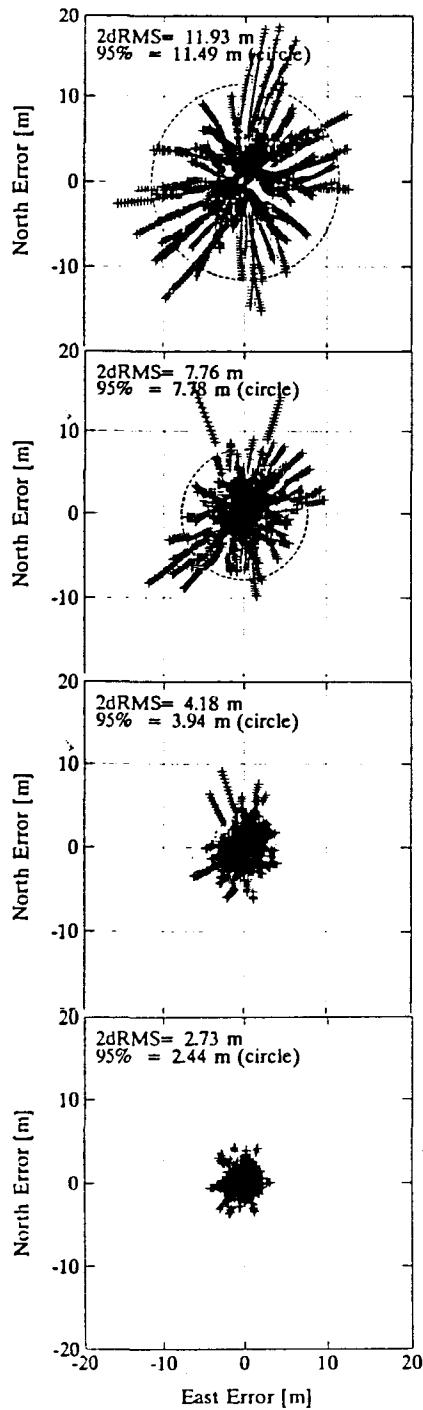


Figure 6. Zero base-line DGPS accuracies for a data rate of 15 bps ($GRI=100$ ms, $CR=1/4$) on the one hour data set (9 SVs, $HDOP=1.3$).

- 1) RTCM Type 1,
- 2) RTCM Type 9,
- 3) Fully asynchronous DGPS ($MTT=4s$),
- 4) Fully asynchronous with Smart DGPS.

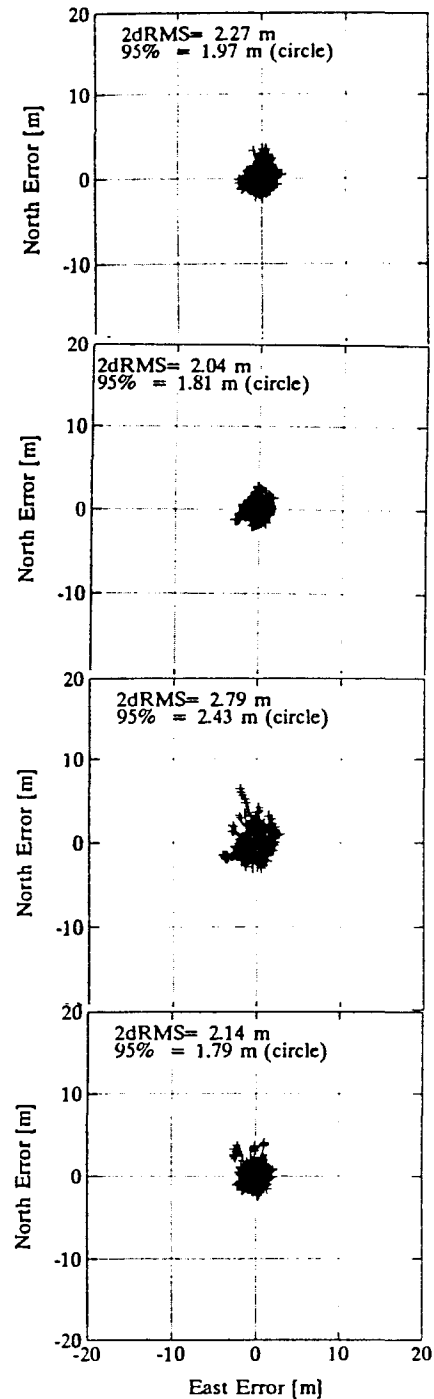


Figure 7. Zero base line DGPS accuracies for the one hour data sets

- 1) RTCM Type 1, 50 bps.
- 2) Fully Asynchronous DGPS 30 bps ($CR=1/2$, $MTT=2s$).
- 3) Fully asynchronous DGPS with increased message length for error correction (93 bits, $MTT=3s$).
- 4) idem, with Smart DGPS

3.3 - Impact of Data Transmission Errors on DGPS accuracy

Without forward error correcting codes (FEC), a data bit error destroys DGPS corrections in a message. More specifically, the probability of message success p is:

$$p = e^{-\alpha M} \quad (4)$$

where α is the (random) bit error probability and M represents the message length. For shorter messages, like fully asynchronous DGPS, the probability of message success is higher. Moreover, fewer pseudorange corrections are destroyed in case of a data transmission error. Therefore, applying shorter messages results in more robust DGPS positioning. The interval of application $[t_1 \ t_2]$ can be described as function of the message length M , the data rate R , the number of satellites G and the number of missed messages Q . The average rms error (eq. 2) can be calculated using the technique described by Enge [9]. For fully asynchronous messaging with message lengths of M bits, the interval of application becomes

$$[M/R \quad (G(Q+1)+1)M/R] \quad (5)$$

Figure 8 and 9 show the estimated rms range errors for Types 1 and 9, and fully asynchronous messaging as function of the (random) BER. To obtain 95% position accuracy, multiply the rms range error by 3.

Figure 8 and 9 show:

1. Fully asynchronous improves the accuracy in case of no data transmission errors
2. In case of data transmission errors, the improvement is even more.
3. Higher data rates can withstand a higher data bit error rate.

For Eurofix data link, with its low data rate and many interferences like atmospheric noise, continuous wave interference and cross rate interference, these properties of fully asynchronous DGPS will be very useful.

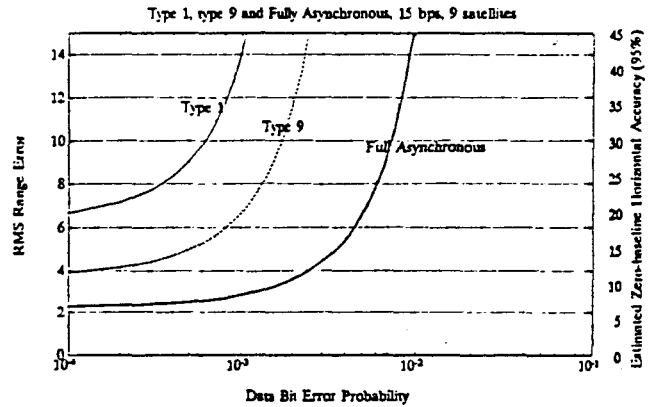


Figure 8. Estimated pseudorange error versus bit error probability for 15 bps data rate.

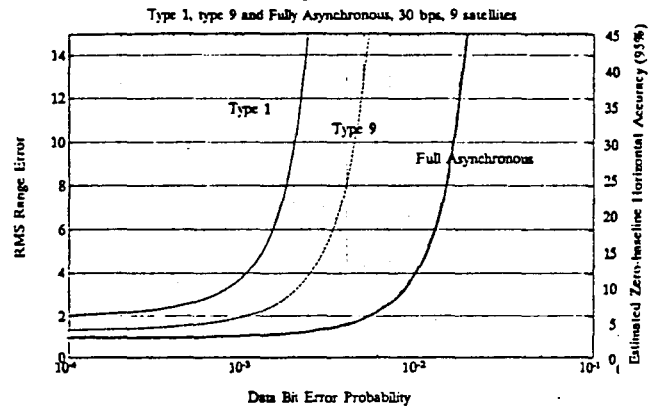


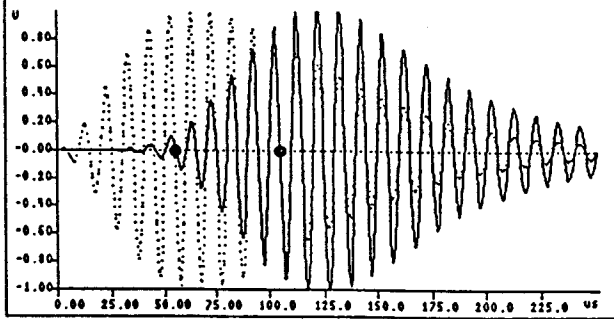
Figure 9. Estimated pseudorange error versus bit error rate for 30 bps data rate.

4 - Data demodulation.

This section treats the Eurofix data demodulation in its simplest form: using a hard-limiter Loran-C receiver which takes an additional polarity sample for detection of the data (fig 3). Range tracking measurements are usually performed at 55 μ s after the start of the burst. The range tracking position is a trade-off between possible skywave interference and low SNR. The post filter amplitude at the range tracking point of the burst is approximately 17 dB below that of the top of the burst.

However, the maximum DGPS base-line length is 600 km. At this distance from a Loran-C transmitting station, skywaves will arrive at least 60 μ s later than the groundwave [14]. Therefore, the data is detected at a higher position in the Loran-C burst compared to the normal range tracking position. Secondly, the skywave will not exceed the groundwave by more than 16 dB.

These worst case skywave conditions allow for a save 105 μ s data detection position when using a 20 kHz, 5th order Butterworth filter (even for an anti-phase skywave (delay 65 μ s) and of a quadrature skywave (delay 62.5 μ s) of +16 dB). Figure 10 shows the filtered burst together with the regular range tracking position (55 μ s) and the 105 μ s data detection position. The range tracker controls the timing of the additional data detection sample.



(solid) band-pass filtering, together with sampling positions for range tracking (55 μ s) and the additional Eurofix data detection (105 μ s).

At this position, the data is detected at only 1 dB under the top of the burst. Moreover, the SNR improves 16 dB compared to the range tracking position. This SNR improvement for the data detection position protects the Loran-C data link effectively against:

- Atmospheric Noise
- Continuous Wave Interference
- Cross Rate Interference

Especially during night time, cross rate is the main interference for the Eurofix data link.

5 - Performance of data link under Cross Rate Interference

This section treats the effect cross rate interference (CRI) on the data detection only. CRI appears as an interference pattern, which repeats after an integer number of GRI's. For this analysis, we assume that the Eurofix data modulation together with the phase coding of the desired signal is uncorrelated with the phase coding of the interfering cross rate signal. In this way, the fundamental interval is reduced to 1 GRI instead of 2 GRI. The length of the interference pattern is given by

$$N_x * GRI_x = N_d * GRI_d = T_{pattern} \quad (6)$$

where GRI_x and GRI_d are the GRI's of respectively the interfering signal and desired data signal. N_x and N_d are the smallest integer values for which the equation is valid.

The cross rate signal steps through the GRI_d fundamental data interval thereby occasionally interfering with the Eurofix modulated bursts. As the interference pattern repeats after N_d GRI_d 's, the number of steps is limited. Moreover, the interfering parts of the cross rate signal are equally spaced. The stepsize dT is given by

$$dT = \frac{GRI_d}{N_d} = \frac{GRI_x}{N_x} \quad (7)$$

This equation implies that only certain, equally spaced, positions of the cross rate signal interfere with a position in the data bursts (the data detection position). For the situation in Delft, the Lessay signal ($GRI=89400$ μ s) interferes with desired Sylt signal ($GRI=79700$ μ s). In this example, $N_d=894$ and $N_x=797$, and the pattern repeats after $N_d * GRI_d = 71.25$ seconds. The stepsize T_d of 100 μ s introduces the quantized amplitude levels of the cross rate interference (fig. 13).

So, the cross rate interference is characterised by mainly two parameters: 1) the step size T_d , depending on the GRI's and 2) the cross rate time offset between 0 and T_d seconds. In case the cross rate signal has its zero crossing at the data detection position, little cross rate interference will be detected. However, when the cross rate time offset changes 2.5 μ s, the cross rate interference is maximum. As the cross rate time offset is related to the user's position, moving will change the effect of cross rate. A time offset of 2.5 μ s equals 750 meter. Figure 14 shows the influence of the cross rate time offset and the existence of a worst case cross rate time offset.

5.1 - Burst Error Rate with Cross Rate Interference

As the additional phase modulation is uncorrelated with the phase coding of the cross rate signal, the burst error probability with cross rate under gaussian noise becomes

$$P_b = \frac{1}{2} Q\left(\frac{A_d - A_x}{\sigma}\right) + \frac{1}{2} Q\left(\frac{A_d + A_x}{\sigma}\right) \quad (8)$$

where A_d is the amplitude of the detection level, A_x is

the quantized amplitudes of the cross rate interference, σ is standard deviation of the gaussian noise and Q is the gaussian error probability function. The cross rate level A_x and the number of cross rate interferences per period is calculated using eq. 6 and 7. The detection level A_d is 1 dB under the top of the burst. With a modulation angle of 36° ($1 \mu s$) and the top of the burst at 1, A_d values 0.52. For a worst case cross rate time offset, the burst error probability for various Signal to Cross rate Ratios (SCR) and SNR's is plotted in figure 11. The results in this figure are for the filter response as used in the measurements in the section 5.2. The SNR is defined at the data detection position by

$$SNR(dB) = 20 \log\left(\frac{A_d}{\sigma}\right) \quad (9)$$

For a worst case cross rate signal (a cross rate signal of +16 dB compared to desired signal), the burst error rate does not exceed 1.4 % for proper SNR's.

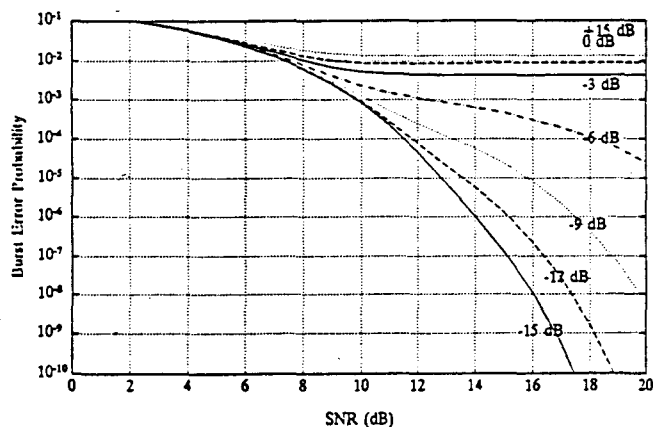


Figure 11. Worst case burst error probability for different cross rate signal power versus the SNR at the data detection position (Lessay (8940) interferes on Sylt (7970)).

5.2 - Measurement Results

Figure 12 shows the setup for testing the performance of the Eurofix data link. For all measurements, the signal of the Sylt station is additional phase modulated. For the measurements of fig. 13 and 14, the simulated Sylt signal, with alternating $1 \mu s$ phase advances and delays, was added to signal received from the antenna. The power of the simulated Sylt signal was set the same as actual received. Data detection was performed at 1 dB under the top. The bandwidth of the applied band pass filter is 7 kHz (-3

dB).

Table III presents the received Loran-C signals and distances to the transmitting stations. The groundwave level of Sylt is appr. 3 dB above that of Lessay.

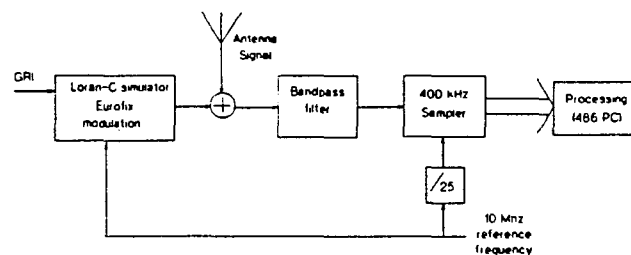


Figure 12. Eurofix test setup.

Station (GRI in 10 μs)	Distance (km)
Sylt (7970)	407
Ejde (7970)	1335
Lessay (8940)	523
Souston (8940)	1014
Ejde (9980)	1335
Estartit (7990)	1108
Baranovich (8000)	1467

Table III Loran-C transmitting stations within a range of 1500 km from Delft.

The measurements show a burst error rate of 0.5%, exactly as calculated in Section 5.2 for a cross rate interference of -3 dB.

5.4 Conclusion for cross rate interference

Cross rate interference is the main error source for the Loran-C data link. However, even for a worst case cross rate signal in Delft, the burst error probability does not exceed 1.5 %. A coding rate of 1/2 is preferred for DGPS performance. The resulting bit error rate can be improved by:

1. Simple bit error correction using a coding rate of 1/4 or 1/6 in stead of 1/2.
2. A coding rate of 1/2 or 1/4 can detect most errors. Using an increased number of parity control bits, detected errors can be corrected.

In this ways, proper DGPS performance can be obtained.

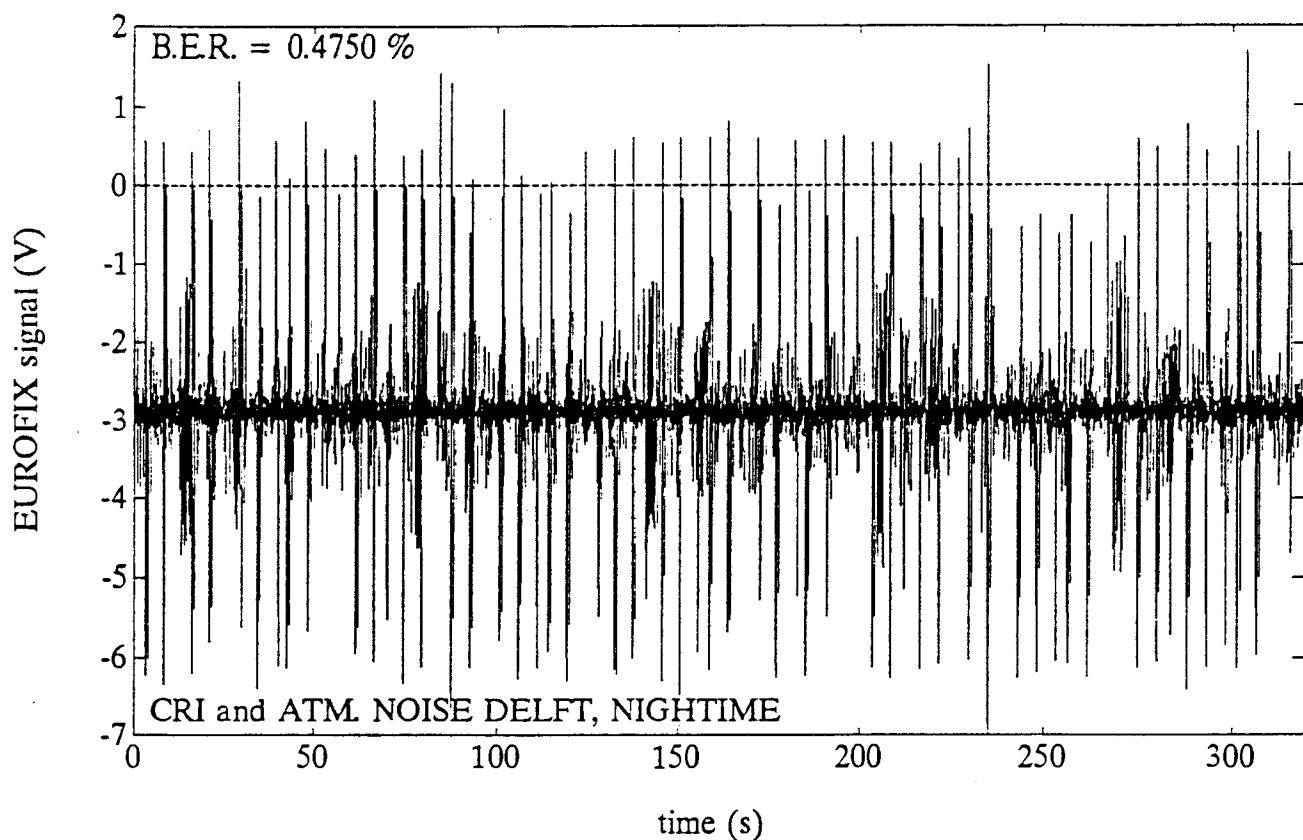


Figure 13. Detected amplitude at the data detection position of Sylt during night-time (4000 GRI's, 24000 bursts, phase advances only and for a worst case cross rate time offset). The threshold (0 V) is only exceeded due to cross rate interference from Lessay. This gives rise to a burst error rate of 0.00475. Also other cross rate interferences are visible, which however do not contribute to the burst error rate.

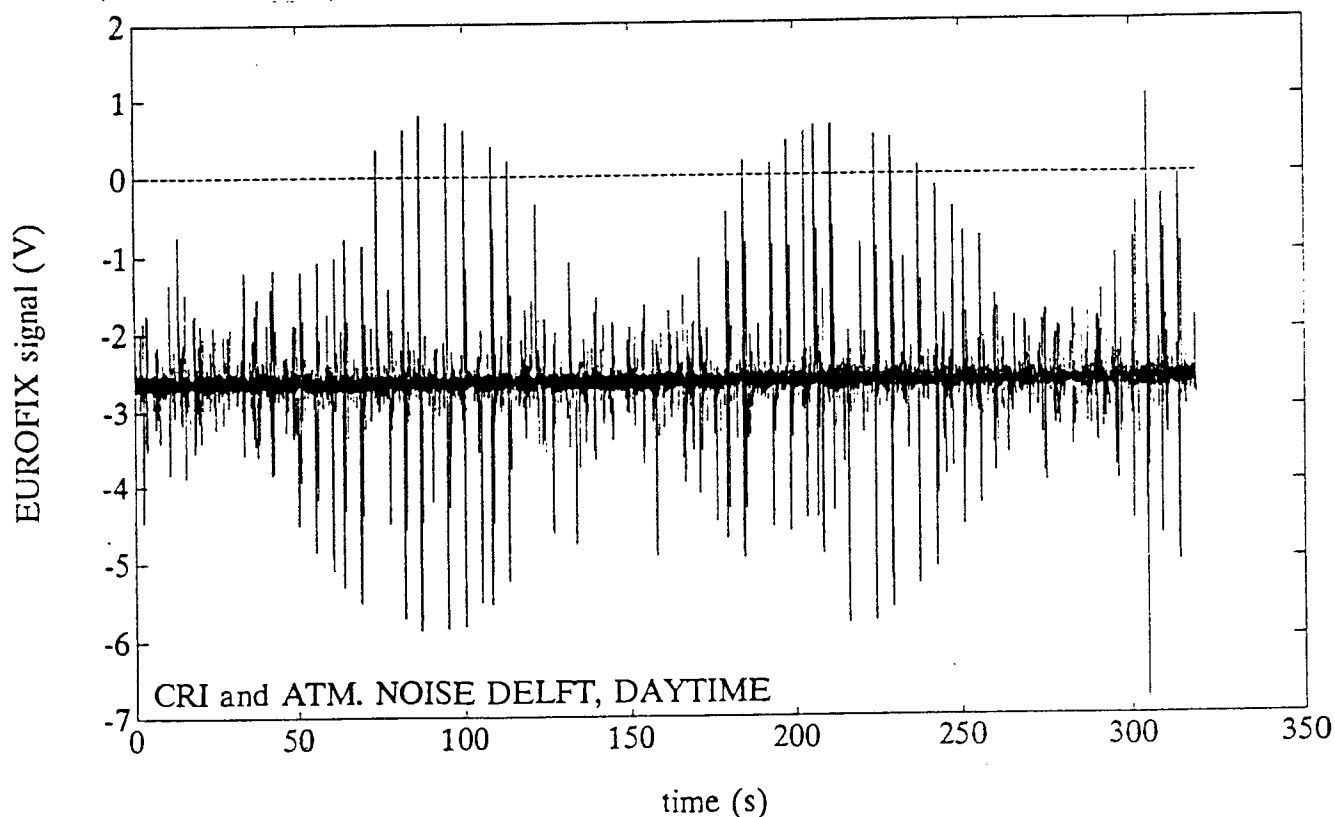


Figure 14. Measurement like fig. 13 during daytime. This figure shows clearly the effect of the cross rate time offset. This offset changes for a moving receiver (moved 4000 m).

6 - Conclusions

The proposed Eurofix system provides continental-wide DGPS services combined with a second, completely dissimilar, radionavigation system to improve the continuity of service. The DGPS accuracies, based on fully asynchronous messaging, fulfil the requirements for harbour approaches as specified in the 1992 Federal Radionavigation Plan. Due to so many interferences in the Loran-C band, especially cross rate interference, some way of error correction will be required for robust DGPS functioning in all circumstances.

7 - Acknowledgement

The Eurofix project, part of the larger University Research Program 'Integrated Navigation for Traffic and Transportation', is partly funded by the Beek committee. The authors would like to thank the Dutch Ministry of Transport and Public Works for all their experienced help, Arjan Noorbergen for his work with the simulator and Durk van Willigen with the whole P&N group for their support.

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For further information please contact

Prof.Dr. Durk van Willigen

Delft University of Technology

P.O. Box 5031, 2600 GA Delft, The Netherlands

Tel: +31 (15) 78 61 68

Fax: +31 (15) 78 17 74

E-mail: <D.vanWilligen@et.tudelft.nl>

SESSION 3

System and Receiver Technology

LORAN Receiver Structure for Cross Rate Interference Cancellation

Benjamin Peterson, Keith Gross and Edward Bowen*

Department Of Engineering
U. S. Coast Guard Academy
New London, CT 06320

*Present Address: USCGC ACACIA, Charlevoix, MI 49720

ABSTRACT

With the recent mid-continent expansion of LORAN in North America, the planned future expansion in Europe, and with LORAN and Pulse-8 sharing the same band in Europe, the dominant source of interference frequently is cross rate LORAN signals. Recent advances in digital signal processing technology have now made it possible to implement in real time digital filters with notches at all of the cross rate harmonics. Our filter is implemented on a SPECTRUM TMS320C30 based board installed in a MS-DOS computer. This is the same hardware we use to implement the Russian VLF/Omega and DGPS MSK receivers. As in those cases, the hardware system is an excellent test platform for basic research and concept evaluation, and is not an "end product." We also tested the system as a filter with analog output in the RF path to the Austron 2000 monitor receiver at a LORAN Station Dana. The manual locking of the receiver is made far easier in presence of strong cross rate interference. We also use the (16 bit) system as a more accurate system (compared to eight bit digitizing oscilloscopes) for recording waveform data. Future enhancements will include the use of GPS time transfer to track TOA's relative to GPS time.

INTRODUCTION

In a companion paper [1], we describe a system that is used to remotely collect LORAN waveform data using a

digitizing oscilloscope. In that system we digitize one pulse per GRI, on one station, at eight bits of resolution. In this paper we describe a system that will allow us to collect data using all pulses on all stations in two GRI's, at 16 bits resolution, and with cross rate interference from as many as two rates cancelled.

HARDWARE DESCRIPTION

Figure 1 is a block diagram of the hardware. The RF comes into the system through an antenna and is amplified and filtered by an analog, sixth order Butterworth bandpass filter with a center frequency of 100 kHz and 24 kHz of bandwidth. This filtered RF is sampled at 140 kHz and 16 bits by a Spectrum TMS320C30 Digital Signal Processing Board. The board is installed in an 80486 PC compatible microcomputer which downloads time constants to the board and uploads the comb filter information. Figure 2 is a block diagram of the comb/notch filter algorithm the TMS320C30 Digital Signal Processor is running in real time at 140 kHz.

Each of the three comb filters is an exponentially weighted average of the last user selected number of phase code intervals. The transfer functions of these comb filters are of the form:

$$H_c(z) = \frac{1 - a}{1 - a z^{-N}}$$

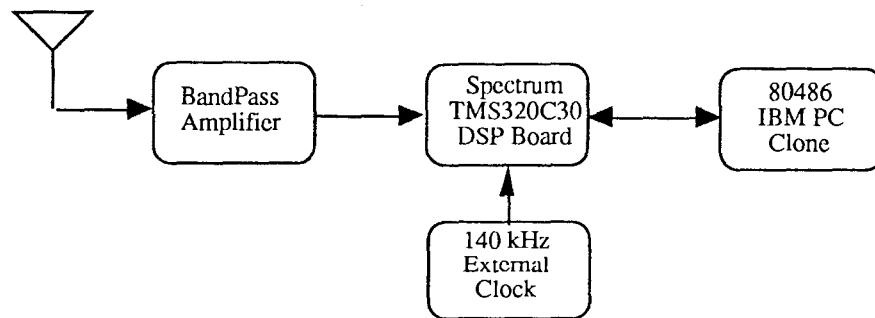


Figure 1. Block diagram of the hardware.

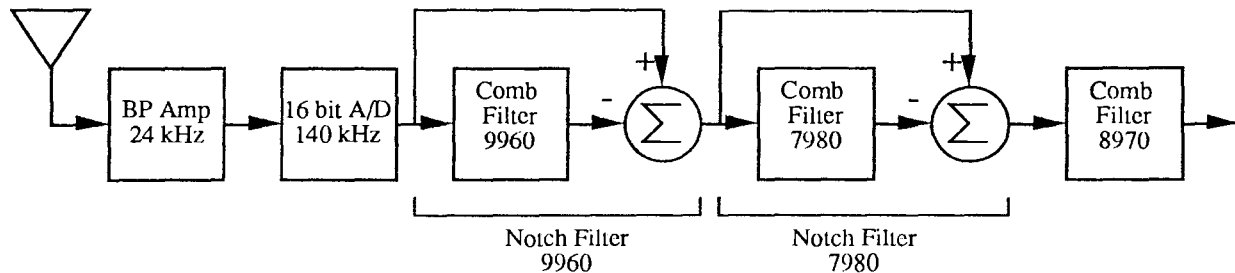


Figure 2. Block Diagram of Processing by TMS320C30.

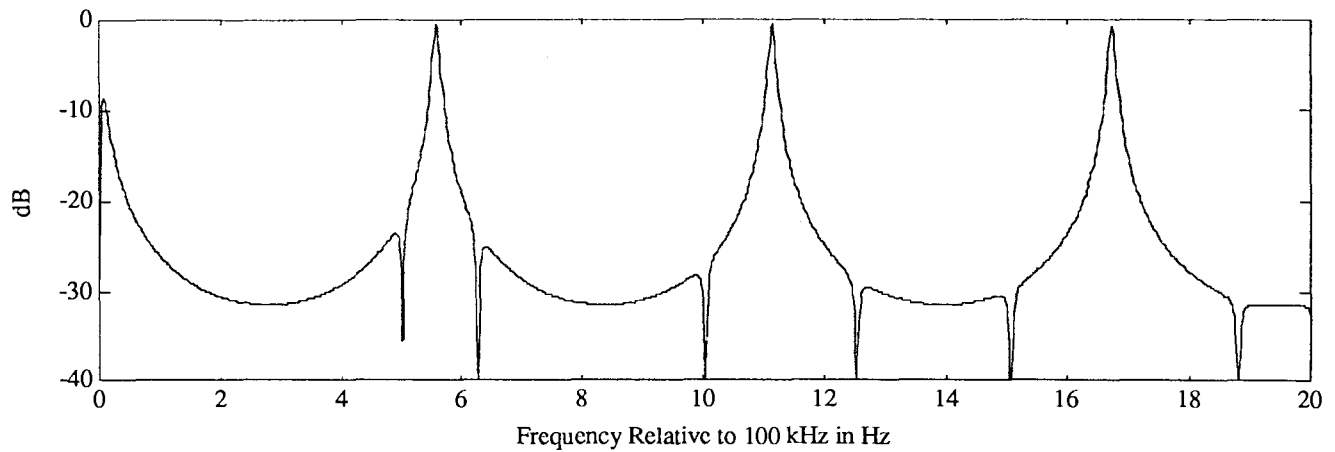


Figure 3. Theoretical response cancelling 9960 and 7980, with comb filter for 8970.

where $\frac{1}{1-a}$ is the time constant of the comb filter in Phase Code Intervals (PCI's) and N is the length of a PCI in sample times. For example for GRI 9960:

$$N = 0.0996 \text{ sec.} \times 2 \times 140,000 \text{ samples/sec.} = 27888.$$

The outputs of the first two comb filters are subtracted from each one's respective input effectively forming a notch filter at the GRI's harmonics. The notch filter transfer functions are given by:

$$H_n(z) = 1 - H_c(z) = 1 - \frac{1-a}{1-az^{-N}} = \frac{a(1-z^{-N})}{1-az^{-N}}$$

Typically, we use the system to cancel the two strongest local GRI's and collect data on a third weaker GRI. The Spectrum DSP board is limited to 64 k 32 bit words of dual port (accessible by both the board and the host) memory and has additional memory accessible by only the board. Since at 140 kHz a PCI can require up to 28,000 words of memory, the data from only the last two comb filters in Figure 2 is accessible by the host. In earlier two GRI versions we subtracted the output of each comb filter from the input to the other. When this parallel scheme is extended to three rates, because the common, synchronous lines are subtracted twice instead of just once, we settled on the serial version shown in Figure 2. Figure 3 shows the theoretical response in the vicinity of 100 kHz for GRI 8970 and cancelling GRI 9960, and GRI 7980.

Figure 4 shows the actual measured frequency response for the same GRI's when the harmonics of all three rates are within a normal receiver's servo bandwidth of each other. This response was measured with an HP35670 Dynamic Signal Analyzer with a resolution of 0.49 mHz. In this example the time constants for the notch filters were set at 16 seconds and the 8970 comb filter at 1.6 seconds. The -3 dB bandwidths are 20 mHz for the notches and 200 mHz for the comb filter. The two notches are 42 mHz below and 33 mHz above the 8970 harmonic. What is important to point out is that we can maintain dynamic performance by maintaining reasonable servo bandwidth but still notch the

cross rate lines within the servo bandwidth, (i.e. the near synchronous portion of the cross rate interference.)

It should also be noted that to accomplish this, the notches must be very narrow. In this example, to obtain notches 20 dB deep, an oscillator accuracy of 1 part in 10^8 is required. This would appear to limit the application to fixed monitor receivers with stable oscillators and not inexpensive mobile receivers. Even if a very stable oscillator were put on a mobile platform such as a plane or a vehicle, the frequency errors due to the Doppler render notches this narrow ineffective.

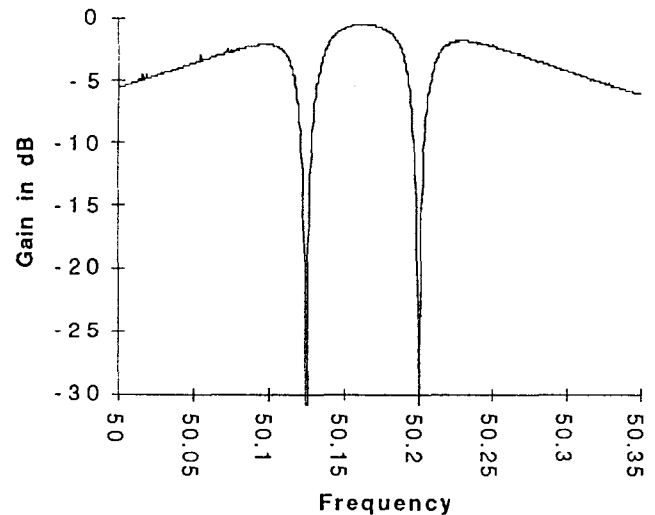


Figure 4. Measured response cancelling 9960 and 7980, with comb filter for 8970.

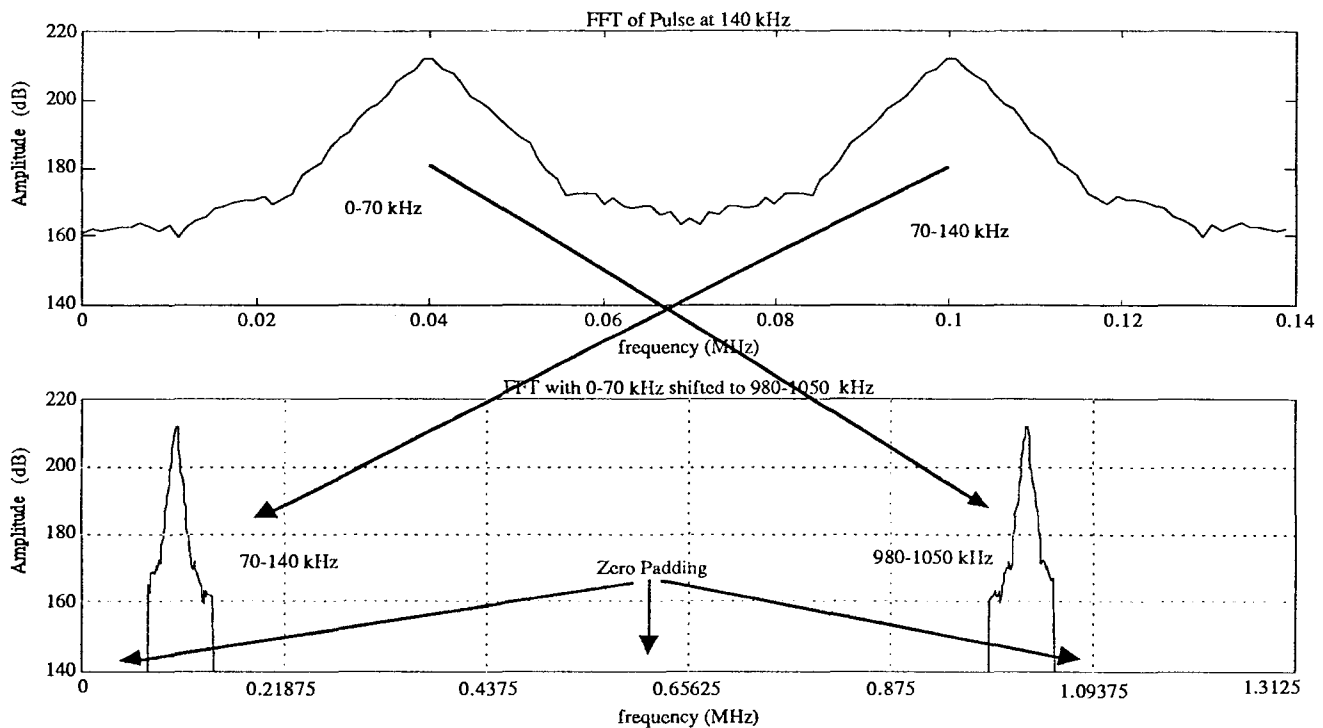


Figure 5. Illustration of zero padding in frequency domain to increase time domain resolution.

PROCESSING BY HOST COMPUTER

The output of the comb filter is uploaded to the 80486 where a matched filter determines where in our comb filter array our first pulse begins. After we find the first pulse, we average over the 16 pulses to form a composite pulse. The composite pulse is written to a file. These files are then processed in MatLab. The resolution in the time domain of our 140 kHz sampled waveform is increased by a Fast Fourier Transform (FFT)/zero padding in frequency domain/inverse FFT technique. The product of this algorithm is a composite pulse sampled at eight times 140 kHz or 1.12 MHz. The steps in the algorithm are illustrated in Figures 5-6. The first step is to take a 128 point FFT on 914 μ sec of data. A 1024 bin frequency domain representation of the signal is generated as follows. The information located in the bins from 70 to 140 kHz remains in the same bins. The information located in the bins from 0 to 70 kHz is then moved to 980 to 1050 kHz. We then zero pad from 0 to 70 kHz, from 140 to 980 kHz, and from 1050 to 1120 kHz. These steps are illustrated in Figure 5. The last step is to take a 1024 point inverse FFT. This will give us a pulse with an effective sampling rate of 1.12 MHz. A plot is given in Figure 6. The crosses in the plot are the sampled data points in the 140 kHz sampled pulse. As you can see there are now seven new points in between each original sampled point for eight times the resolution. Implicit in this algorithm is that the signal has been bandlimited to the 70-140 kHz band. The anti-aliasing filter is a sixth order Butterworth bandpass filter with 24 kHz bandwidth.

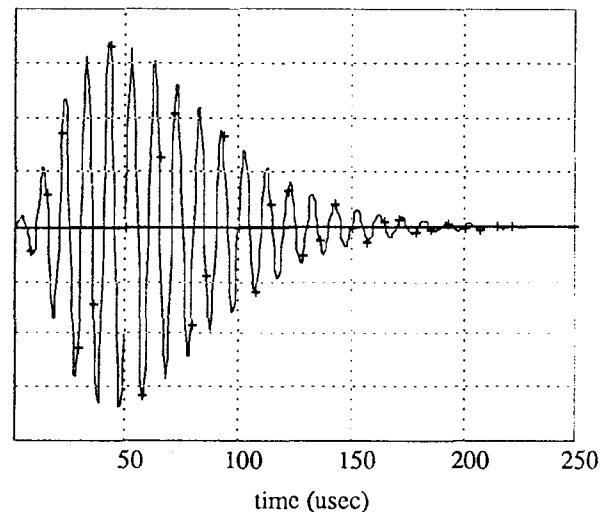


Figure 6. Reconstructed pulse after inverse Fourier transform.

To demonstrate the capability of the system to collect evening skywave data, from New London, we have collected skywave waveforms on virtually every station in the US and Canada, plus Sandur and Angisog. As examples Figure 7

shows one GRI of the comb filter output for 9610 at 0100 EDT on 9 June 1993, and Figure 8 shows the composite pulse of Gillette at the same time.

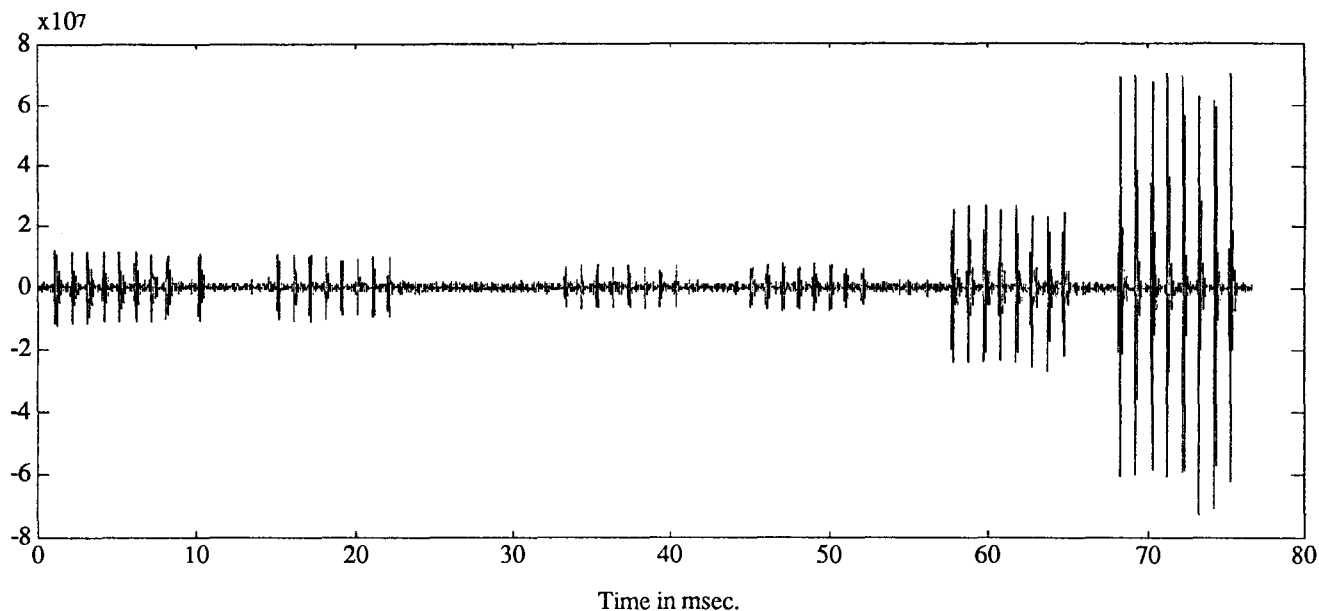


Figure 7. Comb filter output (GRI A) of 9610 at 0100 EDT, 9 June 1993.

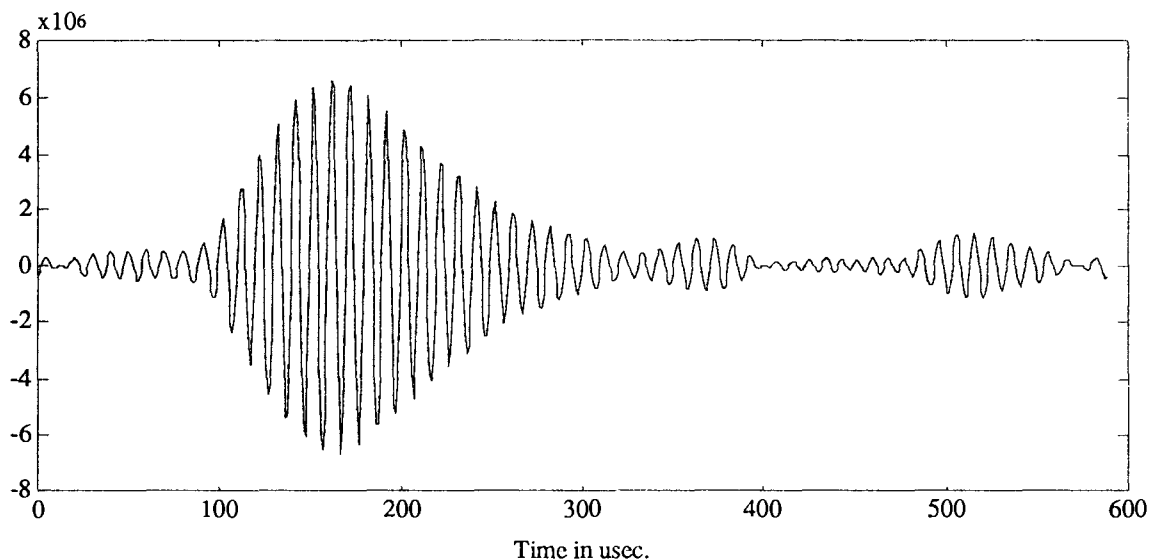


Figure 8. Composite pulse of Gillette on 9610 at 0100 EDT, 9 June 1993.

Figures 9-12 illustrate the effect of cancelling cross rate interference when using both short (20 PCI's in Figure 9-10) and long (2000 PCI's in Figure 11-12) time constants. In Figure 9, the 7980 signals are not visible at all in the

presence of the (asynchronous) cross rate interference, and in Figure 10, the Carolina Beach signal is now clearly visible. The remaining cross rate interference is Seneca on 8970.

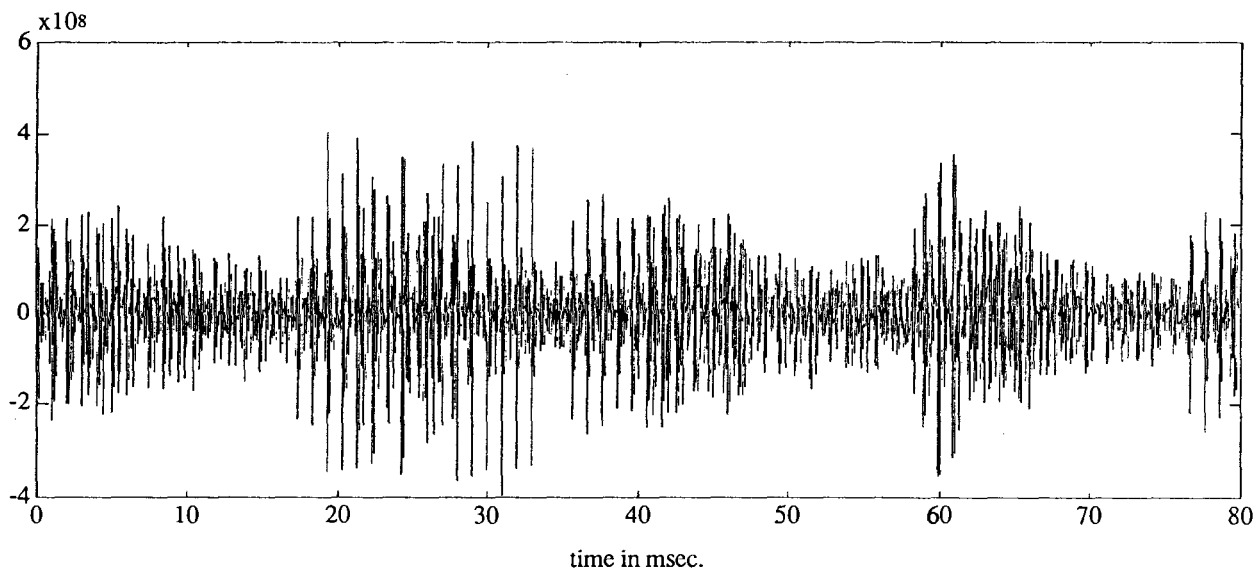


Figure 9. GRI 7980, Time constant of 20 PCI's, no cancelling.

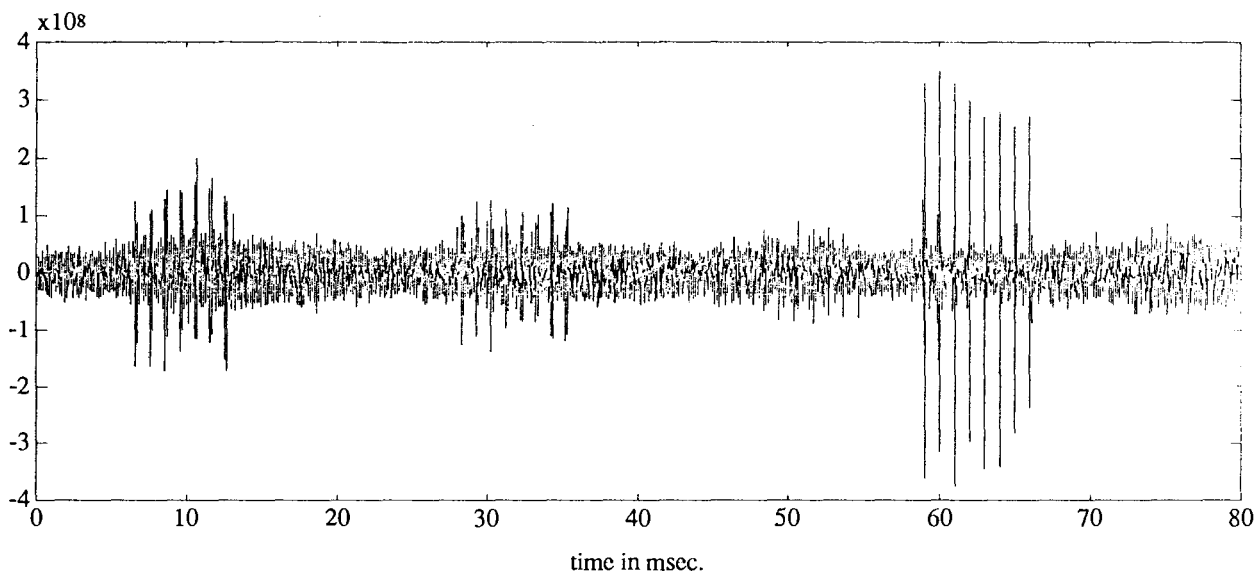


Figure 10. GRI 7980, Time constant of 20 PCI's, 9960 and 5930 cancelled.

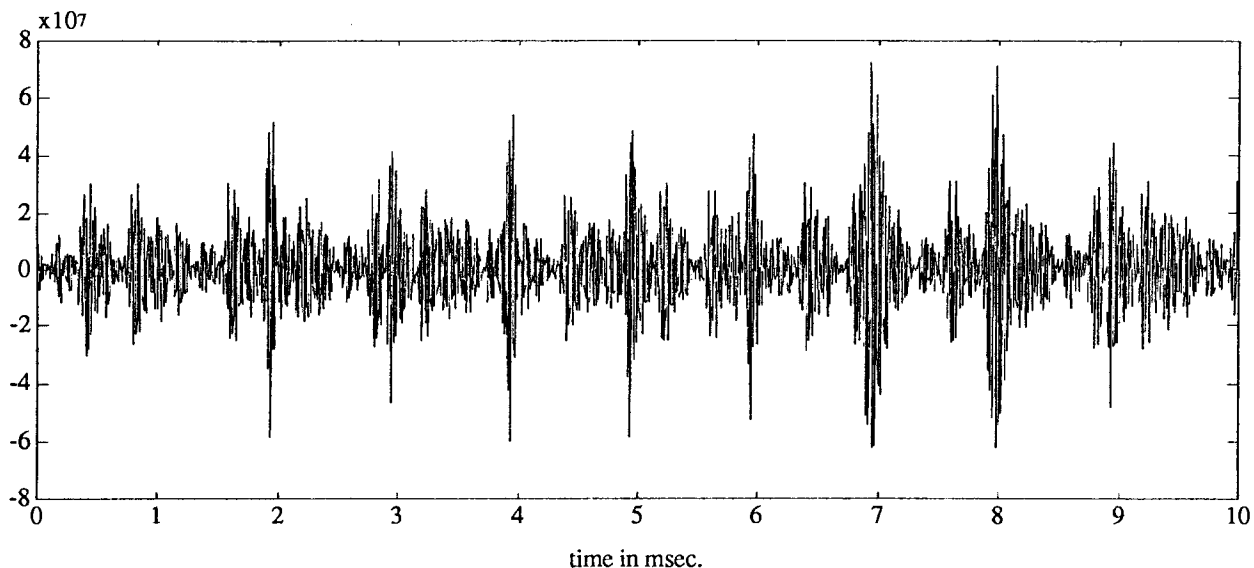


Figure 11. Jupiter, Time constant of 2000 PCI's, no cancelling.

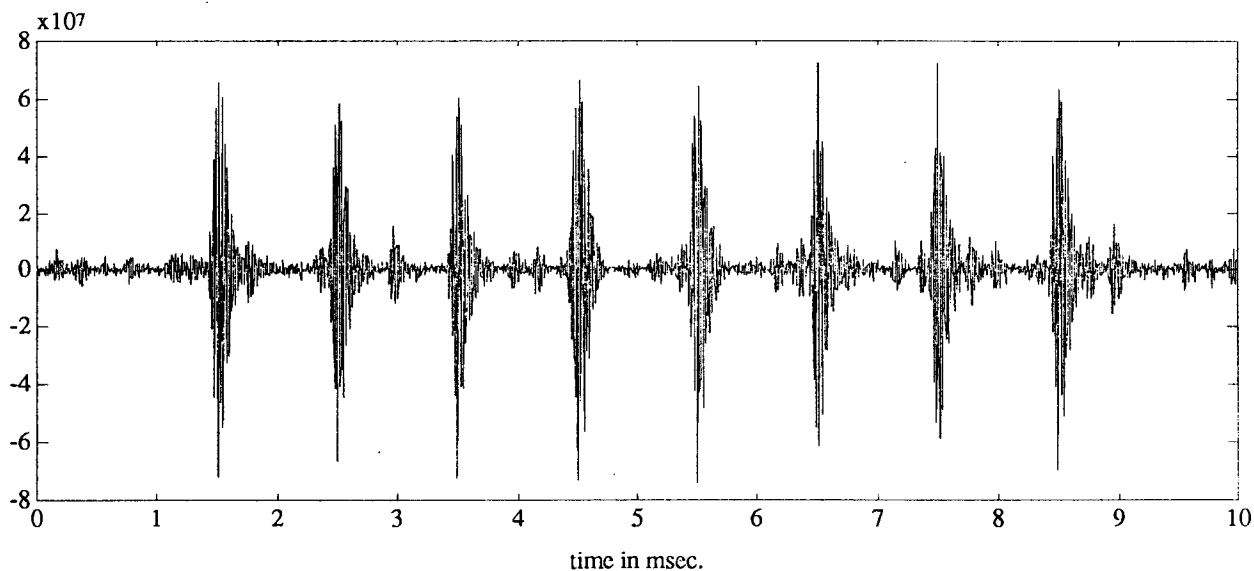


Figure 12. Jupiter, Time constant of 2000 PCI's, 9960 and 5930 cancelled.

Figures 11 and 12 illustrate the need to cancel synchronous cross rate interference when averaging with very long time constants to obtain waveform data on weak signals. In Figure 11 the synchronous cross rate interference (mainly from Nantucket on 9960 and 5930) that remains after averaging with a time constant of 2000 PCI's or 320 sec. makes the Jupiter signal barely visible. In Figure 12, this cross rate interference is cancelled and Jupiter is clearly visible.

USING THE FILTER'S ANALOG OUTPUT

In March, 1993, the Officer In Charge of LORAN Station Dana, Indiana, ETC Jeff Hall, inquired about the feasibility of a filter to eliminating cross rate interference. Due to its central location cross rate interference is a significant problem at Dana, and particularly at night when numerous cross rate skywaves are stronger than the groundwaves they need to track. Figure 13 shows the great circle paths and

distances to other US and Canadian stations and Figure 14 compares the predicted signal strength of the weakest groundwave tracked (Boise City) to those of first hop skywaves from other stations in the US and Canada. We found that at Dana there were 30 cross rate signals for a total of 2950 pulses/second that were 3-16 dB higher than the Boise City groundwave.



Figure 13. Great Circle Distances (in nm) to Dana

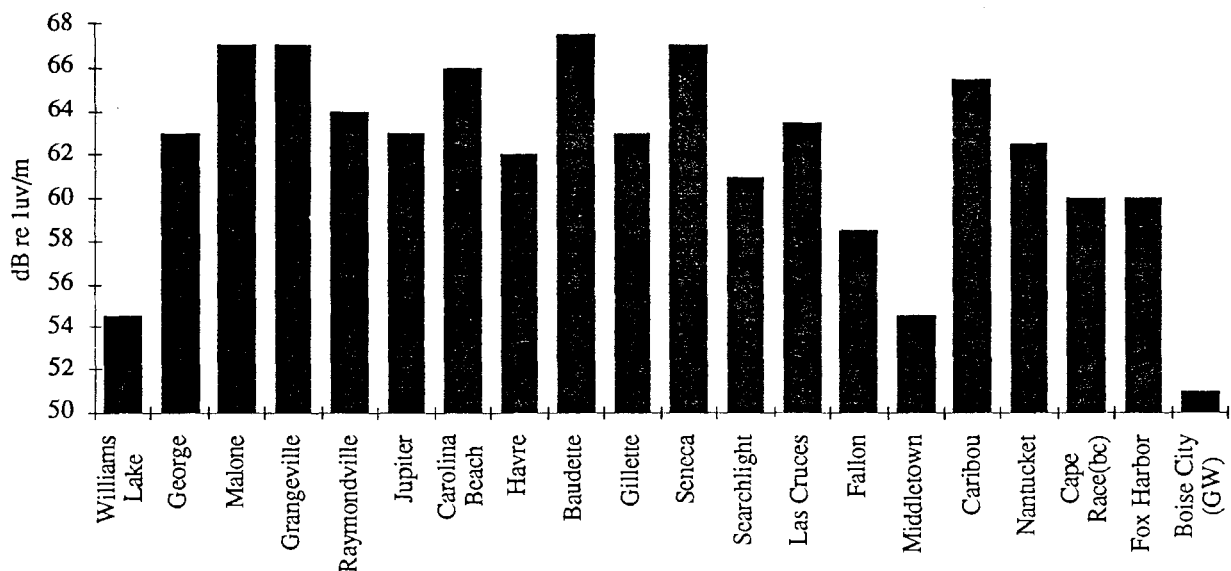


Figure 14. Relative Signal Strengths of 1st hop nighttime skywaves to Boise City groundwave.

On April 19-20, we traveled to Dana to test the system. We installed the system in the RF path of the Austron 2000 receiver so we could process the RF in real time. Our system provided an analog signal that was averaged and with the cross rate cancelled (9960 was cancelled for the 8970 receivers, 8970 was cancelled for the 9960 receiver.) In this case the RF front end of the Austron 2000 receiver effectively accomplishes the same as is done in the MatLab algorithm described above. As shown in Figure 15, the filter output contains two LORAN spectra, one centered at 40 kHz and another centered at 100 kHz. (It actually also contains LORAN spectra centered at harmonics of the 140 kHz sampling frequency ± 100 kHz or 180 kHz, 240 kHz, etc.). The front end of the Austron 2000 receiver is effectively now a reconstruction filter that passes the LORAN spectrum centered at 100 kHz and greatly attenuates the one centered at 40 kHz. Figure 16 is after the reconstruction filter.

Figures 17 and 18 show theoretical time domain pulses before and after the filter. The system worked quite well in that the station personnel were able to lock on the Austron 2000 much easier with our system operating. It should be emphasized this system is intended as the evaluation of concept and not as an installed solution to the cross rate problem.

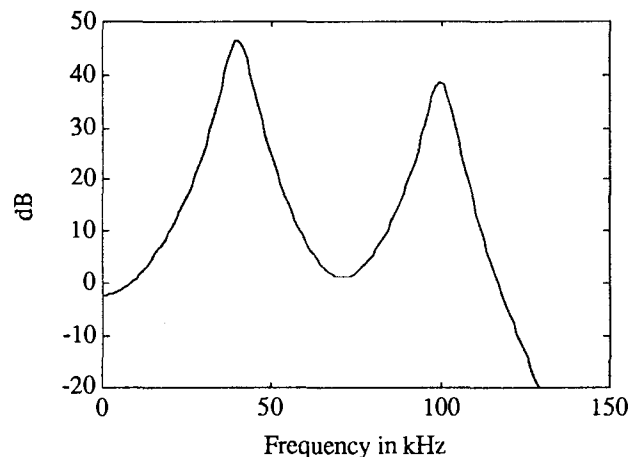


Figure 15. Spectrum before reconstruction filter.

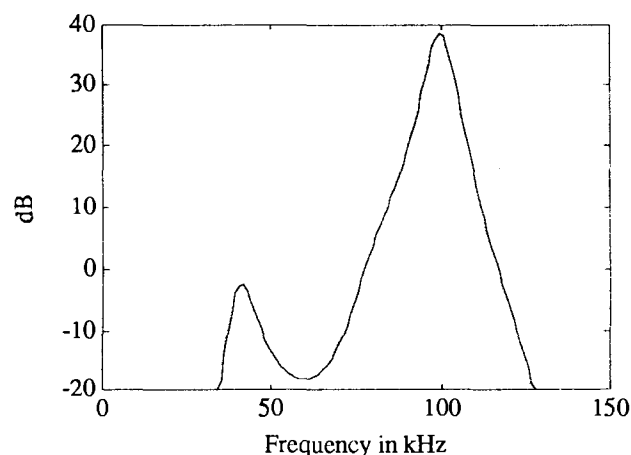


Figure 16. Spectrum after reconstruction filter.

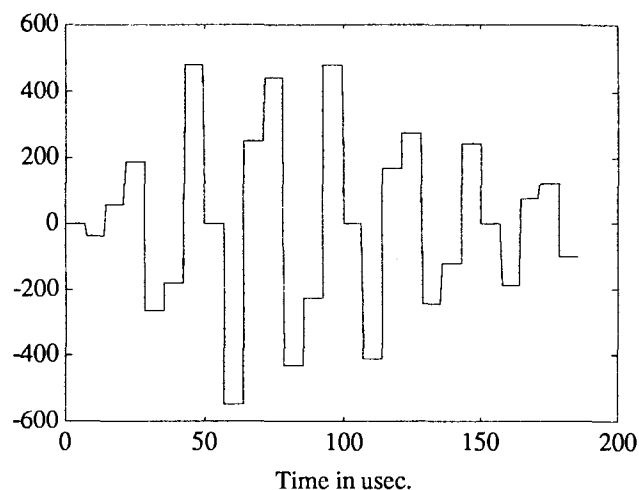


Figure 17. Pulse before reconstruction filter.

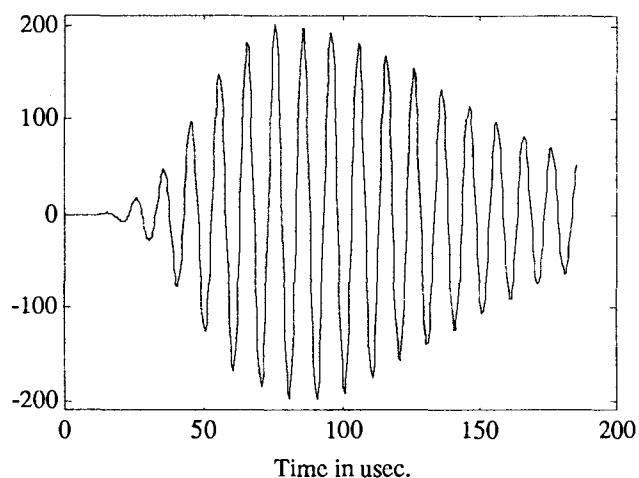


Figure 18. Pulse after reconstruction filter.

ACKNOWLEDGMENTS

This project was funded by the Radionavigation Division of Coast Guard Headquarters, COMDT(G-NRN). We sincerely appreciate the cooperation ETC Jeff Hall, the Officer In Charge of LORAN Station Dana and his crew and ET2 Anthony Fusco, of the Academy EE Section Support Staff.

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Port Clarence Skywave Interference Study

Benjamin Peterson, Keith Gross, Eric Chamberlin, and Edward Sheppard*

Department Of Engineering

U. S. Coast Guard Academy

New London, CT 06320

*Present Address: USCGC ACACIA, Charlevoix, MI 49720

ABSTRACT

The Port Clarence signal on the Gulf of Alaska (7960) chain is frequently declared unusable (blinked) because the envelope-to-cycle difference (ECD) observed at the Fairbanks monitor is out of tolerance. In February, 1993, we installed a data acquisition system in Fairbanks to determine if these out of tolerance conditions are primarily due to early skywaves or other factors. The system uses a modified JET Model 7202 LORAN receiver to provide standard LORAN data (TD's, ECD's, SNR's and signal strengths), as an RF amplifier/filter and to provide a GRI trigger phase locked to the Port Clarence signal for a FLUKE 97 digital averaging oscilloscope. The system is controlled by a GATEWAY 2000 desktop computer. The LORAN data and averaged waveforms are stored and then downloaded via a modem. We are also able to start and stop programs, upload new programs and change parameters remotely. In addition a separate DSP plug-in board implements an integrated Russian VLF/Omega monitor receiver and this data is downloaded as well.

Using a groundwave template of the Port Clarence signal obtained at Galena, we cancel what we believe to be groundwave. We then process the remaining signal to extract skywave delay and amplitude. The Gulf of Alaska Chain Operational Control Officer (COCO) provides the Academy with the times and ECD's of out of tolerance conditions and we look at the waveform in each instance to determine the cause. Our late winter/early spring data indicates most if not all are due to very early daytime skywaves. Unlike data as seen at lower latitudes, the daytime skywaves are as strong or even stronger than those at night.

SKYWAVE DATA ACQUISITION SYSTEM

The block diagram of the system installed at the Fairbanks monitor site in February 1993 is shown in Figure 1. The relative locations of the transmitter at Port Clarence and the monitor are shown in Figure 2. The system is comprised of a Gateway 486 computer, a FLUKE 97 SCOPEMETER (digitizing oscilloscope), a JET 7202 LORAN Receiver, and an antenna. The computer controls the LORAN receiver via a Windows application of a modified Borland C source (BLC) code supplied by the manufacturer. The BLC code allows the user to lock onto a specific station and provides a trigger for the digitizing oscilloscope. The code also provides TD information, signal strength, Signal-to-Noise Ratios (SNR), and ECD values. The computer controls the SCOPEMETER with a QuickBasic program. The RF signal from the JET receiver is connected after the outer two sections of its sixth order bandpass response, after the notch filters and before the middle filter section, and any AGC or clipping. The middle filter section is essentially duplicated externally resulting in combined transfer function of a sixth order Butterworth bandpass response of 24 kHz bandwidth. The digitizing oscilloscope digitizes the RF at 8 bits and 1.25 MHz and averages over 256 pulses. We decided to allow the JET receiver to adjust its notches so we could detect any interference in the LORAN band, but thus far the receiver has found virtually nothing to notch. The averages of 256 pulses are further averaged in the host and a composite pulse of typically 1280 positive and 1280 negative pulses is stored to the hard drive, normally at 10 or 20 minute intervals.

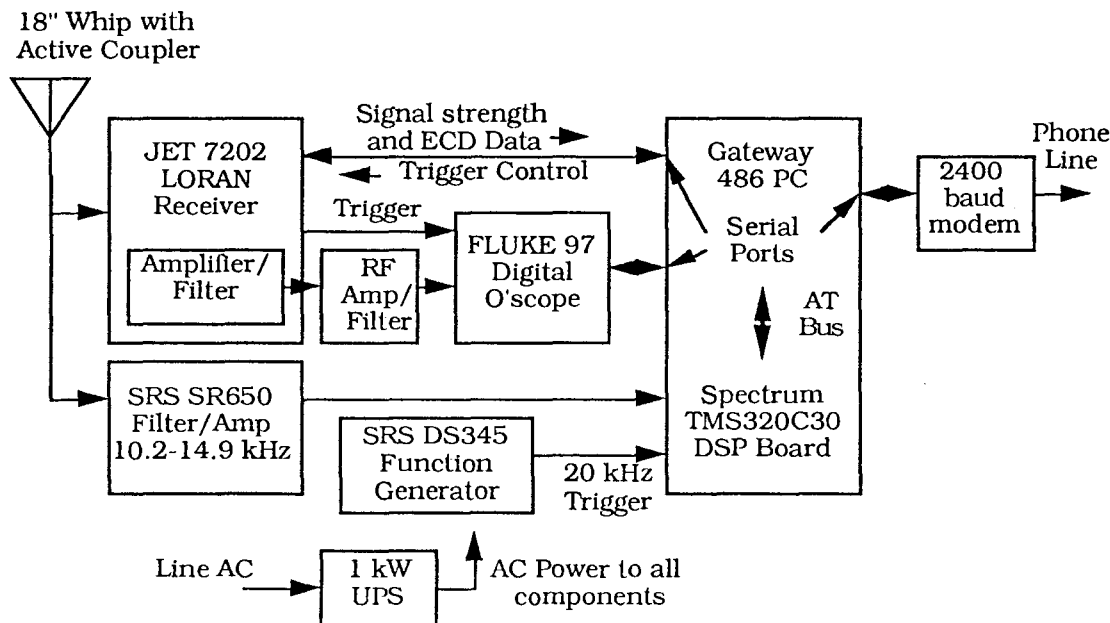


Figure 1. LORAN Skywave/VLF Data Acquisition System(as presently installed in Fairbanks)

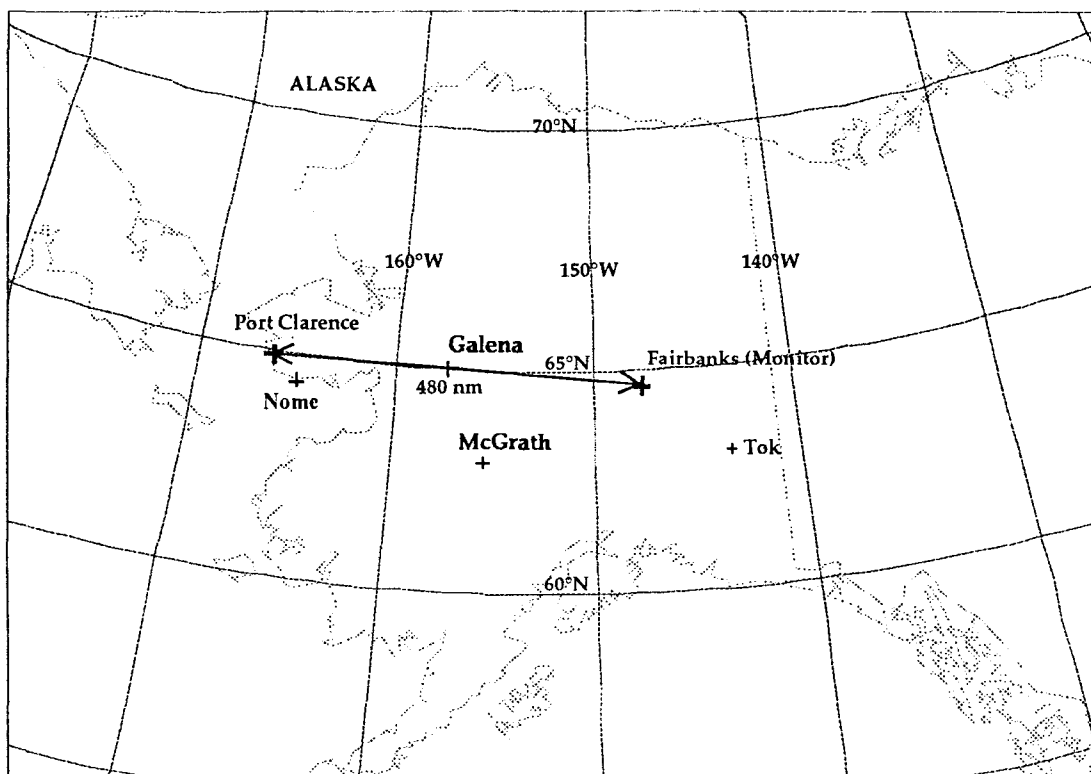


Figure 2. Relative locations of transmitters and monitors.

The data files are organized as minute and day files. There are six minute files, each contains a single waveform, and is overwritten after one hour. The day files contain 72 waveforms over a 24 hour day and are automatically overwritten after one month.

The user interface main menu is shown below.

USER INTERFACE MAIN MENU

F) files	U)pload	D)ownload
H)elp	T)ime	C)hat
R)ead mail	L)eave mail	G)oodby

S)witch directory	
Y) copy a file	(A) display disk space
N) rename a file	(Q) delete a file
B) run BLC.exe	(X) stop BLC.exe
V) run VLFRMT.exe	(P) stop VLFRMT.exe
E) run flukeread	
J) run Rulph's Jet Trigger Code	
W) What is running	

Your Choice (w/o carriage return) ?

Our remote system allows the user to see what programs are currently running, to examine files currently saved in a GATEWAY computer, to download files, to upload code alterations, and make changes to list of users.

The system also monitors the Omega and Russian Alpha navigation systems, using the same antenna signal, a SRS Model 650 filter amplifier, and a Spectrum TMS320C30 based DSP board installed in the same host computer. This path is also used for high resolution spectrum analysis in the VLF.

DATA ANALYSIS

The waveform and other data is downloaded to the Academy via 2400 baud telephone modem for further analysis. In order to analyze the effects of skywave interference, we first separate the groundwave from the skywave for a given received signal. We use a groundwave template adjusted in amplitude to subtract from a given waveform and treat the remainder as skywave. The groundwave amplitude is calculated in a least squares sense using the first 40 μ sec of data. Unlike past efforts [1], where we were digitizing signals from solid state transmitters, the Port Clarence transmitter is the older tube type and as such its signal (other than the leading edge) does not closely follow the standard LORAN pulse equation [2]. In [1], we assumed the transmitter antenna current followed this equation, and used mathematical models for change in the pulse from antenna current to near far field, during propagation, and through the RF front end of our system. In this case we planned to obtain a groundwave template at Nome using an identical RF front as the Fairbanks system. We were diverted by weather to Galena about midway between Port Clarence and Fairbanks (Figure 2). We were able to obtain excellent groundwave data there (Figure 3).

The envelope (shown in Figure 3) is obtained by taking the square root of a linear combination of amplitude squared and slope squared. Due to several pulse building evolutions at Port Clarence and other factors, we no longer consider our groundwave template accurate. Future efforts, described below, will address this issue for the coming winter season. Summer out-of-tolerance conditions are rare and the analysis of summer data has not been a priority.

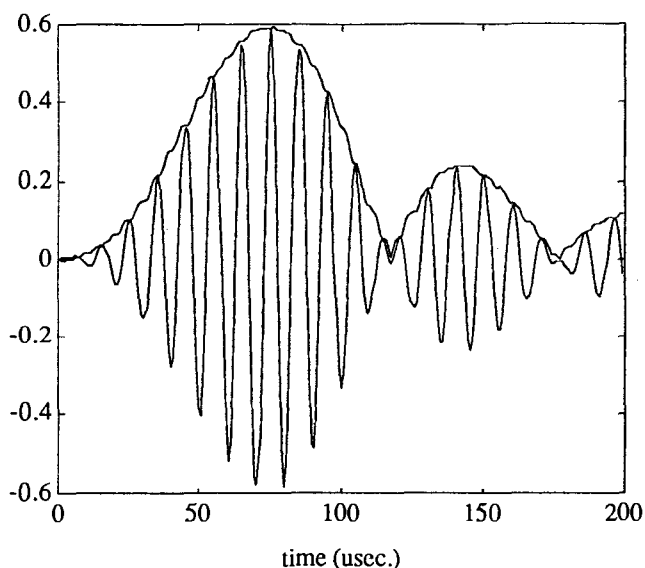


Figure 3. Groundwave Template from Galena.

Figure 4 shows a typical received waveform during an envelope number (or ECD) out-of-tolerance condition as seen by the Austron 5000A Fairbanks monitor. The destructive interference of a very early and large skywave is obvious in the upper trace. The lower trace shows what remains after we cancel what we believe to be groundwave. To estimate skywave parameters we first generate it's envelope as described above and shown in the figure. Next, using the first 80 μsec . of the groundwave template envelope, we iteratively adjust skywave envelope delay and amplitude for the best least squares fit of the data. After estimating skywave envelope

delay, we choose the nearest zero crossing to estimate the skywave (relative to groundwave) phase. This data analysis is done in MatLabTM.

LT Dave Watkins, the Gulf of Alaska Chain Operational Control Officer, or his assistant, provided the Academy with the times and ECD's of out of tolerance conditions. The nominal value is $+0.3 \mu\text{sec}$. with a tolerance of $\pm 1.5 \mu\text{sec}$. Virtually all out-of-tolerance conditions analyzed were negative ECD's. The destructive interference of the skywave causes the ratio of the half cycle amplitude 7.5 μsec prior to the tracked zero crossing relative to the half cycle amplitude 2.5 μsec after the zero crossing to become larger and shifts the ECD as seen by the Austron 5000A negative. The JET receiver uses a more sophisticated (proprietary) algorithm based on more data, but it's measured ECD correlated well with the Austron. We observed no cases where the JET receiver lost lock or selected the wrong zero crossing.

In addition to plotting waveform data for each time interval, we also have produced daily trends for both skywave delay and skywave to groundwave ratio. Figure 5 is a typical plot showing the daily trends for March 7, 1993. We have also compiled cumulative plots of skywave-to-groundwave ratio vs. time, phase delay vs. time, and skywave-to-groundwave ratio vs. phase delay. Figure 6 shows the cumulative trend of skywave/groundwave ratio vs. time for the Port Clarence signal monitored at Fairbanks for the period of February 24, 1993, through April 8, 1993. The plot shows that the skywave-to-groundwave ratio is somewhat larger during the nighttime but not to the same extent as our previous data at lower latitudes [1]. Figure 7 shows the cumulative trend of phase delay vs. time of day for the same period and shows much shorter daytime skywave delays than in [1].

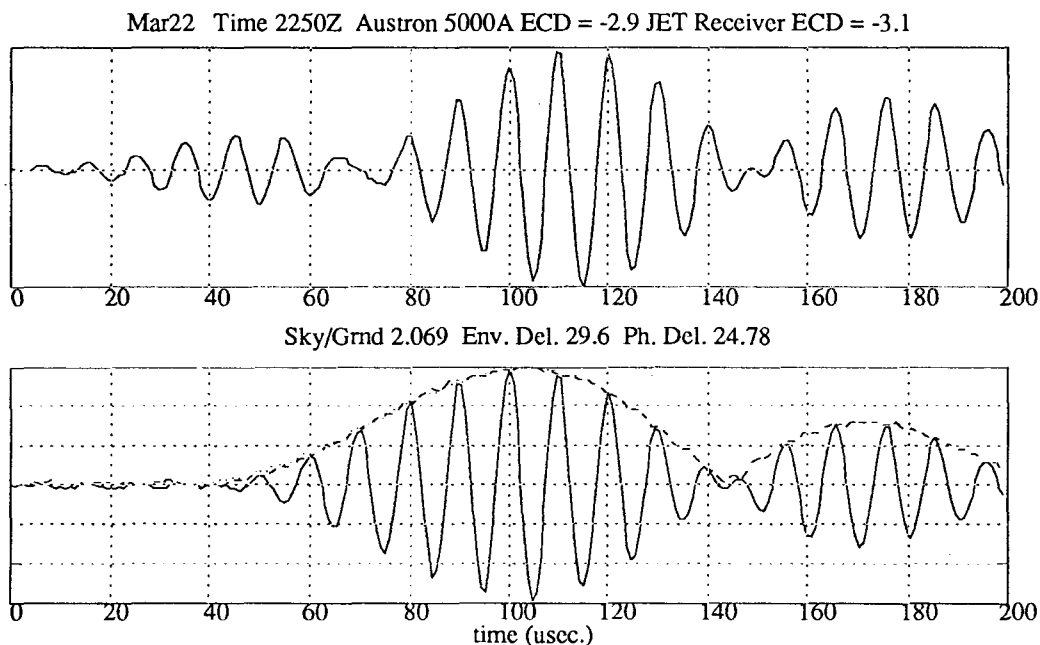


Figure 4. Typical received waveform during an envelope number (or ECD) out-of-tolerance condition.

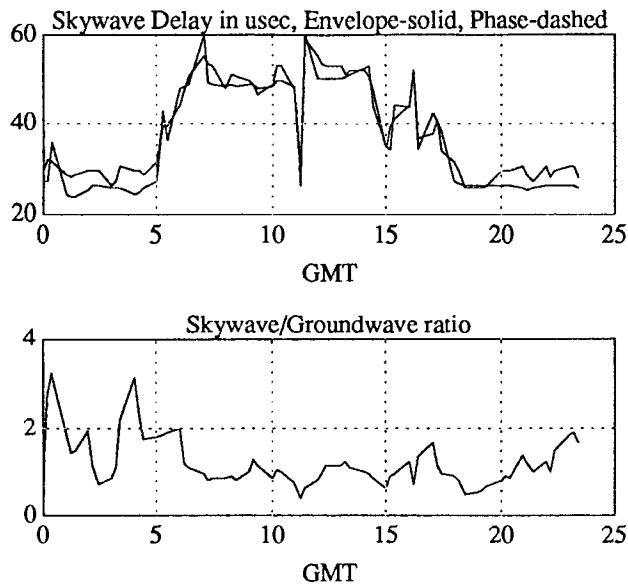


Figure 5. Skywave data summary for 7 March 1993.

Figure 8 shows the trend of skywave/groundwave ratio vs. skywave delay and compares them to minimum LORAN receiver performance specifications for aviation [3] and maritime use (Annex 1 to [4] entitled 'Performance Standards for Shipborne LORAN-C Receivers.') Receivers must be able to track signals with a skywave/groundwave ratio vs. delay to the right and under the solid line for maritime uses and the dashed line for aviation.

Figure 9 shows the skywave/groundwave ratio vs. delay for just the recorded blink times for the Port Clarence signal monitored at Fairbanks between February 24 and March 31, 1993. (NOTE: The A-1 Monitor Fairbanks was down between April 1 and April 10, 1993. The Port Clarence signal was monitored using the A-2 Monitor at Kodiak. The Kodiak Monitor data is not included in the figure.) The figure shows that for all cases when the signal was blinked to the user, the minimum performance specifications were not met.

Figure 10 shows the blink times as a function of time of day for the period (except data from April 1-10 is not included.) In all cases, the blink times for the Port Clarence signal occur during daylight hours. The Port Clarence-Tok baseline was available about 96.4% of the time between March 2 and April 18, 1993 compared to about 99.99% for most baselines operated by the Coast Guard. (It should be noted that virtually all of the blink time was propagation related and not equipment malfunction or operator error. From 2 March to 18 May the total blink time other than propagation was 5 minutes or 99.995% availability.) While we would very much like to reduce this large amount of blink time, to do so is probably neither feasible nor advisable. To reduce blink we could either increase the ECD alarm tolerance at the Fairbanks monitor beyond the standard $\pm 1.5 \mu\text{sec}$. or establish a monitor site closer to Port Clarence where skywaves would be much less of a problem. Since as noted above, skywave conditions during blink periods were consistently outside minimum receiver performance standards, receivers in the vicinity of Fairbanks barely satisfying those standards could have cycle selection problems and users should be warned. Since a significant portion of the use of this baseline is in the Fairbanks area, moving the monitor does not appear advisable.

Skywave to Groundwave Ratio vs. Time (GMT)

24 February - 08 April 1993

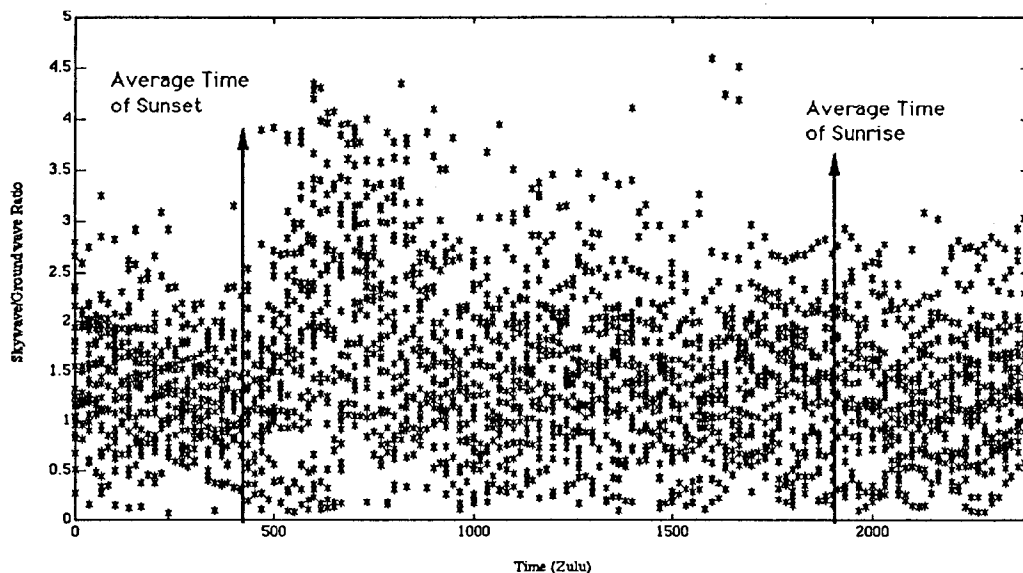


Figure 6. Skywave to groundwave ratios as function of time of day.

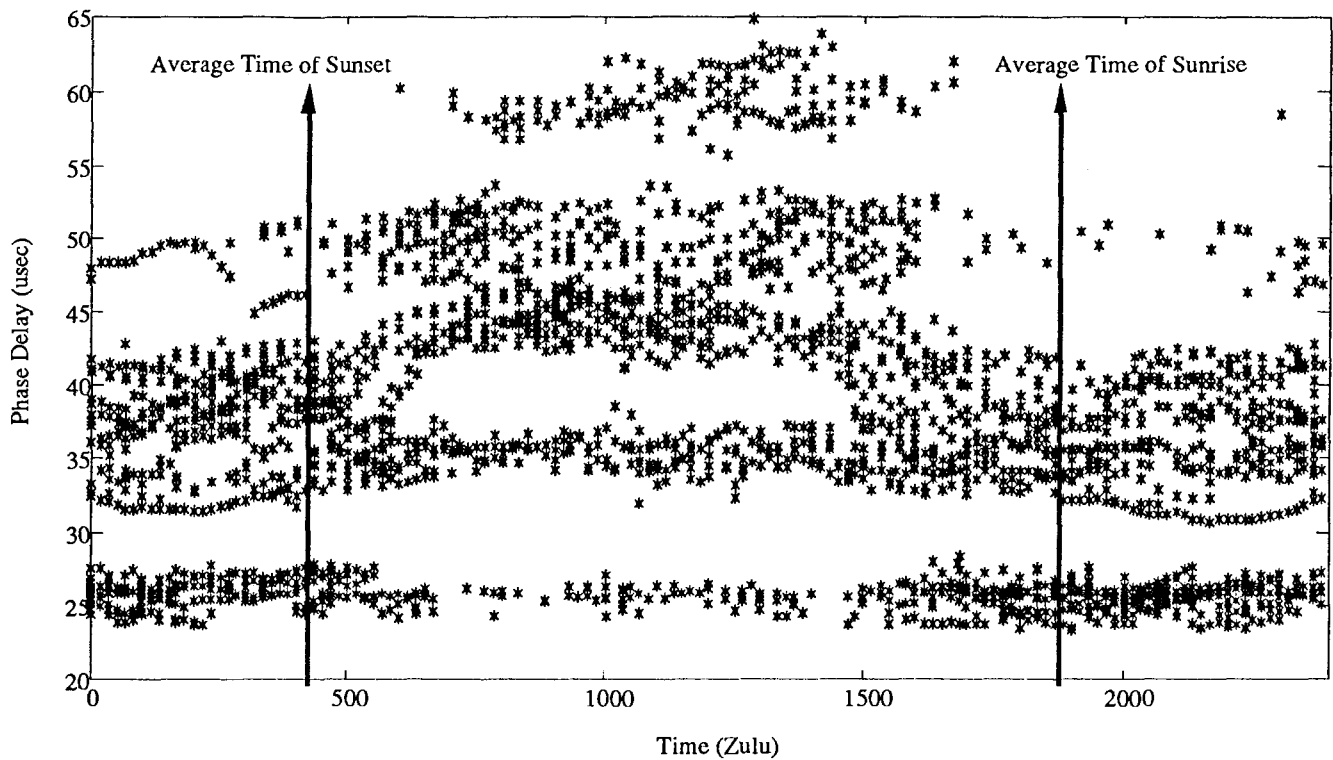


Figure 7. Phase Delay vs. Time (GMT) 24 February - 08 April 1993.

SKYWAVE to GROUNDWAVE RATIO vs. SKYWAVE DELAY
 7960 Port Clarence observed at A-1 Monitor Fairbanks
 24 February - 08 April 1993

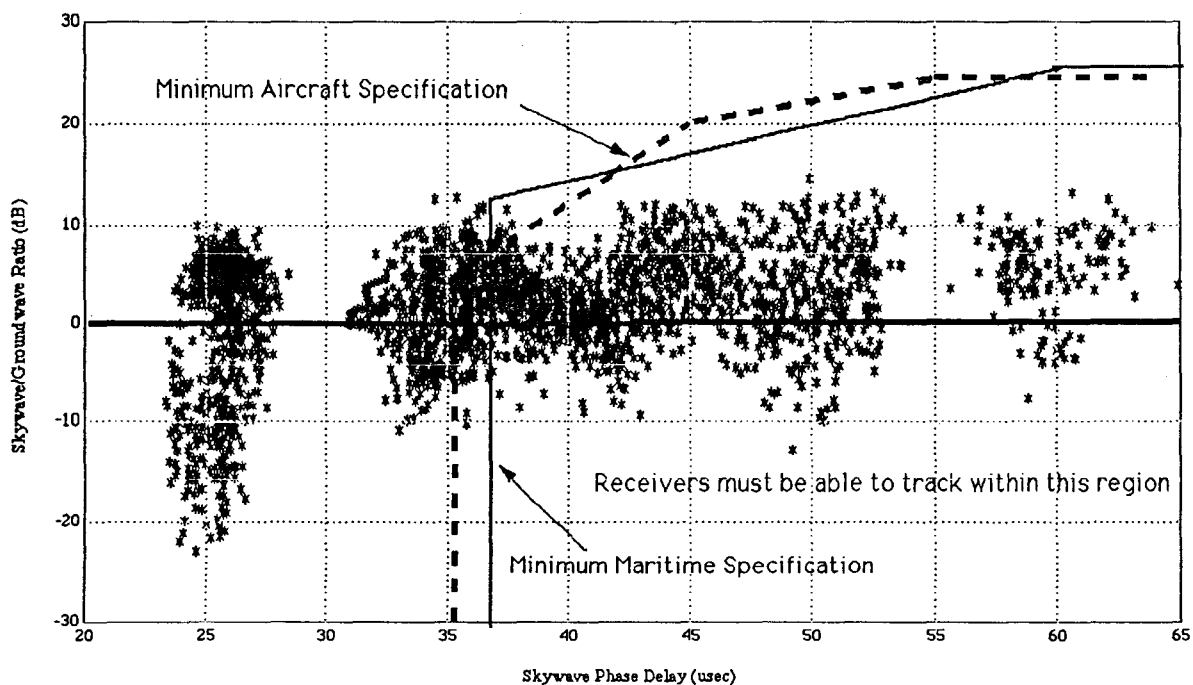


Figure 8. Skywave to groundwave ratios and delay compared to minimum performance standards.

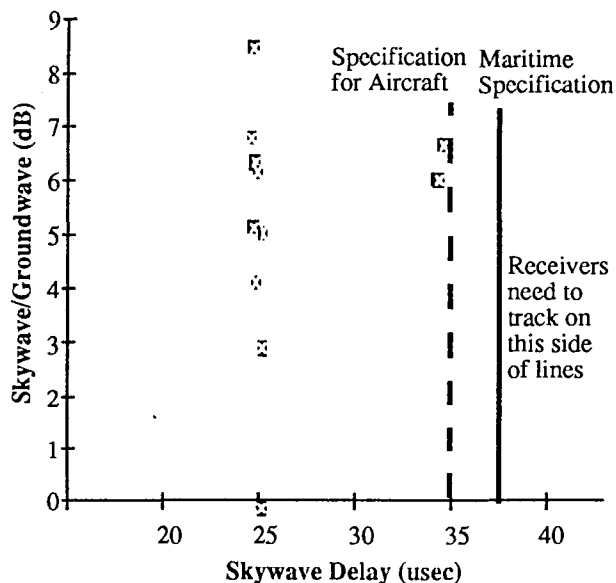


Figure 9. Skywave to Groundwave Ratio vs. Skywave Delay for out of tolerance periods.

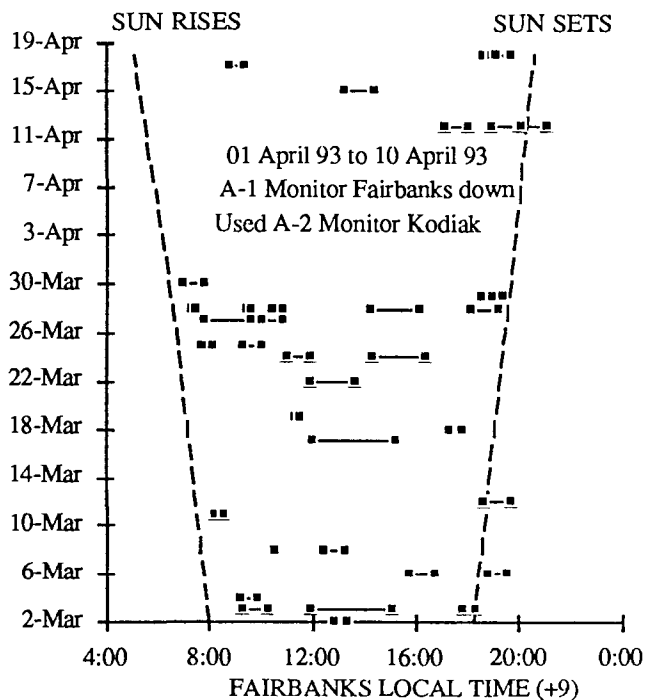


Figure 10. Blink times as a function of time of day for 7960Z as monitored at Fairbanks.

OMEGA/RUSSIAN ALPHA MONITOR

For a number of years the Academy has studied the Russian Alpha system [5], and recently developed an integrated Omega/Russian Alpha monitor receiver [6]. Since the path to New London from three of the five stations in the Alpha system, is directly over the Greenland ice cap (see Figure 11), reliably monitoring these stations has proven

difficult. The propagation paths to Fairbanks from all five stations are excellent and they are monitored easily. Figure 12 shows the average relative signal strength of all the signals in the Alpha epoch.

FUTURE EFFORTS

In a cooperative effort with the University of New Hampshire, LT Al Arsenault, a CG officer in graduate school, recently began work on an MSEE thesis in this area under the joint supervision of Professor Al Frost at UNH and Academy faculty. He will attempt to correlate our observations with solar activity and theoretical predictions of skywave amplitude and delay. In addition, we tentatively plan to install a second, similar, system at the Kodiak monitor site. This will allow us to continuously monitor both Kodiak and Tok both in the near far field for accurate groundwave templates, and at distances where skywaves are a problem. The COCO has also been provided with a portable system that will facilitate acquiring a Port Clarence template when traveling and further Port Clarence analysis.

In addition, the Academy is presently working on the addition of GPS time transfer capability to the monitor system. This will allow for the remote collection of GPS data and absolute LORAN TOA and Omega and Russian Alpha phase information.

ACKNOWLEDGMENTS

The LORAN portion of this project was funded by the Radionavigation Division of Coast Guard Headquarters, COMDT(G-NRN), and the Omega/Russian Alpha portion by the Omega Navigation System Center. We sincerely appreciate the cooperation LT Dave Watkins, the COCO at Kodiak and his staff, the FAA staff in Alaska, particularly Peter Snow in McGrath, and Melanie Totten in Fairbanks, the LORAN branch at the Electronics Engineering Center (EECN) in Wildwood, NJ, particularly LT Stan Carson, Bruce Henzel, formerly with JET, and ET2 Anthony Fusco, of the Academy EE Section Support Staff.

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Figure 11. Great circle paths from Russian Alpha stations to Fairbanks and New London.

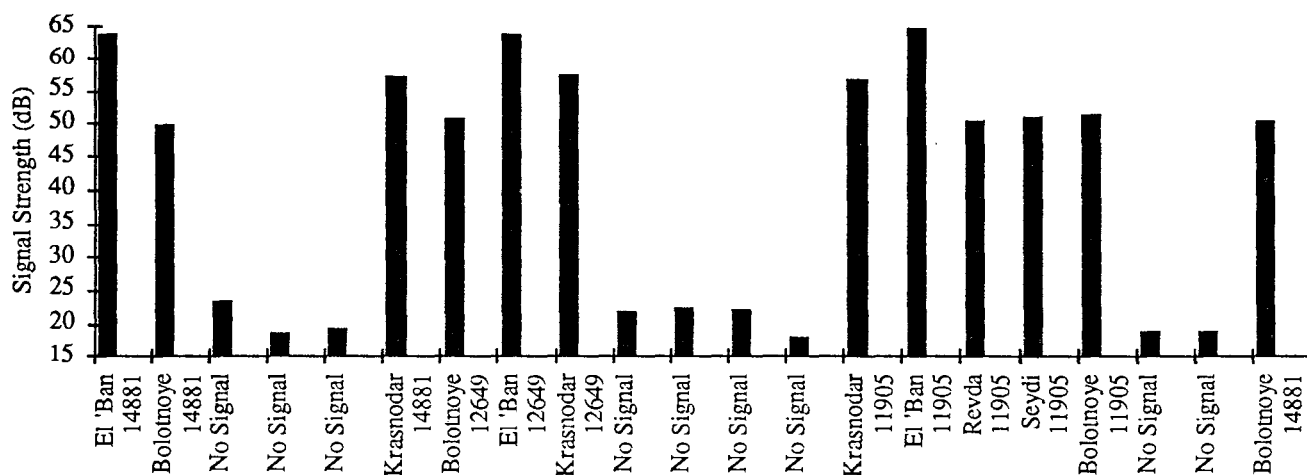


Figure 12. Signal Strengths of Russian Alpha signals (re. arbitrary reference.)

High-efficiency Loran-C interference spectrum analysis by synchronous sampling

Yi Bian and David Last

School of Electronic Engineering and Computer Systems

University of Wales, Bangor

United Kingdom

Email: bian@sees.bangor.ac.uk

Abstract

This paper proposes a new technique for estimating the frequencies within carrier wave interference (CWI), suitable for implementation in Loran-C receivers. The novelty of the method lies in its taking signal samples synchronously with the Loran-C pulses and then ensemble-averaging them in the time domain prior to conventional spectrum analysis. With this technique, each interferer is automatically weighted according to its effect on the operation of the receiver's tracking loops, without requiring knowledge of the tracking-loops' frequency response or the precise frequencies of the interferers. The paper demonstrates that the new method substantially increases the efficiency with which the most insidious interferers may be pin-pointed. In particular, it reduces the memory requirements to levels which impose minimal additional costs upon existing receiver designs; hence we recommend that the technique be incorporated into the next generation of Loran-C receivers.

1 Introduction

Carrier wave interference (CWI) has attracted considerable attention from the Loran-C community in recent years [1, 2, 3, 4, 5], because of the high levels of CWI when Loran-C is used in the continental US and Canada for airborne or land navigation. CWI has also been a major concern of the planners of the new NW European Loran-C system, which is scheduled to provide coverage over the entire region by the end of 1995. In no other part of the world does CWI impose a greater threat to the operation of Loran-C than in NW Europe. Field trials have identified hundreds of interfering transmissions in the region and shown that many of them are synchronous and high powered [6].

CWI may be tackled at both the system and receiver levels. At the system level, judicious selection of

the Group Repetition Intervals (GRIs) of the Loran-C transmissions may substantially reduce the number of interferers which are synchronous and consequently reduce significantly the effects of CWI [7, 8]. In Loran-C receivers, front-end filtering has long been an effective means of CWI suppression but the problem of determining the frequencies of the most insidious interferers, so that receivers can tune their notch filters to them automatically, is still an unsolved problem.

Beckmann [4, 9] proposed implementing a spectrum analyser in a Loran-C receiver using standard Fast Fourier Transform (FFT) techniques. The difficulties he encountered included limited frequency resolution and excessive requirements of memory and computing time. He proposed a specialised spectrum estimation technique, using the Segmented Chirp-Z Transform (SCZT), which substantially reduced the memory size and effectively removed the resolution limitation [9, 10]. Nieuwland [5] subsequently proposed a technique of weighting the spectrum of the CWI by means of a time-domain windowing function. To apply these techniques successfully, however, two basic requirements have to be satisfied: the frequencies of the interferers must be estimated with a precision comparable to the receiver's tracking bandwidth, typically 0.1 or even 0.01 Hz; and the frequency response of the tracking loop must be known accurately.

This paper proposes a synchronous sampling technique and, the corresponding receiver signal processing procedures, for determining the frequencies of the most harmful CW interferers. The technique requires knowledge of neither the frequency response of the tracking-loop nor the precise frequencies of the interferers. It allows each interferer to be weighted automatically according to its effect on the receiver's time of arrival (TOA) measurements. Consequently, the method can substantially improve the efficiency with which the most harmful interferers may be pin-pointed. In fact, it reduces the memory and computing requirements to

the level at which they add only minimally to the costs of receivers.

The rest of the paper is organised as follows. Section 2 reviews the principles by which receivers measure TOAs and Section 3 presents equations which describe the operations of phase-decoding and averaging in a receiver phase-tracking loop. Section 4 describes the proposed new synchronous sampling technique designed for CWI spectrum analysis. Section 5 discusses the properties of accumulated signals and Section 6 the techniques for spectrum analysis. Section 7 compares the new technique with previous ones and Section 8 gives an example to illustrate its operation.

2 Principles of TOA measurement in Loran-C receivers

This section reviews briefly the operational principles of the signal processing used in Loran-C receiver to make TOA measurements.

A Loran-C receiver determines its position by measuring TOA differences (TDs) between pairs of received Loran-C signals. A TOA is determined by measuring the arrival times of a specific zero-crossing of the Loran-C pulses. Three signal processing operations are also carried out: front-end filtering, phase-decoding and averaging (or accumulation) of corresponding samples of the signal. In the discussion which follows, no distinction is made between the concepts of *averaging* and *accumulation* since they result in the same reduction of noise and interference.

Fig. 1 shows the block diagram of a simplified Loran-C receiver. Front-ending filtering is carried out by the Bandpass Filter and Notch Filters blocks. The Phase-tracking Loop and Cycle-selection Loop do the phase-decoding and averaging. The Phase-tracking Loop tracks a zero-crossing of the pulse by locking onto its carrier phase; and the Cycle-selection Loop finds and tracks the correct zero-crossing by calculating the ratio of the two half-cycle peaks (HCPR) which straddle it.

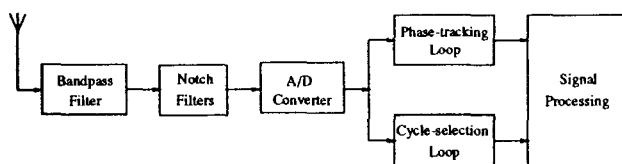


Figure 1: Block diagram of simplified Loran-C receiver

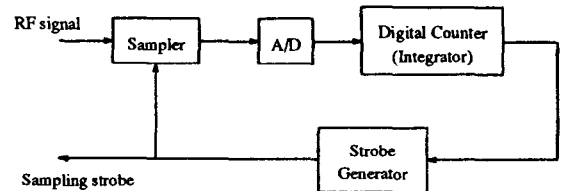


Figure 2: Block diagram of phase tracking DPLL

Fig. 2 shows the block diagram of a digital phase locked loop (DPLL) suitable for use in both linear and hard-limiting receivers. To illustrate the principle of using a DPLL for phase tracking, consider a hard-limiting receiver. The input signal is the received RF following front-end filtering. The A/D converter outputs either +1, if the signal is positive, or -1 if it is negative, at the instants of the samples. These +1 and -1s represent the times of the sampling strobe relative to the zero-crossing; hence they can be used to steer the sampling strobe to be coincide with it. Once the DPLL is in lock, the time of the sampling strobe represents the TOA measurement of the RF signal.

In practice, the sign of the signal may be affected by noise and interference. A Digital Counter (or Integrator) is employed which averages the output of the A/D converter or simply accumulates it until a pre-set limit is exceeded. Note that the Loran-C signals must be phase-decoded before the samples are accumulated; this operation may be accomplished by multiplying the samples by the phase-code of the Loran-C pulse.

In a stationary receiver a simple up/down accumulating counter is sufficient to locate and track the zero-crossing using the mechanism described. Such a DPLL is normally called a 'first-order loop'. In a moving receiver it produces an error proportional to velocity, so a 'second-order loop', in which the strobe is controlled by both the contents and rate of accumulation of a first-order up/down counter is used in most receivers.

In a linear receiver, the A/D converter outputs multi-bit digital signals which represent the amplitude and sign of the signal. The sampling strobe is steered by integrating these numbers.

3 Phase-decoding and averaging

This section analyses the phase-decoding and averaging operations in a receiver phase-tracking loop. The results are useful when formulating and analysing the proposed synchronous sampling technique.

A Loran-C signal consists of a train of Loran-C pulses. Let $x_0(t)$ represent a normalised standard Loran-C pulse. Let $x_L(t)$ denote a Loran-C signal over N periods of 2GRI. It has been shown in [11, 12, 13] that $x_L(t)$ may be described explicitly by:

$$x_L(t) = \sum_{n=1}^N \left[\sum_{m=1}^{16} x_0(t) * \delta(t - t_m) pc(m) \right] * \delta(t - t_n) \quad (1)$$

where t_m is the start time of the m -th pulse within 2GRI, δ is the Dirac function, t_n is the start time of the n -th 2GRI and $pc(m) = \pm 1$ is the phase code of the m -th pulse within 2GRI.

In the presence of noise and interference, the received composite signal may be expressed as:

$$x_c(t) = x_L(t) + x_{int}(t) + e(t) \quad (2)$$

where $x_{int}(t)$ and $e(t)$ are the CWI and noise components, respectively, of the total received signal.

The phase-decoding and averaging operations are carried out on this composite signal. Phase decoding is accomplished by multiplying each pulse by its phase code. Averaging is performed on signal samples all taken at the same point on successive Loran-C pulses. The result of these operations may be expressed by:

$$y(t) = \frac{1}{16N} \sum_{n=1}^N \left[\sum_{m=1}^{16} x_c(t + t_m + t_n) pc(m) \right] \quad (3)$$

where t represents the time of the sampling strobe of the first Loran-C pulse to be averaged and $y(t)$ is the output of the Digital Counter block in Fig. 2. Since it is the value of $y(t)$ that decides the direction in which the sampling strobe is to be steered, the effects of CWI on TOA measurements can be completely evaluated by assessing the changes of $y(t)$ caused by CWI [12, 13]. We will return to this point in Section 5.

4 Synchronous sampling technique

This section describes a synchronous sampling technique designed for analysing the CWI spectrum.

Notch filters must be tuned to the most harmful interferers if they are to be used most effectively. However, all the techniques to allow receivers to identify these which have so far been proposed demand excessive memory and computing resources. These requirements may be substantially reduced by performing

CWI spectrum analysis on synchronously-taken samples which have been ensemble-averaged rather than on samples obtained independently of the phase-tracking operation of the receiver.

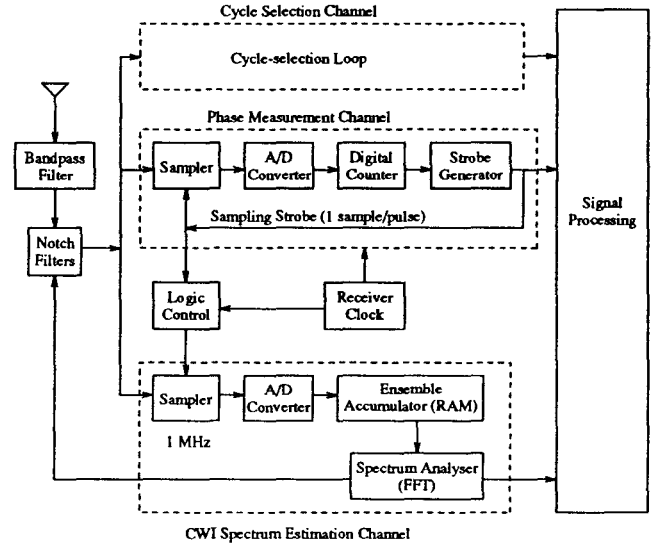


Figure 3: Novel Loran-C receiver illustrating signal processing for CWI spectrum estimation using synchronous sampling technique.

Fig. 3 shows the block diagram of a novel Loran-C receiver which implements the synchronous sampling technique for CWI spectrum estimation. Comparing this diagram with Figs. 1 and 2, it is seen that the conventional operations of phase-tracking and cycle-selection are retained, but a CWI Spectrum Estimation Channel has been added. Note how this new channel is synchronised to the conventional Phase Measurement Channel so that signal samples in the two channels are accumulated in exactly the same way. This synchronisation is accomplished by the Logic Control block which combines the Sampling Strobes from the Phase Measurement Channel with the main Receiver Clock to generate the strobes to drive the Sampler of the CWI Spectrum Estimation Channel.

Let us consider the synchronisation between the Phase Measurement Channel Sampling Strobes and the synchronously-sampled and ensemble-accumulated signals. Let the Standard Zero-Crossings (SZCs) represent the times of the received Loran-C pulses; the receiver tries to track these SZCs with Sampling Strobes. The signal sampling period over which the spectrum is analysed starts with each Sampling Strobe and continues for a time interval defined as the Ensemble Average Interval (EAI). Corresponding signal samples from different EAIs are accumulated; the accumulation is done

by first phase-decoding each sample (as in the Phase Measurement Channel) and then summing corresponding samples.

CWI spectrum estimation uses the accumulated signal, accumulation being performed immediately after a signal sampling; thus it is no longer necessary to store individual signal samples. Clearly, once the sampling rate has been fixed, it is the EAI which determines the amount of RAM needed to store the ensemble-accumulated samples, regardless how many EAI are being accumulated.

Before discussing further the use of the accumulated signals, the effects of the synchronous sampling and ensemble-accumulation operations on the CWI spectrum must be considered.

5 Properties of the ensemble-accumulated signals

Two important properties of the ensemble-accumulated signals will be considered.

Property 1. The synchronous sampling and ensemble-accumulation operations preserve the spectrum of the CWI, with a scaling factor.

To demonstrate this property, we first describe the synchronously-sampled and then *averaged*, rather than *accumulated*, signals; the difference between the two is simply a constant amplitude scaling factor.

In Section 3 we described the phase-decoded and averaged signal samples, as in a TOA measuring phase-tracking loop. The resulting equation (3) may also be used to describe the operations of synchronous sampling and averaging in the CWI Spectrum Estimation Channel. Retaining the notation of Section 3, and letting t denote the time of any arbitrary signal sample, we can express the ensemble averaged signal as:

$$z(t) = \frac{1}{16N} \sum_{n=1}^N \left[\sum_{m=1}^{16} x_c(t + t_m + t_n) pc(m) \right] \quad (4)$$

Note that this equation can be thought of as a generalisation of equation 3 since $y(t)$ there can be regarded as a point on $z(t)$: that is, the point corresponding to the Sampling Strobe.

By taking the Fourier Transform of equation 4, it can

be shown that

$$Z(f) = X_c(f) \cdot R_1(f) \cdot R_2(f) \quad (5)$$

$$\text{where } R_1(f) = \frac{1}{N} \sum_{n=1}^N \exp(+j2\pi f t_n) \quad (6)$$

$$\text{and } R_2(f) = \frac{1}{16} \sum_{m=1}^{16} \exp(+j2\pi f t_m) pc(m) \quad (7)$$

where $Z(f)$ and $X_c(f)$ are the Fourier Transforms of $z(t)$ and $x_c(t)$ (equation 2), respectively.

Equations 5-7 show that the spectrum of $z(t)$, the synchronously sampled and averaged signal, is identical with the spectrum of $x_c(t)$, the original signal, but multiplied by a frequency function $R_1(f)R_2(f)$. More significantly, since the phase-decoding and averaging operations in the CWI Spectrum Estimation Channel are synchronised to those in the Phase Measurement Channel, and since $y(t)$ can be treated as a specific point on $z(t)$, the mathematics for deriving equations 5-7 and the ratios of CWI attenuation provided by the phase-tracking loop are identical to one another [11]. Therefore, not surprisingly, $R_1(f_{int})R_2(f_{int})$, where f_{int} represents the frequency of CWI, is seen to be the ratio of CWI attenuation provided by the phase tracking loop. More specifically, $R_1(f_{int})$ and $R_2(f_{int})$ are the CWI attenuation ratios due to the operations of averaging and phase-decoding, respectively [13]. Consequently, the spectral components of $z(t)$ is simply the CWI spectrum scaled by the corresponding CWI attenuation ratios of the phase-tracking loop. This important observation may be summarised as the following property of the accumulated signal.

Property 2. The CWI spectrum of an ensemble-accumulated signal is identical to the spectrum of the CWI, but scaled by the attenuation ratios provided by the phase-tracking loop of the receiver.

Using this Property, the problem of determining the frequencies of the most harmful CW interferers becomes that of analysing the CWI spectrum from the accumulated signal.

6 Spectrum estimation using ensemble-accumulated signal

This section discusses techniques for analysing the CWI spectrum using the ensemble-accumulated signal. Also addressed are some practical issues affecting the implementation of the technique in Loran-C receivers.

6.1 Fast Fourier Transform (FFT)

The FFT technique is used to analyse the spectrum; the FFT is an efficient algorithm for generating the Discrete Fourier Transform (DFT) which is readily available in digital signal processing (DSP) text books and software packages. Let us consider the principles of the DFT and the use of the FFT.

Let $x(n)$ denote a sequence of samples of signal $x(t)$ at sampling frequency f_s . Let $X(f)$ denote the Fourier transform of $x(t)$ and let $X(k)$ denote the k -th frequency sample of $X(f)$. The DFT of $x(n)$, of length N , is defined as:

$$X(k) = \sum_{n=0}^{N-1} x(n) \exp \left[-j \frac{2\pi n k}{N} \right] \quad k = 0 \dots N-1 \quad (8)$$

In this definition N is the total number of signal samples in either the time or the frequency domain. The time increment between $x(n)$ and $x(n+1)$ is the sampling interval, $\Delta t = 1/f_s$; the frequency increment between $X(k)$ and $X(k+1)$ is the DFT frequency resolution, $2\pi/N$. So the analog frequency resolution of the DFT is

$$\Delta f = f_s/N = 1/(N\Delta t) \quad (9)$$

Computation of the DFT according to equation 8 requires N^2 major calculations (multiplications). By minimising computational redundancy, FFT algorithms can compute the DFT using $N \log_2 N$ multiplications. When N is a power of 2, such as $1024 = 2^{10}$, only this minimum number of multiplications are required.

6.2 Resolution of the CWI spectrum

When implementing the proposed technique in Loran-C receivers, the resolution with which CWI frequencies will be estimated is an important design parameter. Equation 9 showed this resolution to equal the reciprocal of the period of time over which sampling is carried out, which equals $N\Delta t$. To minimise the memory and computation requirements, the resolution should be as low as possible. However, it must be adequate to allow the notch filters to be adjusted sufficiently precisely. We conclude that the resolution should be comparable with, or finer than, the widths of the notch filters: say, half the notch width.

An ideal notch filter would be just sufficient to notch out an individual spectral components of the CWI. In practice, analogue-circuit notch filters with widths in the range 1–3 kHz are generally used. They operate

successfully without causing significant pulse distortion. They are effective in suppressing the broader modulated interferers and also the groups of closely-spaced narrow-band Decca Navigator signals which are major interferers in Europe.

6.3 Estimation of memory size

The size of the receiver memory required is determined by the number signal samples needing to be stored, that is, by the EAI and the sampling rate. For a frequency resolution of Δf and a sampling rate of f_s , the total number samples of the accumulated signal is

$$N = \frac{f_s}{\Delta f} \quad (10)$$

and the duration of the EAI is

$$EAI = N \cdot \Delta t = \frac{f_s}{\Delta f} \cdot \frac{1}{f_s} = \frac{1}{\Delta f} \quad (11)$$

So, for example, with a sampling rate of 1 MHz and the coarsest frequency resolution of 1.5 kHz (half a 3 kHz notch), the EAI is 0.6 ms and only 667 samples would need to be stored. Assuming that double precision (8-bytes) is used, the total RAM is 5.3 kbytes. Even if we adopt the finer resolution of 0.5 kHz, and retain the sampling rate, the required RAM is only 16 kbytes. So we conclude that the memory requirement is not an obstacle to the implementation of the technique.

6.4 Processing power requirement

The computing power required to perform the FFT is dominated by the multiplications. For a standard FFT of radix 2, $N \log_2 N$ multiplications are needed. To estimate the numbers of multiplications for FFTs of 1000 and 3000 samples, we round off the sample numbers to the closest powers of 2: 1024 and 4096. Thus, 10240 and 49152 multiplications, respectively, are required. With today's VLSI technology, general purpose DSP chips which meet this computing requirement are widely available at low cost. Preferably the FFT would be implemented in software using the receiver's micro-processor.

7 Comparisons and discussions

This section compares the proposed technique with the best known existing techniques for CWI spectrum estimation, considering the memory size and computing resources required.

7.1 Beckmann's and Nieuwland's work

Beckmann was among the first to outline a fully-digital implementation of a Loran-C receiver [4]. His novel receiver structure employed a spectrum analyser to determine the frequencies of the most harmful CWI and tune the notch filters accordingly. However, he performed the spectrum analysis directly on samples of the received signal. To account for the degree of synchronicity of the various interferers, he proposed weighting the amplitudes of the individual interferers according to their proximity to the nearest Loran-C spectral line. This required a frequency resolution of the order of the phase-tracking loop: that is, at most 0.1 Hz. To achieve such a high resolution, the received signal had to be sampled for at least 10 seconds. Even if only a 300 kHz sampling rate was used, the number of samples to be stored was at least 3 million. Assuming each sample to occupy 8 bytes, 24 Mbytes memory were required which was prohibitive.

Realising the difficulties of using the standard FFT, Beckmann proposed using an alternative spectrum estimation technique, the Segmented Chirp-Z Transform (SCZT), and the quadrature sampling technique [14]. The SCZT is a modified CZT; in contrast to the DFT, the CZT is flexible in that it can calculate only a portion of the received spectrum. The SCZT divides the received signal into segments, computes the CZT of each, and sums them. The memory for storing the samples of a segment can be re-used once its CZT has been computed.

The SCZT can save significant memory at the expense of algorithm complexity and processing power. It is much slower and requires much more processing power than the FFT. Nieuwland commented: 'In fact, when the segment size equals 1, the much slower DFT implementation of the CZT is reached'[5]. Nieuwland continued Beckmann's work on both the SCZT and the quadrature sampling technique[5]. He showed that the weighting of the estimated CWI spectrum can be done in the time domain and he also tried various techniques to improve the weighting accuracy.

7.2 Discussions

Comparing our technique of synchronous sampling and accumulation with Beckmann's and Nieuwland's methods, it is seen that they need to analyse the spectrum with a resolution comparable with the bandwidth of the phase-tracking loop of the receiver. We require a resolution of the order of 1 kHz, that is, a reduction of at least 10000 times. It is this reduction that so

dramatically saves memory and processing power. It is no longer necessary to use the complicated SCZT algorithm.

Another very important advantage of the synchronous sampling technique is that it always applies the correct weighting to the CWI because the sampling and accumulation of the spectrum estimation channel is precisely synchronised with those of the phase-tracking channel.

8 A case study

This section reports a case study which uses the proposed technique to determine the frequencies of the most harmful CWI. Computer simulations have been carried out and the results are seen to agree well with theoretical analyses.

A computer program has been written which simulates the operation of the proposed technique. Simulated Loran-C signals, together with noise and interference, have been generated in the way as described in [13, 15]. This noisy composite signal passes through a receiver-front-end simulator and is then sampled synchronously. The accumulated samples are fed into a CWI Spectrum Estimation Channel (Fig. 3), which determines the frequencies of the most harmful CWI.

The composite signal contains 6 CW interferers, each of 0 dB SIR, plus Gaussian noise also at 0 dB SIR. The accumulated signal was sampled at 1 Msample/s, and the sampling period (the EAI) was 1024 μ s. Therefore, the resolution of the estimated spectrum is 0.97 kHz. The GRI of the Loran-C signal was 5000, a particularly difficult value in practice since any interfering frequency at a multiple of 10 Hz is synchronous. The six interferers included two synchronous ones (0 Hz 'Difference' (Table 1), that is, frequency separation from the nearest spectral line), one near-synchronous (0.1 Hz Difference), and three asynchronous ones. To assess the effect of the spectral weighting, samples were accumulated over various numbers of GRIs. When no accumulation was used, all 6 interferers were estimated to have signal strengths equivalent to approximately 0 dB SIR.

Next, samples were accumulated over 2, 20 and 100 GRI periods; Fig. 4 plots the resulting spectral estimates, and the columns of Table 1 headed 'Estimated' show the frequency and power outputs of the analysis; the power is with respect to the strongest interferer in each case. The accumulation process reduces the am-

plitude of the synchronous interferer at 85000 Hz by 12 dB and the one at 123420 Hz by 18 dB by virtue of phase decoding alone. The 85000 Hz interferer is the strongest output, and so is set to 0 dB, and the 123420 Hz one is at -6 dB relative to it. Accumulation reduces the near-synchronous interferer at 115000.1 Hz by a little more than that at 85000 Hz because of the additional effect of the loop filter roll-off. However, it attenuates the non-synchronous interferers so dramatically that they cannot even be seen above the noise in the spectrum accumulated over 100 GRIs; only the three significant interferers, and the Loran-C transmission, remain.

Frequency (Hz)	Difference (Hz)	GRI ×	Estimated		Power (dB)
			Freq. (kHz)	Power (dB)	
76334.9	4.9	2	76.2	-5.4	-5
		20			-35
		100			-39
79642.6	2.6	2	80.1	-2.5	-1
		20	80.1	-19.6	-19
		100			-217
85000.0	0	2	85.0	0	0
		20	85.0	0	0
		100	85.0	0	0
111556.9	3.1	2	111.3	-5.2	-5
		20			-33
		100			-37
115000.1	0.1	2	115.2	-1.1	-0
		20	115.2	-0.3	-0.2
		100	115.2	-4.5	-4
123420.0	0	2	123.1	-7.7	-6
		20	123.1	-6.7	-6
		100	123.1	-6.8	-6

Table 1. *Estimated CWI frequencies and powers, illustrating weighting effect of phase-decoding and accumulation. All power levels in dB with reference to strongest component; only signals more than 10 dB above the noise listed. Final column is calculated powers. (GRI=5000).*

To verify the results of the computer simulation, the final column of Table 1 shows the values of CWI power calculated by using equations 6 and 7. The agreement is very satisfactory: the estimated power results agree with the calculated figures to within 1.7 dB and the estimated frequencies agree with those of the interferers within 0.5 kHz. The results have also been compared with Nieuwland's under the same conditions: the agreement is very close, with less than 7 dB discrepancy in most cases. The saving of memory and processing power resulting from the proposed technique may also be estimated by comparing our 100 GRI accumu-

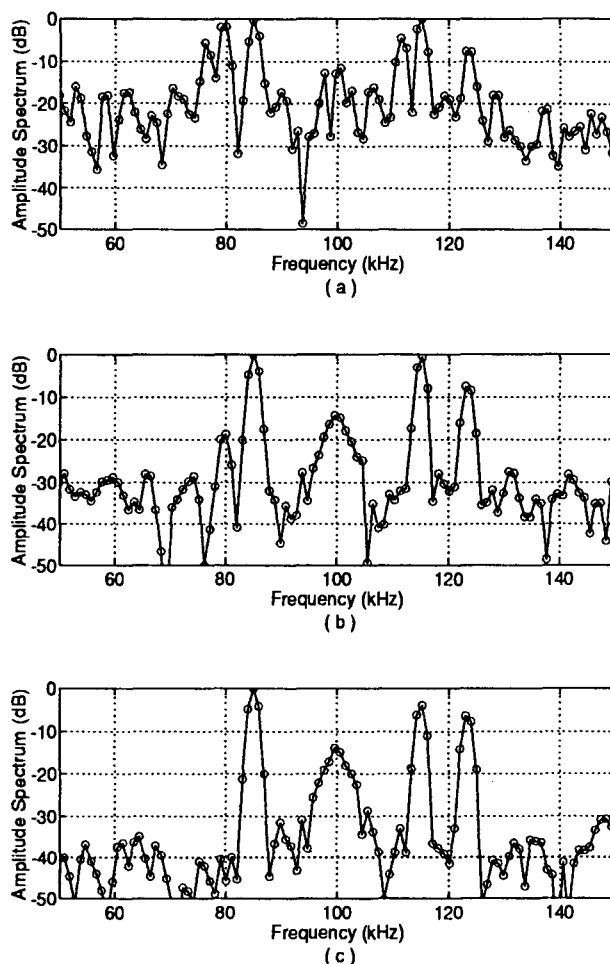


Figure 4: *Estimated CWI spectra using samples ensemble-accumulated over (a) 2, (b) 20, and (c) 100, GRIs. Increasing accumulation reveals Loran-C signal and synchronous and near-synchronous interferers. (EAI=1024 μ s and GRI=5000).*

lated results with Nieuwland's data from 5 s of samples: Nieuwland's simulation processed '250 · 10³ samples of a total 2 · 10⁶ samples'; ours processed just 1024 samples.

9 Conclusions

An effective technique for determining the frequencies of the most harmful CWI is becoming increasingly desirable. This is because CWI levels are significantly higher on and over land than those traditionally met in the marine environment, and because of Loran-C expansion in Europe. This paper has proposed a synchronous sampling technique for analysing the spectra of received signals. With this technique, each interferer is weighted automatically according to its effect on the

operation of the receiver's tracking loops. The new approach substantially increases the efficiency with which the most insidious interferers may be identified. The technique is simple in principle and very easy to implement. Its memory and processing power requirements are at levels which impose minimal additional hardware and time costs. We recommend that the technique be incorporated into the next generation of Loran-C receivers.

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Dr. Yi Bian graduated from Department of Precision Instrumentation of Shanghai Jiao Tong University, P.R. China in 1985, with the highest honours of the year. He completed his M.Sc. in 1987 and continued work on inertial navigation systems as both PhD candidate and research assistant until 1990. Thereafter, in just two years, he completed a PhD in School of Electronic Engineering and Computer Systems of the University of Wales, Bangor, UK, working on signal processing techniques for Loran-C radio navigation receivers. Since 1 October 1992 he has been employed as a Post-doctoral Research Fellow by the University of Wales. His current research interests include signal processing techniques and their applications to communications systems, in particular radio navigation systems and optical telecommunications systems.

Dr. David Last is a Reader in the University of Wales. He was awarded the degree of B.Sc(Eng). by the University of Bristol, England in 1961 and the degree of Ph.D. by the University of Sheffield, England in 1966. Dr. Last is a Fellow and Council Member of the Royal Institute of Navigation, a Fellow of the Institution of Electrical Engineers, and a Chartered Engineer. He has published many papers on radio-navigation systems, especially on applications of the Decca Navigator System and Loran-C. He acts as a Consultant on radio navigation and communications to companies and government departments. He is an instrument-rated pilot and aeronautical user of Loran-C.

Assessment of Near Electric and Magnetic field strengths in the vicinity of Loran-C Transmitting Antennas

by

Michael E. McKaughan, PhD.
Ensign Nathan Rausch, BSEE.

Department of Engineering
United States Coast Guard Academy (de)
15 Mohegan Avenue
New London, CT 06320-4195

Phone 203-444-8538
FAX 203-444-8546

Abstract

Interest in determining levels of electromagnetic fields in the vicinity of a Loran-C transmitting antenna was recently renewed by the planned maintenance of the antenna at Loran-C transmitting station, Cape Race, Newfoundland. While the impetus for this work has collapsed, we believed that a methodology for predicting near-field intensities was worthwhile. Thus, we began a project to assess the accuracy of computer modelling techniques to predict the near-field radiation levels in both electric and magnetic fields. This paper discusses our work to date, and presents results of computer simulations and field measurements. We have been especially interested in our ability to assess the fields encountered by workers climbing an excited Loran-C transmitting tower.

We developed a wire grid computer model of the antenna from civil engineering drawings of the tower. This model includes the essential current carrying members of the tower and the top loading elements. The computer model was analyzed using the method of moments technique computer program Numerical Electromagnetic Code (NEC). Near electric and magnetic field strengths were computed near the tower and inside the structure. Results are presented and compared with measured data collected at the USCG Electronics Engineering Center, Wildwood NJ.

Background

At the Coast Guard Academy we have recently become involved in issues dealing with radiation hazards aboard Coast Guard Cutters. One of these projects investigated radiation hazards posed by the high-frequency (HF) Miniloop Antenna on the 210-foot medium-

endurance class (WMEC) of cutters. During presentation of our results from this work, questions were raised concerning the possibility of investigating radiation levels in and around the Loran-C transmitting tower. In particular the Cape Race Loran-C transmitting antenna. At that time the workers were scheduled to perform preliminary work on the tower while the station continued to transmit. Little information was known of in the literature concerning radiation exposure levels on the tower. If a computer model could be developed to accurately predict the radiation levels on the Cape Race tower, or other LORAN towers, hazards to workers could be predicted and appropriate protective measures could be taken.

Early on in this investigation, the tower at Cape Race collapsed. This immediately lowered the priority of the project. However, we believed that developing a computer model of a 625-foot tower would be useful for future investigations.

In these investigations, no attempt was made to assess biological effects; we were interested solely in assessing near-electric and magnetic field levels in and around the transmitting tower. These assessments were then compared to applicable standards for radiation exposure levels. The Institute of Electrical and Electronics Engineers (IEEE) Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, C95.1-1991 is the current standard accepted by the Environmental Protection Agency (EPA).

Construction of a 625-foot Loran-C Transmitting Tower Model

The 625-foot Loran-C transmitting tower is built like a triangle, or prism. There are three faces of the tower, each five feet across, and 625

feet high. The tower is not tapered. The legs of the tower are constructed of $3\frac{1}{2}$ inch diameter pipes, and are stiffened by a series of tension rods and cross members. The tension rods form an "X" between the two legs bounding each face, and the cross members form a box around each X shape. This pattern is repeated, one X on top of the next, all the way to the top of the tower. Each X is 6 ft. 4 in. tall. The base section of the tower is an 8 ft. 4 in. high inverted pyramid section which mounts atop the base insulator. The base insulator is a large porcelain block attached to a concrete footing. The top portion of the tower is constructed to form a high-voltage corona ring around the tower.

While these details of the tower construction are unimportant to the station operator, we believed that to correctly model the tower, we needed this detail. Our computer model was generated by forming a single 625-foot face of the tower and then rotating this face through an angle of 120 degrees to form the second face, and an additional rotation of 120 degrees to form the third and closing face. The top and base sections were likewise modeled as single faces and rotated. This technique was used to reduce the number of individual elements needed to model the tower and to take advantage of the symmetry of the structure.

Currents in a LORAN tower

Antenna current is directly responsible of the electromagnetic intensity in both near and far fields. The method of moments (MOM) modeling technique calculates the currents in each segment of the model, and then computes the electric and magnetic fields from the currents, obtaining the total field at a point by summing the contributions of the current in each elemental piece of the antenna.

Armed with this information, we carefully analyzed the tower structure to determine which elements would be required in the model and which might be eliminated because of their orientation. We determined that the horizontal elements of the tower structure could be eliminated, since any current in them would be insignificant compared to currents in elements with vertical aspects. Thus, our tower model includes only the vertical legs of the tower and the legs of each X brace.

Because of the insulators in the guy wires and the support wires for the top-loading elements (TLEs) these were also not included in the model.

Initially, we attempted to include in our model the catenary sag in each TLE. This proved to be extremely difficult. Further, because of computer memory limitations, we modeled each TLE as three straight segments.

Numerical Electromagnetics Code (NEC)

The Numerical Electromagnetics Code (NEC) is a computer program developed at Lawrence Livermore National Laboratories through the support of several government agencies, including the Army and the Navy. This program computes the currents induced in a structure, and the electric and magnetic fields produced by these currents. The program uses the method of moments to calculate the results. In order to use the NEC in modeling the fields surrounding a LORAN tower, all the conducting pieces in the tower are described as wire segments by specifying the spatial coordinates of each end point and a radius for that element. The input file for the NEC is a series of one line descriptions or commands. An input file contains the geometry of the model, and the calculations to be performed. The NEC assumes that the current is constant throughout each single segment, so it is important that the segments be a small enough portion of a wavelength for this assumption to be valid.

Computing time was a significant concern, because run time for the computer increases as the cube of the number of segments in the model. A 1300 segment model of a ship took around 12 hours to run on a Macintosh model FX computer with 64 megabytes of random access memory (RAM). The particular version of the NEC that was used to compute the fields for the model of the 625-foot tower allowed a maximum of 1600 wire segments, and the estimate for run time with a 1600-segment model was 23 hours. By using the tower symmetry already mentioned, we achieved a significant reduction in the computational run-time. The final tower model contained 1581 segments. Each computational run on our computer took two hours and thirty minutes. Thus, by using symmetry in the model, we reduced the computational time significantly.

Modeling the TLEs was difficult because their exact catenary was not known. When the tower was built, the TLE's were loaded by tension. While this technique made the tower evenly loaded structurally, the length of each TLE was not known precisely, nor was the amount of sag known. As an estimate for preliminary

modeling purposes, we assumed that the TLEs each sagged below a straight line from the top of the tower to the TLE earth anchor point. At a horizontal distance from the tower base of 450 feet, we assumed the sag to be forty feet. During our field trip to the USCG Electronics Engineering Center (EECEN), Wildwood, NJ, we recorded measurements that showed the sag to be sixty feet at the 450-foot distance from the tower base.

Antenna Feed Model

To retain the symmetry of our model, we could not model the normal single-point feed used at a Loran-C transmitting station. Instead, we used three identical voltage sources in the legs of the base section of the tower. Since the transmitter is generally modeled as a current source supplying a feed drive current, we simply used a resistance in series with each voltage source that would provide an essentially constant current of one third of the total drive current in each tower leg. The voltage source and series resistor were used because the NEC does not have a current source feed implementation. As long as the tower driving point impedance was much less than the series resistance, this configuration would approximate a current source feed.

Field Measurements and Allowable Standards

Both electric and magnetic field strengths were observed along a line, six feet above the ground, extending from the base of the tower at EECEN, to the point where the TLE is attached to the ground anchor. This line was directly under one of the TLE's. A surveyor's transit was set up next to the ground anchor to measure angles between the top of the tower and insulators along the cable. These angles were used to estimate the catenary in the TLE.

The field strength instrument used to take these field measurements was a portable E and H field meter, model HI 3603 from Holaday Industries. This instrument was designed to be used to measure radiation levels from cathode-ray video display terminals. The frequency response of this device was useful beyond 200 kHz. It is the size of a large ping-pong paddle, and has a liquid crystal display. The data values that were gathered behaved reasonably consistent with what was expected, and the values are in an acceptable range. To read from the meter, it was rotated until an orientation was found that gave a maximum value. The output did not constantly

hold a single value, but jumped around about $\pm 5\%$ of the recorded value. There was no averaging function.

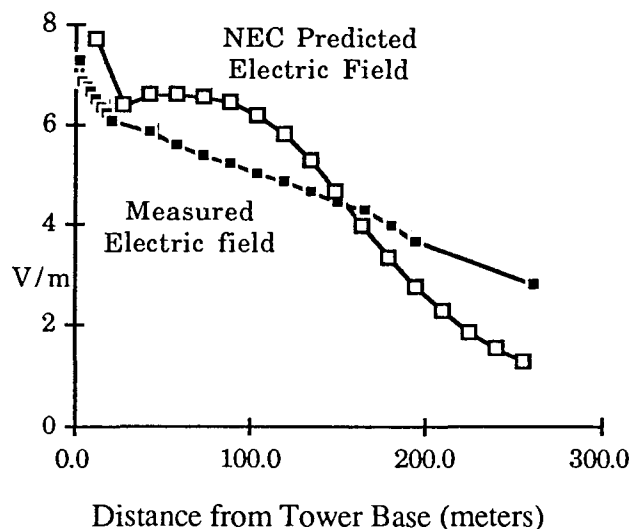


Figure 1. Predicted and measured electric field strengths radially outward from the tower base.

The computer model was used to predict the field strengths at the points where measurements were taken beneath the tower, and these predictions were then compared to what was measured. (Figure 1) The trends of the predicted and measured fields appeared to behave the same.

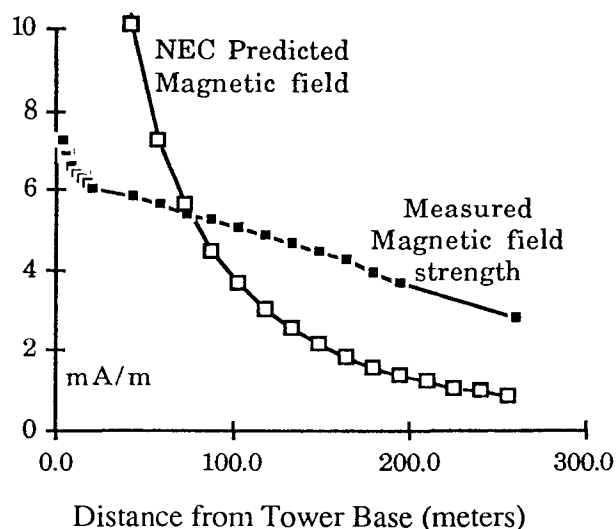


Figure 2. Predicted and measured magnetic field strengths radially outward from the tower base.

The IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic fields, states that the maximum allowable fields that persons may be exposed to at 100 kHz are 614 volts/meter and 163 amps/meter. The measurements that we made under the umbrella and near the base of the tower were about 100 times less than this limit (figures 1 and 2). Measured fields inside the tower were observed to be significantly lower than the levels established by the standard.

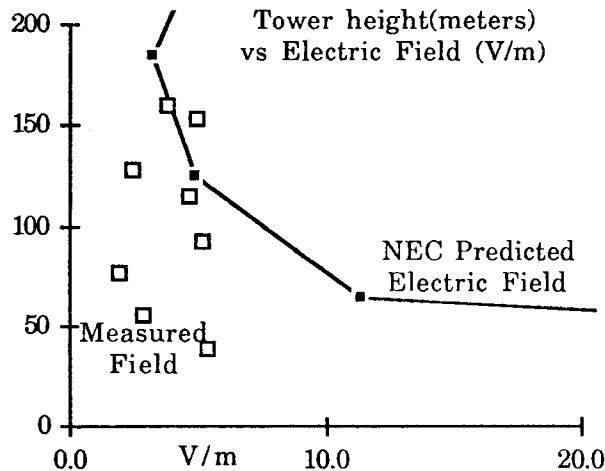


Figure 3. Predicted and measured electric fields inside the Tower

Model Short-comings

Because the model is driven by three individual voltage sources in parallel, the impedance seen by each of these sources must to be found by combining the three sources in a Thevenin equivalent model and then calculating the driving point load. Using this technique, the impedance of the antenna model was computed to be approximately $2.88 - j(130,000)$ ohms. This is a capacitive load as expected, but the value of the capacitance is three orders of magnitude too large.

The real resistance, however is almost exactly correct. Further investigations seem to indicate that the reactive component tends to be in error using extremely small segment lengths. We are continuing to investigate this discrepancy.

Conclusion

For points inside the tower, this model predicts that the strongest electric field strengths will exist at either end, but even these points do not approach the limits set by the IEEE. The strongest electric field that the model is predicting is 370 V/m, which is only 60 percent of the maximum allowed. This model is predicting stronger fields than were measured.

This model tests the limits of our NEC program by using 1581 segments to precisely model a Loran-C transmitting tower. Improvements can be made to the tower by using realistic ground conductivity, and by improving the computer to allow more segments in the model if needed. We expect to continue to develop our computer modeling capabilities through further research.

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Eigen-decomposition techniques for skywave estimation in Loran-C receivers

Yi Bian and David Last

School of Electronic Engineering and Computer Systems

University of Wales, Bangor

United Kingdom

Email: bian@sees.bangor.ac.uk

Abstract

We proposed at last year's WGA Symposium a new concept of receiver design which adaptively adjusts the sampling point to its optimal value in a constantly-changing skywave interference situation. We demonstrated the ability of two novel processing techniques, spectral-division and power-cepstral analysis, to estimate skywave delays for this purpose. This paper reports a new and better skywave estimation method that employs eigen-decomposition techniques. It shows that the problem of estimating the arrival times of skywave components is analogous to that of isolating the frequency components of a composite signal. The paper explains briefly the principle of frequency estimation using eigen-decomposition techniques and identifies a class of high-resolution algorithms. The improved performance achievable with their use is clearly demonstrated by computer simulation and using off-air Loran-C signals. The eigen-decomposition technique is shown to resolve the arrival times of the groundwave and skywave components successfully in situations in which both the spectral-division and power-cepstral methods fail. Incorporating these skywave estimation methods into receivers should significantly improve their timing-measurement accuracy and integrity.

1 Introduction

Most current Loran-C receivers determine the arrival times of groundwave pulses by sampling a fixed zero-crossing on their leading edges. If the sampling time is set too late, such receivers suffer unacceptable skywave errors; if too early they suffer low signal-to-noise ratio (SNR) and signal-to-interference ratio (SIR). At last year's WGA Convention, the present authors proposed a new concept of receiver design which adaptively adjusts the sampling point to its optimal value in a constantly-changing skywave interference environment. To estimate skywave delays ac-

curately, we demonstrated two novel processing techniques, spectral-division and power-cepstral analysis, both based on Fourier analysis techniques.

This paper reports a new and alternative skywave delay estimation method that employs eigen-decomposition techniques. The skywave interference model introduced in [1] is retained in the analysis. We will show that the problem of estimating the arrival times of skywave components is analogous to that of isolating the frequency components of a composite signal; consequently, we can take advantage of recent advances in this class of signal-processing techniques. Studies in superresolution frequency estimation techniques [2, 3] show that eigen-analysis methods have superior performance compared with the Fourier analysis techniques on which the spectral-division and power-cepstral analysis methods are based.

The paper explains briefly the principle of frequency estimation using eigen-decomposition techniques. A class of high-resolution algorithms is identified. These include the Multiple Signal Classification (MUSIC) algorithm, a variant called ROOT-MUSIC, and Estimation of Signal Parameters via Rotational Invariance Techniques (ESPRIT). The performance of techniques of this kind when used to estimate Loran-C skywave delay is studied. Extensive simulation results show that eigen-decomposition based techniques yield higher resolution skywave delay estimates and can operate successfully at lower SNR values.

The organisation of the rest of the paper is as follows. Section 2 presents a signal model and its frequency domain equivalent for use in studying skywave delay estimation. The model is valid for both Fourier and eigen-analysis techniques. Section 3 reviews techniques of skywave delay estimation based on Fourier analysis which were presented in [1]. The limitations of these techniques in terms of the resolution of skywave delay estimates are discussed. Section 4 describes the prin-

ciples of the new eigen-decomposition techniques and methods of applying them to the estimation of skywave delays. The performance of the techniques is studied by computer simulation in Section 5. Section 6 presents results from applying the techniques to the limited off-air data recently made available.

2 Signal models

It was shown in [1] that the received Loran-C signal, consisting of groundwave, skywave, plus noise and interference, may be represented in either the time domain or the frequency domain. The signal model employed for studying skywave delay estimation assumes that the skywaves have exactly the same shape as the groundwave but are delayed and have different amplitudes. In the time domain, the composite signal is described by:

$$x_c(t) = x_g(t) + \sum_{n=1}^N k_n x_g(t - \tau_n) + e(t) \quad (1)$$

where $x_g(t)$ is the groundwave signal and $e(t)$ the total noise and interference. The delays and amplitudes of the skywave components, relative to those of the groundwave, are represented by τ_n and k_n , respectively, the subscript n denoting the n -th skywave component.

In the frequency domain, the composite signal is represented by

$$X_c(f) = X_g(f) \left[1 + \sum_{n=1}^N k_n e^{j2\pi f \tau_n} \right] + E(f) \quad (2)$$

where $X_c(f)$, $X_g(f)$, and $E(f)$ are the Fourier Transforms of $x_c(t)$, $x_g(t)$, and $e(t)$, respectively.

Equations (1) and (2) constitute the signal model to be used for estimating the amplitudes and delays of Loran-C skywaves. Since the estimation of amplitude becomes relatively easy once the delays are known, we will concentrate on delay estimation.

3 Fourier-based techniques

This section reviews techniques for skywave delay estimation which use spectral-division and power-cepstral analysis. Details of these techniques are to be found in [1]. We concentrate here on the limitations of the techniques and we establish the need for further research leading to higher resolution frequency estimation methods.

3.1 Spectral-division method

It was shown in [1] that the Inverse Fourier Transform of the ratio of the spectrum of the received composite signal to that of the standard Loran-C pulse yields impulses which occur at the arrival times of the skywave components. Analytical, this is represented as

$$F^{-1} \left\{ \frac{X_c(f)}{X_0(f)} \right\} = k_g \left[\delta(t) + \sum_{n=1}^N k_n \delta(t - \tau_n) \right] + F^{-1} \left\{ \frac{E(f)}{X_0(f)} \right\} \quad (3)$$

where F^{-1} represents the Inverse Fourier Transform, $X_0(f)$ the spectrum of the normalised standard Loran-C pulse $x_0(t)$ [4] and k_g is a constant related to the amplitude of the groundwave.

Equation (3) establishes the principle of the spectral-division technique for estimating the delay times of skywave components. Computer simulation have shown that this method can detect skywaves and estimate their delay times at SNRs greater than 14 dB. Note that 14 dB is the SNR value *after* front-end filtering, phase-decoding, and averaging in the receiver phase-tracking loops. It should be contrasted with the SNR value of 27 dB, which results in 100 ns (rms) TD measurement errors, and which the US Coast Guard (USCG) have adopted as their minimum SNR value of -10 dB at the receiver input in predicting the coverage of Loran-C chains. This shows that the method operates successfully at values of SNR 13 dB below the minimum specified by the USCG.

3.2 Power-cepstral method

Cepstral analysis is a nonlinear processing technique for analysing data that contain an arbitrary unknown signal and its echoes. As was shown in [1], the method is based on the principle that the logarithm of the power spectrum of a signal containing an echo has an additive periodic component due to that echo. Therefore, the Inverse Fourier Transform of this log-power spectrum exhibits a peak at the echo delay. Mathematically, the power cepstrum of a signal $g(t)$ is defined as

$$\hat{g}_p(\tau) = F^{-1} \{ \ln |G(f)| \} \quad (4)$$

where $G(f)$ is the Fourier Transform of $g(t)$, $\ln$ represents the natural logarithm operation, and F^{-1} is the Inverse Fourier Transform operator.

Thus, by calculating the power-cepstrum of the received composite signal, skywave delays can be estimated. It was demonstrated in [1] that the technique

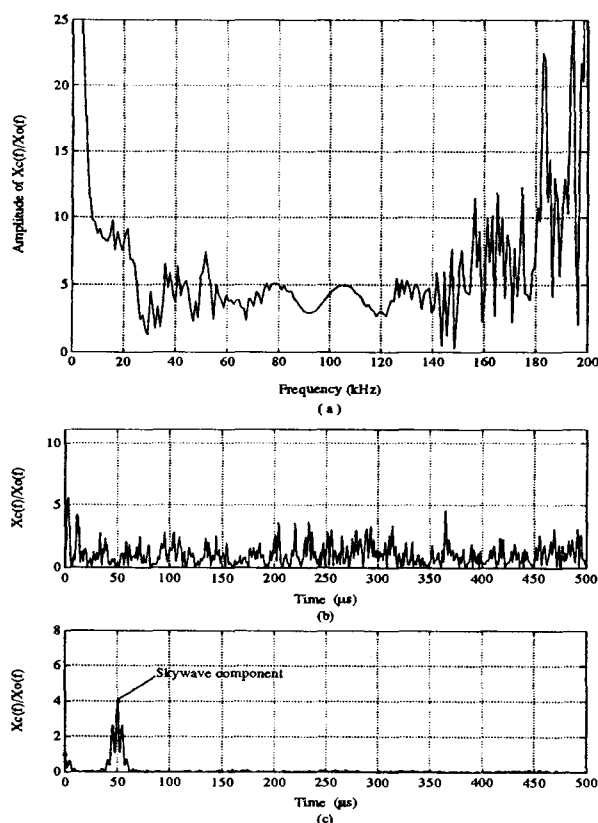


Fig. 1 Illustration of noise amplification in the spectral-division operation. Skywave delay = 50 μ s, skywave-to-groundwave ratio (SGR) = 12 dB, SNR = 40 dB. (a) Amplitude of $X_c(f)/X_0(f)$. (b) Skywave estimation result; the skywave impulse is lost in the noise. (c) Skywave estimation result when a frequency window of 50 kHz width is used.

operated successfully at SNRs greater than 21 dB; that is, 6 dB below the minimum SNR value specified by the USCG.

3.3 Bandwidth limitations of Fourier methods

Loran-C signal energy is concentrated into the 20 kHz frequency band centred on 100 kHz. Outside this band, the spectral components of the composite signal are principally those of the noise and interference. This inevitably affects the skywave delay estimation performance of both the spectral-division and power-cepstral methods.

In the spectral-division method it is seen from equation (3) that the error term $E(f)$ will be amplified significantly if it is divided by an $X_0(f)$ of very small amplitude. For this reason, the direct use of equation (3) requires a very high signal-to-noise ratio if the skywave delay is to be estimated successfully. To illustrate this

point, Fig. 1(a) shows the amplitude of $X_c(f)/X_0(f)$ from 100 to 200 kHz with a very high, 40 dB, SNR. An example of skywave estimation under this condition is plotted in Fig. 1(b); the expected impulse corresponding to the skywave component has been completely lost in the noise.

To overcome the problem, a windowing function has been applied in the frequency domain to suppress the noise frequency components which became amplified in the division operation. A number of windowing functions, including boxcar, Hanning, Hamming and Blackman windows, have been tested. It has been found that the widths of these windows can affect the performance of the skywave estimation system significantly. In contrast, the type of window is not a significant factor. Fig. 1(c) shows that the skywave delay may be estimated successfully at an SNR of 40 dB when a window of 50 kHz width is used.

In the cepstral analysis method, the logarithm operation on the spectrum of the composite signal also magnifies substantially the noise frequency components away from 100 kHz. A similar windowing function must be employed in the log-spectrum domain to suppress these components.

3.4 Resolution limitations of Fourier methods

It is well established in Fourier theory that the spectral resolution of a signal is the reciprocal of the data length of the signal in the time domain. Using this result, and applying the duality principle of Fourier analysis, it can be shown that the resolution of the estimation of skywave delay is equal to the reciprocal of the window width in the frequency domain.

It is clear that noise amplification becomes more significant at lower SNRs and hence the frequency windows employed should be as narrow as possible. Narrow windows, however, reduce the resolution of the skywave delay estimates. This conflicting requirement establishes the need for further investigation into high-resolution frequency estimation techniques.

4 Eigen-decomposition techniques

This section describes briefly the principle of frequency estimation using eigen-decomposition techniques. Considerable research has been directed to these techniques

in recently years because of their superior ability to resolve closely-spaced frequencies of multiple, superimposed, sinusoids from noisy measurements [2, 3, 5, 6, 7, 8, 9, 10]. We will restrict our discussion to two important algorithms: MUSIC and its variant, ROOT-MUSIC.

4.1 The MUSIC algorithm

Consider a signal $x(t)$ that contains K sine waves with constant angular frequencies $\omega_1, \omega_2, \dots, \omega_K$ and constant amplitudes $A_1, A_2, \dots, A_K$. The signal is sampled, together with additive white noise $v(t)$. Let the total number of signal samples be N and let $x(n)$ denote the n -th signal sample:

$$x(n) = \sum_{k=1}^K A_k \cos(\omega_k n + \theta_k) + v(n), \quad n = 1, 2, \dots, N \quad (5)$$

where θ_k is the phase of the k -th sinewave component, and $v(n)$ is the noise component of the sampled signal. The following development uses the assumption that the θ_k are uniformly distributed over $(0, 2\pi)$ and that $v(n)$ has zero mean and a variance σ^2 . Hence the sinewave components are orthogonal to each other when ensemble averaged and are uncorrelated.

Define the $M \times M$ correlation matrix of the signal defined as

$$R_x = \begin{bmatrix} r_x(0) & r_x(1) & \dots & r_x(M-1) \\ r_x(1) & r_x(0) & \dots & r_x(M-2) \\ \vdots & \vdots & \ddots & \vdots \\ r_x(M-1) & r_x(M-2) & \dots & r_x(0) \end{bmatrix} \quad (6)$$

where $r_x(m)$ is the value of the autocorrelation function of $x(n)$ for lag m ; $m = 0, 1, 2, \dots, \pm(M-1)$. It can be shown that R_x may be rewritten in the form

$$R_x = E P E^H + \sigma^2 I \quad (7)$$

where I is the identity matrix, E^H is the conjugate, or Hermitian, transpose of E , E is a Vandermonde-type matrix of dimension $M \times 2K$, and P is a diagonal matrix. The matrices E and P are defined respectively by

$$E = [e(\omega_1) \ e(-\omega_1) \ \dots \ e(\omega_K) \ e(-\omega_K)] \quad (8)$$

where $e(\pm\omega_k) = [1, e^{\pm j\omega_k}, \dots, e^{\pm j(M-1)\omega_k}]^T$, the superscript T denoting matrix transposition, and

$$P = \text{diag}\left(\frac{A_1^2}{4}, \frac{A_1^2}{4}, \dots, \frac{A_K^2}{4}, \frac{A_K^2}{4}\right) \quad (9)$$

Let $\lambda_1 \geq \lambda_2 \geq \dots \geq \lambda_M$ denote the eigenvalues of the correlation matrix, R_x , and q_i the eigenvector associated with λ_i . By definition, we have

$$R_x q_i = \lambda_i q_i, \quad i = 1, 2, \dots, M \quad (10)$$

For $i = 2K + 1, \dots, M$, it can be shown that

$$(R_x - \sigma^2 I) q_i = 0, \quad i = 2K + 1, \dots, M \quad (11)$$

That is,

$$E P E^H q_i = 0, \quad i = 2K + 1, \dots, M. \quad (12)$$

Further, it can be shown that

$$E^H q_i = 0, \quad i = 2K + 1, \dots, M. \quad (13)$$

Therefore, the set of vectors $\{e(\pm\omega_1), \dots, e(\pm\omega_K)\}$ is orthogonal to $\{q_{2K+1}, \dots, q_M\}$. Since $\{q_1, \dots, q_{2K}\}$ is also orthogonal to $\{q_{2K+1}, \dots, q_M\}$ (because the normalised eigenvectors of a correlation matrix form a complete orthonormal basis) we deduce that

$$\text{span}\{e(\pm\omega_1), \dots, e(\pm\omega_K)\} = \text{span}\{q_1, \dots, q_{2K}\} \quad (14)$$

where $\text{span}\{\cdot\}$ represents the set of all possible linear combinations of the vectors enclosed within the braces.

This relationship shows that the signal subspace is equal to the vector space spanned by the eigenvectors of the $2K$ largest eigenvalues. Once the eigenvectors of R_x are known, the angular frequencies of the sinewave components of the received signal may be found by searching for the signal vectors that are orthogonal to the noise subspace. This conclusion leads to the following algorithm of frequency estimation, the so-called MUSIC algorithm:

- Arrange N signal samples $x(1), x(2), \dots, x(N)$ into a signal *data matrix*:

$$X = \begin{bmatrix} x(M) & x(M-1) & \dots & x(1) \\ x(M+1) & x(M) & \dots & x(2) \\ \vdots & \vdots & \ddots & \vdots \\ x(N) & x(N-1) & \dots & x(N-M+1) \end{bmatrix} \quad (15)$$

- Perform singular value decomposition (SVD) of X and find the singular values and singular vectors of X . The eigenvalues of the correlation matrix R_x are the squares of the singular values of X , and the eigenvectors are the right singular vector of X .

- Let $v_1, v_2, \dots, v_{2K+1}, \dots, v_M$ denote the right singular vectors corresponding to the eigenvalues $\lambda_1 \geq \lambda_2 \geq \dots \geq \lambda_M$. Identify the right singular vectors that are associated with the $(M - 2K)$ smallest eigenvalues. Define the matrix V_N and the frequency-search vector $e(\omega)$, respectively:

$$V_N = [v_{2K+1}, \dots, v_M] \quad (16)$$

$$\text{and } e(\omega) = [1, e^{j\omega}, \dots, e^{j(M-1)\omega}]^T, \quad -\pi \leq \omega \leq \pi \quad (17)$$

- Compute the eigenspectrum $S(\omega)$ for varying ω in the interval $-\pi \leq \omega \leq \pi$.

$$S(\omega) = \frac{1}{e^H(\omega) V_N V_N^T e(\omega)} \quad (18)$$

For a real signal in the time domain, $S(\omega)$ is symmetric with respect to $\omega = 0$. The values of ω at which $S(\omega)$ achieves maxima are the estimated angular frequencies of the sinewave components of the composite signal.

4.2 ROOT-MUSIC

ROOT-MUSIC is a variation of the MUSIC algorithm. We define the reciprocal of the eigenspectrum $S(\omega)$ as null spectrum $D(\omega)$. That is,

$$D(\omega) = \frac{1}{S(\omega)} \quad (19)$$

Replacing $e^{j\omega}$ in $D(\omega)$ by the complex variable z results in a polynomial function of $D(z)$. It can be shown [10] that $D(z)$ may be expressed as the product of two polynomials, $H(z)$ and $H(1/z)$, each with real coefficients. The resulting polynomial $H(z)$ has its roots inside or on the unit circle; the roots on or very close to the unit circle represent the signal zeros, and the remaining ones represent extraneous zeros. We may thus perform the frequency estimation by extracting the zeros of the polynomial $D(z)$. However, since the signal zeros are second-order roots of the polynomial $D(z)$, it is more expedient simply to take the root of $D(z)$, and determine the signal zeros from the knowledge that they should lie on the unit circle [10]. This procedure is referred to as 'ROOT-MUSIC'.

5 Performance evaluation

This section evaluates the performance of the MUSIC algorithm when applied to the problem of estimating

skywave delays. The MUSIC algorithm has been incorporated into the existing skywave delay estimation programs and extensive simulations have been conducted. Typical results are presented and compared to those of the spectral-division method.

5.1 Simulation setup

The simulation setup which enables the performance of the skywave delay estimation algorithms to be evaluated remains the same as that described in [1] for assessing the spectral-division and power-cepstral techniques. Fig. 2 shows its functional block diagram; the programs of each functional block are implemented in Pro-Matlab.

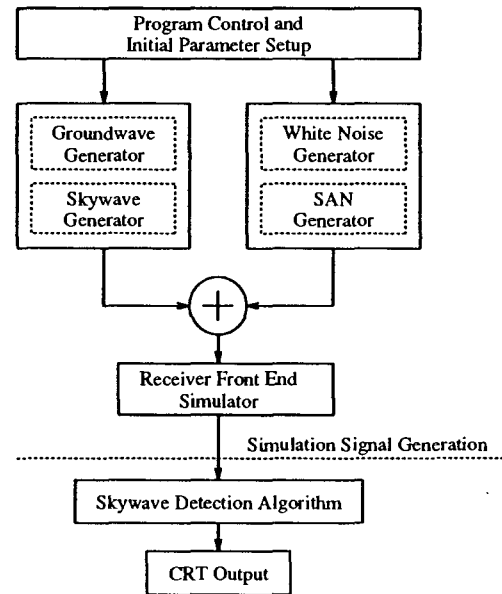


Fig. 2 Functional block diagram of programs which simulate the operation of the proposed skywave detection techniques under noisy conditions (after [1]).

Simulated Atmospheric Noise (SAN) is generated in accordance with the minimum performance standards (MPS) specified in [11, 12]. This noise is added to the separately-generated Loran-C groundwave and skywaves and the resulting sum is fed into the Front End Simulator block to allow the effects of various receiver front-end configurations to be studied. Then the Skywave Detection Algorithm under test is used to estimate the delay of the skywaves from the filtered noisy composite signal.

Fig. 3(a) shows the block diagram of implementations of the MUSIC algorithm for skywave delay estimation. For comparison, Fig. 3(b) shows the equivalent block

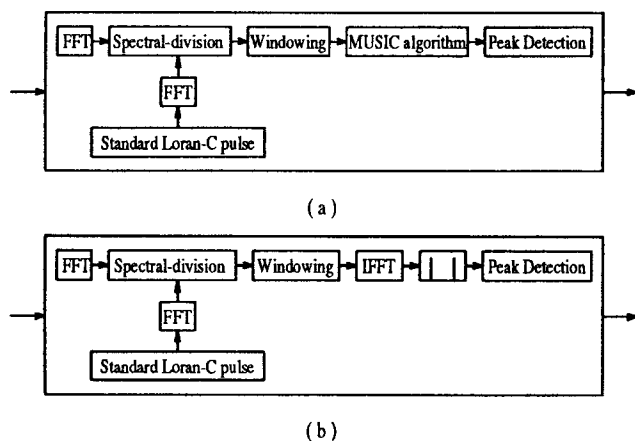


Fig. 3 Block diagram of implementations of skywave detection algorithms, (a), MUSIC algorithm, (b) earlier spectral-division algorithm.

diagram for the spectral-division method. It is seen that the two methods are broadly the same except that the IFFT operation in the spectral-division method is now replaced by the MUSIC algorithm.

5.2 Simulation results

Fig. 4 plots the skywave delays estimated in 100 separate simulations at an SNR of 14 dB. Remember that 27 dB is the SNR value at which the noise results in 100 ns (rms) TD measurement error, and therefore this SNR value is 13 dB lower than the limiting SNR value. A single skywave component 50 μ s later than the groundwave was assumed and a Hanning window of 30 kHz was used. Skywave delays estimated by the MUSIC algorithm are represented by crosses, and the spectral-division estimates by circles.

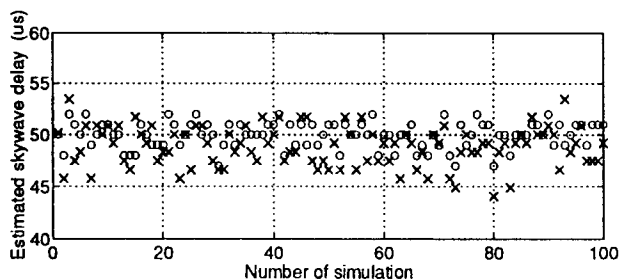


Fig. 4 Skywave delay estimates. The circles are the estimates made by the MUSIC algorithm and the crosses by the spectral-division method. Skywave delay=50 μ s. SGR=12 dB. SNR=14 dB (normally equivalent to an antenna SNR of -23 dB.)

The mean value of the skywave delay estimates calculated by the MUSIC algorithm was 48.9 μ s and their

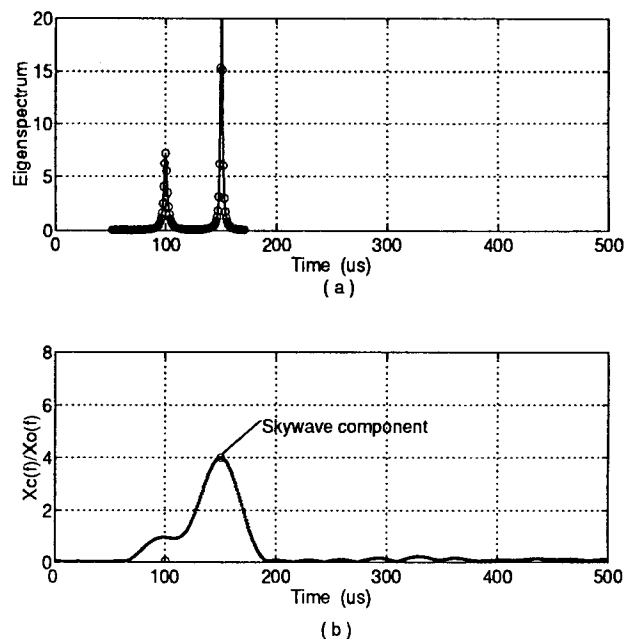


Fig. 5 Results of estimation by (a) the MUSIC algorithm and (b) the spectral-division method when components are separated by 50 μ s. SNR=24 dB. Other details as in Fig. 4 caption.

standard deviation 1.9 μ s. The average bias error of the spectral-division estimates was 0.01 μ s and its standard deviation 1.3 μ s. So under these high-SNR conditions, both methods produced excellent results.

However, an important advantage of the MUSIC algorithm is that it can resolve closely-spaced components. Fig. 5 shows typical results of an estimation when a groundwave component at 100 μ s is followed by a skywave component 50 μ s later: the MUSIC algorithm clearly separates the two but the spectral-division method does not.

6 Results using off-air data

Although extensive computer simulations of the proposed techniques of skywave delay estimation have been conducted, a full assessment of performance of these techniques using off-air data has yet to be made. To allow this assessment to be conducted, a high-quality Loran-C signal acquisition system is currently under development in our Radio Navigation Group at the University of Wales, Bangor. This system is designed to take samples of received off-air signals at 1 MHz rate with a resolution of 12 bits. Once the acquisition system has been completed, off-air data will be collected to allow testing of the proposed skywave estimation

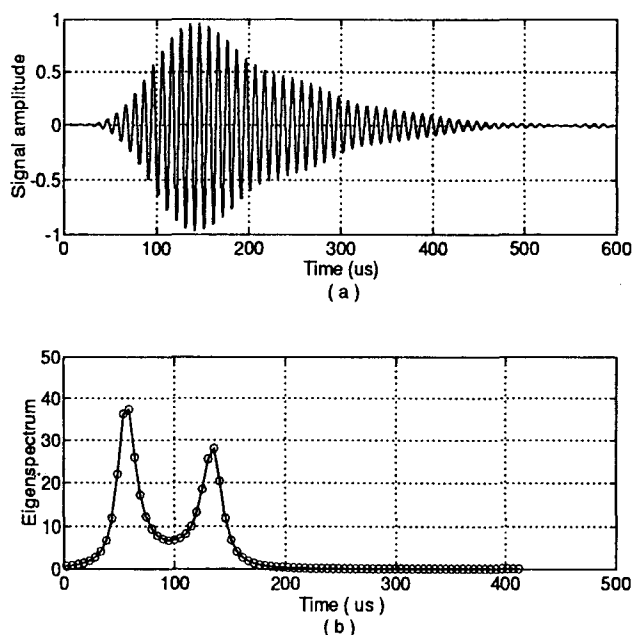


Fig. 6 Off-air data plotted in (a) and the estimated times of its groundwave and skywave isolated by the MUSIC algorithm in (b). The off-air data was supplied by Van Nee of Delft University.

techniques and also of a highly-efficient technique (described elsewhere in this Symposium [13]) for estimating the frequency of carrier-wave interference.

A limited evaluation of the new techniques has, however, been made using off-air data collected by Van Nee of the Delft University of Technology, the Netherlands. We must be cautious when explaining the results of this exercise because of the inherent limitations of this data set. First, the sampling rate was only 250 kHz and so there could be considerable aliasing. Secondly, the resolution was only 8 bits, therefore the quantising error may also cause a problem. Despite these limitations, we have successfully tested all three methods using the off-air data plotted in Fig. 6(a). The data was the average, over one GRI, of the Loran-C signal from Sylt, Germany received at Delft. To account for the effects of the front-end filtering of the sampling system, a set of samples of a standard pulse from a Loran-C signal simulator was also supplied by Van Nee.

Fig. 6(b) shows the estimated start times of the groundwave and skywave components made using the MUSIC algorithm. Results from both the spectral-division and power-cepstral method have not been included since they failed to yield reasonable estimates at this signal-to-noise ratio. The start time of groundwave is estimated to be 55 μ s, that of the skywave 135 μ s and the

skywave delay is estimated to be 80 μ s. This is the first time Loran-C skywave delays have been estimated using an eigen-decomposition technique.

7 Conclusions

Adaptive skywave estimation techniques are desirable since they can be used to adjust in real-time the sampling points in receivers so as to achieve the best possible SNR and SIR while minimising the effects of skywave interference. Further to our research described in [1], this paper has proposed an alternative skywave delay estimation method using eigen-analysis methods. A class of high-resolution frequency estimation techniques, including the MUSIC and ROOT-MUSIC have been identified. The way in which these techniques may be used to improve the estimates of the delay times of Loran-C skywaves have been discussed. Specifically, we have incorporated the MUSIC algorithm into our existing skywave estimation programs and we conducted extensive computer simulations to evaluate the performance of the technique. Simulation results are presented here and compared to those from the spectral-division method. A main advantage of MUSIC is that it can resolve closely-space groundwave and skywave components in situations in which both the spectral-division and the power-cepstral methods fail. The paper has also presented results of the first skywave estimates made using off-air data, albeit of limited rate and resolution.

A high quality Loran-C signal acquisition system is currently being developed and a complete assessment of the techniques will be made in the near future using high-resolution off-air data.

8 Acknowledgements

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Dr. Yi Bian graduated from Department of Precision Instrumentation of Shanghai Jiao Tong University, P.R. China in 1985, with the highest honours of the year. He completed his M.Sc. in 1987 and continued work on inertial navigation systems as both PhD candidate and research assistant until 1990. Thereafter, in just two years, he completed a PhD in School of Electronic Engineering and Computer Systems of the University of Wales, Bangor, UK, working on signal processing techniques for Loran-C radio navigation receivers. Since 1 October 1992 he has been employed as a Post-doctoral Research Fellow by the University of Wales. His current research interests include signal processing techniques and their applications to communications systems, in particular radio navigation systems and optical telecommunications systems.

Dr. David Last is a Reader in the University of Wales. He was awarded the degree of B.Sc(Eng). by the University of Bristol, England in 1961 and the degree of Ph.D. by the University of Sheffield, England in 1966. Dr. Last is a Fellow and Council Member of the Royal Institute of Navigation, a Fellow of the Institution of Electrical Engineers, and a Chartered Engineer. He has published many papers on radio-navigation systems, especially on applications of the Decca Navigator System and Loran-C. He acts as a Consultant on radio navigation and communications to companies and government departments. He is an instrument-rated pilot and aeronautical user of Loran-C.

System Aspects of Cross-Rate Interference

Andre Nieuwland

*Delft University of Technology
Faculty of Electrical Engineering
P.O. Box 5031, 2600 GA Delft, The Netherlands
e-mail: koffie@donau.et.tudelft.nl*

Abstract

This paper gives a brief overview of several aspects of cross-rate interference (CRI), and describes in more detail the situation for dual-rate stations. An algorithm is presented for fast calculation of the loss of pulses due to the blanking applied in dual-rate stations. This loss is a measure for the amount of CRI between the two GRI's. Though not exactly the same, the results obtained for dual-rate stations can be used to estimate the CRI in case of interfering of separate single rate stations as well.

1 Introduction

The long range radionavigation system Loran-C is expanding throughout the world. The continental United States (CONUS) is already covered [1, 2], and North West Europe will follow soon [3].

One of the problems encountered in the design of new and the modification of existing chains is the presence of neighbour chains. The transmitters of these chains broadcast similar signals on the same frequency as the transmitters of the new chain. A receiver inside the coverage area of a certain chain may also receive Loran-C signals from transmitters of surrounding chains. These signals might overlap with the signals of the desired chain, hence reducing the accuracy and reliability of the positioning information. At the same time, the new chain will interfere with existing surrounding chains.

Due to the overlap, a receiver will experience a phase shift of the tracked signal and present erroneous positioning information. If the difference between two interfering Group Repetition Intervals (GRI's) is small, than the duration of the period in which pulses of both rates overlap will be fairly long.

The interfering rate might be received much stronger than

the desired rate due to the low attenuation of the skywaves or proximity of the interfering stations. As a result, a receiver might lock onto the stronger interfering rate and produce unreliable positioning information with an increasing velocity and position error.

For dual-rate stations there is the extra problem of the impossibility of radiating overlapping pulses. If pulses of two rates overlap, than the pulses of one rate are blanked. In this situation, a receiver only receives the unwanted pulses, which introduce even a larger error than in normal overlap situations.

Measures at the side of the receiver can be taken to reduce cross-rate interference (CRI), like disregarding (groups of) corrupted pulses, or by using a special sampling strobe pattern to balance the phase code [4]. These methods are based on disregarding corrupted navigation information, hence reducing the effective cross-rate power but the desired power as well.

A more fundamental solution is to minimize CRI on the transmitter's side by allocating GRI's with low-mutual interference to neighbour chains. In 1974, Roland [5] proposed a time domain approach based on cancellation of CRI within the receiver's time constant, by applying special phasecode patterns and selecting GRI's with common prime factors. One year later, Feldmann et al. [6] described a frequency domain approach to analyze the effect of one GRI on another, to select the relative non-interfering combinations of GRI's. Based on this paper, a method using Fourier series expansion was developed for fast calculation of the cross-rate power between the Loran-C spectrum of an interfering GRI, and the receiver spectrum of the desired GRI [7]. In 1988, the US Coast Guard presented a software package for GRI selection, which assesses CRI by modelling a Loran-C receiver and simulating the input signals, consisting of the two interfering rates, for a certain period of time.

A disadvantage of some of the methods described above is that they are bound to a modelled receiver, e.g. (fast moving) receivers with smaller time constants do not benefit from the balancing of the CRI, unless the CRI is balanced on a short time interval, and are therefore more vulnerable to CRI. Second, the initial alignment of the two interfering rates is in general not considered, though it influences the total amount of CRI experienced. Simulation of cross-rate interference for all possible initial alignment situations might be a very time consuming task. The methods used in [6] and [7] do not depend on the initial alignment. These methods estimate the total cross-rate power by multiplication of the power of all frequency spectral components of the interfering GRI with the receiver transfer function for the desired GRI. Because the power of a frequency component is used, this cross-rate estimation is independent of the (relative) phase of the signals and thus independent of the initial alignment. This will over estimate the cross-rate interference a little, since all components are added "in phase" which is not true in general. The disadvantage of this method is that for each combination of GRI's new spectra need to be calculated, and that the obtained cross-rate interference estimate depends receiver transfer function. For selecting low interfering GRI's in case of dual-rate transmitters, it is possible and useful to apply receiver independent analysis. The main advantage is that combinations of GRI's can be examined on their cross-rate properties by observing the GRI's without limiting the result to any type of receiver. A second advantage of the proposed method is that it is fast and independent of the repetition rates of the two GRI's. Though the method is especially useful for investigating CRI in dual-rate stations, it will provide an estimation (though pessimistic) of CRI in case of geographic separated stations as well.

This paper starts with a brief overview of the regularity in the cross-rate interference pattern. Hereafter, formula's are derived describing the loss of pulses in dual-rate stations, due to cross-rate effects. With these formula's, the maximum loss of information is directly obtained.

2 Aspects of cross-rate interference

If two signals with fixed rates are repeated continuously, than their overlap pattern will repeat with a fixed rate as well (see figure 1). The interval between similar overlap (viz. alignment) situations (T_o) is equal to the product of the two GRI's, when both are mutual prime. In general, the length of the overlap interval (called "cross-over period" in [4]) is equal to the least common factor of the two GRI's. This interval can be calculated by dividing the product of the GRI's by their Greatest Common Divisor (GCD) (see formula 1). In this formula, the GRI's are written in their four digit representation.

$$T_o = \frac{GRI_A \times GRI_B}{GCD(GRI_A, GRI_B)} \times 10^{-5} [sec] \quad (1)$$

This interval will contain GRI_B/GCD periods of GRI_A , and GRI_A/GCD periods of GRI_B .

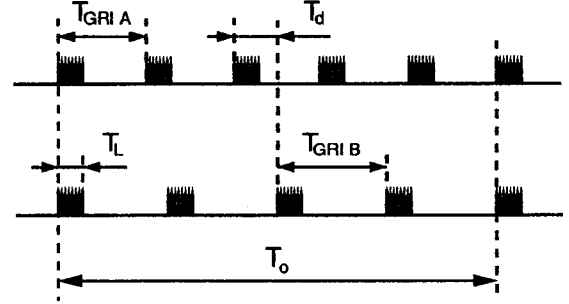


Figure 1: Overlap interval for two GRI's

Besides the interval on which the alignment is periodic, there is the time span in which two pulse groups are actually overlapping. This period of actual cross-over will be referenced as the "cross-over time" (T_c). The maximum cross-over time depends on the difference between the two GRI's. If this difference is larger than the time required for broadcasting one pulse group, the cross-over time will be at most one GRI in case of complete overlap, and at most two GRI's in case of partial overlap.

A special situation occurs when GRI_B is about $2 \times GRI_A$. The pulse groups of the larger GRI are affected several times in a row, whereas the pulse groups of the smaller GRI are influenced only every second time. To obtain the worst case cross-over time, which applies to the longer GRI (GRI_B), the smallest GRI (GRI_A) in the nominator of (2) should be multiplied with the rounded ratio GRI_B/GRI_A . This ratio is 1 if GRI_B is closer to GRI_A than to two times GRI_A , and 2 otherwise.

If the time to broadcast a pulse group is referenced by T_L , than the maximum cross-over time expressed in number of periods of GRI_B , viz. number of successive affected pulse groups can be calculated with formula 2.

$$T_c = 1 + INT \left(\frac{T_L}{|GRI_B - ROUND \left(\frac{GRI_B}{GRI_A} \right) \cdot GRI_A|} \right) \quad (2)$$

In formula (2), INT refers to the integer division, and T_L and the GRI's are in μs .

If the cross-over time is short compared to the receiver's time constant, the interfering rate will only have limited influence on the final result. Van Etten [4] proposed to select GRI's with an high common factor, to obtain overlap intervals (T_o) smaller than the receiver's time constant, and with the cross-rate interference balanced within this overlap interval. Short overlap intervals automatically produce a short cross-over time. Reducing the overlap interval however, is not sufficient to guarantee low mutual interference between two GRI's. If the overlap interval is very short, than even a small cross-over time might be an high percentage of this interval. As a result, interference between the pulse groups of the two rates will occur frequently and for an high percentage of the radiated pulses.

To obtain GRI's with low mutual interference, GRI's need to be selected on sufficient time difference and a small GCD. This will combine a large overlap interval with short cross-over times. Although the maximum cross-over time is short, partial overlap might occur several times within the overlap interval (for $T_{GCD} \leq T_L$). Therefore, an analysis has to be made which relative positions the pulse groups occupy within that interval, and how many pulses are affected.

Because the overlap interval (T_o) is the smallest period between similar alignment situations, all relative time differences appear only once. This implies that there are as many time differences between GRI_B and GRI_A as there are periods of GRI_B within the overlap interval, which is GRI_A/GCD . These time differences are relative to the pulse groups of GRI_A , and is thus accumulated modulo GRI_A . If the same relative time difference would occur more than once, than the interference pattern would be periodic on a smaller interval than T_o , which contradicts the fact the T_o is the smallest period. The spacing T_s between these differences can be calculated with formula (3). N_B is the number of relative time differences between GRI_B and GRI_A .

$$T_s = \frac{GRI_A}{N_B} = T_{GCD(GRI_A, GRI_B)} \quad (3)$$

3 Dual-Rate stations

3.1 Blanking

Some Loran-C stations operate on rates of two chains to provide continuous coverage between these chains. The consequence is however, that these dual-rating stations are periodically faced with the requirement of radiating overlapping pulse groups simultaneously. Therefore, an interval is specified around each pulse group in which only that specific pulse group is radiated. Those pulses of the other pulse group which overlap that blanking interval

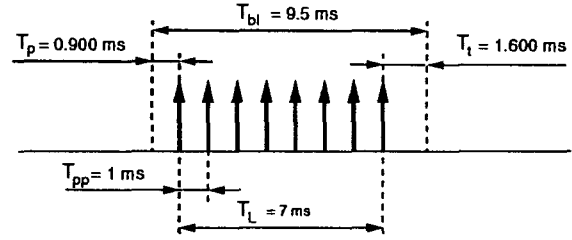


Figure 2: Blanking interval around a Loran-C pulse group

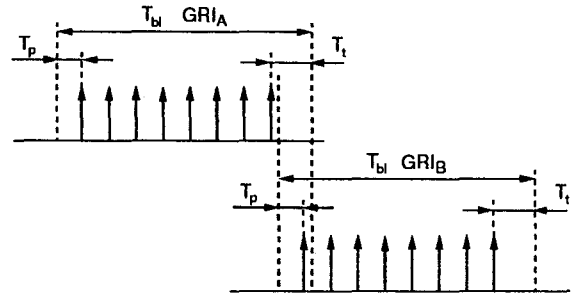


Figure 3: Asymmetrical overlap of blanking intervals

(T_{bl}) are inhibited [8]. The blanking interval for the newer solid state transmitters extends from 900 μs preceding the first pulse of the group (T_p), to 1600 μs trailing the last pulse (T_t), as is shown in figure 2 [8]. The time span in which the actual Loran-C pulses are broadcasted is denoted by T_L .

There are two blanking strategies which can be used: alternating blanking and priority blanking [8]. In case of alternating blanking, both rates are blanked in turn for four periods each. In case of priority blanking, the same rate is blanked every time. Considering this, an exception should have been made on the blanking interval as specified in [8]. If the last pulse of one rate (rate A) should be radiated e.g. 1 ms before the first pulse of the other rate (rate B), than the last pulse of A lies outside the blanking interval of B, and should not be blanked. The first pulse of rate B however, is inside the blanking interval of A, and should be blanked (see figure 3). If priority blanking is used with rate B dominating rate A, than the last pulse of A has to be blanked, although A is outside the blanking interval of B. Ergo, the blanking interval of the dominating rate should extend on both sides of T_L the maximum length of $\{T_p, T_t\}$ in this case T_t .

3.2 Maximum number of blanked pulses

A criterium to judge the cross-rate influence between GRI's is the number of effective radiated pulses (N_{erp}) per time unit. The higher this pulse rate, the higher the information "power" for the receiver and the less the influence of the interfering rate. The larger the interference between two rates, the more pulses need to be blanked and the lower the N_{erp} . To determine the effective pulse rate, the maximum number of blanked pulses need to be calculated first.

The total number of blanked pulses is the sum of all pulses within the blanking interval T_{bl} for every relative position of each pulse group overlapping the blanking interval (see figure 4).

As shown in the previous section, each pulse is repeated every T_{GCD} . To obtain the maximum number of blanked pulses, an initial alignment should be selected such that all pulses together occupy as many positions within the blanking interval as possible. For large T_{GCD} ($T_{GCD} > T_{bl}$) worst case alignment is obtained for any position of the initial pulse group within T_{bl} (position 4 in figure 4). For arbitrary T_{gcd} , the selection of this initial alignment is in general non trivial, since all possible time-shifts within the interval $[0, T_{GCD})$ should be regarded. Trying each possible time-shift (T_{sh}) and selecting the maximum, is a time consuming job since the number of possibilities increases proportional with the increase in GCD. The time complexity of calculating the number of blanked pulses is of the order $\mathcal{O}(n^2)$ for a range of GCD's. As is described below, it's possible to calculate the number of blanked pulse directly, viz. in constant time.

One should remember all pulses are repeated every T_{gcd} . Thus at the initial alignment ($T_{sh} = 0$), the number of positions between the initial alignment and the right edge of the blanking interval can be calculated with (4):

$$\sum_{m=0}^7 INT \left(\frac{T_{bl} - m \cdot T_{pp} + T_{sh}}{T_{GCD}} \right) \quad (4)$$

In this formula, T_{pp} depicts the spacing between successive pulses in a pulse group and m the number of the pulse within that group (4). INT refers to the integer division, and is either positive or zero. It is assumed that pulses on the edge of the blanking interval are blanked as well.

The number of positions of a pulse on the left side of the initial position (positions 2 and 3 in figure 4), is found in a similar way. Every pulse repeats itself each T_{gcd} , between the initial position and the left edge. (see formula 5):

$$\sum_{m=0}^7 \left\{ INT \left(\frac{T_L - m \cdot T_{pp} - T_{sh}}{T_{GCD}} \right) \right\} \quad (5)$$

The exact position of the pulse is denoted by $T_L - m \cdot T_{pp}$, and the left edge is at zero for the initial position since $T_{sh} = 0$.

The total number of blanked pulses, including the initial position is thus (6):

$$\begin{aligned} P_{max} = & \sum_{m=0}^7 INT \left(\frac{T_{bl} - m \cdot T_{pp} + T_{sh}}{T_{GCD}} \right) \\ & + INT \left(\frac{T_L + T_{pp} - T_{sh}}{T_{pp}} \right) \\ & + \sum_{m=0}^7 INT \left(\frac{T_L - m \cdot T_{pp} - T_{sh}}{T_{GCD}} \right) \end{aligned} \quad (6)$$

To determine the initial (right) shift of the blanking interval for a worst case (maximum) number of blanked pulses, formula 6 needs to be maximized. This is done by maximizing the first sum in formula 6, which denotes the number of pulse positions between the initial position and the right edge of the blanking interval. Shifting the blanking interval to the right, causes this sum to increase, but at the the same time the number of pulse positions within the blanking interval at (the left of) the initial position will decrease. It will be clear that since every pulse repeats itself every T_{gcd} , it is only useful look for the desired T_{sh} in the range $[0, T_{gcd})$. Second, any shift larger than the time required to broadcast a Loran-C pulse group, will move a complete pulse group out of the blanking interval, which will never lead to an higher maximum number of blanked pulses.

Selecting the maximum T_{sh} will maximize the first sum in formula 6, but it may reduce the contribution of the second and third term of (6) as well.

Inspecting the last term of (6) shows that the remainder after the division is the time between the left edge of the blanking interval last pulse before the left edge. Any time shift smaller than this margin, will not reduce the number of pulse positions left from the initial position. It will only affect the number blanked pulses at the initial position. To obtain the maximum number of blanked pulses, the time margin is calculated for each m , sorted in increasing order and stored in array. For each m , the time shift required to obtain just another pulse position in the first term is calculated too but stored in array in descending order. If the largest required time shift is smaller or equal to the smallest available time margin, 8 pulse positions

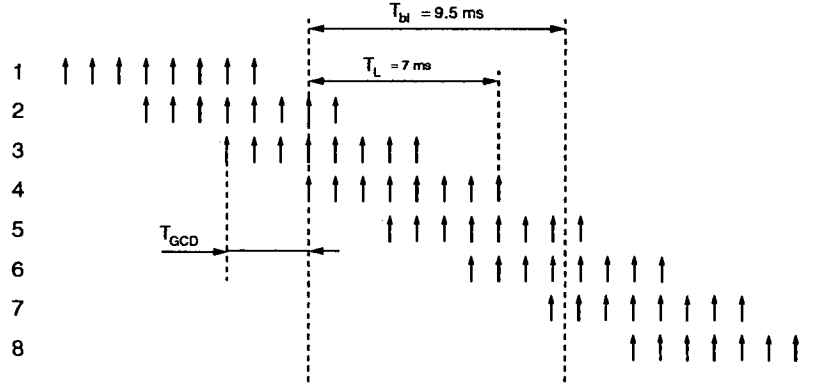


Figure 4: Pulse blanking

range	speedup
1-1000	148
1-2000	366
1-3000	578
1-4000	751
1-5000	1749

Table 1: Computational speedup by using direct calculation

are obtained at the right side, and no pulses (except from the initial position) disappear from the blanking interval at the left side. For each combination, the netto increase in the number of blanked pulses can be calculated, and the maximum increase is added to the number of pulses blanked at the initial position to obtain the maximum number of blanked pulses. Whenever the last term of (6) evaluates to 0, a special case arises. In those cases, the available time is limited either by T_{gcd} (the first repetition of the 0th pulse), or by one of the pulses pulse on the left of its initial position.

With the algorithm described above, calculating the number of blanked pulses is done in constant time, and the number of blanked pulses for a range of GRI's is calculated in linear time ($\mathcal{O}(n)$) instead of $\mathcal{O}(n^2)$. Table 1 lists the speedup gained by using the described algorithm instead of straight-forward calculation.

3.3 Data channel reduction

Communication systems that rely on Loran-C signals to carry data to the user, like e.g. presented by Enge [9], Hoogenraad [10] and later by Van Willigen [11], will suffer from the blanking of the pulses as well.

Number of blanked pulses per bit	% of bits affected
6	7.5
≥ 5	10.8
≥ 4	14.2
≥ 3	17.5
≥ 2	20.8
≥ 1	24.2

Table 2: Percentage of bits missing at least N pulses

Whereas the influence of blanking in normal receiver operation decreases by averaging over a number of pulses, data communication relies on the reception of individual or only small groups of pulses. Increasing the redundancy lowers the influence of blanking but as a result the effective channel capacity will decrease. It is not only the reduction of information power which counts, but also the total loss of bits. Suppose 6 pulses per GRI are used to broadcast one bit. Furthermore, let a dual rate station operate on two reasonable short rates, GRI_A of 5001 and GRI_B of 6001 (priority), using the shorter GRI to broadcast the data. Without blanking, the bit rate will be as high as 20 bps, and there will be 6001 "bits" within the overlap interval T_o .

When a group of 6 pulses is blanked, the corresponding data bit is wiped out completely. It is not difficult to see that in our example this will happen to 451 of the 6001 bits (7.5%) (see formula 6). Furthermore, there are 651 cases within T_o in which at least 5 of the 6 pulses are blanked (10.8%). Table 2 lists the percentage of bits, losing at least a certain number of pulses.

For proper detection of a bit, at least half of the modulated

pulses should be detected without faults. This implies that any group of 3 or more blanked pulses produce the loss of a bit. As listed in table 2, this happens for 17.5 percent of the bits. Consequently, the effective data rate is reduced from 20 bps (ideally) to 16.5 bps (worst case). A bit could be detected properly for the 6.7 percent in which only 1 or 2 pulses per bit are lost, but there will be an increase in the bit-error-possibility.

4 GRI assignment

When selecting GRI's for new (or modified chains), there are not only dual-rate stations involved. The interference between separate stations however, is in basically the same. The difference is that in this case the pulses broadcast by the two stations will overlap, with (in general) different amplitudes. The amount of interference experienced depends on the amplitude of the interfering signal at the point(s) of observation of the desired signal. If the interfering pulses arrive between the desired pulses, the overlap might be only a minor inconvenience (Not that for dual-rate stations, pulses of one group would have been blanked). Skywaves however, might lengthen the periods in which interfering signals are present.

The effect of the interference is dependent on the position of the receiver within the coverage area and the reception of skywaves. Not only the amount of interference experienced is position dependent, the time at which the overlap actually occurs depends on the position as well. Though the situation for separate stations is slightly different, the basic principles are the same. Thus for low cross-rate interference, the same criteria as for dual-rate stations will hold.

In many occasions, there are other factors (e.g. CW interference [7]), imposing more stringent requirements on GRI's than cross-rate interference. Once given the set of allowable GRI's, the extra criteria imposed by the cross-rate interference are that an overlap situation does not extend over a long period of time, and that the amount of effective radiated pulses is reasonable large. Especially receivers discarding or correcting corrupted pulses will benefit, since they combine the reception of pulses at a high rate with only a relative small amount of distorted pulses.

When the GRI's are selected to be mutual prime, the interference pattern is stretched over a long interval, and will be "whitened". The shorter this overlap interval the more periodicity the interference will have. With sufficient time difference between the GRI's, and low correlation between the repetition rates (viz. GRI's are mutual prime), a receiver will have less problems with locking on a chain and maintaining lock, than when there is a high common factor between the two GRI's.

To illustrate the effect of the selection of the GRI's, number of effective radiated pulses (N_{erp}) is calculated (7) for the GRI's 4001 and 9001.

$$\begin{aligned} N_{erp} &= \frac{8 \times \frac{GRI_B}{T_{GCD}} - P_{max}}{T_o} \\ &= \frac{1}{GRI_A} (8 - P_{max} \cdot GCD) \end{aligned} \quad (7)$$

Figure 5 shows the total N_{erp} per second, viz. the total effective pulse rate of the *transmitter*, as a function of the dual-rating GRI. Note that some transmitters might have limitations on the maximum allowable pulse rates. Figure 6, shows the effective pulse rate of two GRI's as a function of the dual-rating GRI. Due to the fact the the selected GRI's are mutually prime to almost all other GRI's, the curve is rather smooth. Very clear is the reduction of the pulse rate with 50 percent for GRI 4001, when it interferes with GRI 8002 (common factor of 4001, thus every second pulse group of 4001 is blanked). A reduction of 100 percent is obtained for the GRI's when they interfere with themselves, a situation which will never occur. For comparison, figure 7 presents the effective pulse rates for two GRI's with a higher common factor with many of the dual-rating GRI's. Clearly shown are the dips in the pulse rate of the GRI's 4100 and 9100 when they have a high common factor with a dual-rating GRI. Figure 8 shows the percentages of the pulses actually being transmitted. Both GRI's 4001 and 9001 lose the same percentage of pulses due to blanking. The actual effective pulse rate of the shorter GRI however, is about twice as large. Ergo, a GRI should be as short as possible and should be relative prime with respect to GRI's of chains in it's vicinity.

5 conclusions

The loss of pulses due to blanking in dual-rate stations can be calculated very fast with the algorithm presented in this paper. Once this loss is determined, the effective pulse rate of the Loran-C station can be obtained easily. The higher this pulse rate, the more information per time unit the receiver can rely on. To obtain maximum effective pulse rates, the GRI's should be short and relative prime. Furthermore, the difference between the two GRI's need to be large enough to prevent a large cross-over time, which might introduce large errors in the position calculated by the receiver. In general, the minimum difference depends on the time constant of a receiver, but whenever the difference is larger than the blanking interval, full blanking occurs only for one GRI at a time. One should be careful though whenever small integer multiples of this time difference come close to

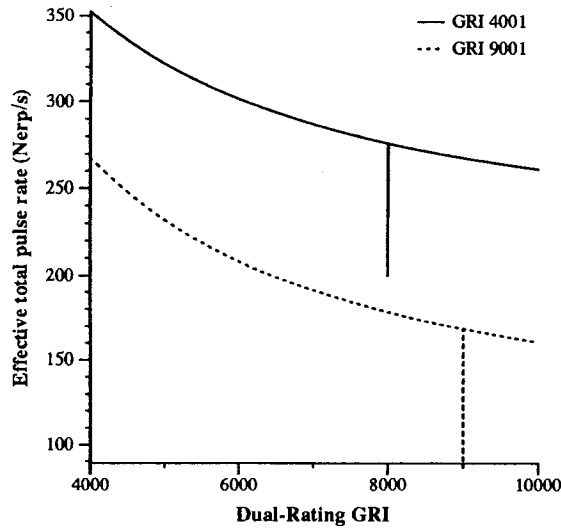


Figure 5: Total effective pulse rate, as a function of the dual-rating GRI

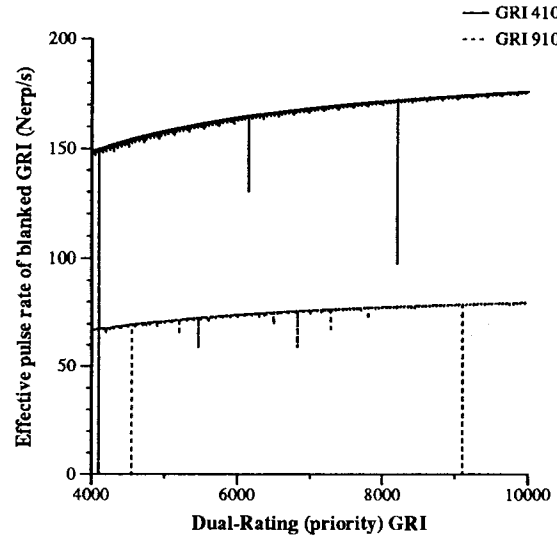


Figure 7: Effective pulse rate of blanked GRI, as a function of the (dominating) dual-rating GRI

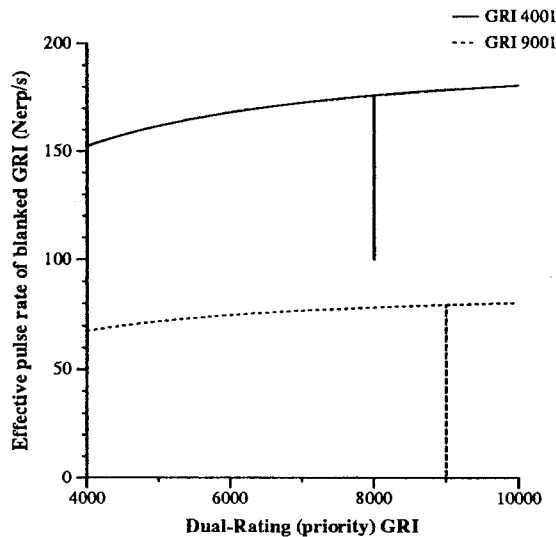


Figure 6: Effective pulse rate of blanked GRI, as a function of the (dominating) dual-rating GRI

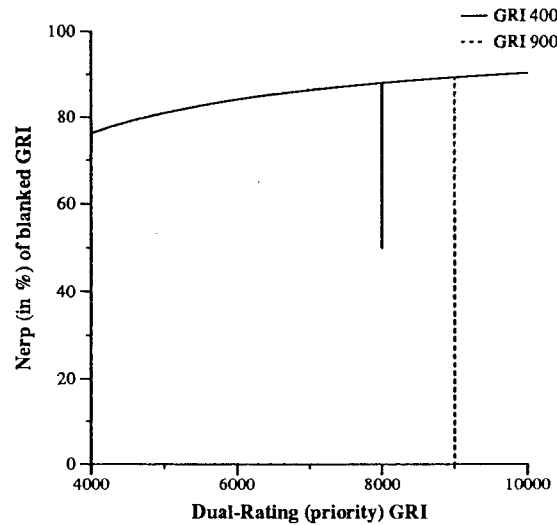


Figure 8: Percent of effective radiated pulses for GRI 4001 and 9001, as a function of the dominating dual-rating GRI's

the two GRI's, since this might introduce some short periodicity in the interference pattern, viz. every time there is (partial) overlap, this overlap is only a little different from the previous overlap situation.

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Biography

André Nieuwland received the Ingenieur (M.Sc.) degree in Electrical Engineering from Delft University of Technology, the Netherlands, in 1991, January 1992, he started a Ph.D. study at the same university. His research is mainly focussed on signal processing and low-frequency radionavigation systems, especially Loran-C. He is a member of the Electronic Engineering Group, where he is involved in the design of the Loran-C and Omega subsystems for the Gollum integrated navigation receiver.

Furthermore, he was actively involved in GRI-calculations for the new North-West European Loran-C chains as well as the Canadian East Coast Newfoundland Chain.

Currently, he is at the University of California, Berkeley, to research the use of formal verification in the design of the Gollum integrated navigation receiver.

OPTIMUM LORAN-C SIGNAL PROCESSING : FIRST EXPERIMENTAL RESULTS

Richard D.J. van Nee and Hein J. Andersen

*Delft University of Technology
P.O.Box 5031, 2600GA
Delft, The Netherlands*

Abstract

A new type of Loran-C receiver is presented, which is much more robust than conventional receivers in the presence of skywaves, carrier wave interference and cross rate interference. The new receiver simultaneously estimates all parameters of groundwave, skywave and interfering signals by solving a set of maximum likelihood equations. Since all Loran signals are processed simultaneously instead of sequentially, the acquisition phase is very fast; a first fix requires about ten seconds of signal. Further, the estimation techniques provide a measure of the solution accuracy which enables the receiver to detect large errors in the estimates of separate Loran signals.

1 Introduction

The performance of Loran-C is primarily limited by skywaves, carrier wave interference (CWI) and cross rate interference (CRI). Most receivers cope with these disturbances by using the first part of the pulses only to avoid skywaves and by using notch filters to suppress interfering carrier waves. Usually, no special measures are taken against CRI, except long averaging times.

However, these methods have three major drawbacks. First, sampling early in the pulse reduces the signal-to-noise and the signal-to-interference ratios by an

amount in the order of 10 dB or more. This is because the bandpass filter widens the Loran bursts, which makes it necessary to choose an early sampling point in order to minimize the influence of skywaves. Second, it is difficult to assure that notch filters remove all synchronous or near-synchronous interferences, especially in Europe with its enormous amount of interfering signals. Third, using many notch filters may cause pulse distortion, thereby increasing the probability of cycle identification errors. The aim of this paper is to demonstrate that all of these drawbacks can be avoided by using special estimation techniques which simultaneously estimate the parameters of groundwave, skywaves and interfering signals. The feasibility of these new techniques is demonstrated by a prototype Loran-C receiver, based upon a 486 PC with a 12 bits A/D converter. An additional advantage of this advanced receiver architecture is fast acquisition, with a time to first fix in the order of ten seconds.

2 Estimation of skywaves and carrier wave interference

In [1], the author described how maximum likelihood theory could be applied to the problem of estimating Loran-C parameters in the presence of noise, skywaves and carrier wave interference (CWI). In the following, a review is

given of this technique and some practical aspects of how to calculate the estimates are discussed.

After I/Q down conversion, phase code demodulation and averaging over T seconds, as described in [1], the Loran-C signal for one specific transmitter can be written as:

$$r(t) = \sum_{m=0}^M a_m l(t-\tau_m) \exp(j\theta_m) + \sum_{k=1}^K b_k \exp(j[\omega_k t + \phi_k]) + n(t) \quad (1)$$

where $l(t)$ is the standard Loran-C pulse shape after filtering, M and K are the number of skywaves -m=0 represents the groundwave- and CWI signals, respectively, and $n(t)$ is noise. The maximum likelihood equations for the unknown parameters can be written as:

$$\hat{\tau}_i = \max_t \left[\operatorname{Re} \left(r(t) - \sum_{\substack{m=0 \\ m \neq i}}^M \hat{a}_m l(t-\hat{\tau}_m) \exp(j\hat{\theta}_m) - \sum_{k=1}^K \hat{b}_k \exp(j[\hat{\omega}_k t + \hat{\phi}_k]) \right) \exp(-j\hat{\theta}_i) \right]$$

$$\hat{a}_i = \operatorname{Re} \left(r(\hat{\tau}_i) - \sum_{\substack{m=0 \\ m \neq i}}^M \hat{a}_m l(\hat{\tau}_i - \hat{\tau}_m) \exp(j\hat{\theta}_m) - \sum_{k=1}^K \hat{b}_k \exp(j[\hat{\omega}_k \hat{\tau}_i + \hat{\phi}_k]) \right) \exp(-j\hat{\theta}_i)$$

$$\hat{\theta}_i = \arg \left(r(\hat{\tau}_i) - \sum_{\substack{m=0 \\ m \neq i}}^M \hat{a}_m l(\hat{\tau}_i - \hat{\tau}_m) \exp(j\hat{\theta}_m) - \sum_{k=1}^K \hat{b}_k \exp(j[\hat{\omega}_k \hat{\tau}_i + \hat{\phi}_k]) \right) \quad (2)$$

The essence of this solution is that estimated undesired signals are subtracted prior to the estimation of a specific desired signal. Since generally no a-priori information is available about the undesired signal parameters, the equations have to be solved iteratively.

If a matched filter is used in the receiver, then $l(t)$ is equal to the auto correlation function of the standard Loran-C pulse. In this case, the best way to find the delay of a received pulse is to estimate its maximum. However, because the actual shape of the Loran pulses around the top is not accurately known, it is better to use a filter with a wider bandwidth than the matched filter. In this case, the delay can be estimated by finding a certain point before the top, for instance using the ratio of two samples at the leading edge of the pulse, just as in a conventional receiver [2].

Just as the groundwave and skywave parameters, the CWI parameters can be estimated in an iterative way [1]. However, in order to reduce the complexity of the calculation, it is also possible to perform the CWI elimination prior to the estimation of groundwave and skywaves by calculating:

$$\hat{b}_k = \operatorname{Re} \left(\frac{1}{T_1 - T_0} \int_{T_0}^{T_1} r(t) \exp[-j(\hat{\omega}_k \tau + \hat{\phi}_k)] d\tau \right)$$

$$\hat{\phi}_k = \arg \left(\int_{T_0}^{T_1} r(t) \exp[-j\hat{\omega}_k \tau] d\tau \right) \quad (3)$$

So the amplitude and phase of a CWI signal are estimated out of a piece of averaged input signal, without trying to subtract Loran pulses. The only disadvantage of this method is that the summation of a CWI signal and a spectral line of the Loran signals is estimated and subtracted. In this way, the method

acts the same as conventional notch filters, which also eliminate a part of the Loran spectral contents.

3 CRI Estimation

After some first experiments, described later on in section 4, it was discovered that cross rate interference (CRI) was at least as important as CWI. Therefore, we tried to find methods to reduce CRI. Theoretically, it is possible to find maximum likelihood estimates analogous to (2), with additional terms to include the cross rate interference; instead of just subtracting estimated skywaves and CWI signals, also the estimated correlation of the received cross rate interfering signals with the phase code of the desired Loran-C signal should be subtracted. If the skywaves and CWI signals are left out, the estimates can be written as:

$$\hat{\tau}_{ij} = \max_t \{ \text{Re} \{ (r(t) - \text{cri}(t)) \exp(-j\hat{\theta}_{ij}) \} \}$$

$$\hat{a}_{ij} = \text{Re} \{ (r(\hat{\tau}_{ij}) - \text{cri}(\hat{\tau}_{ij})) \exp(-j\hat{\theta}_{ij}) \}$$

$$\hat{\theta}_{ij} = \arg \{ (r(\hat{\tau}_{ij}) - \text{cri}(\hat{\tau}_{ij})) \}$$

$$\begin{aligned} \text{cri}(t) = & \sum_{s=0}^S \sum_{\substack{m=0 \\ s \neq j}}^M \hat{a}_{ms} l(t - \hat{\tau}_{ms}) \cdot \\ & \exp(j\hat{\theta}_{ms}) * p_s(t - \hat{\tau}_{ms}) * p_j(\hat{\tau}_{ms} - t) \end{aligned} \quad (4)$$

where * denotes convolution, S is the number of CRI signals and $p_x(t)$ is the phasecode pattern of one particular Loran-C signal x.

The first step to solve this set of equations is to find conventional estimates of the strongest signals of one particular Loran-C chain. Then, based on these estimates, it is possible to make a replica of the cross rate interfering signal $\text{cri}(t)$ which can be subtracted from the input signal $r(t)$ in order to reduce the CRI effects on other chains. To get the best results, this procedure should be repeated iteratively for the other chains, until all CRI is eliminated.

Unfortunately, the method described above has two major disadvantages. First, it requires the estimation of all parameters from ground and skywaves, which makes it time consuming. Second, the shape of the tail of the Loran-C pulses is not known accurately enough to make a good replica of the CRI. However, as discovered in [3], it is possible to circumvent these difficulties by making a simplification in the calculation of $\text{cri}(t)$ in (4). Instead of estimating all individual parameters of one particular signal, it is also possible to just demodulate the signal in the conventional way and use the averaged received pulse -including distortion and skywaves- to form the estimated interference signal $\text{cri}(t)$.

4 Experimental results

In order to test all developed techniques, a prototype Loran-C receiver was built. Figure 1 shows a block diagram of this receiver. After filtering by a fourth order bandpass filter with a 3 dB bandwidth of 6.6 kHz, the input signal is sampled by a 12 bits A/D converter, taking in-phase and quadrature baseband samples every 10 μ s according to the quadrature bandpass sampling technique, which is well described in [2].

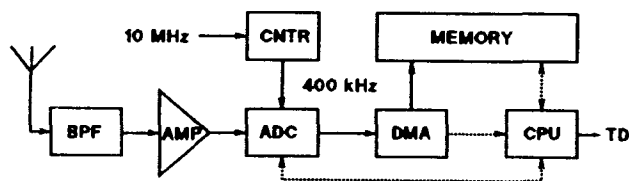


Figure 1: Prototype Loran-C receiver

After bandpass sampling, the signal is averaged over a 2-GRI interval for a certain time which is long enough to get a sufficient signal-to-noise ratio. The 2-GRI averaging has the advantage that only 2-GRI·100 kHz samples (= 32000 for GRI = 80 ms) have to be stored for both the in-phase and the quadrature channel. Note that this 2-GRI averaging concept was previously proposed in [4]. As soon as acquisition has been accomplished, there is no need anymore to store the whole 2-GRI interval; it would be sufficient to just collect samples around expected pulse arrival times.

In order to detect CWI, a FFT is performed on the averaged input signal. Based on this FFT, a number of strongest CWI signal frequencies are estimated as initial frequency estimates for the CWI elimination technique. The advantage of this method is that because of the averaging, all asynchronous CWI signals are largely suppressed already, so the FFT will only show (near) synchronous interferences which are the most harmful to Loran-C. Another advantage compared to the CWI detection method as described in [2] is that the FFT can be taken over a relatively small piece of data, since a frequency resolution of only 25 Hz is enough for the method to work, while in [2,5] a resolution of 0.1 Hz was strived for. The reason for this is that the phase estimates (3) give reliable results for frequency errors less than $1/(T_1 - T_0)$, which is chosen equal to 100 Hz in the prototype receiver. To improve the phase and amplitude

estimates, a more precise frequency estimate can be made by calculating the frequency offset $d\phi/2\pi dt$ from consecutive phase estimates.

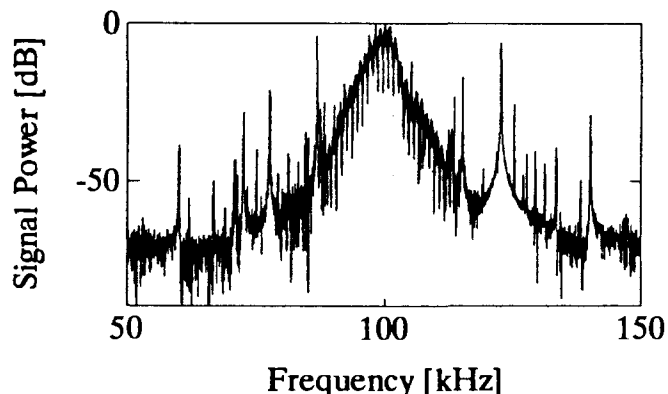


Figure 2: Loran-C spectrum

Figure 2 gives an example of the spectrum of the averaged Loran-C signal. There are clearly some strong (near) synchronous CWI signal present, most probably due to Decca transmitters. Our prototype receiver automatically detects a certain number -at the moment up to 30- of strongest CWI signals outside the 90-110 kHz band and eliminates them from the input signal according to the previously described method. The resulting spectrum after CWI elimination is shown in figure 3.

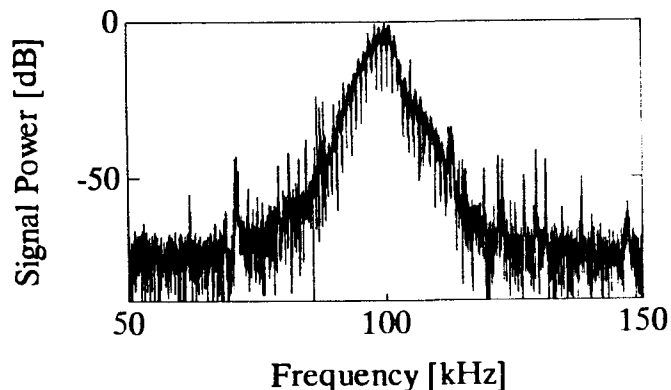


Figure 3: Spectrum after CWI elimination

An example of the skywave estimation technique is depicted in figure 4. In this case, the Loran-C signal from Ejde -about 1340 km away- was used to estimate the parameters of a groundwave

plus one skywave. As can be seen, the remaining residuals in the beginning of the burst are very small, in the order of the noise that is present in front of the burst. Just around the top of the groundwave, however, the residuals become larger. This effect is caused by differences of the tails of the transmitted pulses as compared to the ideal Loran pulse shape, which was also noted in [6]. The strength of the residuals before the estimated groundwave top is compared to a certain threshold in order to detect large errors. This way of increasing the integrity by monitoring the signal was first suggested in [7]. Note that usually, only ten seconds of signal were sufficient to render reliable time differences between Ejde and Sylt.

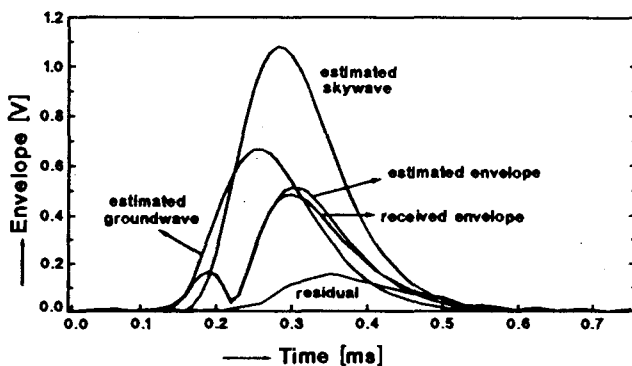


Figure 4: Groundwave/skywave separation

Figure 5a shows a piece of data after averaging 80 GRI of signal for the Lessay chain. In this piece, no bursts from Lessay or Soustou are present, so it should just contain noise. However, most of this 'noise' turns out to be caused by cross rate interference from the Sylt transmitter, which becomes clear if the developed CRI estimation technique is applied. Figure 5b shows the estimated CRI caused by Sylt, which was estimated as explained in section 3. If this estimated CRI is subtracted from the input signal, the 'noise' variance decreases with more than 9 dB and the CRI caused by Sylt seems to be completely eliminated. Of course, this

procedure can be repeated for all possible CRI sources, but in this specific case Sylt -which was 2 dB stronger than Lessay- was by far the strongest source of CRI.

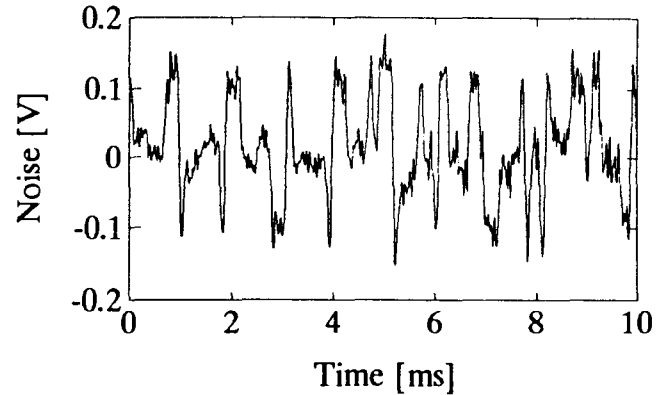


Figure 5a: 'Noise' in the averaged Lessay signal

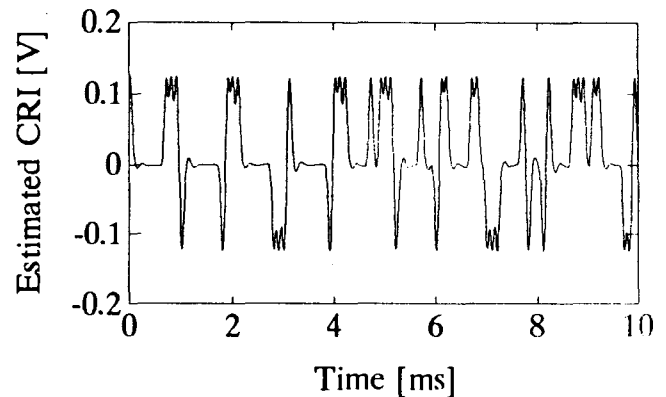


Figure 5b: Estimated CRI due to Sylt

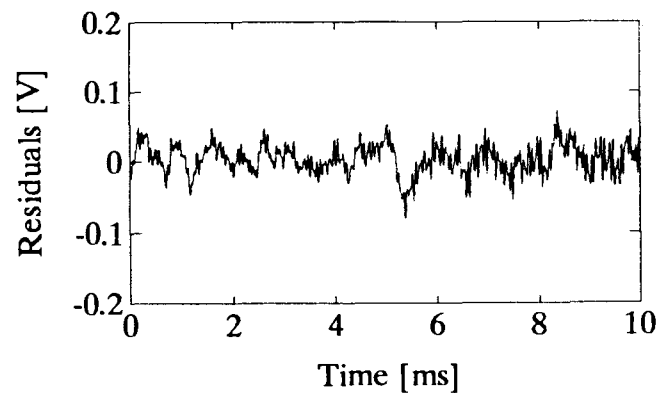


Figure 5c: Noise after CRI subtraction

5 Conclusions

A prototype Loran-C receiver has been built, which has several advantages over conventional receivers. Because of the smart processing of the input signal, the acquisition time is very small, in the order of ten seconds for the weakest Loran signals. An effective method was developed to detect and eliminate (near) synchronous CWI signals. Further, the new receiver is capable of detecting and estimating skywaves. However, care must be taken with this method, since only the shape of the leading edge of the Loran pulses is known. Finally, it was demonstrated that it is possible to largely eliminate cross rate interference by implementing a simplified maximum likelihood estimation technique.

Acknowledgments

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SESSION 3A

System and Receiver Technology

EVALUATION OF A LORAN-C TOWER COLLAPSE

David F. Mazurek

U. S. Coast Guard Academy
New London, Connecticut USA

ABSTRACT

Key findings from the investigation of a corner-guyed 1350-ft Loran-C tower collapse are discussed. The tower collapsed with no warning under cold but otherwise mild conditions. The initiator of the collapse appears to have been the fatigue fracture of a compression-cone insulator eyebolt. The fatigue fracture was a function of insulator design, and was not attributable to an anomalous flaw. As such, insulators of similar design are probably susceptible to similar fatigue failures. Concerns are also raised with regard to the lack of torsional restraint provided by the corner-guy arrangement. Nevertheless, the torsional characteristics of the tower did not appear to have contributed to its collapse.

INTRODUCTION

On the evening of 2 February 1993, the 1350-ft guyed transmitting tower at the Canadian Coast Guard Loran-C Station in Cape Race, Newfoundland, collapsed. The weather during the collapse was cold and calm, with the temperature and wind speed being approximately 12 °F and 22 mph, respectively. There had been no precipitation on the day of the collapse, and no icing of the structure was observed. No station personnel were present when the nearly 30 year old tower failed.

The site was visited a week after the collapse to investigate and document the wreckage. Other U.S. Coast Guard personnel present at this visit included Mr. V. Heu of the Honolulu Civil Engineering Unit and LT J. Hickey of the Providence Civil Engineering Unit. High winds and drifting snow severely hindered the ability to perform a thorough investigation. Thus, the site was revisited in May 1993 to complete the investigation. Mr. Heu also participated in this second visit. Between the first and second visits, portions of the wreckage were moved to enable the installation of a temporary transmitting tower. While efforts were taken to preserve the original state of the wreckage as much as possible, it should be noted that some significant alterations did result.

BACKGROUND

Figure 1 gives a schematic elevation view of the tower, showing that the structure was

supported at five levels by three structural guys per level, and six radial top-loading elements at the top of the tower. Towers which employ the three structural guy per level arrangement depicted are commonly referred to as "corner-guyed" structures. Structural guys for levels 1 and 2 are secured by the same anchors, which are referred to as "A" anchors. Likewise, structural guys for levels 3, 4, and 5 are attached to "B" anchors, while the top-loading elements are attached to "C" anchors. Figure 2 shows a schematic of selected structural details. Each tower was fabricated from galvanized steel, and consisted of three main legs braced by bolted horizontal and diagonal members. The legs were solid and circular in cross-section. The tower was built in prefabricated sections which were secured together using A325 high-strength bolts. There were a total of 45 sections, and their approximate distribution with regard to the guy levels is given in Figure 1. Each connection consisted of bolting flanges which were welded to the legs. Using clevis assemblies, structural guys were attached to padeyes welded on the tower legs. The guys themselves consisted of wound galvanized steel strands.

Each guy assembly contained a number of Lapp-type compression-cone insulators of various sizes and configurations. The insulators are massive and commonly weigh hundreds of pounds apiece. As an example, Figure 3 illustrates one of the insulators used on the 3rd level guys. As shown, the insulator consists of a cast steel frame and a forged eyebolt. The frame is electrically insulated from the eyebolt by the porcelain element or "compression cone". Should the porcelain fail, the failsafe cap is intended to bear against the frame and prevent the eyebolt from pulling through, thereby keeping the guy structurally intact. The universal ring is a stainless steel rocker assembly which is intended to alleviate cyclic bending stresses on the eyebolt. This assembly was a design modification developed in 1965 in response to bending fatigue failures of eyebolts which had occurred on two other guyed towers [Slunder et al. 1969].

The base of the tower was supported by an Austin-type base insulator, which is depicted in Figure 4. The tower rested on a bearing plate and was laterally restrained by a steel shear pin. Except for frictional resistance,

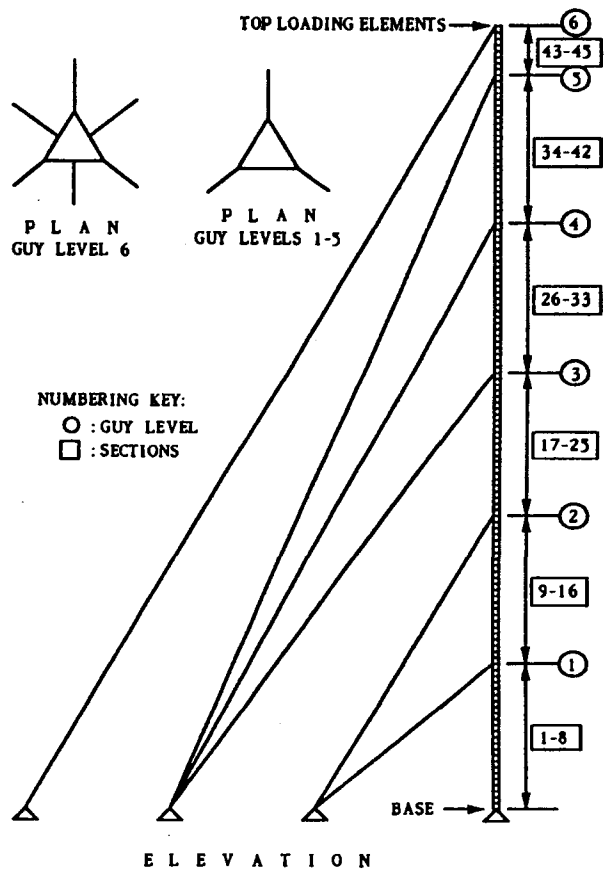


Figure 1. Schematic of Overall Tower

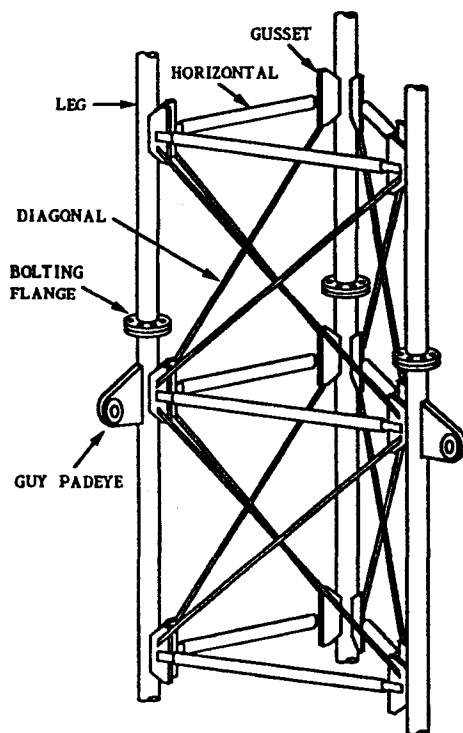


Figure 2. Schematic of Structural Details

the tower was free to pivot about the pin. The insulator itself consisted of 21 oil-filled ceramic cylindrical tubes. The base insulator was primarily intended to support the vertical reaction of the tower. In addition, the lateral beam shear reaction due to wind loading on the tower was also considered in the insulator design. However, any shear applied by torsional action of the tower and resisted by friction between the bearing plates was neglected.

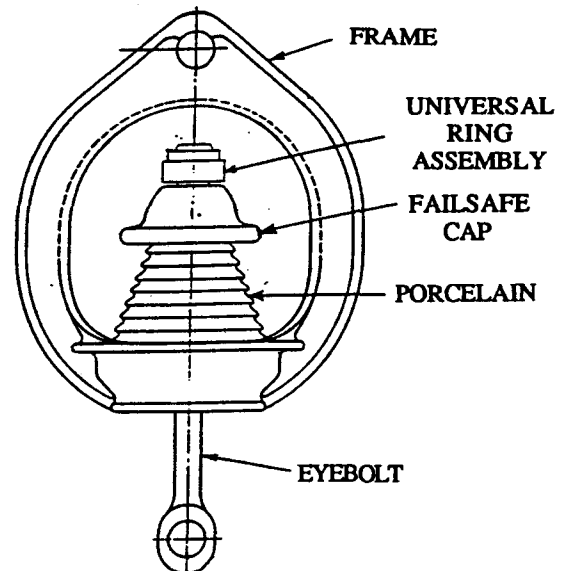


Figure 3. Compression-Cone Insulator

INSPECTION FINDINGS

Figure 5 shows the general layout of the tower wreckage in plan view with respect to landmarks in the transmitter field. The "A" anchors are designated as A1, A2, and A3, where the number indicates which structural guy lane is involved (i.e., 1, 2, or 3). Likewise, B1, B2, and B3 are the labels for the "B" anchors located in structural guy lanes 1, 2, and 3. C1 through C6 are the anchors for the top-loading elements. A new transmitter building had recently been constructed to replace the operations of the old transmitter building. The approximate locations of these structures are also shown.

As Figure 5 shows, the first 21 sections of the tower fell approximately toward north in a rather continuous manner. This segment of the tower, which included guy levels 1 and 2, exhibited no global buckling or doubling-over characteristics. Significant portions of the structure in this area were moved prior to the second visit. These sections experienced heavy damage, primarily as a result of ground impact. At some point in the collapse, these first 21 sections separated from the rest of the structure, with the remaining sections

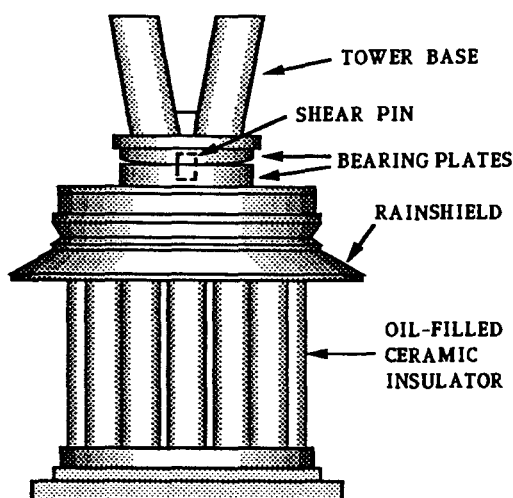


Figure 4. Base Insulator Details

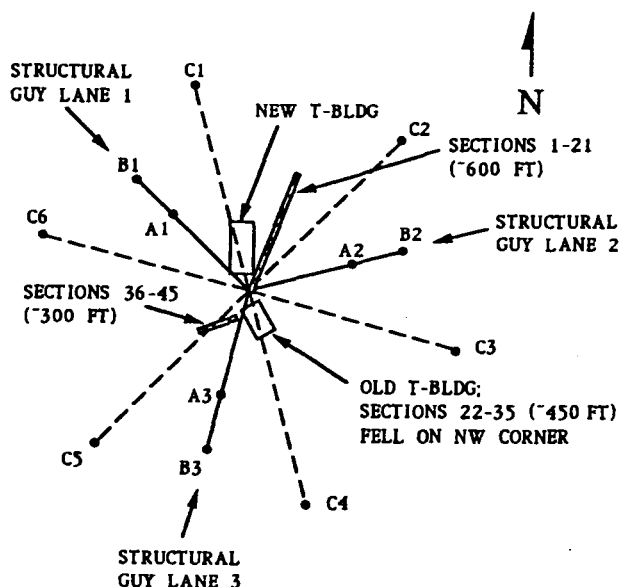


Figure 5. Plan View of Tower Wreckage

dropping straight toward the ground. Sections 22-35 fell directly on top of the old transmitter building, causing heavy damage to the structure. Sections 36-45 were laid out adjacent to the old transmitter building as shown in Figure 5. These sections were all moved prior to the second visit. Remarkably, the top of the tower sustained some of the lightest damage with regard to the structure as a whole, despite falling the greatest distance.

The guys were surveyed to identify any severances which occurred during the course of the collapse. Failures of structural guys which are believed to have occurred as the tower fell are documented as follows:

Guy Lane 1, 1st Level: The guy was severed, apparently as a consequence of it dragging over the eave of the new transmitter building's roof as the lower portion of the tower was tipping over.

Guy Lane 1, 2nd Level: The eyebolt for the second compression-cone insulator from the tower had pulled through the frame. This may have occurred if the guy went slack during the collapse, with the release in tension causing the universal ring assembly to spring loose. This assembly was held in place by an internal split retaining ring, and relied on tension in the guy in order to remain secure.

Guy Lane 1, 3rd Level: The guy failed as a result of a fatigue failure of the eyebolt head on the eighth compression-cone insulator from the tower. Figure 6 shows the location of this fatigue crack. The details of this fatigue failure will be discussed later. This eyebolt head fracture was the only one observed in the field. Subsequent to the eyebolt failure, the guy attached to the insulator frame became severed. It is speculated that this severance may have occurred as the guy recoiled and the insulator impacted with the tower.

Guy Lane 3, 1st Level: The frame of the first compression-cone insulator fractured at its attachment point to the tower. It was evident that this fracture occurred early in the collapse process, since the insulator was found hundreds of feet away from its attachment point on the tower.

Guy Lane 3, 2nd Level: The guy was severed near its connection to a cluster of four compression-cone insulators attached to the tower. As in the previous case, the severed guy was hundreds of feet away from these insulators, indicating that this failure also occurred early in the tower's collapse.

All other guys, including the top-loading elements, appeared to have remained intact until ground impact. Virtually all guys had certain compression-cone insulators which failed upon impact. Many of these insulators experienced fracturing of the steel frame, some of which exposed porosities and voids in the castings.

There were many different types of failures observed that were associated with the tower legs, where most were probably a consequence of the already collapsing tower. Virtually every bolting flange connection on the legs failed upon ground impact. Most of these failures involved fracture of the bolts. However, fractures of both the bolting flanges and the welds of these flanges to the legs were also commonplace. A number of legs were

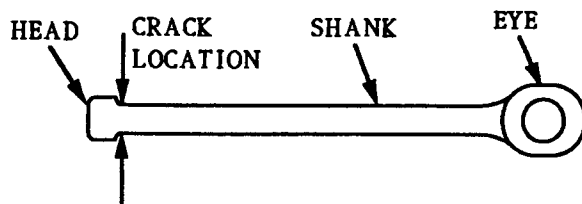


Figure 6. Fatigue Crack Location on Eyebolt

also found which had fractured through the section. In addition, several of the guy attachment padeyes which were welded to the legs broke off upon ground impact.

There were also numerous failures of the horizontal and diagonal bracing members, including buckling and fracturing failures. In addition, many of the bolted connections tore out of the gusset plates welded to the tower legs. Again, the majority of these failures are believed to have occurred upon ground impact.

The base of the tower (Section 1) was virtually unscathed by the collapse. The base insulator on the other hand was shattered, and the remains had been removed prior to the second visit. Observations of the bearing plate at the base of the tower which were made on the first visit suggested that circumferential wear marks indicative of torsional motion may have been present. Closer inspection upon the second visit revealed that the circumferential rings were most likely caused by machining. Thus it remains inconclusive as to whether or not the bearing plates routinely slipped in a torsional manner. It should also be noted that the shear pin which laterally restrains the tower base incurred only slight damage. Although the condition of the reinforced concrete base pedestal could not be examined in either inspection visit, station personnel indicated that it had only received moderate damage.

FATIGUE FAILURE ANALYSIS

The following discussion focuses in detail on the characteristics of the eyebolt fatigue failure mentioned earlier. Again, this failure occurred in the eighth insulator from the tower on the third level guy in the first structural guy lane. The crack occurred just below the eyebolt head as shown in Figure 6. Important features of the failure surface are identified in Figure 7.

As shown in Figure 7, the fatigue crack began at multiple nucleation or crack origin sites throughout the circumference. The crack progressed through the initial slow growth

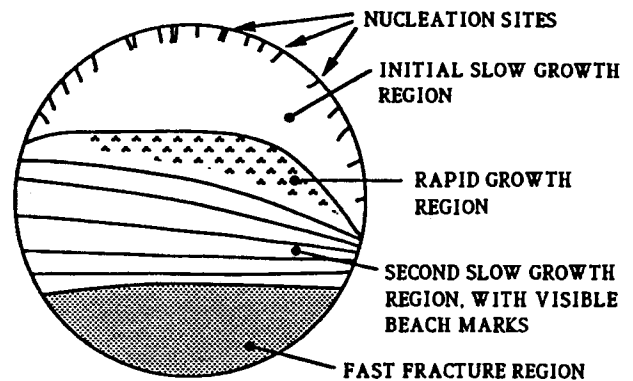


Figure 7. Details of Fatigue Fracture Surface

region over a duration on the order of a million cycles. The crack then continued through a rapid growth region, where it is suspected that the guy was subjected to an inordinately high level of tension. This increase in tension may have been due to extreme ice and/or wind loading. The crack then progressed through a second slow growth region, where beach marks were visible. Rupture finally occurred in the fast fracture region. When the eyebolt was on the verge of this final rupture, the crack progression had reduced the effective cross-section to about 20 percent of the original.

Comparisons of this fatigue failure surface with interpretation charts [*Metals Handbook* 1987] indicate that the crack grew under a state of low nominal stress in the presence of a mild stress concentration. The character of the cyclic loading may have included a combination of alternating tension, torsion, and bending. As mentioned previously, the original insulator designs were determined to be susceptible to bending fatigue failures of the eyebolt head. The universal ring assembly was introduced to alleviate this condition. A torsional component in the cyclic loading could be the result of the tendency of a wound guy to rotate as changes in tension occur. The universal ring assembly would not be effective in mitigating any such torsional effects.

The multiple nucleation sites around the circumference of the eyebolt shaft indicate that no specific material flaw in the eyebolt was responsible for initiating the fatigue failure. Rather, the crack initiation was more a function of the loading and the mild stress concentration present. The stress concentration could have been reduced by providing a more gradual transition from the eyebolt shaft diameter to the head diameter. Initial cracking of the more brittle galvanized coating could also have contributed to forming nucleation sites. Since the crack initiation was associated with the insulator design and was not attributable to an isolated

flaw, it is highly probable that any other comparably designed insulator used in a similar application will be prone to the same type of fatigue failure. Although similar failures or cracking were not observed in the remaining insulators, careful testing may be necessary in order to reveal potential propagating cracks in other eyebolts.

TOWER COLLAPSE THEORY

Study of the layout of the wreckage as shown in Figure 5 and observations of individual details has helped to deduce the collapse sequence of the tower. It is believed that the collapse began when structural failures occurred within the tower between guy levels 2 and 3. These failures resulted in the separation of the upper and lower portions of the tower. The uniform pull of the upper level guys drove the upper tower portion almost straight toward the base of the tower, veering into the third guy lane and crashing into the old transmitter building. The impact with the building broke the fall of the tower top, which finally laid over in its final position and incurred markedly less damage.

In the process of falling, the upper tower portion cut through the lower level guys in the third lane, resulting in their near simultaneous failure. It should be noted that if one of these guys had remained in place significantly longer than the other, its restraint would probably have resulted in global buckling and doubling-over of the lower tower portion, which did not happen. In addition, it is believed that the guy failures of the first two levels in the first structural guy lane occurred well after those in the third lane, and that the pull of the lower level guys in the first and second lanes caused the lower portion of the tower lay over between these lanes.

Various observations were made which support this general failure sequence. First, at Anchor A2, the third level guy in this lane was pinched between the first and second level guys. This could only have occurred if the third level guy (and hence the upper tower portion) had fallen before the lower tower portion tipped over. Second, a tower leg was found which was severely scraped and the lower side of a gusset gouged as the leg dragged over a guy. This leg came from either Section 23, 33, or 35, all of which are above the separation point between the upper and lower portions of the tower. Thus, this leg from an upper section of the structure most likely was falling while the lower portion was still in place. Finally, orange paint residue and rub marks were observed on the failed lower level guys in the third lane, suggesting that these guys must have been in place while parts of

the upper tower portion dragged over them and perhaps caused them to fail.

The issue now is determining what caused structural failures to occur within the tower between guy levels 2 and 3, thereby causing the collapse. The most probable initiator was the fatigue failure of the insulator eyebolt discussed earlier. The fatigue crack propagation was something which occurred over years, and was not a consequence of another failure in the tower. While there is a remote possibility that another tower component may have failed first, the eyebolt was on the verge of final fracture and was most likely the first component that failed. Fracture of the eyebolt would have caused the guy to separate. After separation, the portion of this third level guy which was still attached to the tower would have included seven compression-cone insulators. As Figure 8 demonstrates, the recoil and swinging of this guy segment probably caused the insulators to slam into the tower. Given the mass of the insulators, the magnitude of the impact was probably sufficient to damage enough tower structure to initiate its collapse.

An additional concern of this structure was its guying arrangement. The tower employed three guys per level as shown in Figure 1, commonly referred to as a "corner-guyed" arrangement. Because the lines of action for the three guys would converge on a common point, this arrangement formed a concurrent force system [Hibbeler 1990]. As such, no primary torsional resistance was provided, requiring the tower to rotate before it could develop significant secondary torsional resistance from the guys. If not considered in design, torsional loadings and motion of the tower can contribute to component failures. For example, it was determined that the collapses of two 300-ft corner-guyed communications towers were probably the result of excessive torsional motion, causing the guy insulators, designed for axial load only, to fracture under large bending stresses [Mazurek and Russell 1992].

Perhaps the component of the Cape Race tower most vulnerable to torsional motion was the base insulator. Such motion of the tower could have transmitted significant shear loadings to the base insulator via the frictional resistance between the bearing plates at the tower's base. Failure of the base insulator would have caused the entire tower to drop about three feet. The shock resulting from the impact could have caused the structural failures that occurred between the second and third guy levels. However, because the reinforced concrete base pedestal sustained only moderate damage and the lowest section of the tower sustained virtually no damage at all, it is unlikely that failure of

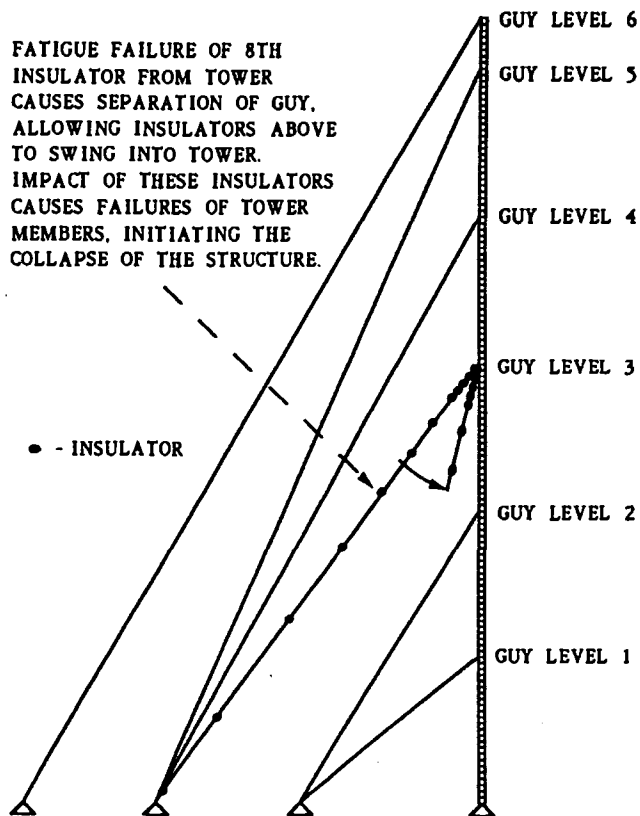


Figure 8. Insulator Initiation of Collapse

the base insulator initiated the tower's collapse.

CONCLUSIONS & RECOMMENDATIONS

Key findings from the investigation of a guyed Loran-C tower collapse have been presented. The initiator of the collapse appears to have been the fatigue fracture of a compression-cone insulator eyebolt. Towers which employ similarly designed insulators should be given careful examination and treated with caution. If subjected to comparable loadings and load cycles, it can be expected that similar insulators will develop the same type of fatigue cracks. Evidently, one insulator failure can be sufficient to initiate the collapse of a tower, and this failure can occur at any time and in any environmental state.

It is recommended that some attention be given to developing a nondestructive inspection method for evaluating the integrity of compression-cone insulators in the field. Since the critical area for crack propagation on the eyebolt is hidden under the universal ring assembly, advanced cracking could exist and yet not be visible. It may be possible to employ ultrasonic methods by sending sound waves down the axis of the eyebolt when

placing the prod on the exposed top of the eyebolt head.

Concerns have also been raised regarding the lack of torsional restraint associated with the corner-guy arrangement employed by this tower. It is recommended that either a torsionally resistant scheme be used, or that careful consideration be given in design to the consequences of not using such an arrangement. Mazurek and Russell [1992] discuss ways to provide torsionally resistant guy patterns.

ACKNOWLEDGMENTS

The author wishes to thank the Radio Navigation Division of the U.S. Coast Guard Office of Navigation Safety and Waterway Services for funding this investigation. D.H. Plantz of the U.S. Coast Guard Academy and A.J. McEvily of the University of Connecticut are gratefully acknowledged for their consultation regarding the fatigue analysis. The expertise and insights provided by V. Heu during the investigations were invaluable. Finally, the assistance and cooperation of the Canadian Coast Guard is greatly appreciated.

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EFFECT OF TRANSMITTER OUTAGE ON LORAN-C COVERAGE IN CONUS

Walter N. Dean

Waldean Engineering Inc.
Wilsonville, Oregon, USA

ABSTRACT

This paper analyzes the effect on the Loran-C coverage in the CONUS of the failure of any single loran transmitter or station. It assumes the use of a multi-chain, master independent, automatic loran receiver.

INTRODUCTION

The existing Loran-C system provides accurate position information for en route navigation under instrument conditions over the entire continental United States with the existing network of transmitting stations. Eight chains, composed of 22 stations, are required to provide this coverage. Despite the high availability of the stations, there are infrequent periods of scheduled or unscheduled transmitter outage.

Despite these outages, a multi-chain, master-independent loran receiver can still operate accurately over a large portion of the CONUS. Such a receiver can track up to 12 stations in at least two chains simultaneously, deriving position information from a composite of the time differences or pseudoranges from all the stations within effective ground-wave range of the receiver. A general limitation is that a chain cannot be acquired without receiving at least a skywave signal from the Master station of the chain, so the assumption on out-

age of a master station is that the outage occurred after chain acquisition.

COVERAGE CHARTS

Two separate charts have been prepared to show the areas affected by transmitter outages, assuming different types of failures. The areas indicated are those in which the estimated position error would become greater than 2.9 nautical miles, the requirement for en route instrument air navigation.

TRANSMITTER OUTAGE

The first analysis assumes that only one transmitter goes down at a time, as might occur if a single rated station went off air or if one transmitter at a dual rated station experienced a failure. When certain stations are removed from operation, a few specific areas are adversely affected, shown in Figure 1. If the 9960 Master goes down, the small area in northern New Hampshire and Vermont loses coverage because then only two stations remain within groundwave range. The East Coast Canadian chain, 5930, provides the supporting coverage in Maine.

If 8970-Y is off air, the area shown in the Upper Peninsula of Michigan and northern Lake Michigan is left without

coverage. If 8290-X goes off, a small area in eastern Montana will lack accurate navigation. Failure of 9610 M, W, or X causes errors in a small portion of southern Arizona.

STATION OUTAGE

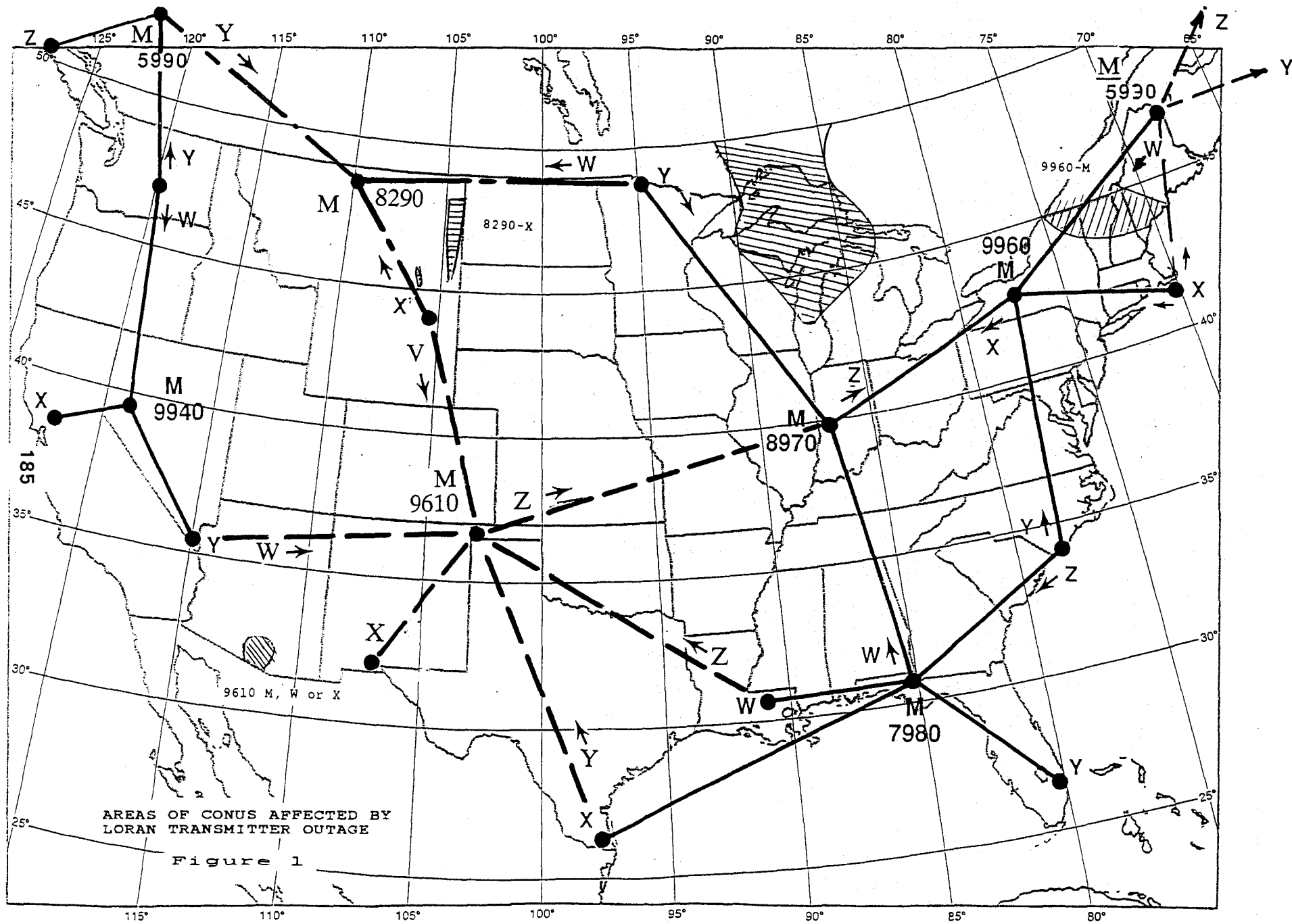
If it is assumed that both transmitters at a dual-rated station are off together, as would be the case in event of a primary power or antenna failure, the areas affected are increased somewhat, because transmitters on two different rates are off the air. The results of these failures are shown in Figure 2. The affected area in the northeast is the same as in the first case if either the Seneca, NY, Nantucket, MA, or Caribou, ME, station goes down. The Michigan area affected is also the same as in the first case if the Dana, IN, Baudette, MN, or Seneca, NY station stops transmitting. A power failure at Gillette, WY, would cause a somewhat larger area in eastern Montana and western Dakotas to lose coverage.

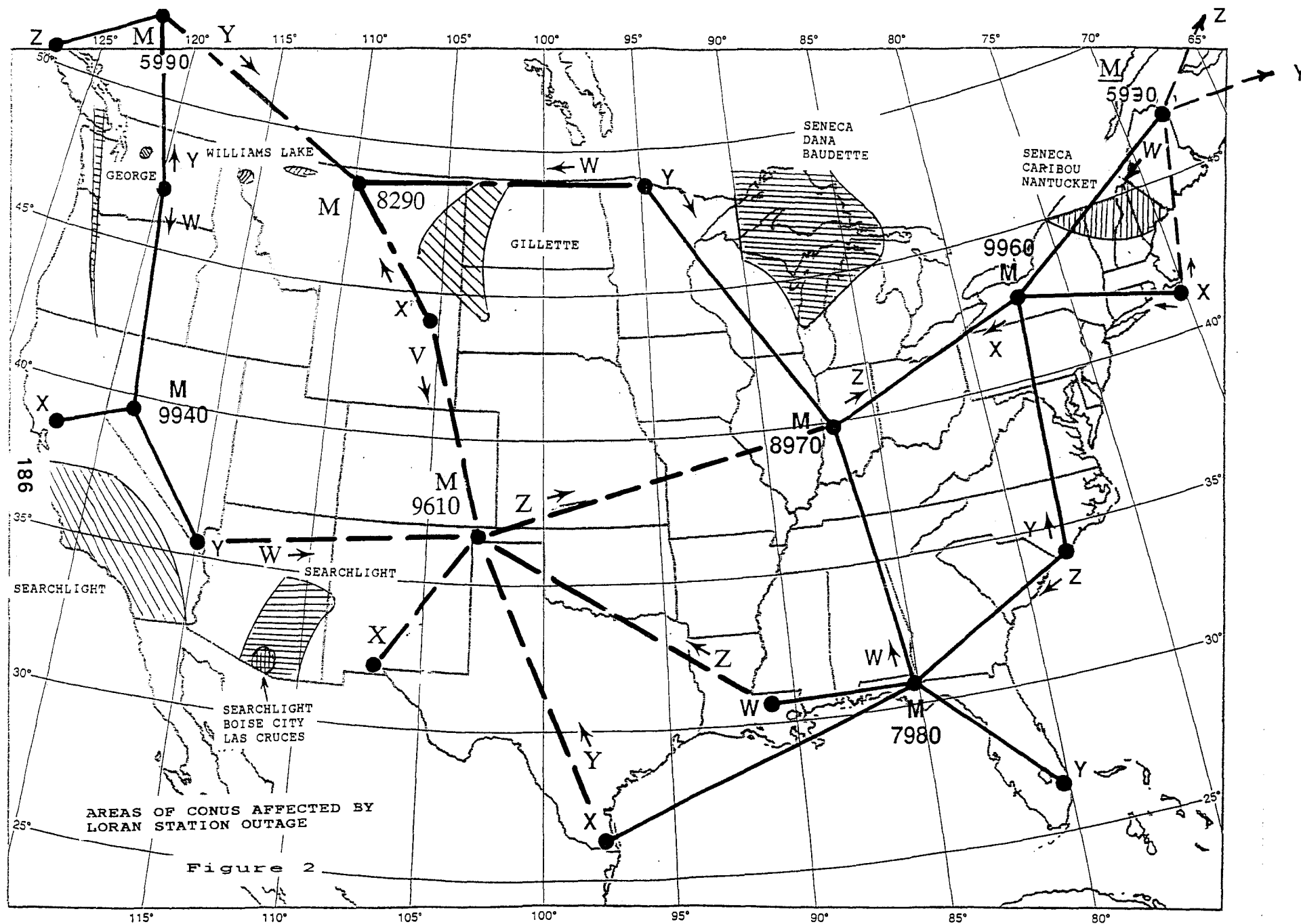
A shutdown at George, WA, causes an area of inaccuracy along a line from about N42-W122 to Puget Sound and a small area in northern Washington. Failure at Williams Lake affects two small areas in western Montana. A shutdown of Searchlight eliminates coverage in southwestern California and in southeastern Arizona. The same small area in southern Arizona is also affected by failures at Boise City and Las Cruces.

In each case, in areas not mentioned, which is the vast majority of the CONUS, loran position accuracies will be within the requirements for en route IFR navigation with a dual-chain master independent receiver.

ACKNOWLEDGMENT

The computer program calculating estimated position error was developed by David Jameson of Arnav Systems, Inc.





The Need for an International Coordinator for the Loran-C System

W. J. THRALL, D. H. ALSIP, and A. N. MASON

USCG Headquarters
Office of Navigation Safety and Waterway Services
Radionavigation Division

September 1, 1993

Biographies

Commander W. J. Thrall has enjoyed 11 years of RA experience. He has been Commanding Officer of Loran Station St Paul, Alaska and Coordinator Of Chain Operations of the North Pacific Chain. He has been Chief of the Loran Branch and prior to his retirement, Assistant Chief of the Radionavigation Division at U. S. Coast Guard Headquarters. He was a Coast Guard representative to IALA, Far East Radionavigation System (FERNS), and the U. S. Department of Defense/Department of Transportation Navigation Working Group.

Commander D. H. Alsip is Assistant Chief of the Radionavigation Division at U. S. Coast Guard Headquarters. He has over 16 years experience in the navigation field, including 8 years of direct involvement in Loran-C, including the installation of Loran-C Station Port Hardy, BC and the Loran-C Remote Operating System. He graduated from the U. S. Coast Guard Academy in 1975 and received his MSEE degree from the Massachusetts Institute of Technology in 1979.

Lieutenant A. N. Mason is Chief of the Domestic Loran-C Section of the Radio-Aids Management Branch at U. S. Coast Guard Headquarters. His background includes over 20 years experience in the Loran-C system. Prior to coming to Headquarters, he served as Commanding Officer of the Loran-C Station at Seneca, NY. He was also involved in the installation of the U. S. West Coast and Gulf of Alaska Loran-C chains. LT Mason received his A.A. degree in Electronics Technology in 1986.

Disclaimer

The content of this paper represents the opinions of the authors, based on their knowledge and experience and are not the opinions of the Commandant or the U. S. Coast Guard.

Abstract

This paper describes some pending changes that world-wide Loran-C operators intend to make in the near future. Plans include station additions, closures, and chain reconfigurations. The paper then discusses, in layman terms, the potential ramifications of these changes, if they are not coordinated world-wide. After reviewing the concept of Group Repetition Interval (GRI), it shows why some GRI assignments should be changed and the importance of both coordinating GRI assignments and notifying Loran-C receiver manufacturers of impending changes to ensure continued maritime and aviation safety.

Introduction

For most of its history, Loran-C has been operated in various regions of the world by the U.S. However, as time passes, more and more nations are becoming operators of Loran-C chains. By 31 December 1994, the U. S. Coast Guard will have turned over the operation and management of its overseas Loran-C facilities in the Northwest Pacific, Northwest Europe and in the Mediterranean Sea. Most of the host nations will continue to operate them, joining other nations such as Russia, India, Saudi Arabia, the Republic of Korea, and China who already operate

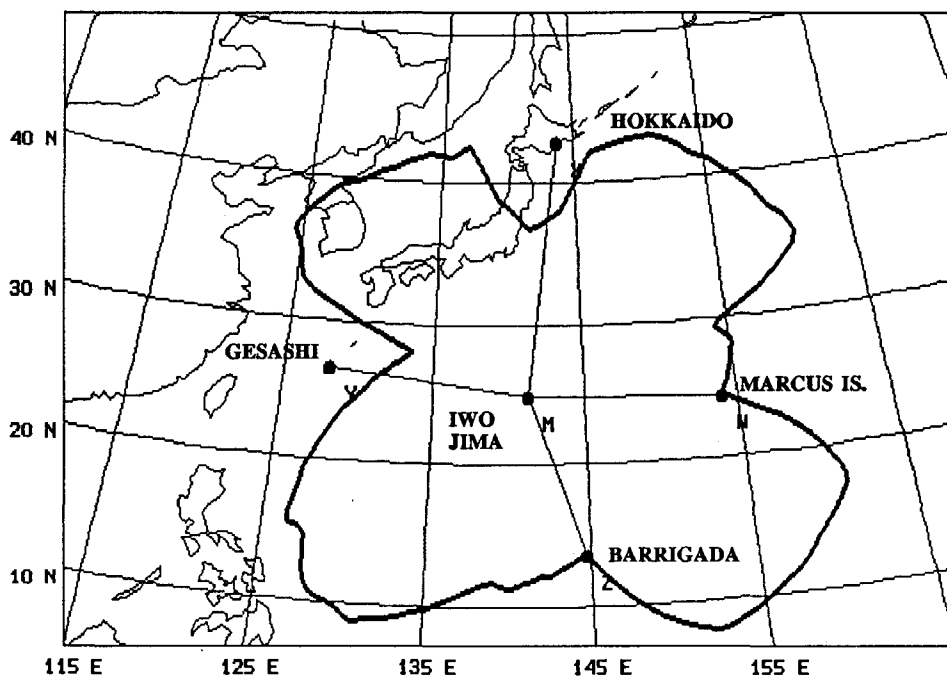


Figure 1 - Current Northwest Pacific Chain

took over the Northwest Pacific Chain, they chose not to use the Loran-C station at Barrigada, Guam. Therefore, the U. S. Coast Guard shut down operations at Barrigada on 30 June 1993. In addition, JMSA is investing in a new Master location at Nii Jima. This will result in the coordinated closure of the old master station at Iwo Jima and the start of operation at Nii Jima sometime before 31 December 1994. **Figures 1 and 2** depict the old and new configuration for the Northwest Pacific Chain.

Loran-C facilities. This shift from operation predominantly by one nation, to international operation will have a significant affect on Loran-C users. Because the new operators are planning changes including new stations, reconfigurations and station closures, if these changes are not coordinated on a world-wide basis, the affect on users could be devastating.

Coming Changes in World-wide Loran-C

Many nations are considering or implementing some very ambitious modernization and expansion plans to ensure continued Loran-C operation. In many cases, this may require reconfiguring existing Loran-C chains because some stations have been or will be discontinued or moved. For instance, when the Japan Maritime Safety Agency (JMSA)

Beyond these changes, there are some stations that have been or will be discontinued. These include: the three stations of the Central Pacific Chain (Upolu

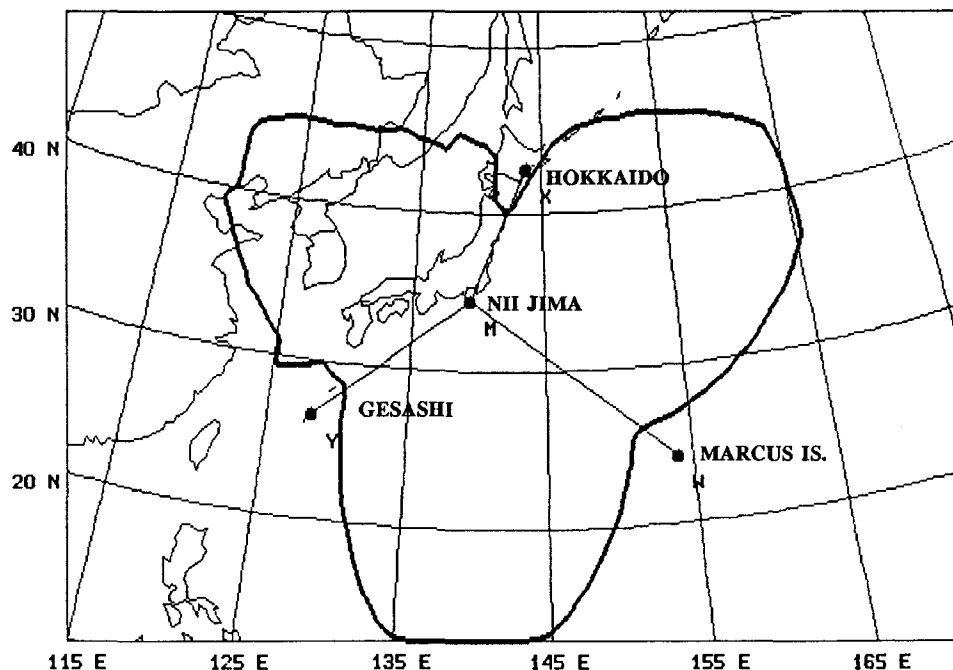


Figure 2 - Planned Northwest Pacific Chain

Point, Johnston Island, and Kure Island); Sandur, Iceland; and Angissoq, Greenland.

The impending closure of Angissoq has impelled the Canadian Coast Guard to invest in a new station -- Comfort Cove, Newfoundland. This reconfigured chain will consist of Comfort Cove as the new master, with Fox Harbour and Cape Race as the Xray and Yankee secondaries, respectively. This new chain is to be called the Newfoundland chain.

The old Labrador Sea and the planned Newfoundland chain are shown in figure 3 and figure 4, respectively.

Northern Europe, too, has been investing in

changes to its Loran-C chains. A new station is expected to be built in west Ireland (Loophead) and Norway is building two additional stations: one at Berlevaag and one at Vaerlandet. Existing station transmitters at Boe and Jan Mayen, Norway are being

upgraded. These changes will result in the creation of a new chain and the reconfiguration of the existing Norwegian Chain. Figure 5 shows the new configuration of the Loran-C chains in the Norwegian/Northwest European area.

All of these anticipated closures and reconfigurations require GRI assignment changes. These changes will provide the first opportunities for international GRI assignment coordination. But coordination of GRIs only addresses part of

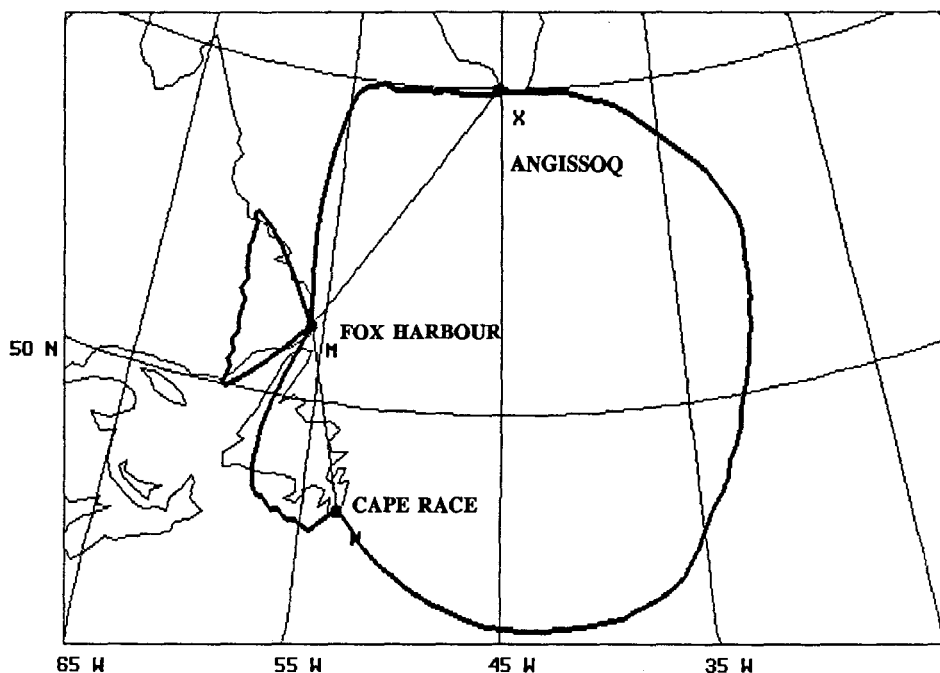


Figure 3 - Current Labrador Sea Chain

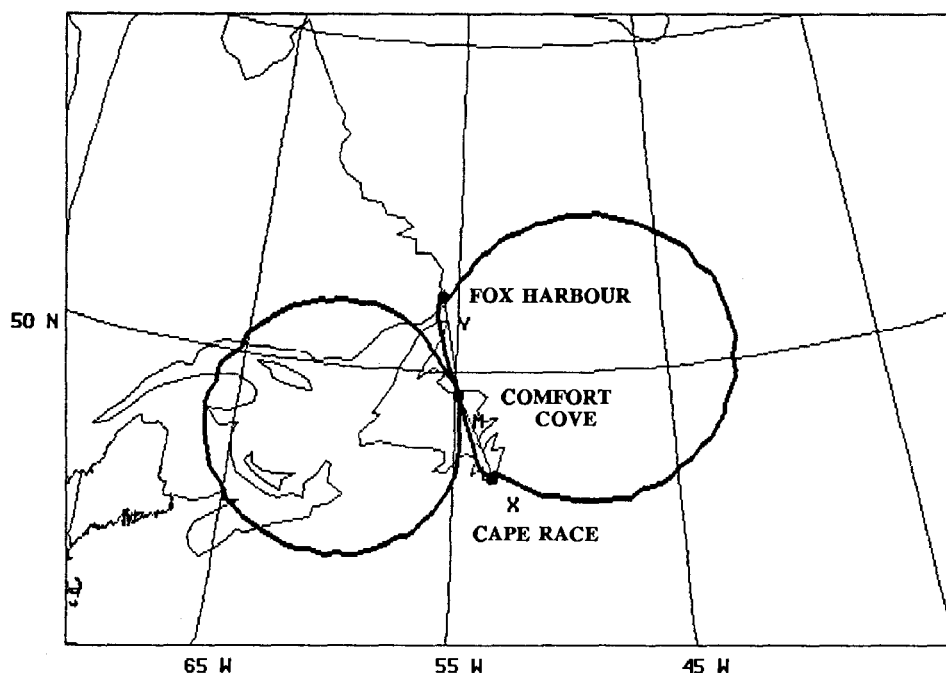


Figure 4 - Planned Newfoundland Chain

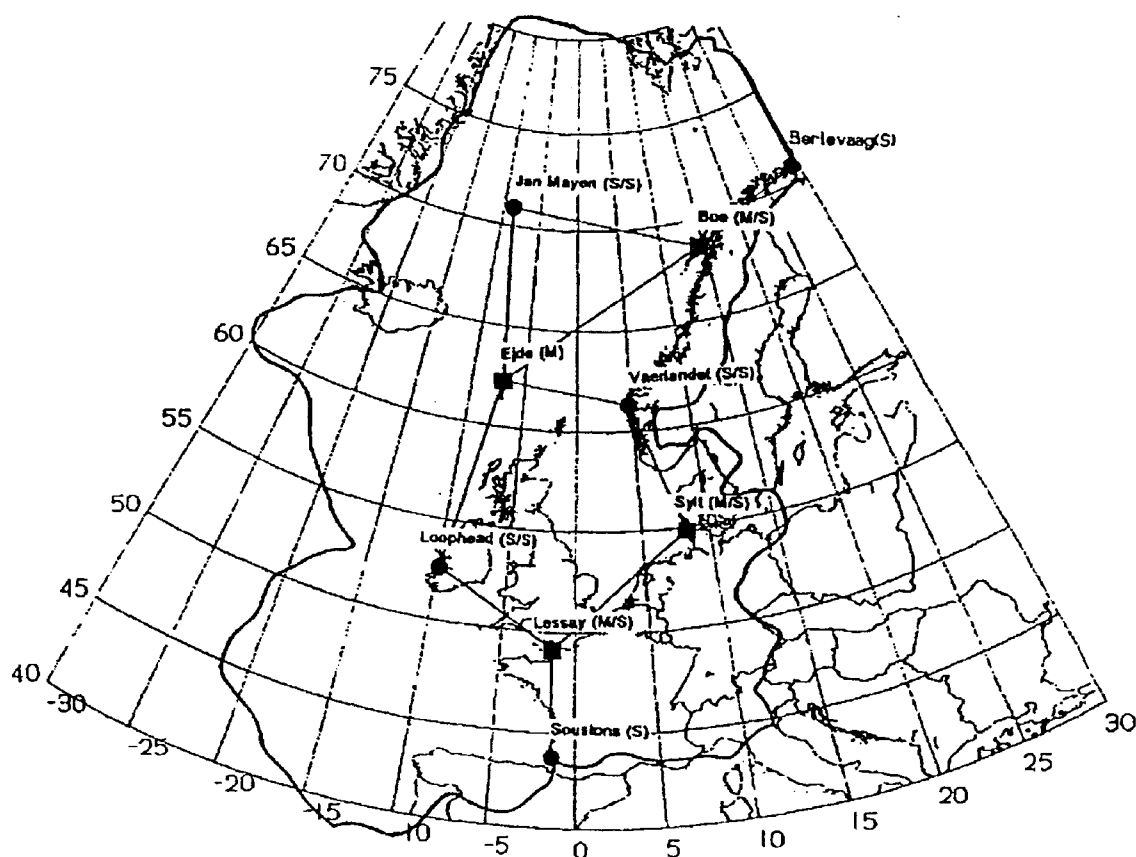


Figure 5 - Planned Northwest Europe Chain Configuration

the concern: the world's receiver manufacturers still must be notified of each of the changes and the timing of each change. This includes providing them with the new latitude-longitude, GRI, coding delay and emission delay. **Table 1** shows this information for the existing Labrador Sea chain as an example.

The Problem

It takes at least three Loran-C stations operating together to provide hyperbolic navigation. If a Loran-C station is discontinued, the navigator loses coverage where that station provided its signal as part of the triad. The Loran-C receiver can't process

GRI: 7930	LABRADOR SEA CHAIN	LATITUDE	LONGITUDE	EMISSION DELAY	CODING DELAY
M	Fox Harbour, NFLD, CAN	52° 22' 35.157" N	55° 42' 28.416" W	--	--
W	Cape Race, NFLD, CAN	46° 46' 32.180" N	53° 10' 28.160" W	13,167.31 μ S	11,000 μ S
X	Angissoq, Greenland	59° 59' 17.270" N	45° 10' 27.470" W	29,565.39 μ S	26,000 μ S

Table 1 - Characteristics of Labrador Sea Chain

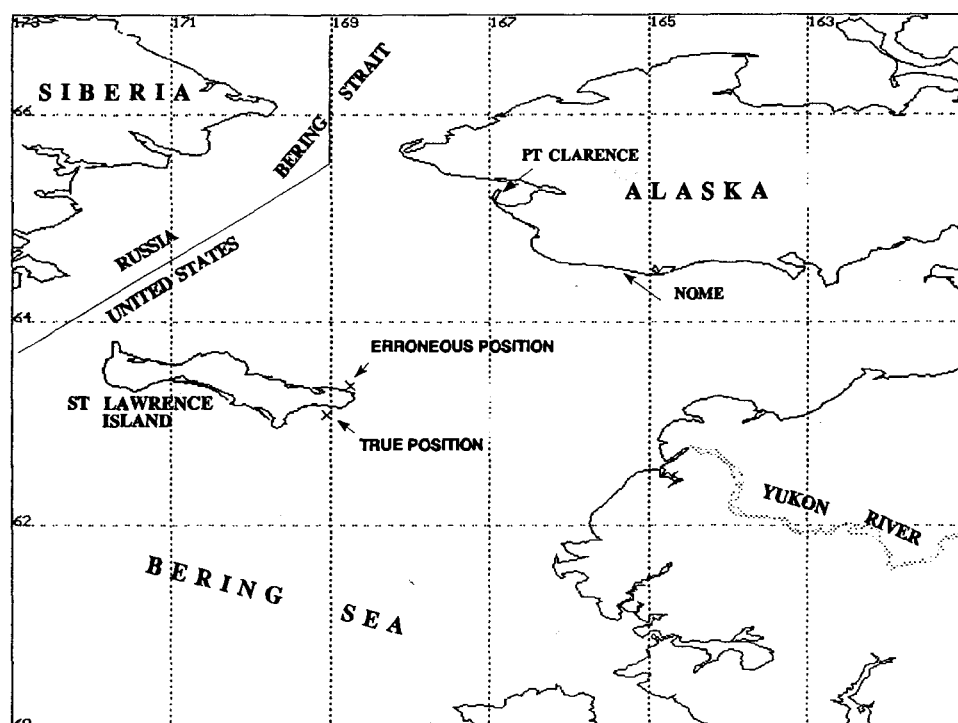


Figure 6 - Position Error Due to New Secondary Station Location

position information without that station's signal. There is no confusion/safety problem to the navigator about whether the positioning information is available or not -- it's not. However, if a station or two are moved or added within a chain, the receiver doesn't automatically adjust its positioning computations. Instead, it continues to provide positioning information based on the old position of the station or stations preprogrammed into the receiver (unless the receiver has been serviced by the manufacturer and the station and chain data updated). This could result in a very surprised navigator (at best) or a very serious accident (at worst). **Figure 6** shows what can happen when a station is moved without the provision for updating the user's receiver internal chain database. The user thinks he/she is located at the north side of St. Lawrence Island in the Bering Sea, because that's what the Latitude/Longitude display on the receiver would say if its database was not properly updated. In reality, the user is over 20 miles away, on the *south side of the island!* A way to avoid such an inadvertent error in this case is for the chain operator to change the GRI. It would then be impossible for an un-serviced receiver to track the signals.

The Purpose

GRI is the numerical identifier used by receiver

manufacturers to differentiate between chains. The number, say 9960, is an abbreviation of the total time in microseconds it takes for the "chain" of master and secondaries to transmit their respective signals before the cycle or sequence begins again (in this example, 9960 would represent 99600 microseconds between the start of each master transmission). Each existing chain has its own unique GRI to identify it from any other.

Millions of Loran-C receivers in use today recognize the

location of transmitting stations based on the GRI. The very accurate position of each Loran-C station has been preprogrammed by the manufacturers into the receivers. This position data, along with the emission delay and baseline length, are used with the measured Time Differences (TDs) to determine the latitude and longitude of the user. That's why it is important to ensure that *all* receiver manufacturers are notified of the proposed changes in a timely and complete manner.

The Promise

Coordinated GRI assignments would ensure continued safety and could substantially reduce interference between new, existing, and reconfigured chains. But who should be the coordinator of any future GRI selection? And who should undertake to notify the world's receiver manufacturers of any changes?

Recommendation

Historically, the U. S. Coast Guard has offered GRI recommendations. These recommendations were based on knowing which GRIs are already in use, recognizing the relationship of the proposed chain and its stations to existing chains in the area, and performing both a computer analysis and a receiver

interference test. The U. S. Coast Guard also notified the receiver manufacturers of any changes. That was an acceptable situation when the U. S. Coast Guard was recognized as *the* international Loran-C operator/coordinator. However, as already mentioned, the U. S. Coast Guard will no longer operate overseas after 1994. Its Loran-C operations will be limited to the continental U. S. and Alaska.

of any Loran-C changes.

The International Association of Lighthouse Authorities (IALA), as an eminent international body that champions safe navigation, seems a likely candidate to act as the new worldwide coordinator of GRI assignment and to see that the world's receiver manufacturers are notified of changes. IALA would maintain an accurate list of available GRIs (all possible GRIs minus GRIs in use) and require petitioning nations perform the basic, initial analysis of determining the minimum GRI physically possible based upon the total transmission time necessary for the proposed chain.

Upon receiving the petitioning nation's minimum GRI analysis, IALA would perform the computer analysis to determine the best GRI choices to limit interference. IALA would then forward their recommendation package to the U. S. Coast Guard and request a simulated receiver test. This international effort and cooperation would ensure an international body is responsible for all GRI assignments. When the new GRI is approved and/or new chain information known, IALA would notify the Committee for International Radio - Maritime (CIRM), for further notification to the world's receiver manufacturers. The IALA nations would see that users are notified of changes through the Notice to Mariners system and updates to charts and publications. Aviation authorities should develop a similar scheme to notify aviation users and receiver manufacturers. This would ensure continued safety of navigation and maintain the confidence of worldwide Loran-C users.

Summary

With the application and use of Loran-C growing, it is critical that safe navigation be maintained. Continued coordination of GRI assignments will go a long way toward ensuring that safety. IALA, as an accepted world leader in championing safe navigation, should be that coordinator, and, if possible, look at reassigning existing GRI assignments based on optimum coverage and reduced interference as well as ensuring receiver manufacturers are provided timely notification

Satellite Navigation Technology

Will U.S. Politics or Safety Determine Its Future?

by John M. Beukers

Panel Debate: *Loran/GNSS Interoperability - The Future of Radionavigation - Is the U.S. Listening?*

The final phase of World War II came to an abrupt end nearly 50 years ago as a result of dropping atomic bombs on Japan. The scientists and engineers responsible for the development of nuclear fusion have since described their mixed feelings on the use of this awesome power for mass destruction as being necessary but tragic. Some were greatly troubled.

However, within months, this somber mood turned to one of euphoria. The possibilities of harnessing atomic energy for peaceful purposes caught the attention of politicians and the public. The scientific community proclaimed that nuclear power would provide the world's energy needs thus ending a reliance upon those with oil reserves.

There followed a mad rush to design and build nuclear power stations for which there was no engineering precedent. The United States, the Soviet Union and Great Britain established priority programs to be the first on line. But, along the way, something frightening happened.

The scientific and engineering community that wanted to proceed with caution found themselves at odds with those with financial interests and countermanded by politicians who looked for national advantage. The scientists and engineers lost control. In the Soviet Union cost became of paramount importance and safety was given a back seat. In the United States commercial enterprise recognized that, to be competitive, nuclear power stations had to be big, but no one really knew much about containment of these monster reactors. It was difficult to predict what would go wrong and to know what possible scenario had been overlooked.

Some say it was inevitable that with the financial and political pressure, major accidents would occur and they did. But in each case the cause of the accident was unanticipated. The resulting public reaction to the disregard of safety, both real and perceived, has been decisive in virtually halting nuclear power programs. Demands for safety and the acknowledgement of total life costs have made the industry non-competitive.

You may ask what this has to do with navigating by satellite. In my opinion there is a strong parallel. A convincing argument can be made that - **without a significant redirection of U.S. government thinking** - we could be headed in the same direction.

The day before the House Hearing on the subject of the *Future of Satellite Technology in Aviation* in July, I had the

opportunity to meet with members of the staff of a number of Representatives and Senators to discuss the subject of satellite technology. Frankly, this was a disturbing experience. This is not an environment of scientific understanding. Minds are easily swayed by the lobbies of special interests. I got the distinct feeling that we in science and engineering are losing the initiative and handing control to politicians by default.

Are we following in the footsteps of the nuclear industry? How fail safe are our designs? A few years back there was a massive solar prominence that created an unprecedented magnetic storm on earth that effectively closed down the whole of Canada's power grid and degraded the performance of a number of satellites. Are GPS satellites immune from all anticipated and unanticipated levels of solar activity? Have those responsible for safety looked into this? What is the failure sequence and will this be a soft landing? A few years ago something unexpected happened. Much of the U.S. AT&T long distance telephone system failed because of a bug in a new software program. Will our satellite system be secure from software failure and what will be the extent of any resulting disruption? Do software quality assurance procedures satisfy safety criteria? And what of our training program for satellite system operators? Are these career positions? What qualifications are required and what testing is conducted?

Does the proposed combination of GPS and GLONASS for a GNSS have the inherent design and infrastructure to meet the safety requirements of civil aviation and how will the safety of using this combination be established?

Those with the responsibility for safety of flight must be given time for their analysis and we must not let their findings and recommendations be overruled by company directors attempting to make airlines profitable or for politicians to do right by their constituents.

It is my opinion that the movement towards a satellite-only solution to global navigation is a wasteful and unacceptable digression. We need to focus on a Global Navigation System (GNS) consisting of a complementary mix of terrestrial and space-born systems used in concert for redundancy.

If we ignore the history of the nuclear industry and proceed down the satellite only, sole-means path, satellite positioning technology for civil aviation may well end up on the U.S. technology scrap heap along with MLS and other potentially beneficial, but poorly introduced, technologies.

SESSION 4

Aviation Uses

INTEGRATED GPS/LORAN-C RECEIVERS; A PERSPECTIVE ON USER ACCEPTANCE, INTEGRATION SCHEMES, AND CERTIFICATION STATUS

Robert Anoll
Systems Control Technology, Inc
Tel (202) 646-4830 Fax (202) 646-4790

ABSTRACT

This paper reviews the status of augmenting GPS with Loran-C to satisfy the required navigation performance of an airspace. Specific issues discussed are its acceptance by the aviation community relative to other options, RTCA SC-159's developing position on the recommended means of integration, and the status of the draft GPS/Loran-C Minimum Operational Performance Standards (MOPS).

INTRODUCTION

When the aviation community looked closely at the navigational performance delivered by GPS, they soon realized that this system does not, by itself, satisfy the required navigation performance of an airspace. Specifically, GPS delivers insufficient availability of position information with integrity [Table 1]¹. To satisfy this deficiency, a receiver which hybridized GPS and Loran-C was one of the first combinations analyzed as a potential solution. However, in the past few years considerable research has gone into

investigating other augmentations. The author presents a perspective on how well the receiver will be accepted by the aviation community in light of recent developments and the working group's interim conclusions and status.

ACCEPTANCE BY THE AVIATION COMMUNITY

After developing a supplemental GPS MOPS, RTCA Special Committee-159 (GPS) was tasked to continue its work and develop a sole-means GPS-based MOPS. The committee concluded that the navigational systems on which to develop certification procedures, for other than precision approaches, would be GPS augmented with GLONASS, GPS Integrity Channel, Inertial and Loran-C (GPS by itself was dismissed as an option). Possible other augmentations were dismissed due to known deficiencies, a lack of interest, and a shortage of expertise/manpower. In the author's opinion, GPS/Loran-C is emerging as the most desirable near-term navigational system for those who do not plan to venture into oceanic airspace. Its limitations in oceanic airspace may also not be insurmountable.

This conclusion has been reached by as much of a process of eliminating other augmentations as it is from the strengths of GPS/Loran-C. Integration with GLONASS was initially greeted with considerable enthusiasm but that enthusiasm diminished for several reasons. First, the Russians have publicly made conflicting statements about their country's willingness to maintain the system. Second, continuous wave interference from mobile communications systems and SATCOM remains a problem. Third, many pundits, particularly those in the European aviation community, strongly object to completely relying on two military systems; particularly since both could become inoperative for the same reasons. Of these three reasons, Russian statements about the uncertain future of GLONASS may prove the most daunting and by itself make users reluctant to purchase the receiver.

The GPS Integrity Channel (GIC) would enable GPS to satisfy the required navigational performance but is still a number of years away from being operational. The United States Government also continues to deliberate

TABLE 1 AVAILABILITY OF POSITION INFORMATION WITH INTEGRITY GPS WITH BAROMETRIC AIDING [24 SATELLITES WITH 3 FAILED]						
EN-ROUTE PHASE OF FLIGHT						
	A	B	C	A - AVAILABILITY		
JFK-LAX	94	45	70	B - AVERAGE OUTAGE (MINUTES)		
SFO-NRT	96	25	60			
DFW-CDG	99	20	30	C - MAXIMUM OUTAGE (MINUTES)		
TERMINAL PHASE OF FLIGHT				NON-PRECISION APPROACH		
	A	B	C	A	B	C
SFO	94	30	75	86	26	100
DFW	92	22	55	79	38	80
ORD	93	26	80	81	35	125
JFK	88	58	140	78	79	210
ATL	92	30	90	80	42	180

¹21 satellites will be usable at least 98% of the time.²

on whether to attach a user charge on GIC and to determine if GIC, with differential capability, is counter to U.S. national security (since selective availability was introduced for national security reasons).

An inertial augmentation, while a seemingly obvious choice for the high-end user, has limitations that may prevent it from gaining wide acceptance. From the certification point of view, important integration issues still have to be understood before a MOPS can be written and this problem is compounded by the lack of standardized requirements, algorithms, and interfaces for inertial systems. SC-159 has concluded that this would require a long-term effort to which they are reluctant to commit at this time. Instead, the Committee opted to develop a MOPS based on a navigation system that provides position determination using GPS only when GPS has integrity and transfers to a non-integrated inertial system when it does not; a true hybrid solution is not being considered. From the user point of view, performance should be adequate to satisfy only oceanic airspace requirements and perhaps domestic en-route airspace requirements.

In contrast, navigation based on GPS/Loran-C is hindered by few technical or political obstacles. The system will enable aircraft to operate everywhere that Loran-C provides coverage with the difference in signal frequencies and controlling agencies giving it superior redundancy. Perhaps more importantly, the hybrid receiver will cost only slightly more than a GPS receiver and the aviation community has extensive experience with Loran-C and is gaining experience with GPS.

A major problem of the hybrid GPS/Loran-C system is the lack of Loran-C coverage in some oceanic airspaces. However, that may turn out to not be a problem. The FAA's Satellite Operational Implementation Team is examining the possibility of using GPS as a sole-means system in oceanic airspace. Some on the Satellite Operational Implementation Team believe that many assumptions which affect GPS availability may be relaxed due to the less demanding accuracy requirements in oceanic airspace. If GPS by itself would be usable in oceanic airspace, then a GPS/Loran-C receiver could simply operate without Loran-C in oceanic airspace where Loran-C does not provide coverage.

As RTCA SC-159 learns more about GPS/Loran-C and the alternatives, it seems likely that a GPS/Loran-C receiver will become the first to be approved as a sole-means wide-area navigation system. This will be a significant change and a step forward from the current

requirement of VOR equipage. While it is important that this change be done safely, the aviation community can take comfort in knowing that either of these dissimilar navigation systems approach the capabilities necessary to satisfy sole-means performance requirements. The challenge therefore remains in ensuring that these systems are properly integrated.

INTEGRATION

Several means of integrating GPS and Loran-C have been proposed in studies on this subject. While each has its advantages, the committee believes the one being described in the draft GPS/Loran-C MOPS delivers a high degree of algorithm transparency, meets all requirements, and incorporates well-understood techniques. The discussion that follows is a review of the Working Group's interim assumptions and recommendations. These may change as the working group further understands the issues.

Overview

A block diagram of the receiver is illustrated in Figure 1. The inputs from GPS, Loran-C and tentatively barometric altimeter are fed into the navigation computer which then makes a best estimate of the user position based on all lines of position.

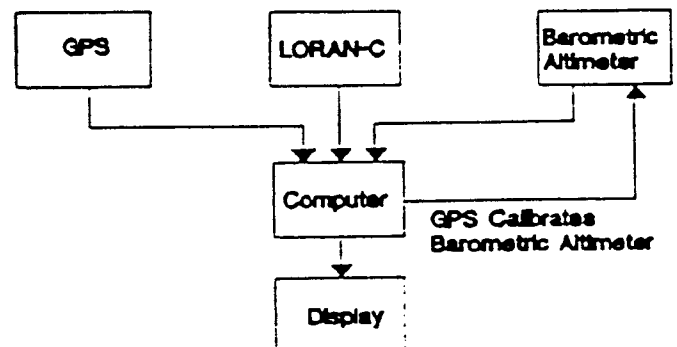


Figure 1 Primary Navigational Mode

Lines of position from Loran-C are assumed to be based on time-differencing techniques rather than pseudoranges. While pseudoranging has advantages, the use of time-differencing permits reduction of Loran-C line-of-position errors through the use of the FAA's National Field Office for Loran Data Support (NFOLDS) corrections. Other advantages are time differencing;

- 1) eliminates one additional unknown from the measurement vector,
- 2) enables Loran-C to operate in a manner consistent with most Loran-C receivers in the United States,

- 3) eliminates the need for a test pulse to determine receiver front-end delays, and
- 4) reduces the complexity of the fault-detection-and-exclusion algorithms.

The need for integrating the barometric altimeter in the system is being reviewed by the Working Group and the decision will be based on availabilities achievable with and without the augmentation. If the barometric altimeter is incorporated, it will be calibrated using GPS when GPS has integrity and when the vertical dilution of precision is less than 5.³

The computer's algorithms will have both a primary mode of operation which will use all inputs (GPS, Loran-C and barometric altimeter when required) and a mandatory reversionary mode which will use Loran-C only. The primary mode will be used whenever the algorithms can provide position information with integrity. In the very rare event in which the algorithm can't satisfy performance requirements, the receiver will automatically transfer to the reversionary mode. The Working Group feels that this reversionary requirement ensures the highest level of user confidence in the system at a relatively small additional cost. In the reversionary mode, the receiver can be used as though it were stand-alone Loran-C receiver. As a result, the GPS/Loran-C MOPS will state that the receiver in the reversionary mode shall satisfy the requirements of the Loran-C MOPS.

Fault-Detection-and-Exclusion Algorithm

Many of the GPS/Loran-C integration issues involve the receivers' capability to autonomously detect and exclude biased lines-of-position. The recommended baseline algorithm for providing position information with fault detection and exclusion uses a linearized over-determined solution with the data components weighted according to relative accuracies. The general form of this equation is expressed as;

$$W\delta y = WH\delta x \quad (1)$$

where:

- W - Weighting matrix
- δy - Change in the measurement vector
- H - Data matrix
- δx - Change in the user state vector

For the GPS/Loran-C/barometric altimeter combination, the W and H matrices can be written as (equations 2 and 3);

$$W = \begin{bmatrix} 1_{11} & 1_{12} & \dots & 1_{1n} & \frac{\sigma_{sv}}{\sigma_1} & \dots & \frac{\sigma_{sv}}{\sigma_1} & 0_{1,p-1} \\ 1_{21} & 1_{22} & \dots & 1_{2n} & \frac{\sigma_{sv}}{\sigma_1} & \dots & \frac{\sigma_{sv}}{\sigma_1} & 0_{2,p-1} \\ 1_{31} & 1_{32} & \dots & 1_{3n} & 0_{3,n+1} & \dots & 0_{3,p} & \frac{\sigma_{sv}}{\sigma_{baro}} \\ 1_{41} & 1_{42} & \dots & 1_{4n} & 0_{4,n+1} & \dots & 0_{4,p} & 0_{4,p-1} \end{bmatrix} \quad (2)$$

$$H'' = \begin{bmatrix} g_{11} & g_{12} & g_{13} & 1 \\ g_{21} & g_{22} & g_{23} & 1 \\ \dots & \dots & \dots & \vdots \\ g_{n1} & g_{n2} & g_{n3} & 1 \\ l_{n+1,1} & l_{n+1,2} & 0_{n+1,3} & 0 \\ \dots & \dots & \dots & \dots \\ l_{p1} & l_{p2} & 0_{p3} & 0_{p4} \\ 0 & 0 & b_{p-1,3} & 0 \end{bmatrix} \quad (3)$$

The weighting matrix characterizes GPS errors as normally distributed with no bias and one standard deviation equal to 33.3 meters ($\sigma_{sv} = 33.3$). Loran-C errors are characterized as being normally distributed with zero mean. Values for the standard deviation of its errors are still being discussed but will likely be 82.5 meters ($\sigma_{loran} = 82.5$) during the non-precision approach and 327 meters ($\sigma_{loran} = 327$) during all other phases of flight. The Working Group is also discussing the merits of providing an error estimate based on the receiver's calculation of signal-to-noise ratio, range, and power of the transmitter.

SC-159 recommends using parity space techniques to exclude biased lines-of-position⁴. Basically, this means equation 1 undergoes a Gram-Schmidt Orthogonalization (QR) and can be rewritten as

$$R\delta x = Q^T W \delta y \quad (4)$$

where R is an upper-triangular matrix and has rank equal to the rank of H. Errors are identified by the "parity vector" using the equation

$$p = Q_p^T W \delta y \quad (5)$$

with the dimension of the parity space equal to the last $m - n$ rows. Since its rows are orthogonal to the measurement vector, its columns then span the parity space of H. The parity vector must detect and exclude an out-of-tolerance bias in the presence of noise. The algorithm can therefore exclude with only a specified

probability. A detailed discussion of this algorithm can be found in Reference [4].

While other algorithms have demonstrated equivalent performance, parity-space techniques have the advantages of being applied to a generic system, minimizing the number of assumptions, and having undergone sufficient analytical rigor.⁵

Performance

The MOPS is being written in such a way as to make clear that the integration assumptions provide a baseline means of integration only. Manufacturers may choose alternative integration schemes as long as they satisfy the minimum requirements and delivers at least equivalent availability to that of the baseline fault-detection-and-exclusion algorithm.

With the baseline integration, the receiver will satisfy the sole-means requirements for all phases of flight except for precision approaches. The integrated system will provide an increase in availability with fault detection and exclusion of about two orders of magnitude over that of GPS alone with two or more satellite failures⁶. System accuracy will be sufficient for the receiver to be included in the FAA's GPS Non-Precision Approach Overlay Program.

While the availability will be high, the Working Group has not yet addressed the issue of navigation with Loran-C chain outages. Will the receiver be permitted to be flown in an area where the Loran-C chain has been NOTAMed out of service? If so, is a prediction of its capability to complete the flight required and what are the additional constraints? The working group should resolve both questions at the next meeting.

CERTIFICATION STATUS

SC-159 has projected that the GPS/Loran-C MOPS will be approved around the end of the second quarter of 1994. With a timely release of the Technical Standard Order, the hybrid GPS/Loran-C receiver could become the first receiver certificated as a wide-area sole-means navigation system. The other working groups in SC-159 have projected that they will take far longer to complete their project.

FUTURE COURSE

GPS can provide new opportunities and challenges for the Loran-C community besides integrated GPS/Loran-C receivers. In addition to the increased availability

discussed in this paper, hybrid GPS/Loran-C has shown that it can deliver higher accuracy than GPS (through Kalman filtering)⁷ and improved coverage/availability in mountainous areas⁸ and the "concrete canyons" of the city. All of these capabilities should be exploited and can be done so with minimal cost to the government and to users.

Applications for this combination are not limited to the aviation community. The intelligent vehicle highway system (IVHS) community is also looking toward hybrid GPS/Loran-C for navigation services. Experts in the community acknowledge that the complementary nature of the systems make it a superior combination when masking would otherwise pose a problem for GPS.

With respect to the integrated aviation receiver, SC-159 has completed the third draft of the GPS/Loran-C MOPS but acknowledges that a substantial amount of work still needs to be done. Future meetings will focus on understanding and documenting the integrated receiver's availability, continuity, integrity and accuracy. In addition, the generic GPS test procedures will have to be refined for this application. As always, anyone is invited to attend RTCA meetings or submit comments.

Acknowledgements

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About the Author

Robert Anoll is a Systems Engineer with Systems Control Technology, Inc who supports the FAA's System Engineering Branch for Navigation and Landing. He is also Chairman of SC-159 GPS/Loran-C MOPS Working Group.

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Loran-C Noise Model Development for RTCA SC-176, SC-159, and TSO-C60b

James V. Carroll

*U. S. Department of Transportation
Volpe National Transportation Systems Center
Cambridge, Massachusetts, USA*

Jay A. Weitzen

*University of Massachusetts Lowell
Lowell, Massachusetts, USA*

Abstract

A new Loran-C simulation facility was developed and used to support the implementation of radionavigation systems into the National Airspace System. This paper describes how recent simulation studies have shown that upgraded IFR approach documents and procedures governing Loran-C are needed, so that the implementation can proceed in a timely and effective manner.

1. Introduction

The FAA is moving at a rapid pace to incorporate GPS for use in the National Airspace System (NAS). The agency already has approved GPS on a supplemental basis for IFR navigation, certified the first receivers, and released the first GPS (overlay) approach plates. Once DoD declares "initial operational capability" for the GPS constellation, expected sometime this fall, the FAA is expected to authorize use of GPS receivers in the NAS.

Analysts working on performance and operational requirements for IFR approach navigation systems, however, are coming to the conclusion that GPS may not by itself meet the FAA's integrity and availability requirements for nonprecision approaches (NPA). Therefore, a navigation system which combines Loran-C and GPS is worth meaningful consideration.

Recent work at the Volpe Center has shown that Loran-C availability approaches that of VOR [4,5]. This and related work have shown that Loran can meet the FAA NPA integrity requirements as a supplemental navigation aid. Further, Loran and GPS are highly complementary navigation systems

that can result in an efficient combined system architecture. Loran-C and GPS can provide an acceptable sole means navigation system for the NAS.

The requirements for Loran-C and for Loran/GPS have been examined at the Volpe Center as part of ongoing support to the FAA in its mandated efforts to incorporate Loran-C into the NAS. This support has been in the form of field and laboratory analysis of Loran-C, and via active participation in the activities of the various commissions and working groups - for example, the Radio Technical Commission for Aeronautics (RTCA) Special Committees SC-176 and SC-159 - which have been chartered to develop and upgrade the requirements.

This paper discusses Loran-C certification issues. It describes recent activities at the Volpe Center related to certification of Loran-C for NPA. These activities include recommended changes in the NPA certification documents which have been adopted by RTCA SC-176.

2. Review of the Issues

What is Atmospheric Noise? For years, those involved in approach certification have been plagued by discrepancies in the computation of atmospheric noise by Loran receivers. Despite some commonality, each receiver seems to use unique methods to compute the signal-to-noise ratio (SNR). Some receiver vendors do not claim to compute an SNR, but use instead a "signal quality measure."

The definition of SNR in TSO-C60b is precise,

and should be used where possible¹: SNR in decibels (dB) is

$$\text{SNR} = 20 \text{ Log}_{10}(S_{\text{rms}}/N_{\text{rms}}).$$

The Loran-C signal strength, S_{rms} , is the RMS level of a continuous wave signal having the same peak-to-peak amplitude as the Loran-C pulse envelope 25 μsec after the beginning of the pulse. The noise level, N_{rms} , is the (true) RMS voltage after filtering the noise by a single resonator L-C filter having a center frequency of 100 kHz and a 3 dB bandwidth of 30 kHz.

This basic definition of SNR would be adequate and consistent if all manufacturers used and displayed it, and if the insertion loss of the filter, due to resistance in the inductor, were uniformly removed. Using this basic definition, SNR is precise regardless of the receiver or noise model used.

Other measures of noise are receiver-specific and often are taken at the output of the receiver's signal processor which suppresses the impulsive lightning noise component. Hence, depending on the nature of the noise and the processing used, the signal quality measure at the output of the signal processor may range from 0 to 20 dB more than the true, TSO-defined SNR. Output signal quality is used as the measure in the Loran-C monitors and in the certification process. Problems caused by differences in displayed signal quality and true SNR have propagated throughout the Loran-C certification and operation process.

Field comparisons of various receiver SNR and signal quality measurements show discrepancies of up to 16 dB, and so it makes no sense to force each of these receivers to flag integrity warnings at a -6 dB threshold of their choosing.

How Adequate Are the Requirements? The Volpe Center has conducted a detailed analysis of Loran receiver field performance with respect to the operational requirements set for Loran-C by the FAA. Some of the conclusions from this analysis are that:

¹ In this paper, the relevant requirements documents are the FAA Technical Standard Order TSO-C60b, "Airborne Area Navigation Equipment Using Loran-C Inputs" (1988), and the Radio Technical Commission for Aeronautics document RTCA/DO-194, "Minimum Operational Performance Standards for Airborne Area Navigation Equipment Using Loran-C Inputs" (1986).

1. Many requirements imposed on the Loran system are overly conservative.
2. Some requirements reflect outdated receiver and/or test equipment technology, and can be upgraded or eliminated.
3. Some requirements are in error, and need correction.

Many of the requirements are conservative because they were imposed at a time before there was adequate data on Loran approach performance. Conservative performance margins were appropriate. Subsequent technology advances coupled with a better understanding of Loran-C performance indicate that many of these requirements should be changed.

An example of an existing, overly-conservative requirement is the one that the course deviation indicator full scale deflection now must be ± 1.25 nmi for Loran-C, while GPS may use ± 0.30 nmi. Loran and GPS cannot be used in combination for NPA without having the same CDI full scale value, because this value dictates the airspace needed to fly a nonprecision approach. Recent Volpe Center simulation studies, summarized in this paper and in [1] and [2], support a series of earlier studies and flight tests [3] which conclude that Loran can perform quite adequately using the ± 0.30 nmi value.

Other requirements on Loran, such as minimum SNR at an airport, are much more stringent than for other navaids in the NAS. Furthermore, Loran-C is the only navaid in the NAS that has different certification requirements for multiple flight phases, *i.e.*, en route, terminal, and NPA. There should be only one set of certification requirements (NPA) for Loran, just as there is only one set for VOR, NDB, *etc.*

An example of an error in the current TSO-C60b is the failure to account for insertion losses such as those in the 30 kHz filter used in receiver certification testing. These losses affect the accurate calculation of signal-to-noise ratio by the receiver.

Many of the changes recommended by the Volpe Center are the result of the development and use of the Loran Simulation Laboratory at the Volpe Center's Center for Navigation [2]. The most

unique feature of this facility is the more realistic atmospheric noise model developed by the Volpe Center. This model can generate a controlled and repeatable environment in real time, so that Loran receivers can conveniently be characterized and tested in the lab [6].

Why Make Changes? There is a need to replace the atmospheric noise models currently allowed by TSO-C60b. Manufacturers currently adjust their receivers to obtain optimum performance on an unrealistic model. The need for a realistic simulation noise model goes beyond the desire for a more accurate and reliable certification process. If high correlation can be established between simulated and field noise, then there is great potential for significantly reducing the number of approach certification flight tests. In addition, there would be more confidence in the testing process as a whole, and field results could be predicted with high certainty, thereby enhancing the effectiveness of field test programs.

3. Goals and Objectives

A major objective of the Volpe Center Loran activity was to develop an accurate, controlled Loran-C simulation facility to meet the goal of providing a repeatable environment for the characterization of Loran receivers.

Another important goal was to provide a realistic, comprehensive testbed for analyzing Loran-C performance with respect to governing operational requirements and standards. In the past, adequate real-time modeling of atmospheric noise influences was technology-limited, with a result that the relatively primitive noise models gave irregular and uncertain TSO certification test results.

The Volpe Center Loran simulator has enabled analysts to achieve the following objectives:

Displayed versus calibrated SNR values have been computed for several receivers, thereby characterizing their relative performance from a known, common reference.

A solid engineering basis was developed for the NPA certification process. Performance thresholds currently in the requirements documents soon will be replaced by "data based" thresholds. Receiver flagging will be standardized and performance-

based when subject receivers are characterized in a common testbed.

The certification process can be accelerated. The simulation facility can automate much of the process, and up to 90% of the required flight tests could be replaced by simulation approaches.

These objectives justify for using realistic noise models in the simulator.

4. Atmospheric Noise Model

The real-time atmospheric noise model developed by the Volpe Center is based on extensive analytical and field research. The development of the noise model and the simulation facility by the Volpe Center, and the use of this facility to address various Loran receiver performance issues, are described in detail elsewhere [1,2,4,5,6,7]. Highlights of the noise model development are described in the following paragraphs.

Atmospheric noise is the dominant source of natural noise in the 100 kHz Loran band. Atmospheric noise consists of two components: (i) a low level white Gaussian component due to the background continuum of signals; and (ii) a high dynamic range, non-stationary, impulsive component due to the noise from lightning. Unfortunately, noise sources currently used to test, calibrate, design, and certify Loran-C receivers bear little resemblance to realistic atmospheric noise wave-forms.

A model based on a high degree of temporal and spectral correlation with the basic statistical properties of real atmospheric noise has been developed at the Volpe Center [6,7]. This model incorporates the two noise components, and has the (time-varying) form:

$$y(t) = n_1(t) + X(t)A(t)n_2(t)$$

where y is the output noise, n_1 is the Gaussian background noise, A is a time-varying multiplicative intensity (magnitude) function derived from the inverse of a Chi-square process, n_2 is an independent Gaussian noise source modulated by the intensity function, and X is a two-state [0,1] switching function which turns on the impulsive noise component $A(t)n_2(t)$. $X(t)$ is a double Markov process, and the entire model has statistics which are complicated, but well-defined

and readily simulated in real time.

5. Simulation Projects

The Loran simulation facility has been used to characterize the performance of Loran-C receivers. It is available to support the approach certification efforts of manufacturers intending to apply for Supplemental Type Certificates for NPA. Furthermore, the facility corroborated field results from the Loran Site Evaluation System, and from a Volpe Center project which gathered and analyzed extensive Loran-C data at over twenty airports in the U.S. It also was used to simulate NPA at selected airports for the purpose of evaluating the adequacy of a ± 0.30 nmi full scale deflection for a course deviation indicator [1].

Noise Characterization of Receivers. To investigate different noise models and different ways of computing SNR, several receivers were tested using three different noise models: 1.) a pure Gaussian model, 2.) a simple atmospheric model consisting of Gaussian and impulsive components, and 3.) the Volpe Center model. The first two models are allowed by TSO-C60b. Approval for use of the Volpe Center model has been accepted by the RTCA.

For receivers connected to the Loran simulator, the signal level was fixed at 62 dB μ V, and the noise level was varied in 3 dB increments to change the true SNR. A standard MWX Loran-C triad, GRI 9960, was used, and there was no sky wave, cross chain, or other narrow band (CWI) interference.

Receiver 1 (Figure 1) is a high quality, albeit not an NPA, aviation receiver which uses hard limiting noise processing. It presents signal quality as the SNR at the output of the nonlinear processor. For equal input noise levels, this receiver shows a 12 dB increase in the displayed SNR when the Volpe noise model is used, and a 6 dB increase using TSO-atmospheric noise, both relative to pure Gaussian noise. Receiver 1 was calibrated by the manufacturer using Gaussian noise.

Receiver 2 (Figure 2) calculates signal quality on a 0-100 scale, and shows that the signal quality measure using the Volpe model is 9 dB greater than that using Gaussian noise. TSO noise again is 6 dB greater than Gaussian noise. Impulse or spike suppression for this receiver is different from Receiver 1.

Receiver 3 (Figure 3) displays SNR as the output signal quality measure and shows that SNR based on the Volpe Center noise is 12 dB greater than Gaussian noise, and SNR based on the TSO model is 6 dB greater than Gaussian noise. This receiver also was calibrated using Gaussian noise.

Receiver 4 (Figure 4) displays true SNR rather than processed SNR. The noise estimates for the different noise models consequently are closer to each other, particularly at mid to high SNR levels.

As a result of this experiment, it was found that the noise model being used affects the displayed SNR, and that the type of noise processing used influences how well the receiver's signal quality measure matches true atmospheric noise.

Although this testing validates the relative accuracy of the Volpe Center noise model, further analysis was needed to correlate this model with real noise, and thereby validate the model's absolute accuracy. A large Loran signal database gathered at over twenty airports in the U.S. was used for this correlation.

Three Loran receivers were used to gather the data. Two of the Loran receivers were used in the correlation study. The 24 hours of Loran data gathered at a rate of several measurements a minute represents possibly the most comprehensive data base for Loran signals at airports. Airport features including approach parameters were modeled in the simulator, and several hours of simulation data were gathered.

Figure 5 shows a very high degree of correlation at the middle and upper SNR levels, where more than 98% of the SNR field measurements resided. The lower SNR levels show more divergence, but are proportionately less significant.

6. Recommended Changes to RTCA/DO-194 and TSO-C60b

As a result of studies like those described above, recommendations have been made to the FAA to modify Loran-C NPA regulations. Some of the modifications to MOPS RTCA/DO-194 governing Loran-C NPA accepted by RTCA Special Committee 176 include:

- revision of the Loran-C error budget

- revision of sections governing CDI display
- modification of equipment test procedures sections governing atmospheric noise generation
- revision of Appendix H (Noise Sources for Laboratory Testing of Loran-C Receivers)

Modifications to FAA TSO-C60b governing Loran-C NPA accepted by RTCA Special Committee 176 include:

- complete revision of Section (a)(1)(x), Atmospheric Noise model
- addition of Section (a)(1)(xi), Noise Power Calibration

These changes are detailed in RTCA paper 32-93/SC176-8.

Highlights of the Changes. As a direct consequence of developing and using a realistic atmospheric noise model, pending major changes to the Loran-C NPA requirements include:

- CDI full scale deflection is set at ± 0.30 nmi (consistent with the value allowed GPS receivers)
- NPA integrity threshold for signal-to-noise ratio remains at -6 dB, *but*:
 - use Volpe Center noise model
 - keep the noise measurement external to the receiver
 - apply the threshold to the current TSO SNR definition explicitly
- no 8 dB correction can be added to the SNR computation in hard-limiting receivers [7]
- use only the formula specified in TSO-C60b for computing SNR

The expected reduction in the number and variety of NPA certification flight tests is a major benefit of accepting the recommended changes to the MOPS and TSO. Most of the interpolation in the test parameter space could be done in the simulator, and not by flight test. In addition, the approach certification process could be streamlined greatly, for example by requiring only

one certification covering all phases of flight. Also, implementing the recommended changes will result in certification being a test of the receiver, and not of the Loran-C system.

7. Summary and Conclusions

The Volpe Center has developed a realistic, state-of-the-art Loran-C simulation system. A key element of this system is a new atmospheric noise model which replicates accurately the essential properties of actual atmospheric noise.

The simulation facility already has been used to characterize several commercially available Loran-C receivers, and to analyze the effect of different CDI full scale deflections on Loran IFR approaches. The atmospheric noise model in the Loran simulator has been correlated with Loran measurements gathered at several U.S. airports.

These activities have led to specific recommendations for changes to requirements and procedures for certification of Loran receivers for nonprecision approaches. If these recommendations are implemented, the certification process should become considerably more streamlined, cost effective, reliable, and predictable - without compromising any of the essential certification standards.

As a result, in part, of the efforts reported here, it is hoped that the FAA will upgrade the Loran NPA requirements as recommended, and continue the work to develop requirements for a combined Loran/GPS system. This will aid greatly in clarifying the role of Loran in the NAS. Then, Loran-C and GPS vendors will have much clearer direction for their business planning.

The atmospheric noise model has been widely recognized as undoubtedly the most realistic model available, which should be used wherever practical. The Volpe Center Loran simulation facility is a national resource, ready to serve the needs of the navigation community.

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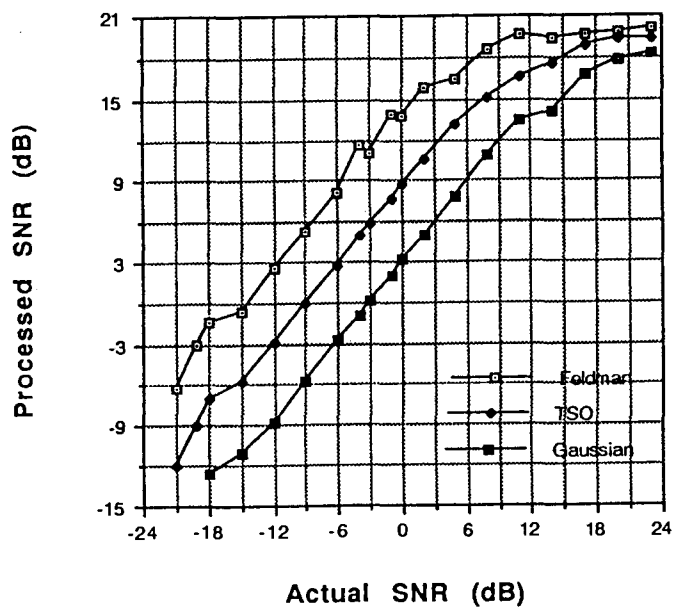


Figure 1. Processed SNR vs Actual SNR for Receiver 1

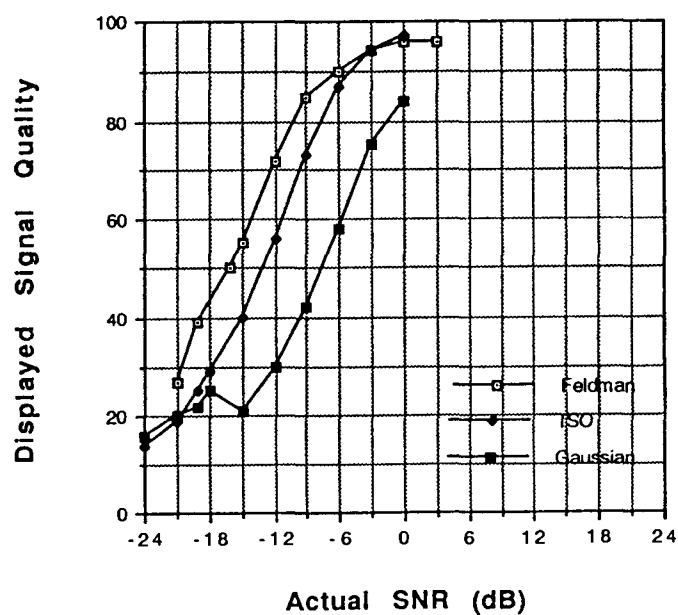


Figure 2. Processed SNR vs Actual SNR for Receiver 2

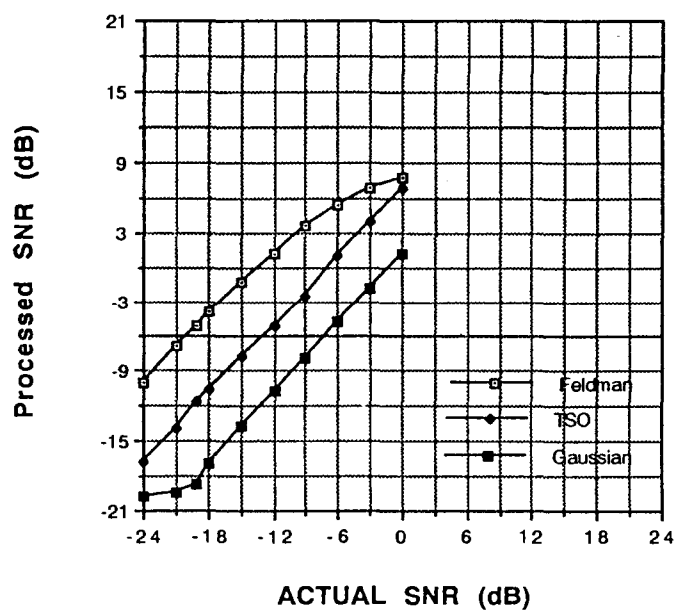


Figure 3. Processed SNR vs Actual SNR for Receiver 3

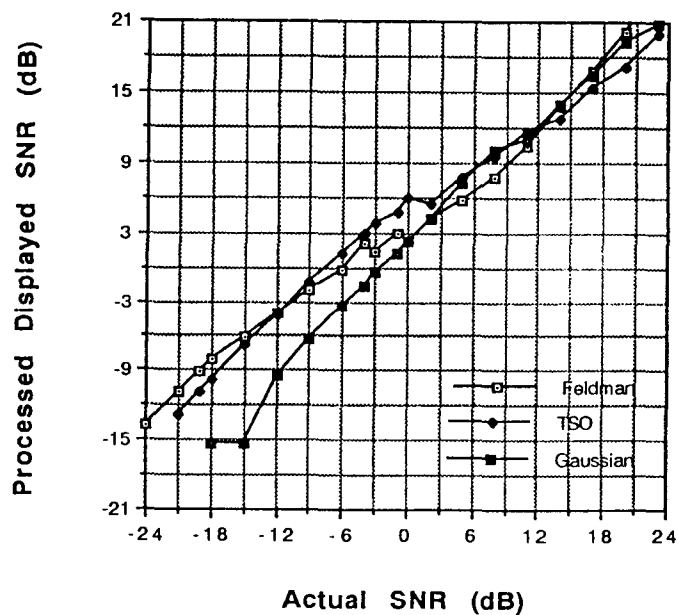


Figure 4. Processed SNR vs Actual SNR for Receiver 4

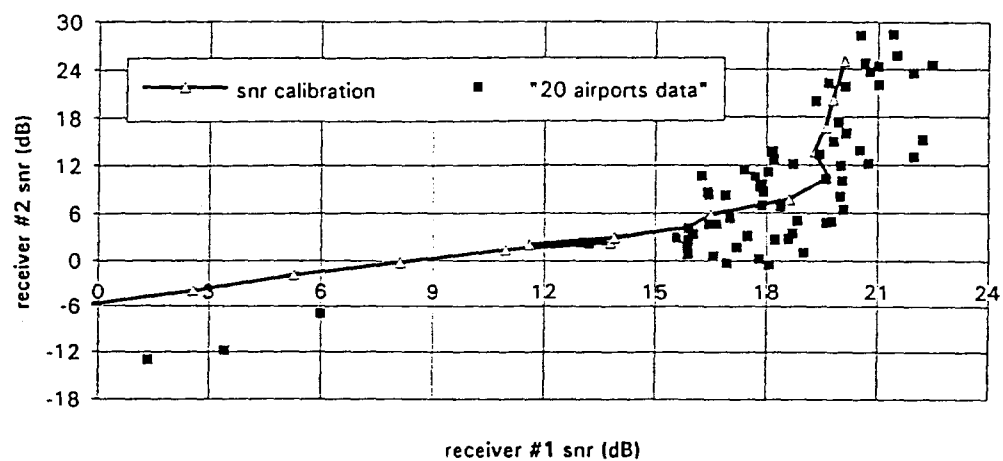


Figure 5. SNR ; Receiver #1 vs Receiver #2, Simulated and Field Data.

FUTURE NAVIGATION/LANDING AID NEEDS
OF GENERAL AVIATION
Martin L. Shuey
AOPA

Introduction

Since 1980, despite Federal Aviation Administration (FAA) foot dragging, Loran C has been installed in over 120,000 general aviation aircraft. With industry pressure the mid-continent gap was filled, timing improved and Congress approved money for improving Loran C operations. In fact, there are over 1,000,000,000 users of Loran C worldwide which includes land, marine, and aviation users.

This non-mandated system provided such a tremendous benefit to the aviation users that they purchased these sets for the perceived benefits which have proven to be real. The FAA has declared the system fully operational and abolished the program office. Loran C now resides under the operational side of the FAA in the Navigation and Landing division.

This should be the end of the story with everyone being happy, but it isn't, and the saga continues.

General Aviation (GA) Requirements

GA's needs can be divided into two basic categories - VFR and IFR. The latest FAA data available (1991), which indicates 43.8% (303,193) registered pilots were IFR rated. There were 198,475 GA aircraft listed by the FAA of which 117,335 have a glideslope (precision approach equipment) installed. In addition, 138,829 have 720 channel radios and 123,473 have a 200 channel VOR installed. These figures would indicate that approximately 120,000 (60.4%) GA aircraft are certified for IFR use and 303,193 (43.8%) of the pilot population is qualified for IFR flight.

In contrast, it is important to recognize the VFR operators' needs in a navigation/landing aid. The VFR pilot wants to go from one point to another along the most direct path available without using the Air Traffic Control (ATC) system.

For VFR pilots, this translates to using your eyeball to locate prominent landmarks using a sectional chart. As far as VFR aircraft are concerned, installing any new piece of navigation equipment, requires that the user see a big benefit for any money spent. With the advent of a low cost Loran C unit the pilots' expectations were fulfilled. Not only did this inexpensive Loran C box provide direct routings, but also it provided a wealth of information to the pilot. TCA/ARSA alert

information is normal in all units available today. In addition emergency information is available, frequencies, runway length, DME, wind, track, bearing, present position information, etc. The list keeps growing due to the data base capability. The benefit was readily seen and accepted by the pilot resulting in over 84,000 (42.7%) Loran C sets installed for VFR purposes according to FAA statistics. The primary reason these sets were purchased was due to the benefits perceived by the user at a reasonable cost.

The IFR pilot needs to have all information to fly the existing IFR route structure and approaches. In order to have an IFR pilot upgrade the existing equipment, there must be tangible benefits. Loran C IFR units have been installed in 13,745 (6.9%) general aviation aircraft. While IFR Loran C has the same capability as the VFR box not many have been sold. The primary reason can be attributed to one fact - there are no IFR approach Loran C units being sold. While some benefits are present, i.e. direct routing (RNAV), DME, and emergency information, it is apparent that everyone wants an approach capable box before upgrading their current IFR capability with Loran.

The outside observer will note that the total number of Loran C sets referred to originally was 120,000 aviation receivers installed in GA aircraft, yet the total number of IFR and VFR boxes do not add up to 120,000 sets. This discrepancy is due to the lag time in producing FAA statistical numbers. The manufacturers have sold over 120,000 airborne Loran C sets in the United States according to Aircraft Electronics Association (AEA).

General Aviation IFR Operations

As previously stated there are approximately 120,000 general aviation aircraft that can utilize the IFR system. Why are they not equipped with IFR Loran C equipment? The most obvious reason is the chicken and the egg cliché. All of the Loran C IFR approaches are not authorized for use since there are no IFR approach receivers certified. Why should an aircraft owner purchase only an IFR enroute box? They won't and haven't.

Another reason is the emerging Global Positioning System (GPS) technology and the user is waiting to see if a GPS IFR approach box is approved before a Loran C IFR approach box. As of the printing of this paper at least two GPS manufacturers have produced an IFR approach box for general aviation. It appears that GPS has won the race and may replace Loran C. At least that is what the FAA would have you believe.

Loran C vs. GPS for General Aviation

The lack of education by the FAA and industry makes it difficult for the end user to make a decision on what to buy. It also fosters competition between the two systems with each claiming to be better. The one question that rarely gets answered is whether either system will suffice as a sole means of navigation now or in the near term of future, i.e. 2,000. The answer is no, but a Loran C/GPS box will provide a sole means capability. Even the manufacturers have recognized this by combining both systems into a single box.

It is technically feasible for either system to become a sole means navigation system, but the cost may not be worth the effort when a combination box will suffice for general aviation and provide a Category I approach capability to virtually every airport/heliport in the country. In fact, a cost benefit study may show that the FAA could probably shut down VORs and NDBs and provide a free Loran C/GPS box to every aircraft and save money, but that's another story.

The general aviation pilot that flies in the IFR environment wants to go from point A to B via the shortest possible distance. Either system will do that. Loran C or GPS are transparent to the pilot in that either system will provide direct navigation via the CDI. In addition, the data base and physical operation of the sets are the same. Each system has its own inherent limitations and neither can provide a sole means of navigation capability. The airlines are matching GPS with INS to provide a sole means capability. General aviation cannot afford INS. As a result, it makes sense to combine Loran C with GPS to provide a sole means capability. The cost is right.

The Future Need for GA IFR Operations

Loran C/GPS will last well into the next century. If GPS can provide for a sole means capability then GA will already be equipped. There will probably be a requirement for some type of data link to provide real time information to the air traffic controller. This would only require the addition of a data link to send the Loran C/GPS position information and altitude down to the ground. An uplink would provide a collision avoidance system at virtually no cost other than a CRT display. Throw in the weather and you probably have the equipment necessary to last the life of the airframe.

One added benefit would be if a user fee is initiated, you could revert to Loran C and go VFR.

Summary

For the foreseeable future the marriage of Loran C and GPS will provide the most cost-effective navigation capability for general aviation be it VFR or IFR operations. This common sense approach is the right way to go and is affordable for general aviation.

**The State's Views of Area Navigation
System Development**

by Tom Thomas, Chairman

**NASAO LORAN-C GPS Utilization
Standing Committee**

October 21, 1993

Thank you for the opportunity to speak before you today. I'm here today to bring you up to date on the National Association of State Aviation Officials (NASAO) involvement, continued interest and strong support for the aircraft navigational use of LORAN-C.

In order to put things in perspective, it is important to review a little of the history of NASAO and our organization's involvement in air navigational systems.

Back in 1930, at the Cleveland Air Races, a series of tragic aircraft accidents elevated the need to establish an organization/agency to work toward promoting air safety. Directly out of these events came NASAO and the Civil Aviation Agency (CAA). The role of the CAA, today the Federal Aviation Administration (FAA) is fairly well known. NASAO and individual state involvement in aviation activities is less well known.

Through the CAA there was the ability to have broad oversight in establishing uniform guidelines and procedures to be applied at a national level. For all practical purposes, this worked quite well as the aviation industry continued to develop and grow.

In most cases the federal government was able to move and grow with the increase in aviation technology and needs. Initially the federal role was in setting safety guidelines for pilots and in developing an airport system. Once in place, or actually while doing this, the need to navigate back and forth between the airports became more and more pressing.

The aircraft is a time machine. It replaced ships, wagons, trains, automobiles, and even now trucks. In order to move freely and regularly between the system of airports, a navigational system was necessary. The directions explored and eventually exploited include low frequency loop-arc radio ranges, nondirectional A.M. radio beacons, very high frequency OMNI ranges, ultra-high frequency, tactical air navigational facilities and precision localizer and instrument landing systems. Now today we have OMEGA and of course LORAN and GPS for enroute instrument navigation. As late as last month I flew in an aircraft that used celestial fixes as a means for enroute navigation. That system dates back a few years and, surprisingly is still in use and practiced today.

Today we all here have seen, or should have seen and many have been able to use LORAN-C for enroute navigation, by land, air or by sea. I've had the opportunity to use LORAN-C regularly in general aviation aircraft for enroute instrument navigation throughout the last decade.

In order to get a better perspective on the states' interest in LORAN-C as a means for instrument navigation, we need to look at what states have done in the NAVAIDS spectrum at the local level. After doing that, I'll cover what we in Wisconsin have done in the line of planning to use LORAN technology and what we are continuing to work on and for.

States are actively committed to provide better access to their respective airports systems. To date states and local airport sponsors have installed and are currently operating slightly over 700 NDB's, 64 VOR's, 88 LOC's and 11 ILS's. Two states, Minnesota and Michigan have also developed and installed microwave landing systems, incidently which they are currently offering for sale. Again, states were in the forefront in the development, installation and actual use of MLS, perhaps jumping the gun just a bit. In Wisconsin, our non-fed NAVAIDS include 50 NDB's, 3 VOR's (2 with DME), 6 SDF/LOC's and 3 ILS's.

All of this has been accomplished at considerable expense and that expense had to be justified by the need. These facilities were in most cases, not programmed or fundable by the Federal Aviation Administration, or were so far down the FAA priority list, they would never have meet their eligibility criteria. These local needs, were clearly seen by local and state agencies to justify the cost of installation.

In late 1988, we began a project to develop our NAVAIDS system plan, financed in part through a grant from the FAA and it was completed and published in late 1990. The primary purpose of the Wisconsin Navigational Aids System Plan:2000 is to establish a statewide system plan to provide continuous, all-weather access to communities throughout the state. In order to accomplish this, we had two objectives. The first objective was to establish precision approaches at all airports in the system plan that basically had 500 or more actual instrument approaches. The second objective was to establish NPA's to all other airports in the plan "... through the use of LORAN-C or other means ...". The plan actually recommends LORAN-C instrument approaches at some 51 airports.

It states further "The Department of Transportation will continue its commitment to maintain and replace existing NAVAIDS at Wisconsin State Airport System Plan airports. The Department will also continue to review sponsor requests for NDB facilities until the FAA's LORAN-C program is fully operational." Since 1990, three new NDB's have been installed where we had designated a LORAN-C approach as one of our top 10.

Perhaps the primary motivation for our enthusiasm with LORAN is the minimal state and local costs associated with establishing this type of instrument approach procedure. The recommendations in our NAVAIDS plan are designed to directly benefit the users of Wisconsin's aviation system as well as move Wisconsin's economy forward into the 21st century.

It's worth mentioning that in our plan published in 1990, we stated it may "... eventually be incorporated as a supplemental navigational aid to GPS." We went on to state that the FAA was currently (1990) evaluating the first 500 LORAN-C approaches and expects publication in late 1991. Well, it's now late 1993 and we're all still waiting.

My personal experience with LORAN-C began with the Air National Guard KC97 Boeing Strato Cruiser. I marvelled at how well the national guard navigators could find Europe and Hawaii, almost on the dime so to speak. My navigators during my tour with the regular Air Force were good, but all we had for over water navigation were celestial and dead reckoning. I recall being relieved several times when we started picking up a VOR or TACAN while coasting in. Most often it was a radar fix from ATC followed by an ident. to verify our location (which was often some distance from where we thought we were.) So I first flew using LORAN for navigation well over 20 years

ago. This ended in 1978 as I transitioned into a different National Guard Aircraft which did not have LORAN receivers. My LORAN experience was renewed in 1984/85 when we installed 2 Texas Instrument LORAN-C units in our Cessna 182 and 210. Since then I've flown IFR enroute with LORAN-C criss-crossing the state and the country. I firmly believe in the integrity of the system and its value as a positive, safe reliable navigational aid for pilots.

No matter how hard we all work to eliminate risk, we never can totally; we can only reduce it. In flying, we are taught to have a back-up. Even with the newest technology now in the forefront, GPS or GNSS, we will need a back-up.

Even with all the significant investments we've seen made by individual states in navigational facilities, it doesn't take a rocket scientist to see the need for some redundancy. This entire program is based on the management of risk. After weighing and balancing things, we determine when the co-efficient of safety is acceptable. Christopher Columbus, who used basic celestial navigation, did that a couple of times. Many before and after him have done the same, some successfully and others not, often tragically.

Because of the great potential savings for aviation through the use of LORAN-C for nonprecision approaches, many states have invested a significant amount of time and money toward accomplishing that common end. Quite simply, LORAN-C could replace all nonprecision instrument approach aids. This could be accomplished at no cost to the individual state(s).

In order to come up with a uniform development of LORAN-C approaches, it was decided by the initial LORAN-C working group which included state aviation organizations, equipment manufacturers, the US Coast Guard and the Federal Aviation Administration, that each state submit 10 airports they considered to be the top priority to receive a LORAN-C NPA procedure. We did that some 5 years ago, and as of last month, the FAA officially completed design work on the first 125 LORAN-C RNAV SIAP's. Interestingly, 2 of those were in Wisconsin, the first being East Troy, our top choice, and second, Oshkosh's Wittman Field that we did not have on any of our lists.

And now, what we need next, and have needed all along, is an FAA-certified receiver so we can fly the approaches that have been produced. We are excited about the potential certification of the ARNAV 5000 and 7000 series units. We hope other LORAN-C manufacturers continue on their development of certifiable receivers.

We are firmly committed to LORAN-C. As in the past, the state's are also exploring new innovations on the leading edge of technology, namely GPS/DGPS. In Wisconsin, we installed a Differential GPS transmitter on the roof of the airport terminal in Oshkosh last May. In June, we started flying Category 1 precision approaches to Runway 36 at Wittman Field for demonstration purposes. In the initial approaches we noted occasional erratic movement of the command steering bars. The erratic movement was narrowed down to appearing only when Satellite 19 was in the constellation over head. Satellite 19 signals were analyzed and found to vary significantly from other signals from visible satellites. However, 19's signals were within the design limits of the transmitter. Satellite 19 was deprogrammed from the constellation sensors of our DGPS unit and subsequently, all erratic movement of the GPS command steering bars ceased. DOD was notified and they conceded the signals did fluctuate, however they were within acceptable limits and therefore no action would

be taken to improve them. This was published in the Filter Center of the July 26th issue of Aviation Week.

As mentioned earlier, Category 1 approaches were demonstrated earlier this year, specifically at the annual Experimental Aircraft Association Convention and Fly-In. We were able to demonstrate its effectiveness to a number of individuals from Washington, including Congressman Bill Klinger, Ranking Minority Leader of the House Aviation Subcommittee and a special passenger, our own President, Dale Johnson who is here with us today. We are now in Phase II, which will basically be obtaining full certification of a Special Category 1 approach at OSH. Included in this will be redesign of the software which will make flying the approach easier from the pilot's standpoint.

What we see for the future is a combination of LORAN-C and GPS/DGPS as the long range and terminal air navigation system. Our energies, enthusiasm and available resources are committed to development and implementation of such a balanced system.

Again, thank you for this opportunity to speak to you all and I'll be available for questions if time permits.

TJT:raw:84209

Formulation of a Signal Availability Requirement for Navigational Aids in the National Airspace System

Karen L. Van Dyke
U.S. Department of Transportation
Volpe National Transportation Systems Center

Abstract

The FAA has initiated a project to define the availability requirement for radionavigation aids in the National Airspace System (NAS). To date, no rigorous availability standards for navigational aids have been established. This study, which focuses on the availability of navigational aids for nonprecision approach, is a first step towards the determination of the availability requirement.

The two nonprecision approach navigation systems considered in this analysis were VOR and Loran-C. This paper is based on a study for the FAA which was completed earlier this year [1].

In order to evaluate availability performance, a Markov model of a generic nonprecision approach was developed. This model was used to investigate and compare the availability of VOR and Loran-C, when used as sole-means nonprecision approach systems.

An extensive database of VOR and Loran-C outages was compiled and processed at the Volpe Center. These outages were based on recorded data from the FAA and USCG. These data were used to derive the parameters for the Markov model evaluation.

The results of this study demonstrate that the availability for a Loran-C approach is approximately 99.8%, while the availability for a VOR approach exceeds 99.99%. However, if a second approach can be attempted, the

availability of Loran-C is comparable to VOR. The reason for this is that the majority of Loran outages are momentaries (outages lasting less than one minute). Methods for momentary reduction are also discussed in this paper and their effect on the increase in Loran availability.

This study is the first step towards the determination of an availability requirement in the NAS. This project is continuing with the development of the availability requirement definition. In conjunction with the requirement definition, additional work is being performed which extends the existing database of availability performance for both navigation systems.

Introduction

The Federal Radionavigation Plan (FRP) states that "the availability of a navigation system is the percentage of time that the services of the system are usable by the navigator" and that "signal availability is the percentage of time that the navigational signals transmitted from external sources are available for use" [2].

Availability is defined in this analysis as the probability that the signal usefulness will be high during a nonprecision approach to allow the aircraft to land.

The FAA is currently in the process of defining a signal availability requirement for all radionavigation systems in the NAS. An availability standard, which is based on extensive analysis, has yet to be established. This paper

contains the availability performance results of two navigational aids, when used for nonprecision approach. This analysis is an important element in the development of an availability standard for navigational aids in the NAS.

The general approach taken in this study was to compare the availability performance of VOR and Loran-C. The rationale for this approach is that VOR is the most widely used and accepted navigational aid for all phases of flight in the NAS. Since the performance characteristics of VOR are acceptable, they will have significant bearing on the establishment of an availability requirement. It should be emphasized, however, that the availability performance of VOR does not set the availability requirement.

The FAA has designated Loran-C as a supplemental en route navigational aid in the NAS. However, aircraft with supplemental type certified Loran receivers that meet the requirements of FAA Technical Standard Order TSO-C60b can be approved for nonprecision approaches.

The first goal of this study was to use data recorded by the operators of the systems to evaluate the availability performance of VOR and Loran. Another goal was to derive recommendations to improve the availability of Loran-C beyond its current performance.

To determine the availability of each navigation system for the initial approach, as well as for subsequent approaches, a Markov model was developed. The model simulates a nonprecision approach and computes the probabilities of the aircraft being in various states of navigation and/or fault during this phase of flight. The output of the model is the probability of flying a successful approach.

Data Collection

The data used in this study were based on outage information recorded by the operators of the VOR and Loran-C systems, the FAA and USCG, respectively.

The FAA does not require its radionavigation facilities to report outages lasting less than one minute (momentaries). However, there are a number of field service centers in the CONUS which have autolog systems.

VOR data from the FAA New England Airway Facilities Center, located at Windsor Locks, CT were used for this study. The Windsor Locks facility, which has an autolog capability, records data for 38 sites. Every time a VOR, VOR/DME, or TACAN facility experiences an outage, a message is generated automatically and forwarded to Windsor Locks. A second message is generated when the affected system returns to normal operation.

VOR data for the year September, 1990 to August 1991 were used in this analysis. A database was generated which contained:

1. Time and Date of Outage
2. Station ID
3. Duration of Outage

A total of 549 data points were selected for the study database. In the raw data, recorded outage durations ranged from several seconds to over 24 hours. Notice to Airmen (NOTAM) outages were included. However, there were three outages lasting longer than 24 hours which were purged from the database. Also, multiple short term outages, resulting from maintenance work, were replaced with a single outage lasting from the first occurrence to the last recovery.

The total signal failure rate for VOR is determined from:

$$RT = \text{Rate Total} = \frac{\# \text{outages}}{[(\# \text{minutes in year}) \cdot (\# \text{stations reporting})]}$$

$$RT = \frac{549}{(365 \cdot 24 \cdot 60) \cdot (38)} = 0.0000275$$

Loran-C data are available from the U.S. Coast Guard. USCG control of Loran stations is handled by the Atlantic Area and Pacific Area Commands. The reports that they publish tabulate two types of outages: unusable time (UUT) and momentaries.

Three and a quarter years of data, collected from January 1989 to March 1992, for the Northeast U.S. chain, Group Repetition Interval (GRI) 9960, were used in this study. Data in this chain were used from three stations: M-Seneca, W-Caribou, and X-Nantucket. This triad is the approach monitor triad for most of the New England airports.

There were a total of 1113 momentaries and 105 long term outages recorded in the database. NOTAM outages also were included in this database.

For momentaries, the month and year of the outage, as well as the total number of momentaries which occurred during the month were recorded. The month, year, and duration of the outage were recorded for long term outages.

The total signal failure rate for Loran-C is:

$$RT = \text{Rate Total} = \frac{\# \text{outages}}{(\# \text{minutes in year} \cdot 3.25 \text{ yrs.})}$$

$$RT = \frac{1218}{(365 \cdot 24 \cdot 60 \cdot 3.25)} = 0.000712$$

Analysis Parameters and Markov Model

The availability requirement for nonprecision approach demands that navigational signals be functioning at all times during the approach. If the signal is lost during the approach, the airborne receiver must inform the pilot within 10 seconds, and the pilot must then execute a missed approach. In the absence of any warning from the navigational avionics, the pilot continues the approach and the system is said to be available.

The basic assumption in this analysis is that the navigation signal is operating properly at the time the pilot crosses the final approach fix.

A generic nonprecision approach used for this study is modeled as shown in Figure 1.

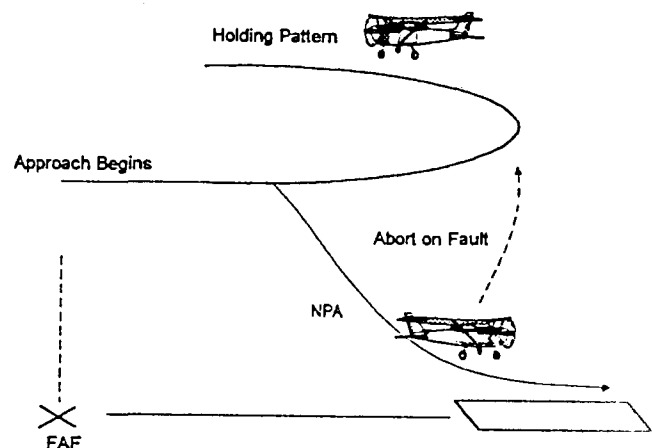


Figure 1 Model of a Nonprecision Approach

A Markov model was developed to compute the probabilities of the aircraft being in various states of navigation and/or fault as the aircraft proceeds along the nonprecision approach. A ten state Markov model was used for this analysis. The key states, as shown in Figure 2, are:

1. On Approach: Starting at the Final Approach Fix (FAF), assumed to be five nautical miles (nmi) from the runway, if a fault occurs, the aircraft must execute a missed approach. The

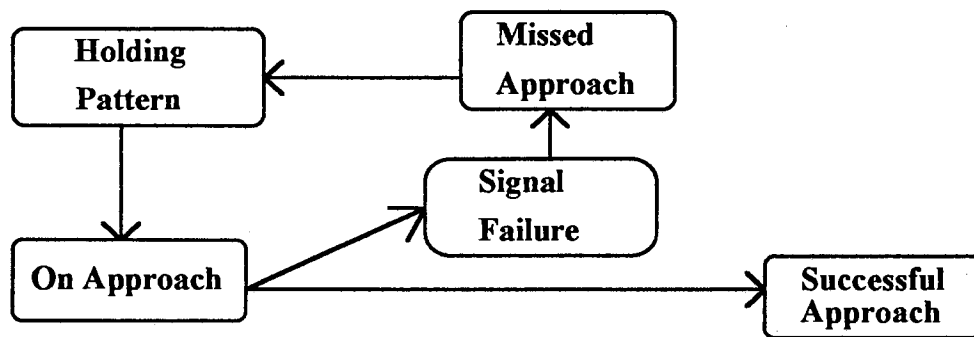


Figure 2 Markov State Diagram

pilot may then either enter a holding pattern and attempt another approach, or head for an alternate airport. Otherwise, if there is no fault, the nonprecision approach flight phase continues

2. Successful Approach: If there are navigational signals available throughout the approach, the aircraft lands. In this study, the airborne navigational equipment is assumed to be operational at all times.

3. Signal Failure: This state is entered when a fault in the navigational signal occurs during a nonprecision approach.

4. Missed Approach: When the airborne navigational equipment detects a fault in the navigation signal and displays a warning to the pilot, current procedure requires that the pilot head to the missed approach point (using timing, heading, etc.) and execute a missed approach.

In this study, it is assumed that the pilot, following the execution of a missed approach, enters a holding pattern and attempts another approach. The probability of performing a successful approach is determined for each attempt. If the pilot decides to fly to an alternate airport, after executing a missed approach, the signal availability is determined by the number of approach attempts made at the first airport.

5. Holding Pattern: If a missed approach is executed, the aircraft enters a holding pattern to make another approach. During this holding pattern, there may be recovery from the fault in the navigation signal.

The sequence for multiple approaches is:

- 1) Navigational signals are lost during the approach
- 2) The onboard navigation system detects the signal loss and warns the pilot
- 3) The pilot executes a missed approach and enters a holding pattern
- 4) Another approach is executed provided the navigation signal is available at the FAF.
- 5) Up to five approach attempts are simulated in the model.

A nonprecision approach can be modeled as a series of first order Markov processes, since the events representing change from one condition (state) to another can be represented as a Poisson process. That is, the probability of transition from one state to another, conditioned on the previous state, is independent of how long the system has remained in the previous state. The probabilities at a given instant of time are represented by the vector P .

In a first order Markov model, the probability of being in a state in one interval is only dependent on P in the previous interval, and on the

transition matrix between one interval and the next. Thus P at the next interval of time, $i+1$, is

$$P_{i+1} = \Phi \cdot P_i,$$

where Φ is the transition matrix of values that depend on the approach stage.

Transition from navigation to fault states is dictated by the mean time to signal failure (MTTF) for the various signal failure modes. Transition from fault back to navigation is defined by the mean time to recovery (MTTR) for various failure modes. The values for MTTF and MTTR are determined from the VOR and Loran-C databases which were discussed in the previous section.

The clustering of recovery times in these databases indicate distinct fault modes. Fitting routines are used on the raw data to identify the number of fault modes. Each fault mode is characterized by MTTF and MTTR parameters.

A theoretical histogram of the number of faults versus their outage duration is developed and used to hypothesize the number of fault modes and their anticipated MTTRs. A specialized fitting routine is then applied to obtain a least squares fit between the theoretical histogram and that generated from the database.

A gradient search technique is used to improve the estimates of the MTTRs. An estimate of the fraction that each fault mode contributes to the total number of faults results is obtained.

If the number of selected fault modes and the initial estimates of the MTTRs are reasonable, then the sum of the fractions will be very close to 1. The expected value of MTTR used in the model will be very close to the MTTR obtained by averaging all outage duration times in the database. The results for VOR are shown in

Table 1. There are three modes of failure for the VOR data.

Table 1 Markov Model Parameters for VOR Data

Type of Failure	Fraction	MTTR (min.)	MTTF (min.)
Momentary	0.2936	0.2*	124,190
Medium Term	0.1340	3.0	271,336
Long Term	0.5738	208.0	63,493

* In the Markov analysis, this value was changed to 0.5 min. since a momentary can last from 1 to 59 seconds and it was felt that the MTTR from the algorithm is optimistic.

This table demonstrates that the majority of VOR outages are long term (lasting more than one hour) and less than 30% of the outages are momentaries.

As shown in Table 2, there are four types of failure for Loran-C. It is clear from this data that the Loran system is affected greatly by momentary outages. In fact, over 90% of all Loran outages are caused by momentaries.

Table 2 Markov Model Parameters for Loran-C Data

Type of Failure	Fraction	MTTR (min.)**	MTTF (min.)
Momentary	0.9159	0.11	1,532
Short Term	0.0227	2.78	61,811
Medium Term	0.0548	15.29	25,638
Long Term	0.0078	340.00	180,733

** The Volpe Center has conducted tests to determine the amount of time required for Loran-C receivers to reacquire a triad, following restoration of the signal at one of the stations in the triad. A signal-to-noise ratio of -6 dB or better is required for Loran signals during

nonprecision approach. For a signal-to-noise ratio of -6 dB, the average recovery time for airborne receivers was approximately 40 seconds. This time interval has been added to the MTTR for short, medium, and long term outages. For momentaries the MTTR was raised to .5 min. as was done for VOR, and then the 40 seconds was added resulting in a MTTR of 1.1 min.

Two approach speeds were simulated in the Markov model: 90 Kt and 120 Kt. The distance traveled in the holding pattern is assumed to be 19 nmi. For the 90 Kt scenario, the time to execute the NPA is 3.3 min. and the holding pattern time is 12.7 min. In the 120 Kt case, the time to execute the NPA is 2.5 min. and the holding pattern time is 9.5 min.

Results

Tables 3 and 4 demonstrate the results for VOR and Loran-C availability for 90 Kt and 120 Kt approach speeds, respectively. It can be seen that on the initial approach attempt VOR has an availability exceeding 99.99%, while the availability for Loran is approximately 99.8%.

**Table 3 VOR and Loran-C Availability
90 Kt Approach Speed**

Nav. System	Approach 1	Approach 2	Approach 3
Loran-C	99.768%	99.992%	99.996%
VOR	99.991%	99.995%	99.995%

However, if more than one landing attempt can be made, VOR and Loran have almost an equivalent probability of successful approach. This result is due to the fact that the majority of Loran outages are momentaries and the probability of experiencing a momentary on two subsequent approaches is quite small. On the other hand, if VOR is out at the beginning of an approach, it is likely to remain out during subsequent approach attempts.

**Table 4 VOR and Loran-C Availability
120 Kt Approach Speed**

Nav. System	Approach 1	Approach 2	Approach 3
Loran-C	99.822%	99.993%	99.996%
VOR	99.993%	99.996%	99.996%

Figure 3 provides a side by side comparison of VOR and Loran availability for NPA, using both approach speeds.

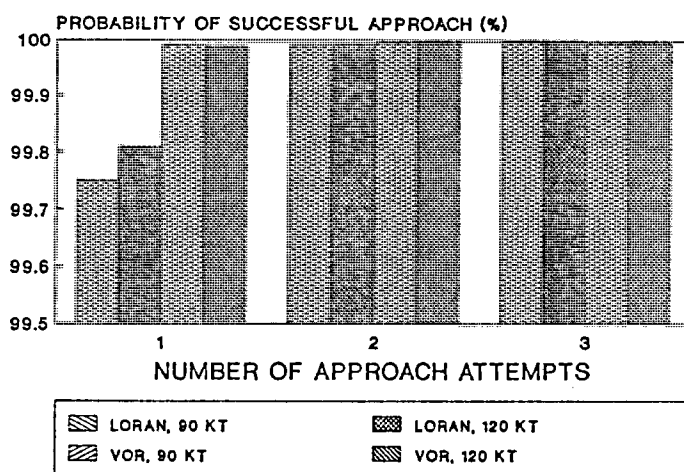


**Figure 3 Comparison of NPA Availability
Using VOR and Loran-C**

Setting an availability requirement for nonprecision approach navigation is related to safety. Using Loran-C, the probability of a missed approach on the initial attempt, caused by lack of signal in space, is only 1 in 500. If a second attempt is allowed, the probability of having to perform another missed approach or of being rerouted is less than one in 10,000.

This appears to be acceptable, especially when it is estimated that it would take an IFR rated general aviation pilot approximately 15 years to make 1,000 approaches. For example, if the availability requirement for radionavigation aids was no more than one missed approach per year for a typical IFR rated GA pilot, then the acceptable availability level would be 98.5%. In

this case, both Loran and VOR would far exceed the requirement. The conclusion is that Loran-C availability is comparable to VOR for nonprecision approach navigation.

Impact of Reducing Momentaries on Loran-C Availability

A study was performed in 1992 which examined Loran-C outages in the CONUS for both tube type (TTX) and solid state (SSX) transmitters [3]. This study is included as Appendix D of Ref. [1]. The primary causes of momentaries are:

- Primary Power Interruptions
- Lightning Strikes
- Switching of the Coupler Network (SSX)
- Vacuum Tube Failures (TTX)
- Operational and Maintenance Procedures

This study indicates that Loran-C momentaries can be reduced significantly at a reasonable cost and provides recommendations on how to improve the transmitters.

In order to determine the impact of reduced momentaries on NPA availability, additional Markov analysis was performed. The failure rates for momentaries were reduced by 50% and 70% of the original value. These results are shown in Table 5 and Figure 4.

Table 5 Loran-C Availability on First Approach with Momentary Reduction

Approach Speed	100% of Momentaries	Reduced by 50%	Reduced by 70%
90 Kt	99.77%	99.86%	99.91%
120 Kt	99.82%	99.89%	99.93%

The results demonstrate that reducing momentaries will significantly increase the probability of a successful landing on the first attempt. There is more than a twofold improvement in Loran availability when the number of momentaries is reduced by 70%. In

fact, the availability on the first attempt approaches that of VOR. Also, recall that for the second and subsequent approaches, Loran-C and VOR are approximately equivalent even without the reduction of momentaries.

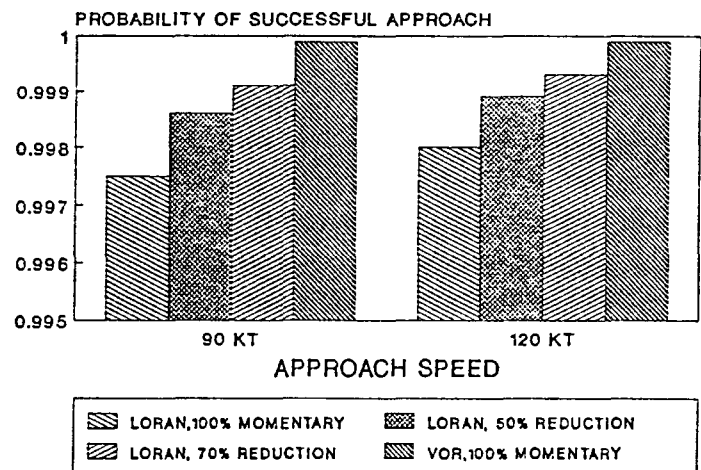


Figure 4 Comparison of NPA Availability with Different Loran-C Momentary Rates

During the course of examining the causes of Loran-C outages, it was noted that Canadian operated Loran-C stations had significantly fewer momentaries than U.S. stations operating in the same chains. In particular, the Port Hardy, British Columbia and Fox Harbor, Newfoundland Loran stations reported momentary outages which were ten times less than those reported by U.S. stations.

A survey of the Port Hardy Loran station was performed to determine why there were so few momentaries [4]. This study is included as Appendix E of Ref. [1]. The primary reasons were:

1. Solid State Transmitter
2. Good Location (Few occurrences of lightning and mild temperature - very little ice or snow).
3. Reliable Power
4. Experienced Personnel (Canadian Coast Guard does not rotate its staff, resulting in personnel with 10-12 years at the same station)

5. Operating Procedures - Personnel conscientious about not inducing unnecessary momentaries. Port Hardy personnel have developed their own preventive maintenance checks.

Future Work

Phase II of this study is now underway to examine the nonprecision approach availability of VOR in the Southwest Region, as well as for all Loran-C chains in the CONUS. This analysis should eliminate any possible regional effects which may have existed in the Northeast region data used for the Phase I study. NDB and GPS data may also be included in this study.

Another consideration in developing the signal availability requirement is pilot acceptability. Pilot acceptability refers to the willingness of the pilot to use a particular navigational aid in attempting a nonprecision approach. Preparation is now taking place to conduct a pilot survey. Tolerance of signal outages also needs to be considered from an Air Traffic standpoint as well.

Conclusions

In this study, extensive databases of Loran-C and VOR outages were used to determine the outage and recovery characteristics of both systems. These results were then applied to a Markov model to evaluate and compare the availability of the two systems during nonprecision approaches.

The results of this analysis demonstrate that both Loran-C and VOR have a high availability for nonprecision approaches. On the initial approach attempt, VOR has an availability of greater than 99.99% and Loran provides an availability of approximately 99.8%. However, on subsequent approach attempts, VOR and Loran provide essentially the same availability.

Momentaries account for the greatest portion of Loran-C outages. Reduction of these

momentaries substantially improves the availability of Loran-C for nonprecision approach navigation.

This study is the first step towards the determination of an availability requirement in the NAS. Additional outage information is being gathered for these navigation systems and a pilot survey will be conducted to address the acceptability question. When fully defined, the signal availability requirement will apply to all current and future nonprecision approach navigational aids.

Acknowledgments

The author would like to thank the FAA project sponsor, George Quinn, and the Volpe Center program manager, Mike Moroney. The author also wishes to recognize the technical contributions of the following individuals: James Carroll, Frank Castillo, and Ray Boutotte of the Volpe Center; James Rome of the University of Massachusetts Lowell; and Greg Leeming of Sanders Associates.

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Development and Use of a National Simulation Laboratory at the Volpe National Transportation Systems Center

BachYen T. Dao

Volpe National Transportation Systems Center
Cambridge, Massachusetts, USA

ABSTRACT

The Volpe National Transportation Systems Center (Volpe Center) Simulation Laboratory can simulate the airborne Loran-C environment including atmospheric noise, cross rate, and narrow-band interference. It can generate signals from up to four chains simultaneously, and can simulate en route flights and nonprecision approaches.

Recently the laboratory was used to evaluate Loran nonprecision approaches flown with a course deviation indicator (CDI) full scale deflection magnitude of 0.30 nautical mile (nmi), as opposed to the current requirement of 1.25 nmi. The 0.30 nmi CDI setting would allow the FAA to produce joint Loran and GPS approach procedures.

This paper describes the Loran-C simulation system at the Volpe Center lab and also discusses selected projects which were done with this system.

INTRODUCTION

To receive FAA Certification, Loran-C navigation receivers must comply with the specifications of TSO-C60b. There is not, however, a Loran-C receiver currently used in the aviation community that is certified to execute IFR nonprecision approaches. Volpe Center has developed a simulation laboratory that can evaluate Loran-C aviation receivers for compliance with TSO-C60b.

Currently, the FAA certification procedure for Loran receivers is lengthy and expensive. Certification typically requires from 3 to 6 months and literally hundreds of flight hours. The Volpe Center laboratory can reduce the time and cost to certify airborne receivers by conducting simulated

flights in lieu of some flight tests. The FAA retains certification authority and would use the laboratory data to determine how well a receiver meets C60b requirements.

In addition to the economic and time considerations, it should be noted that actual flight tests may not provide a detailed set of environmental conditions and signal outages to allow for a comprehensive evaluation of a candidate receiver. The Volpe Center laboratory can emulate varying weather conditions as well as seasonal and diurnal effects. Furthermore, all scenarios can be repeated accurately.

The certification of airborne Loran receivers also includes an evaluation of bench test results submitted by manufacturers. The Volpe Center National Loran Laboratory can independently corroborate bench tests by employing the new, realistic atmospheric noise model developed by the Volpe Center and adopted by the Radio Technical Commission For Aeronautics (RTCA).

EQUIPMENT AND ITS FUNCTIONS

The Loran Simulation System shown in Figure 1 consists of an ANI 2500 Loran Signal Simulator, an atmospheric noise simulator and data logging computer.

a) Loran Simulator ANI-2500

The ANI-2500 was designed to generate realistic dynamic Loran signals. The system can simulate as many as four chains with up to seven stations per

chain (a total of up to 28 stations). The simulator also produces Gaussian and TSO-C60b atmospheric noise, and two continuous wave interference (CWI) sources. Each station's time-of-arrival (TOA), groundwave and skywave level, ECD (ground wave and skywave), and skywave delay are continuously updated by a personal computer. Loran parameters are updated, using Loran signal propagation models, to simulate "real world" Loran signals at any test position on earth. The test position can be programmed from a keyboard or from disk command files to go through selected maneuvers. Narrow-band interference can be simulated with two CWI digital synthesizers. Simulator data are taken from an RS-232 compatible interface for remote data logging.

Signals for up to four Loran chains can be generated simultaneously. A list of Loran stations is stored in a changeable ASCII text file. Three propagation models are provided:

- (i) land using 0.005 mho conductivity
- (ii) seawater using 5.0 mho conductivity
- (iii) an FAA model with Secondary Phase Factor (SPF) computed from the DMA seawater model in the Minimum Operational Performance Standards (MOPS) for Airborne Area Navigation Equipment Using Loran-C Inputs (RTCA/DO-194).

Flights can be simulated in two modes: (1) simulated position controlled by ground speed and track, and (2) simulated position following the great-circle path between waypoints. Loran groundwave signal level and ECD, as well as skywave signal level, delay, and ECD, can be manipulated.

b) *The Volpe Center Atmospheric Noise Model*

The noise model is a real-time implementation of the atmospheric noise model described in [1]. The Volpe Center atmospheric noise model was developed in 1991 and it was adopted by the RTCA in 1992. The model is implemented in the simulator through the use of:

- (i) Waveform Generator HP 8904A
- (ii) 486 microprocessor-based PC with 16Mbyte RAM and 33MHz clock
- (iii) Software

Atmospheric noise consists of two components: (1) background white Gaussian noise and (2) impulsive noise. The impulsive component of the Volpe Center atmospheric noise model is randomly distributed in time, with varied amplitudes and duration. TSO-C60b atmospheric noise model pulses are Poisson distributed in time, and have a fixed amplitude and a 30-microsecond pulse width^{1,2}.

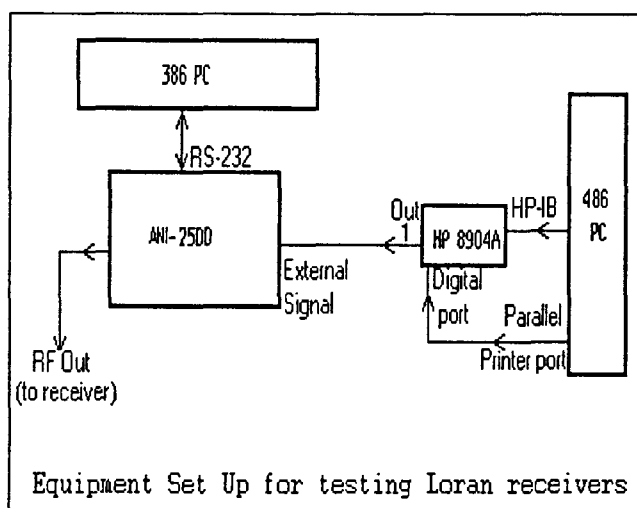


Figure 1

c) *Loran-C Receivers*

The Loran-C receivers evaluated to date in the lab have been off-the-shelf airborne receivers obtained directly from the manufacturers. Unfortunately, the Volpe Center has not been able to obtain a nonprecision approach Loran receiver for testing.

d) *Calibration and Control*

All equipment and models are calibrated before testing and use. DC power supplies, oscilloscopes, spectrum analyzers, and data-processing PCs contribute to the utility of the lab.

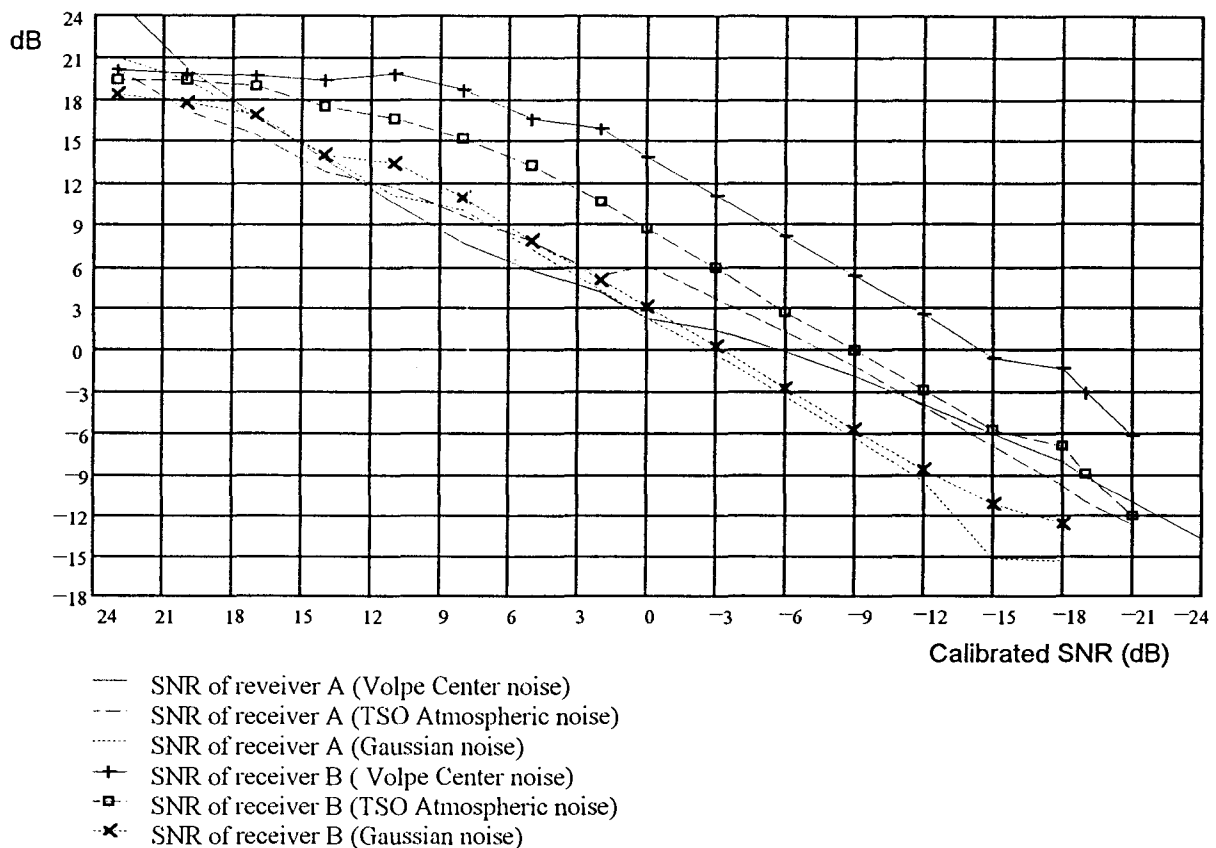


Figure 2

Loran-C signals are produced and used (Figure 1) at the RF output of the ANI-2500. Loran-C signals, with atmospheric noise, interference and all side effects to the signals such as skywave, delay, and ECD, are combined. Using a 386 PC, through the RS-232 interface, all parameters affecting the receiver input signal can be adjusted from either command files or keyboard commands. The tests can be simulated statically or dynamically. The noise signal is calibrated with the set up shown in Figure 1, before any use of the RF output signals.

SELECTED APPLICATIONS

a) Characterization of LORAN-C Receivers

Since atmospheric noise is non-Gaussian, receiver manufacturers have incorporated sophisticated nonlinear processing to mitigate the effects of noise.

The techniques tend to eliminate the high dynamic range excursions which are typical of impulsive lightning. Thus, depending on the nature and percentage of noise which is impulsive, much of the noise power could be eliminated by the receiver processing. The more dynamic the nature of the impulsive noise, the greater the benefit of sophisticated signal processing. Conversely, the less dynamic (or the more Gaussian), the less advantage results from the signal processing in the receiver. Since receivers generally are calibrated in the factory using Gaussian noise, which actually represents a worst-case situation to sophisticated receivers, manufacturers erroneously add 8dB to their SNR measurements, based on the assumption that any impulsive components will be of the equivalent ratio, and will be removed by processing.

Several different receivers were tested using different noise models. Of particular interest in the analysis were two receivers categorized by their

SNR processing. Receiver A computes SNR using an rms noise estimate at time periods when the signal is not present. The result represents an estimate of the true rms SNR. Although receiver B computes an estimate of the true rms noise level, it appears to compute the signal-to-noise quality measure at the output of its nonlinear processing circuits, which tends to mitigate greatly the effect of impulsive noise. The receiver uses a zero crossing hard limiter which has been calibrated using Gaussian noise.

Figure 2 compares the measured SNRs for both receivers A and B, for the three different noise models (Gaussian, TSO-C60 Atmospheric, and Volpe Center).

When the noise source is purely Gaussian, the SNR values presented by receiver A (true rms) and receiver B (processed) are very close.

Using TSO-C60b atmospheric noise, receiver B SNR was approximately 2 to 6 dB greater than that computed using true rms SNR as measured by receiver A. This indicates that receiver B removed much, but not all, of the effect of the spikes. Since the SNR improvement factor was on the order of 4 dB rather than 8 dB, it would seem that the manufacturer of receiver B could show better performance by using Gaussian-noise-SNR plus 8 dB rather than the TSO-C60b-atmospheric-noise SNR.

With the Volpe Center noise model, the ratio of the total noise to background noise was on the order of 12 dB. The SNR improvement observed on the processed receiver (receiver B) ranged from about 6 to 12 dB, indicating that the nonlinear processing was providing significant improvement. TSO-C60b permits the addition of 8 dB to SNR obtained from using Gaussian noise. This is valid only if (1) the receiver is capable of removing the entire effect of spike noise and (2) the ratio of the power in the total noise to the background noise is 8 dB. If the mix is different, as is most likely in real world situations, the result will be misleading.

Therefore, a receiver which may have satisfied all the tests specified in TSO-C60b could give

erroneous SNR readings if the ratio of the total noise to Gaussian noise is less than the 8 dB margin provided by TSO-C60b.

b) Loran-C CDI Sensitivity Effects

In an effort to accelerate the development of approach procedures for both Loran-C and GPS, the FAA requested the Volpe Center to conduct laboratory signal simulations of Loran-C receiver performance with a ± 0.30 nmi full scale deflection of a non-numeric Course Deviation Indicator (CDI). Loran-C nonprecision approaches (NPA) currently require a full scale deflection of ± 1.25 nmi, while GPS NPA require a full scale deflection of ± 0.30 nmi. Approach procedures could be developed for joint Loran-C and GPS use if both systems required the same full scale CDI deflection. In addition, less airspace would be needed for Loran NPA using the ± 0.30 nmi full scale deflection.

Approaches were simulated at four airports at which extensive Loran-C field measurements were made. Two SNR thresholds were used for the NPA simulation: -6dB and -9dB. The -6dB threshold is the current operational minimum allowed by TSO-C60b. The SNR threshold was applied to the Loran-C station in the approach triad which had the lowest signal strength at the airport. Note that this SNR level applies to the (true) environmental noise, and does not, in general, match the receiver's SNR measurement. The receiver SNR readings generally are better. The signal strength for each station in an approach triad was computed as part of the simulator set up process.

Simulations were run using Category A and B aircraft approach speeds of 90 and 120 knots, respectively. The aircraft speed was constant throughout the approach. Prior to actual approach simulations, static characterization tests were run to establish receiver CDI output properties, such as linearity and symmetry. The tested receiver was TSO-C60b-certified for en route and terminal area navigation, and the manufacturer claims it is in the process of acquiring a supplemental type certificate (STC) for nonprecision approaches. Hence, the receiver did not have NPA features (such as a filter

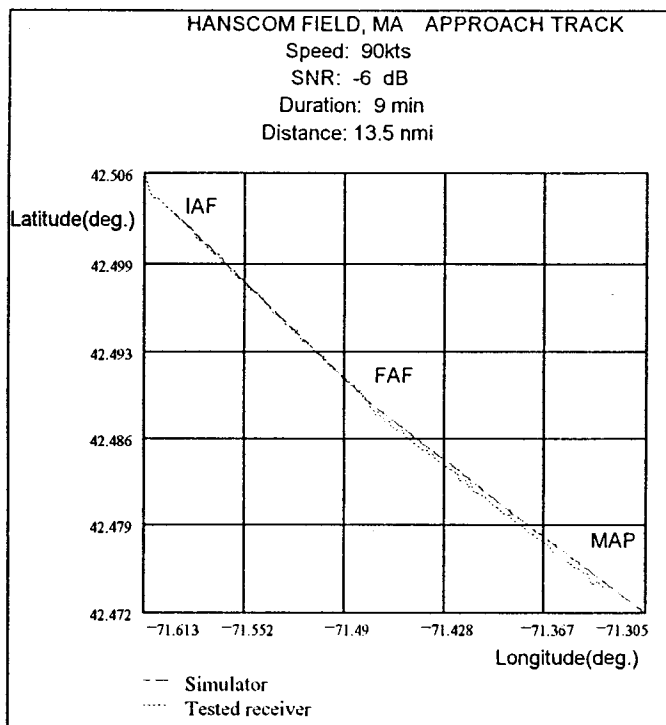


Figure 3

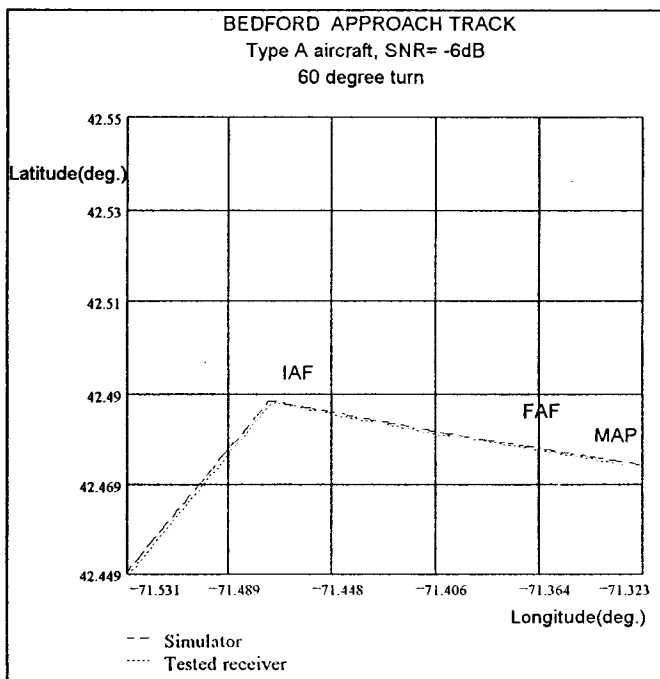


Figure 4

on the CDI output) when it was tested.

The four airports used in this analysis were: Salem (SLE), in Salem, Oregon; Orlando Executive (ORL), in Orlando, Florida; Hanscom Field (BED),

in Bedford, Massachusetts; and Lakefront (NEW), in New Orleans, Louisiana. Figure 3 shows a standard approach track for runway 11 at Hanscom Field, Bedford, MA, generated by the simulator. Turns to final approach heading of 60 and 120 degrees also were simulated at Hanscom Field. Figure 4 shows the 60 degree scenario. In Figures 3 and 4, the simulator track plots as the dashed line, and the receiver position measurements plot as the dotted line. In both cases, a 90 knot approach was flown at the -6 dB minimum noise threshold.

The cross track error data were recorded and plotted as CDI with full scale deflection settings of ± 1.25 and ± 0.30 nmi. Figures 5 and 6 show the CDI distributions of simulated NPA at Hanscom Field for the 1.25 and 0.30 CDI settings, respectively. The number of CDI measurements is shown on the vertical axis, and the CDI deflection in "dots" is shown on the horizon. The horizontal units mimic the onboard CDI, which scales ± 5 dots to indicate full deflection. The distance between dots is about 1500 feet when the ± 1.25 nmi setting is used, and about 360 feet for the ± 0.30 nmi setting.

The spread of cross track errors is plotted in Figures 5 and 6 in histogram format, in which the height of the bars is proportional to the number of CDI readings falling within the horizontal range spanned by the bar. The width set for the bars is 0.25 dots. In Figure 6 (± 0.30 nmi scaling), the cross track error clusters very well around the mean value of 0.26 dots (95 feet). The standard deviation is 0.276 dots (100 feet). This is excellent performance considering the sharp turn to final approach.

The runs shown in Figures 3, 4, 5, and 6 are typical of all of the simulations run in this study. In none of the simulations did the CDI "peg" at either full scale deflection value, and there were no rapid jumps of the CDI needle from dot to dot. Mean cross track errors in all simulations were less than two dots, and had small variances. The results made possible by using this simulator strongly suggest that a CDI full scale deflection of ± 0.30 nmi is feasible and practical for Loran-C NPA at representative airports, and in marginal noise

conditions. The Volpe Center hopes to conduct follow-up testing of the approach receiver when it is available.

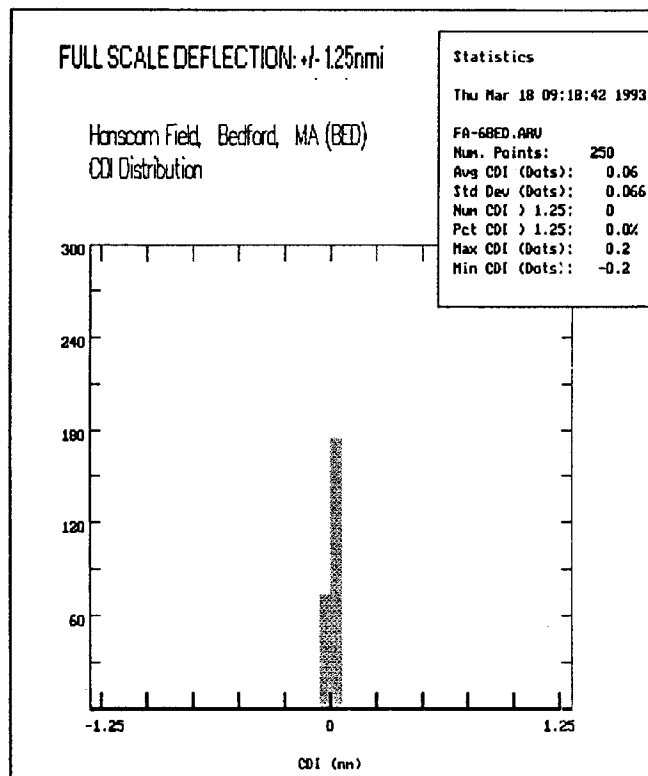


Figure 5

c) TSO-C60b Bench Tests

The Volpe Center has developed a system that generates time-varying Loran-C and noise stimuli which can produce real time test scenarios, including those detailed under FAA Technical Standard Order TSO-C60b. The Volpe Center intends to permit Loran receiver manufacturers and designers to verify the performance of their receivers with respect to TSO-C60b requirements, by having their receivers tested in the Volpe Center simulation laboratory.

A Test Plan has been developed in accordance with the procedures specified in the RTCA/DO-194 and TSO-C60b. This plan is automated and ready to implement as soon as NPA Loran receivers are available.

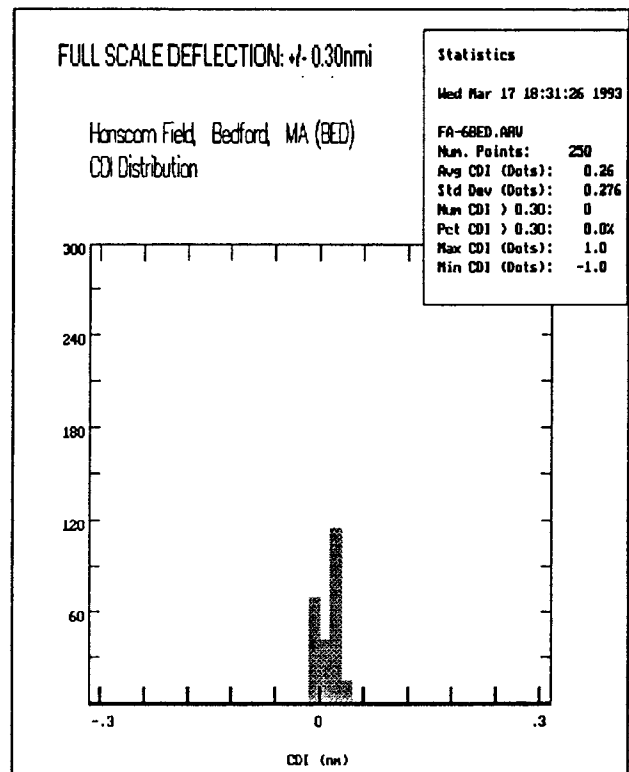


Figure 6

CONCLUSION

Over 150,000 Loran-C airborne receivers are now in use in general aviation aircraft and there is a dire need for NPA qualified receivers. Concomitantly, there is a strong need to develop and implement realistic certification procedures and operational requirements for Loran NPA. The Loran simulation lab at the Volpe Center can enhance this effort by providing a comprehensive, yet cost effective simulation and testing environment, for candidate receivers. Using this facility should greatly reduce the number of expensive certification flight tests, while at the same time providing realistic, accurate, and repeatable test data. This facility also can provide data to assist the FAA in the certification process and it can be used to evaluate other Loran-C test equipment.

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BIOGRAPHY

BachYen T. Dao is a project engineer at the U.S.DOT, Center For Navigation of the Volpe Center in Cambridge, MA. She has been working on Loran-C systems since 1990. Prior to this she worked on fiber optic communication systems from 1987 to 1990, also at the Volpe Center. She received the B.S. degree in Electrical Engineering from UCLA in 1985. Ms. Dao is a member of the Wild Goose Association.

LORAN/GNSS A COOPERATIVE SOLUTION TO RUNWAY INCURSIONS

By Edward J. Fraughton
TERRASTARR, INC.
2398 West North Temple
Salt Lake City, Utah 84116
October 1993

Abstract

This paper examines new art that proposes using Loran, GPS, GLONASS or other signals to prevent unwanted airport traffic intrusions. In a dynamically active, high speed broadcast environment, each cooperative target craft combines its own special identification code with real-time position information and a variety of other messages. These position messages are intermittently broadcast in an omni-directional pattern using a dedicated two-way "L" band data radio transceiver, a computer and software. Targets can be tracked from inside the cockpit, at actively controlled airports or at completely remote locations. The report also addresses Differential Positioning and other integrity issues vital to safe implementation of the prescribed technology for expansion of Loran/GNSS utility. The equipment and methods used represent an evolutionary, reliable, low cost method for managing surveillance, precision navigation, collision avoidance, and emergency location needs within a broad range of mixed air, land, marine and low earth orbit applications.

Introduction

Under FAA supervision, a runway incursion detection system using the prescribed method is currently being tested at the Salt Lake City International Airport. The purpose of these tests is to demonstrate the feasibility

of tracking aircraft and ground-based service vehicles using Long Range Area Navigation (Loran C) and the Global Positioning Satellite) GPS system. The technology is being developed under U.S. Patent 5,153,836, a "UNIVERSAL DYNAMIC NAVIGATION, SURVEILLANCE, EMERGENCY LOCATION, AND COLLISION AVOIDANCE SYSTEM AND METHOD."

Since some aspects of this project are still proprietary, the paper will emphasize feasibility issues over technical solutions, and hopefully, provide a sound basis to show why Loran C should be kept intact and expanded upon rather than abandoned too quickly to other solutions that may or may not be superior or more cost effective.

Overview

The primitive wanderings and observations of man led to several extremely important inventions. Among them were the calendar, the wheel, the sundial, map and compass. The sail, the astrolabe, the telescope and mechanical timepiece followed, bringing with them, the sextant. Through this, a universal standard navigation method was born which is still in widespread use today. This standard allows navigators to establish an exact position fix from any location on earth. Industrialized nations of the world generally use latitude, longitude and altitude for defining a position fix.

This thesis proposes a combination of yesterday's navigation art with today's electronic earth and celestial navigation technology. It suggests expanding present uses of Loran C and the system of satellites commonly referred to as GNSS (Global Navigation Satellite System) to a next logical stage: creating a *virtual* navigation environment that is not dependent upon (or vulnerable to) a single signal source.

Grid (Fixed Point) vs. Station Referencing

Some 500 years ago, sailors began to venture beyond the horizon, across the ocean's vast unmarked surface. It would have been virtually impossible to keep track of one's position on earth's revolving turbulent surface without some form of navigational aid, so a grid-based referencing system was invented. Later, craft that travelled by land, water, or flew through the air found out that electronic surveillance tools could easily compute a position in space by cross-referencing to other electronic stations. Radar miraculously detected signal reflections that bounced off objects, so bearing and range could be determined without a need for grid referencing. The grid was soon supplanted by a series of electronic referencing stations, VOR (omni-direction long range radios), NDB's (Non-Directional Beacons), ATC (Air Traffic Control) radar stations, transponder radios, etc. Each system has its advantages, each also exhibit some disadvantages.

Potential of the Loran/GNSS Method

Because of the development and recent popularization of Loran C, GPS, GLONASS and other systems, a great opportunity now exists for improving the ancient art and the modern day science of navigation. Both worlds: fixed point (grid), and station to

station referencing, can now be brought together into a single cohesive (and complementary) system that truly operates in the fourth dimension. For example, by using Loran C and GNSS navigation, we now have the ability to navigate to any location on earth by True North rather than having to rely exclusively on a magnetic compass. Using today's tools, a pilot can continuously calculate his/her own position within a dynamic framework of space and time, and do so with extreme rapidity and precision. This information can be used not only to plot and track one's own position, but positions of other traffic navigating within a pre-defined geographic area of interest. Specific target information, topographical features, and other discreet messages can be transmitted, received and displayed on electronically drawn 3-D maps. This can be done at low cost without the need for additional ground-based equipment or personnel.

TCAS Method vs. SCAN Method

In an attempt to address the need for pilots to be able to detect other airplanes for collision avoidance purposes, the FAA recently introduced and mandated a system called TCAS (Traffic Alert and Collision Avoidance System). This system is extremely complex and expensive and its overall performance has fallen short of expectations¹. TCAS uses interrogation dependent radar transponders that operate at 1030mhz and 1090mhz.

Loran C, GPS and GLONASS have presented a marked improvement in the way people now navigate. In less than a decade, aircraft pilots have moved from a zig-zag, VOR based station-to-station referencing system to one that permits more efficient long range direct routing. Along with providing a much greater safety margin in today's crowded airspace, this advance in

technology promises to provide greater savings in fuel costs, reduced travel times, and more efficient traffic management. To further advance this new technology, the author recommends an improved philosophy of occupying airspace. This concept suggests that each pilot: 1) should constantly know his/her position in space within a predictable level of integrity, and 2) should periodically report that position.

Prudent use of Loran C and GNSS, in combination with a new high speed digital radio described within this report, would offer the pilot and ground based controller a much higher utility than that presently offered by TCAS, radar, or any other single source navigation system in use today.

Benefits to Users of a New Surveillance Tool

What would be the expected result of implementing such a simple concept? Pilots would not only be constantly aware of their own position, but the presence of any other craft passing within a predetermined range. At a glance, each pilot could identify another craft by noting its unique craft ID number, craft type, distance, heading, track, altitude, speed, climb/descent rate, and know the presence of a voice or data communication frequency being monitored by its pilot. Traffic alerts and collision warnings would notify each pilot well in advance of any potential hazard. Airports, VOR stations, obstructions, restricted areas, and geographic land features could be constantly portrayed on a display to the pilot. The system would use data exchanges for such routine chores as listening to ATIS (Advanced Traveler Information Service), filing flight plans, responding to Notams (Notices to Airman), downloading weather charts and briefing reports, receiving differential error correction information, or notifying approach control of one's intentions.

Such a system could easily provide runway incursion protection at any airport, whether that airport is controlled or not.

The device proposed would also provide improved emergency notification and rescue service over the ELT (Emergency Locator Transmitter) currently required on aircraft. Should any kind of emergency occur, a pilot would be able to instantly announce to anyone within listening range, the exact nature of the emergency. Identity, air speed, altitude, and position could be closely monitored by any observer so that search and rescue operations could be launched immediately. Even without sending an emergency alert, any downed craft could be detected immediately.

Runway Incursion Test System

Loran C and GPS data is providing positioning source information for the runway incursion demonstration test system. Corrected, these signals should be able to provide better, more complete information than radar. The system described should serve runway incursion prevention and emergency needs for landing, departing and taxiing aircraft and runway service vehicles.

Brief Technology Description

The technology being employed during these tests consists of using current off-the-shelf Loran and GPS (or GLONASS) receivers, typical IBM compatible desktop and laptop computers, and a dedicated high speed data radio. The radio functions as an independent unit of unique design with its own micro-controller, micro-processor. When a Loran, GPS, GLONASS, altimeter, or other position reporting device is incorporated into same package as the radio, The entire unit is then capable of locating its

own position and automatically transmitting and receiving position reports independent of any other devices. Other than the positioning signal source, it thus becomes its own stand-alone surveillance system.

Each craft first finds, and then broadcasts (strokes) its own position as a block of data. Between position broadcasts, the radio receives incoming reports and messages from other craft operating within range. In the air, that range may be set at 40nm, where on the ground, it may be only 4nm.

Static positioning data from Loran and GPS signals is currently being gathered and analyzed to determine the accuracy and relative positioning of each separate system at the test site. Methods for correlating the inaccuracies are being studied as well as methods of correcting discrepancies. For example, data has been collected from Loran C and from GPS units. The antenna location was surveyed to the nearest 1/1000th second. The Loran antenna is mounted 10 inches north of the GPS antenna. Equipment being used are an ARNAV 50i Loran and a Rockwell NavCoreV.

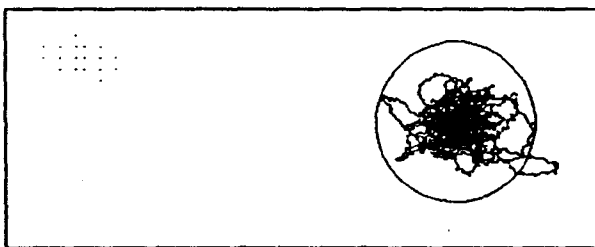


Figure 1.

Relative position solutions for Loran (upper left) and GPS (circle right) show a 450 meter displacement for Loran, though its solution is more stable than GPS.

GPS scores high in placing its position within ± 100 meters of the antenna location. Averaging out the DOD induced error over time should offer ± 20 meters of precision.

Figure 2.

Loran position solution pattern shows 3129 reports plotted over 18 lat/lon coordinates. Each circle represents an area 10 feet in diameter.

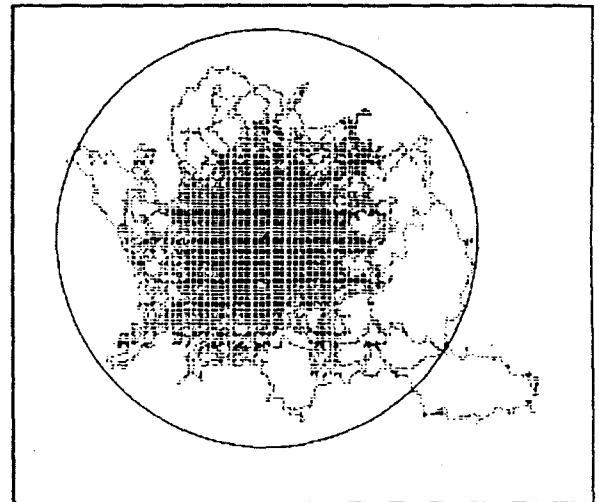
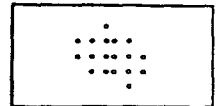


Figure 3.

GPS position accuracy of data collected over 12 hours is depicted within a 100 meter circle. Small circle in center is surveyed antenna location.

The Loran signal record is quite stable, in fact more stable than that of GPS using SPS (Standard positioning Service) with SA (Selective Availability) on. As shown, the 3129 position solutions plotted over 18 dots, creating an elliptical pattern measuring approximately 60 x 100 meters. Counting the number of times position solutions plotted over the same dot, the highest concentration of plotted positions falls on only 6 dots, an area 12 x 38 meters (39 x 123 feet) for 79.4% of total hits. The next larger pattern results in 3063 hits over a 14 dot range covering 70 x 35 meters (230 x 123 feet), or 97.9% of hits. The last covers 3113 hits over 20 spots for a range of 100 x

Point Frequency of Loran Position Reports										Data Collected 10/13/93 14:35 to 15:36 GMT	
										Sub Totals	
40.77333										4	4
40.77317			4		69	233		97	12		415
40.773	10		177		864	1045		208	14		2318
40.77283	14		97		213	60		6			390
40.77267					2						2
*NORTH											Total Hits
Total #→	24		278		1148	1338		315	26		3129
WEST-111	111.9627	111.9626	111.9625	111.9624	111.9623	111.9622	111.9621	111.962	111.9619	111.9618	
										Sub Totals	
40.77333								0.1%			0.13%
40.77317			0.1%		2.2%	7.4%		3.1%	0.4%		13.26%
40.773	0.3%		5.7%		27.6%	33.4%		6.6%	0.4%		74.08%
40.77283	0.4%		3.1%		6.8%	1.9%		0.2%			12.46%
40.77267					0.1%						0.06%
*NORTH											Total %
Total %→	0.8%		8.9%		36.7%	42.8%		10.1%	0.8%		100.0%
WEST-111	111.9627	111.9626	111.9625	111.9624	111.9623	111.9622	111.9621	111.962	111.9619	111.9618	

Figure 4. Loran data shows a high concentration of position hits around 6 points (2484 hits for 79.4%) which describes an area of only 38 x 12 meters (125 x 39 feet).

38 meters (328 x 123 feet), or 99.5% of total hits, for a total area resolution still 50% better than that achieved by degraded GPS.

Of course, Loran position solutions on the ARNAV 50i are resolved only to the nearest hundredth of a minute, so each plotted point correctly depicts Loran's highest built-in resolution limit.

12 hours of GPS SPS data collected illustrates the constant meanderings of the position solution with SA on. During one short 12 minute period, position solutions moved over an area of less than 30 feet, acting as if SA might have been turned off. Altitude, with few exceptions, continued to show a wide constant dither of ± 300 meters (984 feet).

Observances of GPS 2-D position drift going beyond the 100 meter range were also recorded, proving the 95% time parameter of the SA rule is also purposely induced.

It is clear that the same techniques do not apply for correcting Loran and GPS position errors. For Loran, the table above analyzes the number of hits to each of the 18 solution points. It shows clearly that several points receive a much higher number (%) of hits than others.

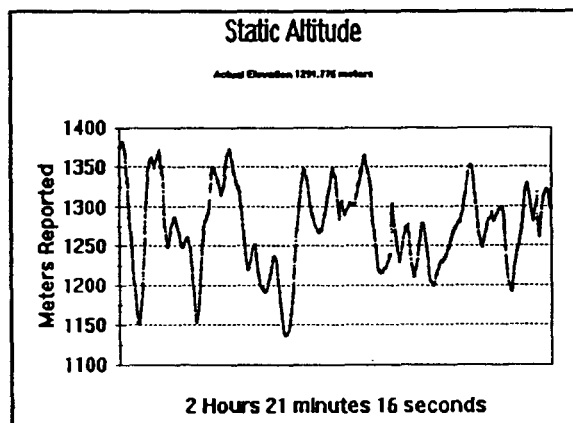


Figure 5. GPS altitude varies widely (245 meters) over a specific time period, making barometric altimeters necessary when DGPS is absent.

Even though Loran's resolution pattern appears to be finer than that of GPS with SA, the best Loran position result is still much farther from the known antenna location than the worst GPS solution (by 350 to 450 meters). This is predictable because frequency ranges, signal properties and operational characteristics are different, and each respond in dissimilar ways from environmental effects. However, Loran positioning problems should be quite easily resolvable.² One obvious solution appears to be to simply move the entire grouping of Loran solutions to a new geographic location nearest the antenna position. This solution may or may not prove wise, particularly when the antenna is mounted too close to the ground. An objective should be to apply the best known error correction techniques possible to correct Loran precision.³ In this test however, geographic correction, a simple time correlation technique, and position averaging will be used. The objective is to demonstrate that Loran can be resolved to an area 40 x 40 feet.

Software

In addition to software used by the lab to monitor and resolve position information coming from Loran, GPS or other sources, extensive software has been written to use the technology inside the aircraft, service vehicles, and at a master control traffic observation center while conducting real-time runway incursion tests. At the test site, data will be monitored from the tower, while each target being tracked reports and receives data from other mobile targets.

The Radio Requirement

The surveillance radio being designed for aircraft applications is referred to as the SCAN (Surveillance for Collision Avoidance Navigation) radio. In order to understand its capabilities and intended uses, some general

performance characteristics are described:

The ability to monitor high numbers of inbound, departing, and taxiing aircraft and service vehicles operating on the ground will ultimately require two-way exchanges at high data rates. With deference to other modulation schemes and their limitations, a multiple channel radio that utilizes a single frequency in the "L" band range for both transmit and receive modes was selected. Since no suitable off-the-shelf radios could be located, a new dedicated design was begun. The SCAN radio specification suggests: each aircraft would transmit a 250 bit message at one second intervals. Without applying Phase Shift Keying (PSK) or any other method of improving data frequency rate, that would provide a saturation density of 100% for 4,000 distinct standard length data messages.

1000 separate craft would allow for 75% free air time and a probability level of 99.8%. Adding PSK in quadrature (QPSK) would increase free air time to over 87.5%. However, land vehicles may not need to broadcast position information each second in order to be effective. Also, not all ground-based vehicles need to be portrayed at all times on a display that carries aircraft targets. Multiple channels allow for a variety of alternate purposes where appropriate.

A "polite" operating scheme and modulation that preserves the stronger of two signals that might inadvertently collide, further enhances the system's capability. Although the radio is being designed to transmit differential correction data to aircraft, that capability will not be demonstrated in these initial tests. At the airport site, the radio and computer link can also fuse data from several other important sources to resolve what has been an important topic of the FAA, the Airport Surface Traffic Automation (ASTA) plan.

Data Stream

The data stream length is flexible. In normal mode, data consists of an identification code number (N number), craft type identification, identification of position source information, latitude, longitude, altitude, time, velocity north, velocity east, velocity altitude, and other possible messages. The transmission cycle should take no more than 250 microseconds including key-up, key-down time.

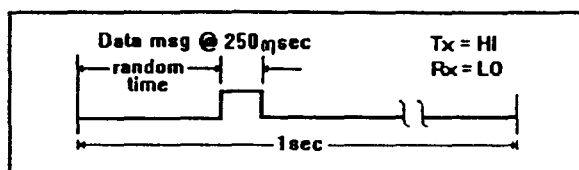


Figure 6

Analysis of Potential Signal Sources

Initially, static Loran and GPS recordings are being made near the Salt lake International Airport to determine the amount of normal drift and the effects of built-in degradation due to SA and other natural or unnatural anomalies. Fortunately, the effects of GPS SA are becoming well known. A major undertaking by members of the Institute of Navigation (ION)⁴ over the past few years has centered on applying GPS differential positioning (DGPS) and other error correction techniques to fix the purposely induced errors and other signal ambiguities. A grave danger in using GPS for single source primary navigation is: the error budget called for in official government agreements guarantee the DOD GPS signal will provide SPS with SA to civilian users within 100 meters, but.... *only 95% of the time.*⁵ That means for every 24 hour period, GPS could be operating outside the 100 meter accuracy range for an average time of 72 minutes, a disappointing number to someone who needs ± 100 meters accuracy

100% of the time.

Russia's GLONASS system operates without a degraded signal and seems to provide normal resolution within ± 20 meters. An obvious advantage of using either GPS or Glonass centers on their potential for high precision 2-D positioning as well as their ability to determine altitude with a fairly high level of integrity. The universal time stamp also gives them a definite advantage over other systems, particularly when differential positioning is being applied. And, if the signal is monitored over time, GPS does know its location within a probable 30 meter range, something not too likely with Loran without using a known reference point.

Loran has been in place since 1940 and has proven itself stable, reliable, and affordable. A simple but practical method of dealing with Loran signal errors is to simply measure the receiver output within a specified time frame while also comparing its reported position to a known fixed reference and computing a time delay error (TD). On a limited basis, this method will be applied during these initial tests. Since this is a feasibility test only, no extensive amount of time or energy will be spent trying to correct signal propagation errors or to fix environmentally produced negative effects. Even though the potential for accuracy appears to be much higher for GPS when differential corrections are applied, these tests should prove that Loran is a completely stable, reliable platform, and in many situations, more reliable than using GPS in its uncorrected (SA) state.

In some respects, the 1992 Federal Radionavigation Plan (FRP)⁶ describes Loran C and GPS accuracy using Standard Positioning Service (SPS) as nearly equal. The imposition of SA imposes a predictable GPS accuracy resolution to ± 100 meters horizontal and ± 140 meters vertical 95% of

the time. While repeatable accuracy for GPS using SPS remains at that same level, Loran C shows repeatable accuracy of 60 to 300 feet (10 to 100 meters), or 3 times better than Standard GPS. Loran availability is rated at better than 99%, reliability at 99.7%.

Conclusions

Experience in monitoring the Loran C vs. GPS signal from a known reference point shows the Loran C signal with good geometry to be extremely consistent and stable over long periods (days and weeks) when compared to the degraded GPS signal incumbered with SA. In other words, once Loran decides where it is, it stays there. Loran is limited in its ability to be precise about finding its location fix and suffers from the fineness of the data available to the user from its data port. Typically, Loran C instruments give information to the user only in degrees, minutes and tenths of minutes. Since the receiver (computer) computes to the nearest hundredth of minutes, that is figure used in these tests. The most common CDI (Course Deviation Indicator) is sensitive only to the nearest .25 nm, or 463 meters (1519 feet) leaving a bit to be desired when trying to use the Loran in taxi tests. One hundredth of a minute in latitude represents 18.5 meters (60.8 ft), so using the data I/O port is absolutely necessary.

Static monitoring reveals a normal Loran dither no greater than .04 minutes, day after day. Rounding up or down by another .005 brings roughly a maximum .05 error of 92.6m (303.8 ft). This doesn't account for other error anomalies due to poor geometry, effects of signal propagation, or even using different brands of receivers for computing a position solution. Since the Loran signal does not appear to dither drastically and tends to toggle up or down by single increments to the nearest hundredth minute,

and since the signal does not give the user a time stamp to mark its signal by, DLoran (Differential Loran) will be applied by comparing the receiver position solution to another received from a fixed monitoring station to the nearest comparable time. If the TD is outstanding, this method may not prove efficient. Never-the-less, the test should display whether or not this simple method is practical for placing aircraft or service vehicles at proper relative positions on an airfield in the real world.

DGPS is easier to handle on the receiver side, and the results should be more predictable and precise than Loran. Time, heading, and 3-D velocities add another level of precision that is extremely helpful. With Loran, those measurements are merely averaged from past positions. The reason for needing to use differential error correction techniques in these tests is to properly place aircraft and runway service vehicles over an illustrated computer map of the airport at the traffic control tower. Aircraft approaching other aircraft or service vehicles too rapidly will be warned with electronic alarms. These alarms will also be presented at the traffic controller location, so one can see the importance for accuracy in the development of reliable software algorithms. Relative spacing of aircraft using different signal sources without the benefit of correcting differential errors is a central issue, both at the airport site and while enroute.

Observations

As the practicality of portraying runway incursion targets on a computer display becomes apparent, finer methods of presenting the information with the highest levels of accuracy should be pursued, particularly when using Loran.

Interoperable units⁷, i.e., units that use

multiple signal sources such as a hybrid Loran/GPS/GLONASS mix, that have built-in differential correcting mechanisms, or units that consider carrier wave characteristics, make pseudorange adjustments, filter noise and make other anomaly adjustments should help resolve availability, reliability, and integrity issues to move basic service to a higher, more significant level of usefulness.

In order to monitor other targets' relative positions with confidence, it becomes extremely important for the user to know the signal source and level of precision available to each of the other users. If the signal source and level of precision is not known, the results could be catastrophic.

Note: *Relative* measurements between GPS units are estimated at 1 meter horizontal and 1.5 meters vertical.⁸ No relative dimensions are specified for Loran C. That information, if available, would be very useful.

Status

TERRASTARR is currently gathering data from static antenna positions for observation purposes and is experimenting with various error correcting techniques.

Data will soon be collected from scheduled test flights and taxi operations. Differential positioning will be applied only for correcting the placement of aircraft and ground craft symbols over a computerized airport map (and eventual transmission to pilots).

The SCAN high speed data transceiver is a key element in the Loran/GNSS concept.

The user software interface has various menu selections designed for user-friendliness during these tests. It will accommodate 2-way data communications in a simulated test mode only.

Results will be compiled and submitted to the FAA for review and analysis.

Recommendations

This project proposes a new application of existing Loran/GNSS technology.

Further refinement of applying differential error corrections, particularly for Loran C, need to be further pursued and refined.

Loran and GNSS equipment manufacturers should work together to develop a universal standard for determining position results within the highest levels of accuracy to improve service. They should also work cooperatively toward establishing a common data interface and I/O data format.

It is a mistake for Loran manufacturers to encourage users to replace existing Loran C with other non-Loran equipment. Instead, a renewed commitment should be made to better utilize and further refine, Loran technology.

Redundancy, availability, reliability, accuracy, as well as status "blink" capability, are all extremely important Loran virtues that should be advocated and promoted to users.

Leaving a pilot, a nation, or the world with any single source navigation system is a perilous course, particularly if a failure (induced or non-induced) could cripple or corrupt the system.

Loran is highly compatible with other systems, is relatively inexpensive, is easy to work with and relatively trouble free. In many situations, availability of the signal is much better than satellite systems because Loran operates at a low frequency and uses a simple modulation scheme.

To be more effective, Loran needs to give information to the user with greater precision as the need demands. This is extremely important where differential positioning techniques need to be applied and where Loran directly competes against GNSS.

Loran needs to find a position solution with greater accuracy. Adding UT (universal time) to the signal may be a great asset.

GPS altitude is unreliable. Barometric altimeters are recommended, even where differential positioning is being applied.

Both Loran C and GNSS systems would perform at a higher levels of efficiency if they would seek to use their capabilities interoperably. Availability, reliability and integrity would improve, as would another extremely important component, redundancy.

Special Thanks

To: Bill Mears, David Kendall, Jainmin Li, and Leonard Wojcik for outstanding work in helping bring to life a new miracle.⁹

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5. 1992 Federal Radionavigation Plan DOT-VNTSC-RSPA-92-2/DOD-4650.5, page A-38
6. 1992 Federal Radionavigation Plan, DOT-VNTSC-RSPA-92-2/DOD-4650.5
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BIOGRAPHICAL DATA

EDWARD J. FRAUGHTON: President, TERRASTARR, Inc., born 1939, Park City, Utah, B.F.A. Graduate School, University of Utah 1962. Originator of the Surveillance for Collision Avoidance Navigation (SCAN) system concept, design and patent development, Ed has guided TERRASTARR through its first several years of operation. Actually, Ed is best known for his outstanding achievements in the field of art. In sculpture, Ed has earned an international reputation which resulted in his most recent honors: a retrospective exhibit in 1993 at the prestigious Gilcrease Museum in Tulsa, Oklahoma, and a Gold Medal from the National Academy of Western Art for an inspiring portrait of Abraham Lincoln titled, "The Candidate." He has successfully managed his own art production and bronze casting businesses for over 30 years. A pilot with a devout interest in flying, in 1991 Ed served on the RTCA "Automatic Dependant Surveillance Committee." In 1990, he was a delegate to a U.S./Soviet Moscow Conference on Law and Bilateral Economic Development. From 1982 to 1988, Ed served on the selection committee of President Reagan's "Commission on White House Fellows." In 1990, he co-authored a paper with Leonard Wojcik, "A Loran Based Collision Avoidance System." The paper, which outlined a new concept for expanding Loran/GPS use, was presented at the 1990 international Wild Goose Association (WGA) Technical Symposium.

AN AUTOMATIC ANTENNA POINTING MECHANISM

Dr J.P. Bickerstaff
R.D.Cooper
David Earl

(Consultant, Daventry, Northants, England),
(Director, MetRoaTech, Clipston, Leics, England),
(Director TV2, Loddington, Northants, England).

ABSTRACT

The paper describes the use of an electronic positioning system, with Loran-C, GPS, or Decca as candidate systems, as a component in an automatic antenna alignment system for a narrow beam video link between land, sea, or air mobile vehicles and a fixed base station. The principle is simple - given a known base station location (i.e. waypoint) and a derived vehicle position then the required absolute pointing direction is calculable (i.e. bearing). Using an electronic compass to reference the mobile vehicles heading then this can be converted to a relative pointing direction, which is calculated and implemented by a servo-system. Real world applications of such a system may present different performance requirements, according to the performance of the mobile vehicle (and whether its full performance is likely to be needed whilst maintaining the link).

OVERVIEW

We are all used to the modern style of live news and sports reporting, with 'as-it-happens' video even to the extent of 'driver's eye' views from the cockpit of racing cars during major events. We are also used to an ever increasing presentation quality of the various media, including Television, which therefore present a double-barrelled challenge to the technology - getting better quality results from more difficult situations. We all take it for granted that integration and miniaturisation will deliver.

On-the-spot or moving scenes can be video recorded, but this does not satisfy the live requirement, whilst cable links are only suitable for fixed sites, and even then can be awkward and slow to install. Radio links offer much more freedom. Typically this is achieved using a small omni-directional transmitter in conjunction with the mobile camera, and a relay station close by since the range available with this technique is only a mile or two. The relay station must then be set up with a line of sight link to the base. This will work for a confined area, such as coverage of a track event, but where a wide area coverage is needed the camera transmission may have to be relayed by a series of intermediate mobile relays, all with restricted range. Traditional Outside Broadcast links are shown diagrammatically in figure 1. Clearly the use of highly

directional, high gain antennas could increase ranges between relays, improve quality of the links, and be more economic of power, if only a simple method of maintaining the alignment of the antennas could be achieved during mobile operations. This is what the Autotracker achieves.

PRINCIPLE

Almost any modern electronic navigator is programmable with waypoints, and will then calculate the bearing and course-to-steer to the defined waypoint. Substitute the base station co-ordinates for the waypoint, and the bearing becomes the pointing direction for the directional antenna. This is hardly a new idea, and indeed antenna control systems have been built before (NURAD, BMS) with varying degrees of sophistication using electromechanical technology, manual or Loran-C derived position data, and a magnetic compass for the heading reference. Autotracker embodies these basic principles, with newer technology and some unique developments.

The electronic position sensor establishes the mobile unit location, which is used together with the programmed base station location to calculate the absolute bearing to which the antenna must be pointed. Of course the mobile unit vehicle itself might be pointed in any direction, so an electronic compass is needed to establish the vehicle heading. The difference then establishes the relative direction in which the antenna needs pointing:

$$\text{pointing direction} = \text{bearing} - \text{heading}$$

A servomechanism is then used to achieve this antenna pointing. When such a system is fully automated it enables camera-transmitter mobiles to link to much more distant fixed relay stations, or alternatively a multiplicity of short range omni-directional camera-transmitters can be linked to a local mobile relay which is enabled to maintain a long distance link to the base station even whilst moving. These scenarios are shown in figure 2.

TV2 AUTOTRACKER

The Autotracker system is illustrated diagrammatically in figure 3. The camera video and audio signals are selected, this choice including a TELENVAV modulated option which will be described more fully later. The

selected signal is then mixed with an r.f. carrier, and amplified for transmission from the antenna - as indeed would normally be the case in current systems.

In the controller section an electronic positioning sensor provides the location data, and a self-calibrating fluxgate compass provides the heading data. The computer then derives the relative angle required, and controls the motor servo-mechanism with an 8-bit shaft encoder providing the feedback on antenna relative angle. For a slow moving situation (or stationary installations which would still benefit from the automated operation of set-up) it is practicable to smooth the compass output sufficiently to obtain the accuracy required, but in a fast changing dynamic situation this can result in excessive tracking delay, and errors. A small modern solid-state gyro is therefore integrated into the system enabling the software to track in the presence of more rapid mobile vehicle movements such as will be made by land vehicles and airborne platforms.

The equipment so far described enables the transmitting antenna to track the fixed receiver site during both position and attitude changes of the mobile transmitting vehicle, which may therefore use a high gain, narrow beam antenna. Enhancement of the link quality and range also requires the receiving antenna to be high gain, narrow-beam, and therefore steered to track the mobile's position. Since the receive site is fixed the dynamics of this operation are determined by the link range, and the speed of the tracking mobile station. This may be slow enough for manual methods, but requires an additional information link for the receiving site to track the transmitter, and could equally benefit from automating.

TELENAV MODULATOR

To maintain the high gain video link so far described requires the fixed receiving site to obtain information of the position of the mobile transmitter, which is already established when using the Autotracker. A video link exists, if it could be used also to carry the position data then no separate radio/telephone link would be necessary. Taking a 10 mile link as an example, with an activity whose centre could move at 30 mph (1/2 mile per second) the angular change at the receiving antenna is 3 degrees/minute. A 3 degree shift within the antenna beam pattern is likely to be acceptable, thus an update rate of once per minute would be acceptable, a very low data-rate. MetRaoTech, joint developers of the Autotracker with TV2, have just such a device available in their TELENAV equipment.

TELENAV is a video modulator/demodulator designed to encode video signals with data from any electronic

navigation system which has available standard NMEA messages. It can be used for many purposes (e.g. photographic identification, surveillance, mapping) but frequently the user will want the pictures uncorrupted by superimposed data, yet with easy (and visual) access. TELENAV achieves this by putting the data into the signal digitally on the unused scan lines between picture frames - in a similar manner to the broadcast TV 'Teletext' services. Each line of a TV picture, American NTSC or European PAL, represents approximately 64 uS, and the system bandwidth is of the order of 5 MHz, such that even a single line per frame offers an adequate vehicle for the data. The system is illustrated diagrammatically in figure 4. In practice TELENAV achieves of the order of 1 position fix per second. The same TELENAV equipment is used as a decoder. Typical uses for the stand-alone TELENAV are to encode video camera signals before recording onto tape, and decode replayed tapes when the hidden information is required again, the user selecting that information and format which requires displaying. TELENAV can be equipped with a built in monitor, and when in use to encode video signals the monitor alone can be programmed to visually display the information for operator checking.

Embedded into the Autotracker TELENAV enables the determined position to be relayed from the mobile back to the receiving site, where it can be used to control receiver antenna alignment. The transmitter encoder is embedded in the Control Unit where it can display locally on screen the current position for operator information, although on the transmitted video the information is only encoded in hidden digital form, so that the relayed pictures are still suitable for direct broadcasting.

ACCURACIES

1. Positioning systems.

The angular error is greatest for the shortest links, but as very short links do not require high gain steerable antennas a minimum of 3 miles (5 km) might be appropriate. Taking a position error of 200 metres as representative leads to an angular error estimate of approximately 2 degrees. In this regard absolute, rather than repeatable, accuracy is the more important since calibrations are very undesirable - the objective being an automated installation. This favours satellite systems such as GPS, but with reasonably well charted (or calculable) errors Loran-C can also deliver adequate position accuracy for the purpose.

2. Heading sensor.

Although a gyro provides the dynamic azimuth attitude sensing it is referenced to a compass, which determines

the heading, and therefore pointing, accuracy. Older magnetic compasses could be seriously affected by the installation environment, and the purpose of Autotracker is to be portable rather than a permanent fixture so that hardware compensation is not appropriate. However modern flux-gate compasses represent a significant improvement and with good auto-calibration can deliver 3 degree accuracy.

3. Antenna position sensor.

An 8-bit encoder is used to monitor and feedback the antenna pointing angle relative to the mobile vehicle. This implies a resolution of 1 1/2 degrees, sufficiently small not to be a major part of the overall error budget.

4. Mechanical alignment.

The system has to be internally aligned (antenna axis to encoder, etc.), and the servo-mechanism contains small error components such as backlash. Each of these can be contained below 1 degree, so that an overall figure of 1 degree would be representative.

5. Dynamics.

In addition to the static errors there are also dynamically induced errors due to tracking delays or overshoots. A performance of +/- 4 degrees for a 360 degree/minute turn rate has been achieved, and higher rate turns up to 45 degree/second can be tracked under auto-azimuth control.

CONCLUSION

An Autotracker system such as described above has been built, in two major units (the antenna head, and control unit), incorporating isolated DC supplies and EMC precautions to minimise hazards and maximise the ease of installation. The pilot system has successfully been used for a number of live broadcasts, an example is illustrated in Figure 5. Here a Dhow race is being covered, by a variety of cameras travelling on board chase boats and helicopters. These relay their signals to a travelling 'mother ship' which carries an Outside Broadcast unit where the video can be selected, and production processed. Using the Autotracker system this ship was able to maintain a 100 km link to the shore based receiver, where it could be fed into a conventional distribution system. Reliance on the alternative multiple links, which in this case often utilised mid-point helicopters (as shown) was therefore minimised.

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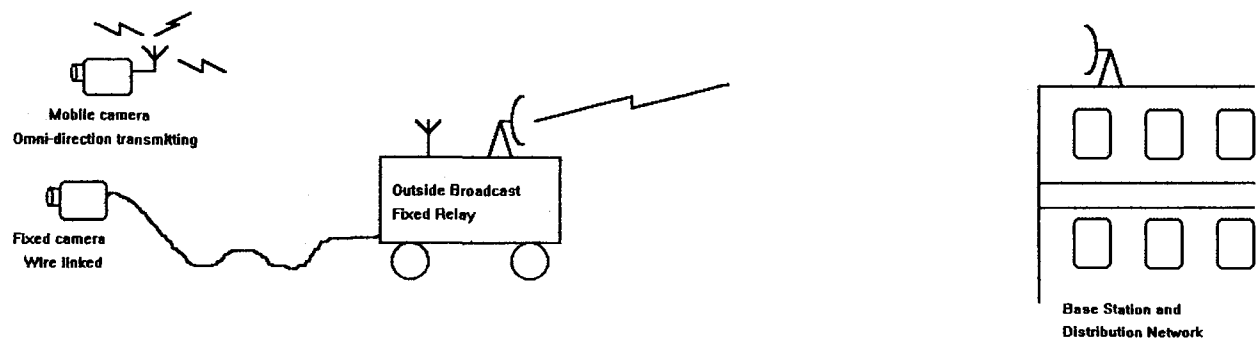


FIGURE 1. CONVENTIONAL OUTSIDE BROADCAST RELAY

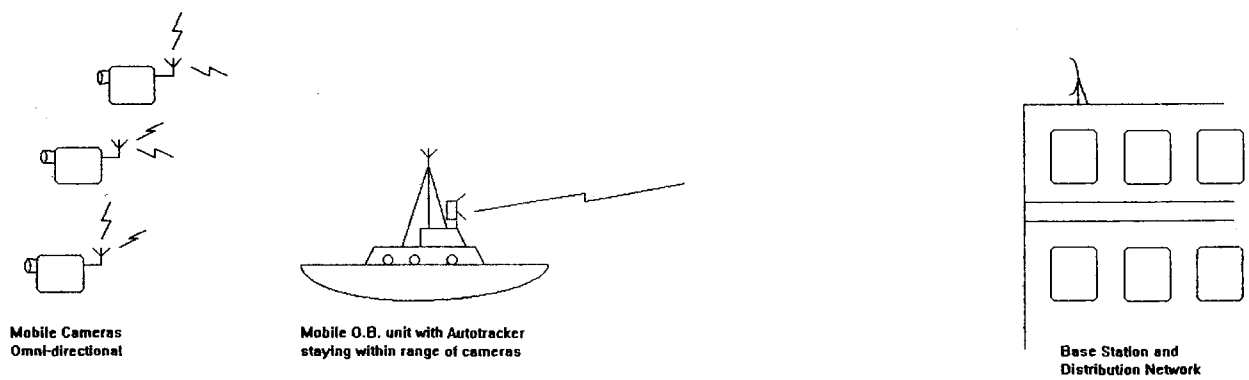
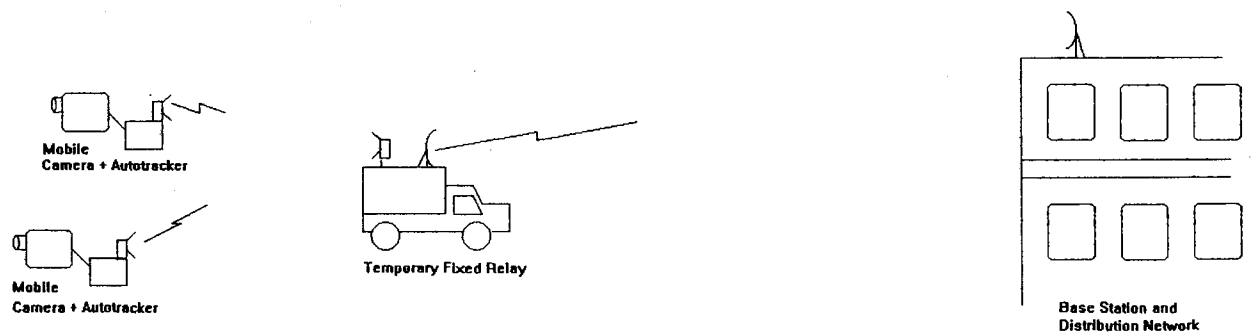


FIGURE 2. O.B. RELAYING WITH AUTOTRACKER

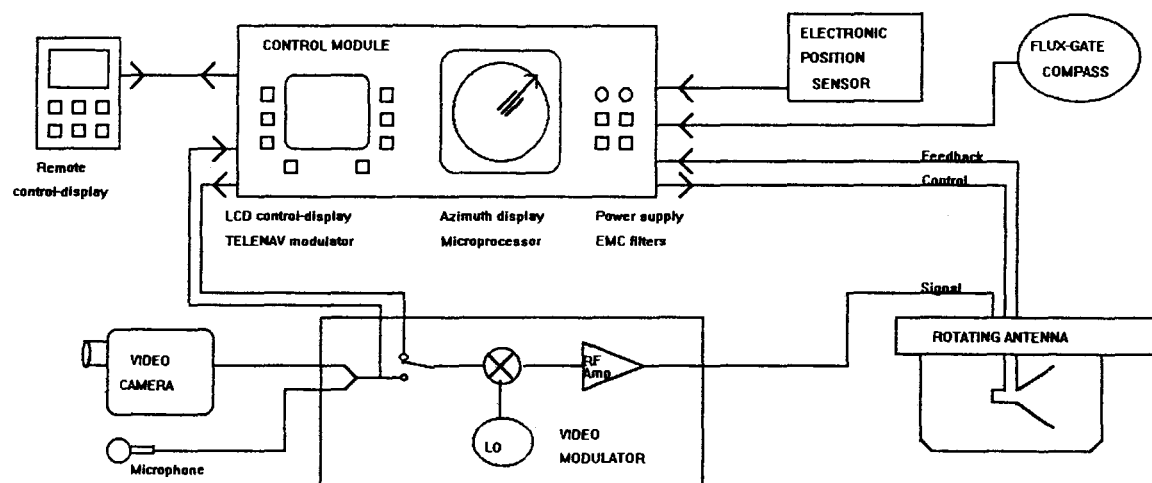


FIGURE 3. AUTOTRACKER BLOCK DIAGRAM

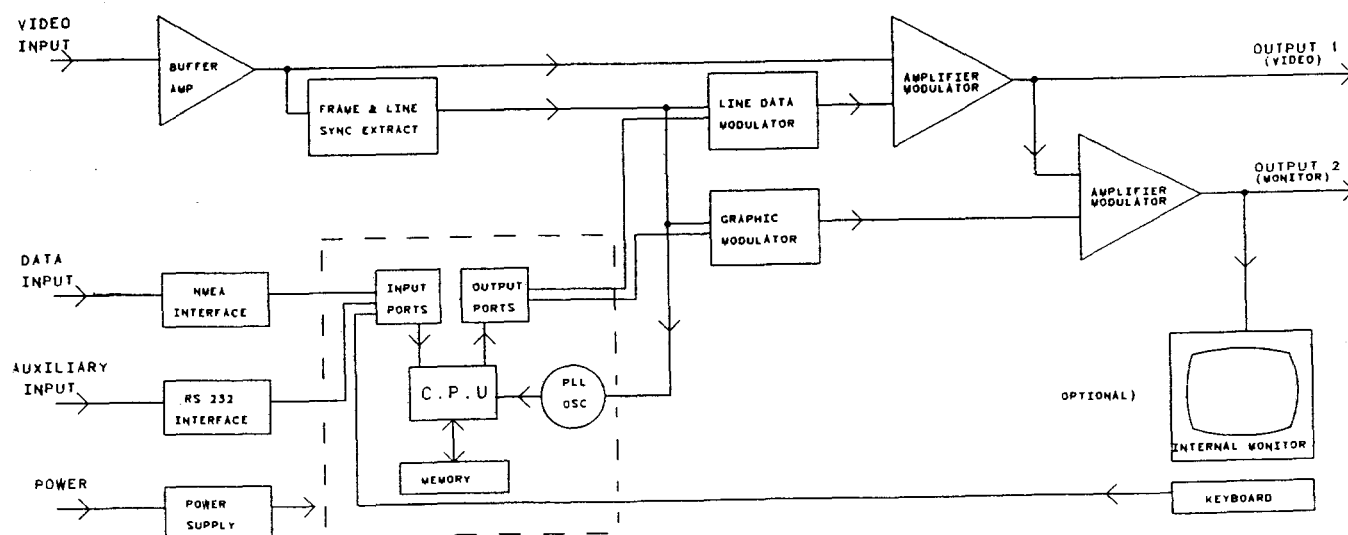


FIGURE 4. TELENV BLOCK DIAGRAM

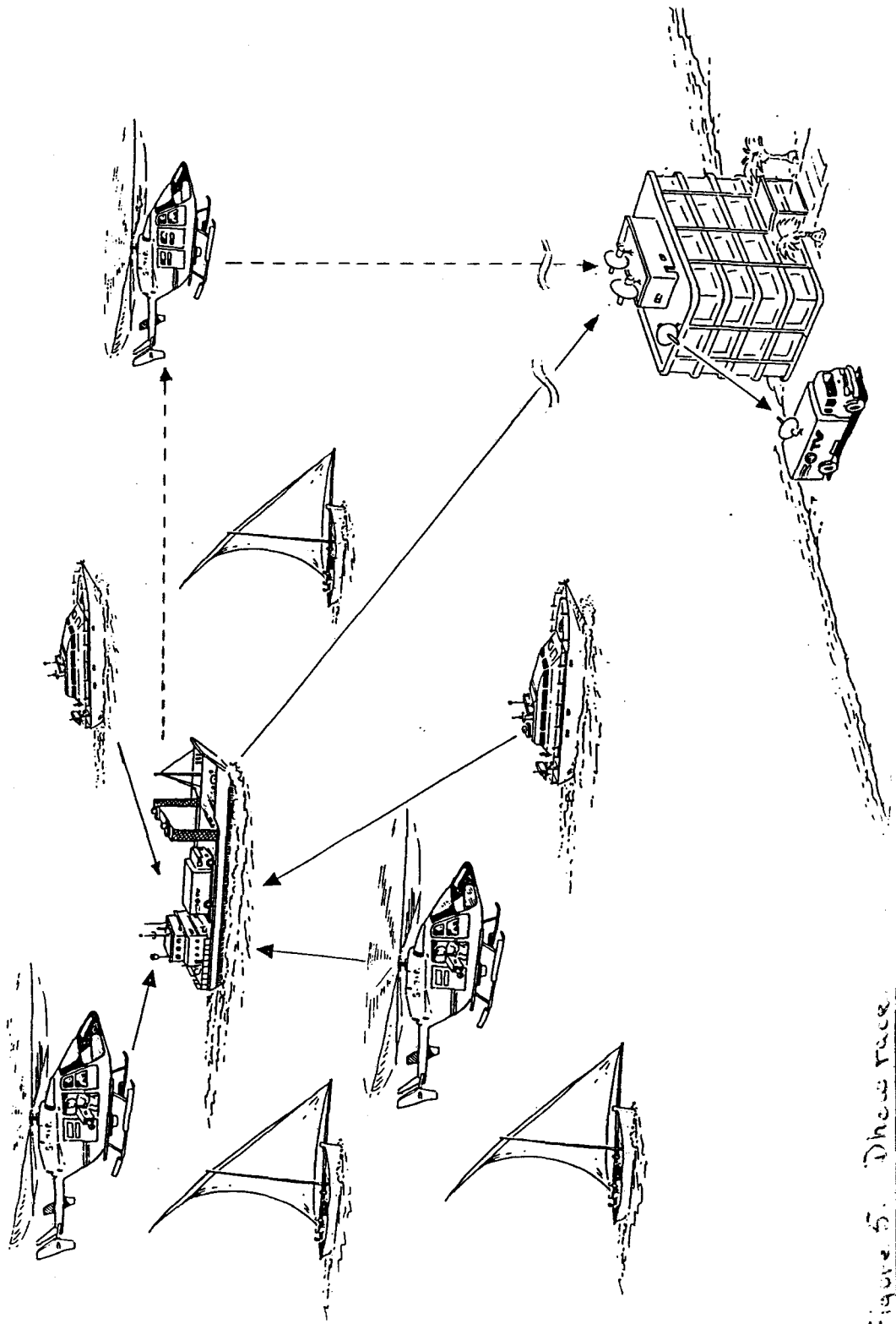


Figure 5. Dhow race

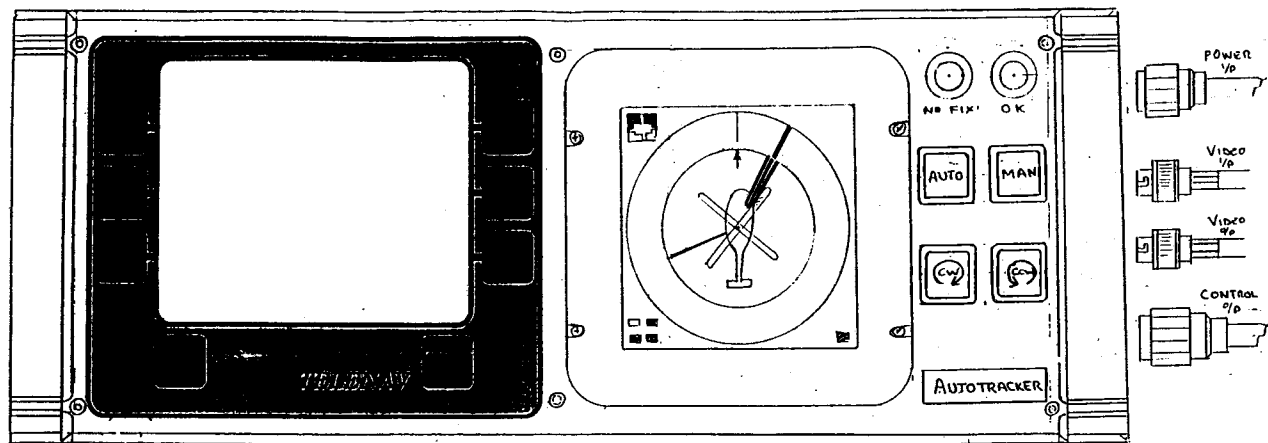


Figure 6. Control Module.

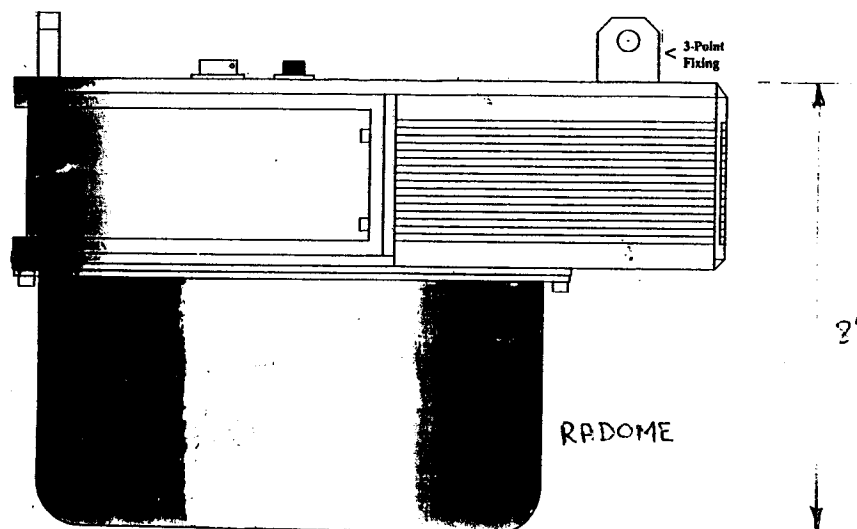


Figure 7. Rotating Antenna.

SESSION 5

Land/Marine Uses

A statistical evaluation of the effects of carrier-wave interference on the performance of Loran-C receivers

David Last and Yi Bian

School of Electronic Engineering and Computer Systems

University of Wales, Bangor

United Kingdom

Email: bian@sees.bangor.ac.uk

Abstract

A great deal of work by many researchers has been devoted to characterising the receiver timing measurement errors caused by carrier-wave interference (CWI). At last year's WGA Convention, the present authors reported a fully analytical approach and presented examples of the results of detailed simulations of receiver performance in the presence of single interferers at frequencies from 50 to 150 kHz. In practice, and especially in Europe, receivers may experience a large number of interferers simultaneously. Assessing the receiver's performance in this situation deterministically requires knowledge of the frequency, amplitude and phase of each interferer.

In contrast to previous work, this paper studies the problem of multiple interferers using statistical methods. For the first time, both the phase-tracking and cycle-selection performance of receivers are quantified in terms of the probabilities that they will operate correctly within arbitrarily-set error limits. Characteristic functions are used to compute these probabilities. The analysis is presented in general terms which are valid for any number of CW interferers. However, specific attention is paid to two limiting cases: a single dominant interferer and a large number of interferers of comparable strength. The relative sensitivities of the phase-tracking and cycle-selection functions of the receiver to interfering signals are also compared using statistical arguments.

1 Introduction

At last year's WGA Convention, the present authors reported a fully analytical approach to characterising CWI effects on Loran-C receivers. It extended Frank's [1], Van Willigen's [2] and Beckmann's [3] work on CWI by considering quantitatively the effects of CWI on the phase-decoding and integration operations of both the phase-tracking and cycle-selection loops of

the receiver. These systematic analyses, supported by large-scale simulations of receiver performance in the presence of single interferers at arbitrary frequencies between 50 and 150 kHz, shed new light on this old problem.

In practice, however, a receiver normally experiences a very large number of interferers that contribute simultaneously to errors in timing measurements. Assessing the receiver's performance in this situation generally requires knowledge of the frequency, the Signal-to-Interference Ratio (SIR), and the phase of each interferer, together with Loran-C signal parameters such as GRI and Envelope-to-Cycle Difference (ECD). In contrast to earlier work described in [4,5] where deterministic methods were used, this paper will study the problem of multiple interferers using statistical methods.

The study of the statistics of the errors of timing measurements is complicated by a number of factors: (1) the number of interferers is not easy to define, (2) parameters such as the GRI, SIR and ECD of the received Loran-C signals may occur in a range of combinations, and (3) complex schemes and various algorithms for phase measurement and cycle selection are employed in different receivers. Another complicating factor is an ambiguity concerning the error statistics in this context: these may be in either time or space. For stationary receivers, statistics in time should be used. For moving receivers, both apply; strictly, the joint statistics of time and space should be employed.

In this paper we will treat the phases of the CWI relative to those of the Loran-C signals as the main source of randomness and other factors as deterministic parameters. Analyses will be presented in general terms which are valid for any number of interferers. Specific attention will be paid to two limiting situations: a single dominant interferer, and a large number of interferers of comparable strength. These analyses give an estimate of the CWI effects in the less common situa-

tion of a small number of similarly-strong interferers.

Section 2 will analyze the phase-tracking errors in the presence of a single CW interferer. The probability distribution function and probability density function (pdf) will be used to quantify the error statistics. Section 3 will show that the phase-tracking error in the presence of a multiplicity of interferers is the sum of the errors due to individual interferers. Characteristic functions and Fast Fourier Transforms will be used to calculate the pdf of this total phase-tracking error. Section 4 and 5 will present analyses of the cycle-selection operation, equivalent to those in Sections 2 and 3, respectively. The influence of receiver signal processing on the error statistics will be discussed in Section 6. Section 7 will compare the relative sensitivity of phase-tracking and cycle-selection to CWI.

2 Phase measurements: a single interferer

Let us consider the steady-state response of a linear receiver to a single interfering signal. For simplicity, it is also assumed in this analysis that there is no noise. According to [2] the phase measurement error T_e due to a single interferer (prior to considering the effects of front-end filtering, phase-decoding and integration in the receiver phase-locked loops) is due to the phase difference between the phasor sum of the signal-plus-interference and the signal alone. It is thus a function of the SIR and of the phase of the interferer relative to the Loran-C signal:

$$T_e = \frac{10}{2\pi} \arcsin \left(\frac{I}{C} \sin \phi_{int} \right) \quad (1)$$

where I is the amplitude of the interferer, $C = \sqrt{I^2 + S^2 + 2IS \cos(\phi_{int})}$, and S is the amplitude of the envelope of the Loran-C pulse at the sampling point. The term 'relative phase', and the symbol ϕ_{int} , will be used to signify the phase of the interfering signal with respect to that of the Loran-C pulse. Normally, the signal-to-interference ratio (SIR) at the input to the receiver is defined as

$$SIR = \frac{S}{I} \quad (2)$$

Thus, for a known SIR, the phase-measurement error depends only on the relative phase of the interference. In our earlier deterministic analyses [4,5], the worst-case phase was considered and the corresponding maximum phase-measurement error evaluated. In this paper, in contrast, we will treat the phase-measurement

error as a random variable T_e and assume that the relative phase, ϕ_{int} , is uniformly distributed over $[0, 2\pi]$. Further, when a large number of CWIs are considered, the phase of each will be assumed to be independent of the others. A powerful justification for these assumptions is that, taking the whole coverage area, the phases of interferers and the Loran-C groundwave signals are uniformly distributed.

Positive and negative values of phase-measurement errors are distinguished in the following analysis for convenience of mathematical treatment. Therefore the limits of phase-measurement error are the earliest and latest measured times of arrival; in contrast, the modulus of T_e corresponds to the generally-accepted phase-measurement error in the deterministic analyses in [4,5]. We will also assume that t_e represents any arbitrary phase-measurement error limit; the probability that the error is less than t_e , denoted by $P\{T_e \leq t_e\}$, is then equal to its cumulative distribution function (cdf), $F_{T_e}(t_e)$, evaluated at the value t_e :

$$F_{T_e}(t_e) = P\{T_e \leq t_e\} \quad (3)$$

By substituting (1) into (3), it is shown in [6,7] that $F_{T_e}(t_e)$ can be explicitly expressed as

$$F_{T_e}(t_e) = \frac{1}{2\pi} \left\{ \pi + 2 \arcsin \left(\frac{C}{I} \sin \frac{2\pi}{10} t_e \right) \right\} \quad (4)$$

Note that this equation is derived under the condition that ϕ_{int} is uniformly distributed over $[0, 2\pi)$ and that it is valid only for $t_e \in (-\frac{10}{2\pi} \arcsin \frac{I}{C}, \frac{10}{2\pi} \arcsin \frac{I}{C})$. Further, it is easy to verify that

$$F_{T_e}(t_e) = \begin{cases} 0 & \text{for } t_e \leq -\frac{10}{2\pi} \arcsin \frac{I}{C} \\ 1 & \text{for } t_e \geq \frac{10}{2\pi} \arcsin \frac{I}{C} \end{cases} \quad (5)$$

Differentiating $F_{T_e}(t_e)$ in (4) and (5) with respect to t_e gives the pdf of T_e

$$f_{T_e}(t_e) = \frac{d}{dt_e} F_{T_e}(t_e) = \begin{cases} \frac{2}{10} \frac{C}{I} \frac{\cos \frac{2\pi}{10} t_e}{\sqrt{1 - (\frac{C}{I} \sin \frac{2\pi}{10} t_e)^2}} & t_e < \left| \frac{10}{2\pi} \arcsin \frac{I}{C} \right| \\ 0 & \text{elsewhere} \end{cases} \quad (6)$$

Figs.1 and 2, using (6) and (4), respectively, plot the pdf and cdf of the phase-measurement errors for a set of arbitrarily-chosen SIR values. The maximum and minimum phase-measurement errors correspond to the values of t_e at which $F_{T_e}(t_e)$ takes the values 1 and 0, respectively.

Of greater practical importance is the probability of the magnitude of the phase-measurement error being less

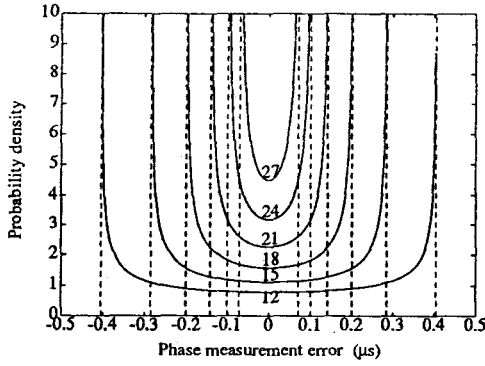


Figure 1: Probability density of phase measurement error due to single CWI. Numbers are SIR in dB. Dashed lines are corresponding maximum errors.

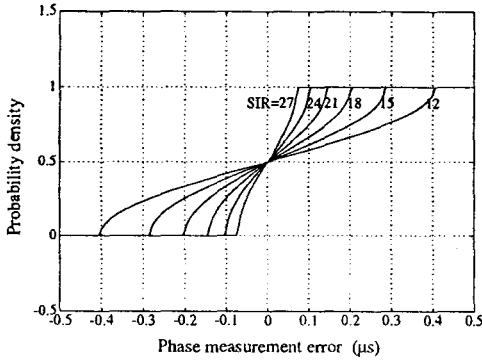


Figure 2: Cumulative distribution of phase measurement error due to single CWI.

than an arbitrary limit. This probability is

$$P\{|T_e| \leq t_e\} = P\{-t_e \leq T_e \leq t_e\} = \frac{2}{\pi} \arcsin\left(\frac{C}{I} \sin \frac{2\pi}{10} t_e\right) \quad (7)$$

According to (7), the probability of any phase-measurement error may be calculated against the error magnitude [7]. Curves for various SIR values may be normalised with respect to their corresponding maximum errors. It is shown in [7] that all curves have identical shapes after normalisation. It is also shown that, in the presence of a single interferer, the probability that the phase-measurement error is less than its rms value (3 dB below its maximum) is approximately 50%; and the probability that $|T_e|$ exceeds 1 dB below its maximum is approximately 30%.

3 Phase measurements: multiple interferers

When many interferers are being received, the total phase-measurement error is some combination of the errors due to the individual interferers. The analysis

of such complex situations may be made tractable by imposing certain practical limitations. For instance, Loran-C systems cannot meet their fundamental accuracy specifications [8,9] if the phase-measurement error exceeds approximately $0.1 \mu s$. Figs.1-2 and references [4,5,6] show that, with a single interferer, this limit is reached at an SIR of 24dB. Equation (1) shows that at this, and higher, SIR values the phase-measurement error is almost inversely proportional to the SIR; thus the total phase-measurement error due to multiple interferers is approximately equal to the sum of their individual phase-measurement errors. That is,

$$T_e = \sum_{k=1}^K T_{ke} = \sum_{k=1}^K \frac{10}{2\pi} \frac{I_k}{S} \sin \phi_k \quad (8)$$

where K is the number of interferers, T_{ke} is the phase-measurement error due to the k -th interferer alone and I_k and ϕ_k the amplitude and relative phase, respectively.

Since each interferer can be considered to be independent and each ϕ_k is uniformly distributed over $[0, 2\pi]$, T_e is the sum of K independent, identically distributed, random errors T_{ke} . Hence the probability distribution function of T_e , $f_{T_e}(t_e)$, is the convolution of the pdfs of all interferers [10]:

$$f_{T_e}(t_e) = f_{T_{1e}}(t_e) * f_{T_{2e}}(t_e) * \dots * f_{T_{Ke}}(t_e) \quad (9)$$

To calculate $f_{T_e}(t_e)$ explicitly from this equation requires a $K - 1$ dimensional integration in which pairs of functions, $u(t)$ and $v(t)$, are convolved iteratively $K - 1$ times:

$$u(t) * v(t) = \int_{-\infty}^{\infty} u(t) \cdot v(\tau - t) d\tau \quad (10)$$

By definition, the lower and upper limits of this integration are $-\infty$ and ∞ . In practice, these limits are the minimum and maximum values of the total error due to the K interferers. According to (8), they are calculated as

$$(T_e)_{max} = \sum_{k=1}^K (T_{ke})_{max} = \sum_{k=1}^K \frac{10}{2\pi} \frac{I_k}{S} \\ (T_e)_{min} = \sum_{k=1}^K (T_{ke})_{min} = - \sum_{k=1}^K \frac{10}{2\pi} \frac{I_k}{S} \quad (11)$$

Even given this simplification, direct evaluation of (9) still demands excessive computing power. A practical method for calculating $f_{T_e}(t_e)$ is to use the properties of the characteristic functions (CF) of random variables

and to recognise the analogy between the CF and the Fourier Transform (FT).

The characteristic function of $f_X(x)$, the pdf of random variable X , is defined by

$$\Phi_X(\omega) = \int_{-\infty}^{\infty} f_X(x) e^{j\omega x} dx \quad (12)$$

The pdf and CF of a random variable are uniquely related to one another, and the CF of the sum of a number of independent random variables equals the product of the CFs of those variables [10]. Thus, if we define $\Phi_{T_e}(\omega)$ as the CF of T_e , and $\Phi_{T_{k_e}}(\omega)$ as the CF of T_{k_e} , we have

$$\Phi_{T_e}(\omega) = \Phi_{T_{1_e}}(\omega) \cdot \Phi_{T_{2_e}}(\omega) \cdot \dots \cdot \Phi_{T_{K_e}}(\omega) \quad (13)$$

Notice that the CF is identical to the Inverse Fourier Transform (IFT) of the pdf of a random variable, except for a constant coefficient. Therefore, the pdf can be treated as the FT of its CF except for that coefficient. More specifically, these relations can be written as

$$\Phi_{T_e}(\omega) = F^{-1} \{2\pi f_{T_e}(t_e)\} \quad (14)$$

$$f_{T_e}(t_e) = F \left\{ \frac{1}{2\pi} \Phi_{T_e}(\omega) \right\} \quad (15)$$

This allows us to employ computationally-efficient Fast Fourier Transform (FFT) algorithms to solve the problem of calculating the pdf and CF of each T_{k_e} and T_e .

We will now consider two specific cases which allow this general method to be simplified.

3.1 Two interferers

The pdf of the phase-measurement errors caused by two interferers has been calculated by this method for a range of SIR combinations (Fig. 3). The SIR of the stronger CWI is 24 dB and the parameter which generates the family of curves is the difference between the SIR values. Numerically integrating each curve yields the corresponding cdf of the phase-measurement error, that is, the probability of an error's being less than any arbitrary limit.

The pdf and cdf may be normalised with respect to the maximum phase-measurement error due to the stronger CWI alone [7]. These normalised curves depend only on the differences between the SIR values and not on the values themselves; thus, the pdf and cdf for a given maximum phase-measurement error may be found directly from these normalised curves [7].

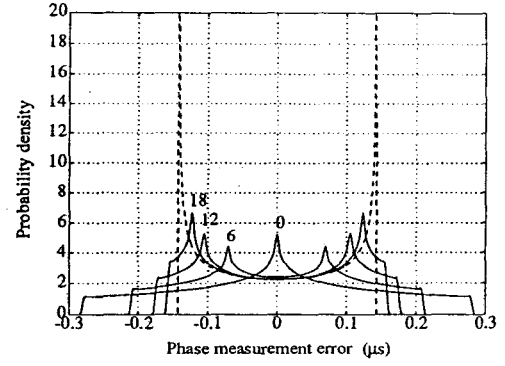


Figure 3: Probability density of phase measurement error due to two CWIs. Numbers are SIR differences between stronger and weaker. SIR of stronger = 24 dB. The dashed line results if only the stronger exists.

3.2 Many interferers

The central limit theorem tells us that, in the presence of large number of interferers (none of which is statistically dominant), the pdf of T_e can be approximated by a Gaussian distribution [10]. The mean and variance of this distribution will be the sums of the means and variances of the phase-measurement error due to each interferer. From (8), we may simplify the phase-measurement error due to the k -th CWI to

$$T_{k_e} = \frac{10}{2\pi} \frac{I_k}{S} \sin \phi_k \quad (16)$$

Therefore, provided each CWI is independent, we get the mean and variance we seek:

$$E(T_e) = E\left(\sum_{k=1}^K T_{k_e}\right) = \sum_{k=1}^K E(T_{k_e}) = 0 \quad (17)$$

$$\text{var}(T_e) = \sum_{k=1}^K \text{var}(T_{k_e}) = \sum_{k=1}^K \frac{25}{2\pi^2} \left(\frac{I_k}{S}\right)^2 \quad (18)$$

If a small number of interferers are dominant, the central limit theorem will not hold. In this case (17) and (18) may be regarded as a first estimate of the error statistics.

4 Cycle-selection: a single interferer

Loran-C receivers find and track the correct cycle for phase measurement by establishing the ratio of the half-cycle peaks (HCPR) which bracket the zero-crossing being tracked and then comparing the measured HCPR with its stored expected value [4,5]. CWI causes errors in HCPR measurements which result in ECD measurement and cycle-selection errors. It is shown in [4,5] that

this HCPR error due to a single interferer is:

$$R_e = \Delta_0 \frac{A_1}{A_2} \left[\left(\frac{1}{A_1} + \frac{1}{A_2} \right) \sin(5\pi f_{int}) \cos(\phi_{int}) + \left(\frac{1}{A_1} - \frac{1}{A_2} \right) \cos(5\pi f_{int}) \sin(\phi_{int}) \right] \quad (19)$$

where Δ_0 is the amplitude of the CWI and A_1 and A_2 those of the two half-cycle peaks, and f_{int} is the frequency of the interferer.

The cdf of R_e is found to be [7]

$$F_{R_e}(r_e) = P\{R_e \leq r_e\} = \frac{1}{2\pi} \left[\pi + 2 \arcsin \left(\frac{A_2}{\Delta_0 A_1 A} r_e \right) \right] \quad (20)$$

for $r_e \in \left(-\frac{\Delta_0 A_1 A}{A_2}, \frac{\Delta_0 A_1 A}{A_2} \right)$, and that

$$F_{R_e}(r_e) = \begin{cases} 0 & \text{for } r_e \leq -\frac{\Delta_0 A_1 A}{A_2} \\ 1 & \text{for } r_e \geq +\frac{\Delta_0 A_1 A}{A_2} \end{cases} \quad (21)$$

By differentiating (20) and (21) with respect to r_e , the pdf of $f_{R_e}(r_e)$ may easily be found. Having obtained the pdf and cdf of HCPR, the pdf and cdf of the measured ECD errors may now be determined by using the known curves which convert HCPRs into ECDs [4,5]. The measured ECD error represents the time difference between the zero-crossing used for phase-tracking and the corresponding point calculated from HCPR. Clearly, incorrect cycle-selection will occur if the magnitude of measured ECD error exceeds 5 μ s.

5 Cycle-selection: multiple interferers

In the presence of multiple interferers, the relationship between measured ECDs and HCPRs remains unchanged, so we will concentrate on errors of HCPR measurements. The measured HCPR may be expressed as

$$Ratio = \frac{A_1 + \Delta_1}{A_2 + \Delta_2} \quad (22)$$

where Δ_1, Δ_2 are the instantaneous values of the sum of the K interferers at the instants of the two half-cycle peaks. Thus

$$\Delta_1 = \sum_{k=1}^K \Delta_{0k} \sin(+2\pi f_k 2.5 + \phi_k) \quad (23)$$

$$\Delta_2 = \sum_{k=1}^K \Delta_{0k} \sin(-2\pi f_k 2.5 + \phi_k) \quad (24)$$

where Δ_{0k} and f_k denote the amplitude and frequency of the k -th CWI.

In practice, $\Delta_1 \ll A_1, \Delta_2 \ll A_2$. Using these constraints, it is shown in [7] that the HCPR measurement error is

$$R_e = \sum_{k=1}^K \Delta_{0k} \frac{A_1}{A_2} \left[\left(\frac{1}{A_1} + \frac{1}{A_2} \right) \sin(5\pi f_k) \cos(\phi_k) + \left(\frac{1}{A_1} - \frac{1}{A_2} \right) \cos(5\pi f_k) \sin(\phi_k) \right] \quad (25)$$

Comparing the above with (19), it is seen that the total HCPR error equals the sum of the errors due to the individual interferers:

$$R_e = \sum_{k=1}^K R_{k_e} \quad (26)$$

Thus, the techniques developed in Section 3 for calculating phase-measurement errors may also be used to calculate the HCPR errors. Interested readers may find details of the formulae in [6,7].

5.1 Two interferers

The error statistics of ECD measurements in the presence of two CWIs are now calculated. By convention, we assume that the phase-measurement point is the third positive-going zero-crossing of the Loran-C pulse. Fig.4 shows the pdf of the ECD error. It is seen that, in contrast to phase-tracking, cycle-selection is more sensitive to CWI close to 50 kHz than close to 100 kHz.

5.2 Many interferers

As with phase-measurement errors, given that the total HCPR error is equal to the sum of the errors due to the individual interferers, its pdf can be approximated by a Gaussian distribution. Further, it can be shown [7] that the mean of R_e equals 0 and that the variance of the HCPR is

$$\sigma_{R_e}^2 = var(R_e) = \sum_{k=1}^K \frac{1}{2} \left(\Delta_{0k} \frac{A_1}{A_2} A \right)^2 \quad (27)$$

As before, the ECD errors may be obtained directly from these HCPR errors [4,6,7].

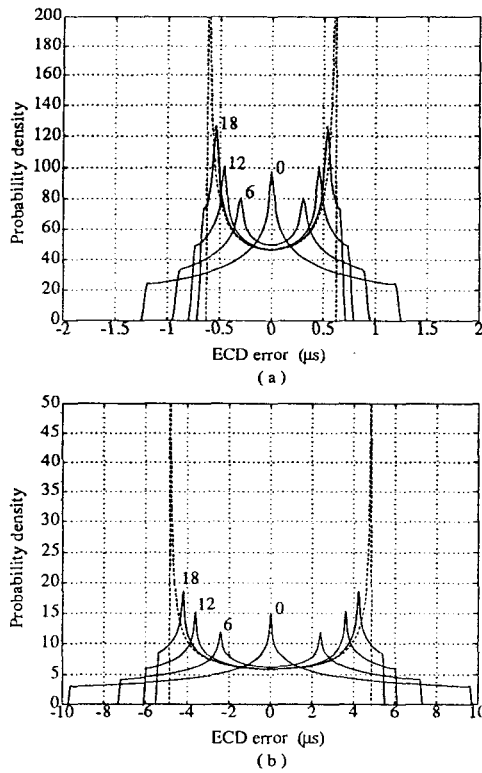


Figure 4: Probability density of ECD error due to two CWIs. SIR of stronger = 30 dB. CWI frequencies: (a) close to 100 kHz, (b) close to 50 kHz. Other details as in Fig. 3 caption.

6 The influence of receiver signal processing

The three principal signal-processing operations carried out by a Loran-C receiver are phase-decoding, integration in the phase-locked loops, and front-end filtering. Although such operations form part of both the phase-tracking and the cycle-selection functions, the cycle-selection loops normally have much narrower bandwidths and much longer integration times than the phase-tracking ones.

The effects of these processing operations on receiver performance in the presence of a single CWI was studied in [4]. There it was shown that the attenuation of interference is strongly frequency-dependent. In particular, synchronous, near-synchronous and asynchronous interferers are all attenuated by phase-decoding and by integration over a period equal to twice the Group Repetition Interval (2GRI). Only asynchronous interference is further attenuated by integration over longer periods.

The attenuation of the amplitude of interference by

front-end filtering affords equal protection to the phase-tracking and cycle-selection operations. The distortion of the Loran-C pulse shape which it causes, however, leads to a much greater deterioration of cycle-selection performance than of phase-tracking. This is because phase-tracking is sensitive only to the amplitude of the envelope of the Loran-C pulse, while cycle-selection is additionally affected by changes in the shape of the envelope, which modify the HCPR.

6.1 Phase-decoding and integration

In the case of a single CW interferer, phase-decoding and integration both attenuate interference without affecting the Loran-C pulse [4,5]. This remains true in the presence of multiple interferers. The attenuated amplitudes of the individual interferers as a result of phase-decoding and integration may be determined and used to calculate the error statistics of phase-tracking and cycle-selection.

As was shown in [7], CWI attenuation may be obtained by evaluating the effects of phase-decoding and integration on the Loran-C signal and the CWI independently. The total interference consisting of K interferers is expressed as

$$x_{int}(t) = \sum_{k=1}^{(t)} x_k(t) \quad (28)$$

where $x_k(t)$ is the k -th CWI.

It is also shown in [7] that this total interference is attenuated by phase-decoding and integration to

$$y_2(t) = \frac{1}{16N} \sum_{n=1}^N \left[\sum_{m=1}^{16} [x_{int}(t) * \delta(t + t_m + t_n) pc(m)] \right] \quad (29)$$

where t_n and t_m are the epochs at which the n -th 2GRI and the m -th pulse within that 2GRI start. Further, it can be shown that the attenuated CWI equals the sum of the K attenuated individual CWIs:

$$y_2(t) = \sum_{k=1}^K y_{2k}(t) \quad (30)$$

where $y_{2k}(t)$ is the attenuated k -th CWI.

The significance of this relationship is that it allows us to use the results established for a single interferer in [4,5] to calculate each attenuated CWI and then employ their sum as the total interfering term. The methods described in Sections 2-5 may then be used to evaluate the phase-tracking and cycle-selection performance statistically.

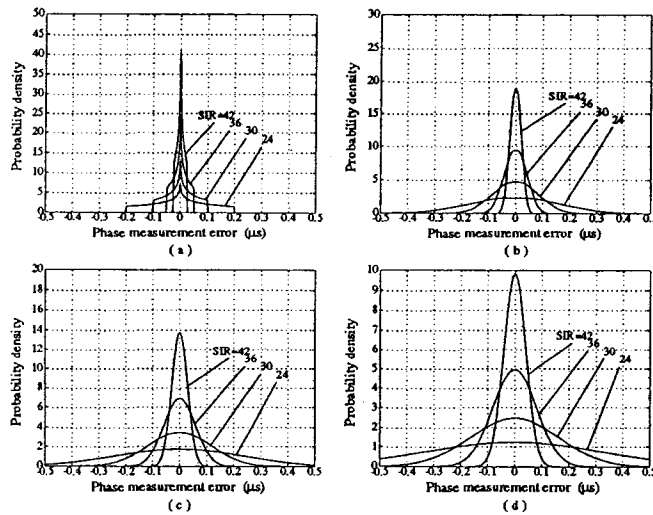


Figure 5: Probability density of phase measurement error due to CWIs of equal amplitude. A 5th-order Butterworth bandpass filter is used: centre frequency = 100 kHz, bandwidth = 20 kHz. Sampling point = 65 μ s. The number of CWI: (a)=2, (b)=5, (c)=10, (d)=20.

6.2 Front-end filtering

Since front-end filtering is a linear operation, its resultant is simply the sum of the filtered Loran-C and interfering signals. Again, the methods of Sections 2-5 may be used to evaluate receiver performance by employing the SIR and HCPR values of the filtered signals.

7 Results

We present sample results for various numbers of CW interferers of equal strengths to illustrate the application of this statistical analysis. Figs. 5 and 6 show the probability density of phase-measurement and cycle-selection error for various SIR values.

The standard 5th-order Butterworth bandpass filter, adopted by the North-West European Loran-C Technical Working Group for predicting the coverage of their proposed Loran-C systems, was used to simulate the effects of front-end filtering. The bandwidth of the filter is 20 kHz and its centre frequency 100 kHz. The sampling point is the nearest zero-crossing to 65 μ s following the start of Loran-C pulse. The SIR values indicated take into account the gains provided by signal processing operations; the corresponding values at the receiver input may easily be calculated as shown in [4,5].

It is seen that the error statistics of both the phase-tracking and cycle-selection operations quickly become

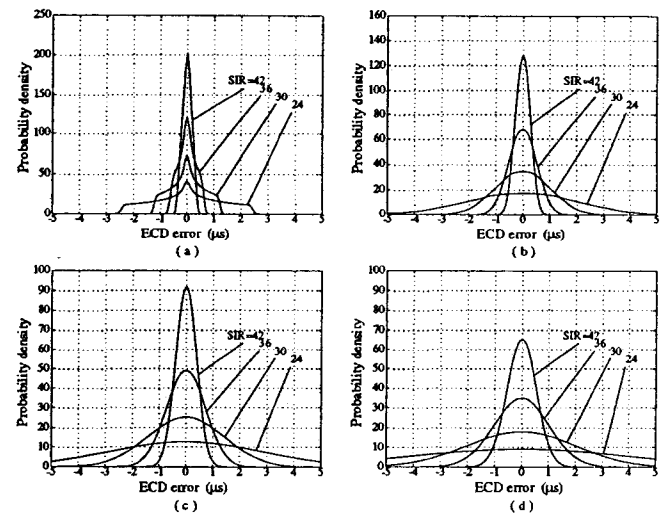


Figure 6: Probability density of ECD error due to CWIs of equal amplitude. Other details as in caption Fig. 5.

Gaussian-like, for more than a small number of CWIs. Thus both kinds of error may be quantified simply by their variances, as given in (18) and (27).

8 Comparison between phase-tracking and cycle-selection

For a statistical comparison of the relative sensitivities to CWI of phase-tracking and cycle-selection, the probabilities of their error magnitudes being less than certain limits are calculated [6]. For a single interferer, the same conclusion as previously [4,5] may be drawn. When the number of interferers increases, however, cycle-selection tends to become progressively more sensitive to interference of any frequency, compared to phase-tracking. The reason is that, although both probability density functions have long tails, cycle-selection is required to be more reliable, given the more serious consequences of failure. Thus greater regard must be paid to these low probabilities in the tails of the distributions.

9 Conclusions

For the first time, the effects of large numbers of interferers have been modelled statistically, using the assumption that their phases are uniformly distributed. The performance of both phase-tracking and cycle-selection has been quantified in terms of the probabilities that the receiver will produce results which lie within their respective error limits. Characteristic functions of the errors of the phase-measurement and HCPR measurements have been employed as a practi-

cal vehicle for calculating such probabilities.

The methods and results of the analysis have been further developed for certain situations which are typical in practice. In the case of a single dominant CWI, there is no significant difference between the statistical results obtained here and the results of the deterministic method developed in [4,5,6]; in this specific case the deterministic method may be preferred because of its simplicity. Where a large number of CWIs of comparable strength are received, however, the error statistics may be simplified to just the mean and variance of the phase-measurement or ECD error, as appropriate. If there are a small number of dominant CWIs, either method will give an approximate result, and the statistical approach will also yield an accurate solution.

The paper has compared the relative sensitivities of phase-tracking and cycle-selection to interference. It has shown that the number of CWIs is an important factor which affects result of the comparison, in addition to those already established in [4,5]: the characteristics of the front-end filters, the synchronicity of the interferers, and the integration time. In the presence of multiple CWIs, substantial phase-measurement and ECD errors may occur, albeit with low probabilities. Cycle-selection is the more sensitive to large numbers of CWIs since the probability of incorrect cycle-selection must be maintained at a lower level than that of excessive phase-tracking errors in view of its more serious consequences.

10 References

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Dr. David Last is a Reader in the University of Wales. He was awarded the degree of B.Sc(Eng). by the University of Bristol, England in 1961 and the degree of Ph.D. by the University of Sheffield, England in 1966. Dr. Last is a Fellow and Council Member of the Royal Institute of Navigation, a Fellow of the Institution of Electrical Engineers, and a Chartered Engineer. He has published many papers on radio-navigation systems, especially on applications of the Decca Navigator System and Loran-C. He acts as a Consultant on radio navigation and communications to companies and government departments. He is an instrument-rated pilot and aeronautical user of Loran-C.

Dr. Yi Bian graduated from Department of Precision Instrumentation of Shanghai Jiao Tong University, P.R. China in 1985, with the highest honours of the year. He completed his M.Sc. in 1987 and continued work on inertial navigation systems as both PhD candidate and research assistant until 1990. Thereafter, in just two years, he completed a PhD in School of Electronic Engineering and Computer Systems of the University of Wales, Bangor, UK, working on signal processing techniques for Loran-C radio navigation receivers. Since 1 October 1992 he has been employed as a Post-doctoral Research Fellow by the University of Wales. His current research interests include signal processing techniques and their applications to communications systems, in particular radio navigation systems and optical telecommunications systems.

CALCULATION OF ECD VARIATIONS OVER INHOMOGENEOUS TERRAIN USING MILLINGTON'S METHOD

David Last, Mark Searle & James McCulloch

School of Electronic Engineering & Computer Systems
University of Wales, Bangor, Gwynedd LL57 1UT, United Kingdom
(e-mail: jdl@sees.bangor.ac.uk)

ABSTRACT

The phenomenon of Envelope-to-Cycle Difference (ECD), which can limit Loran-C coverage, is considered. The accepted practice for determining ECD uses Sherman's semi-empirical curve which shows the rate of change of ECD with range for various values of ground conductivity. Recently Peterson, using new ECD measurements, has produced a curve similar in form to Sherman's, but with significant quantitative differences. These discrepancies highlight the problem of generalising curves of ECD change from limited empirical data.

A new, more scientifically rigorous, method of calculating ECD is introduced. The Loran-C pulse is deconstructed into its constituent frequency components and the delay and attenuation of each component is calculated. The distorted pulse is then re-synthesised and the ECD computed. Results for paths of homogeneous ground conductivity are compared with Sherman's and Peterson's curves. Inhomogeneous paths are treated for the first time, using Millington and Millington-Pressey techniques.

INTRODUCTION

The leading-edge of a transmitted Loran-C pulse is very precisely defined [1]; the antenna current from the start of the pulse to its peak is described by:

$$i(t) = A(t - \tau)^2 \exp\left[\frac{2(t - \tau)}{65}\right] \sin(0.2\pi t + PC) \quad (1)$$

where A is related to the peak antenna current, t is the time (μs) and PC the phase-code.

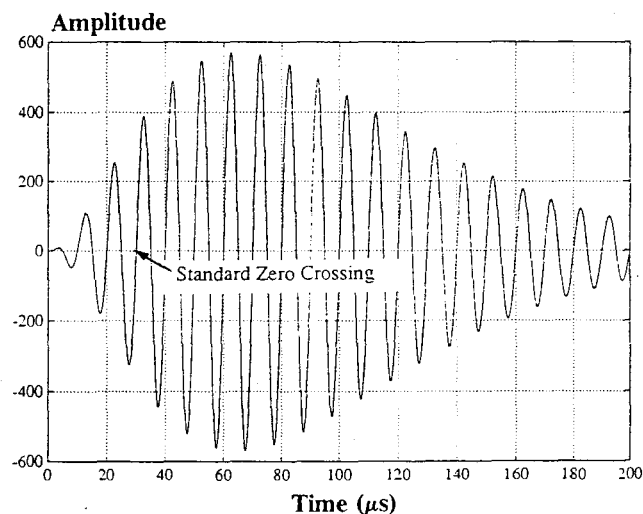
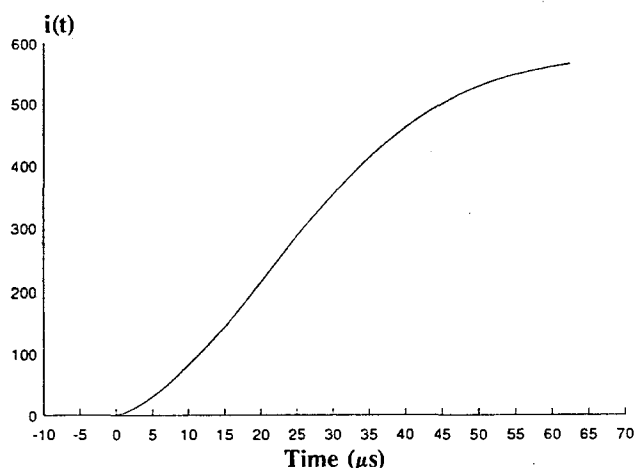
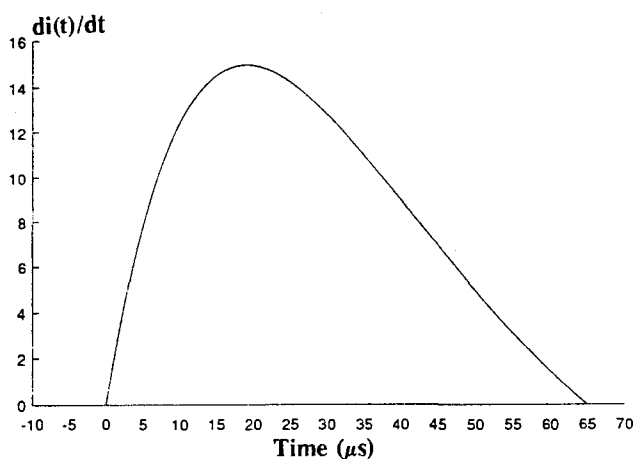


Fig. 1 Ideal Loran-C pulse

The term τ is the Envelope-to-Cycle Difference, or ECD, the most mysterious and least understood of the major parameters of the Loran-C system. Receivers determine the time-of-arrival (TOA) of pulses (Fig. 1) by tracking a specific zero-crossing of the signal. Let us assume that this is the Standard Zero Crossing (SZC): the third positive-going one, 30 μs after the start of the pulse. To locate this specific zero-crossing, the receiver uses the precisely-defined leading edge of the envelope (Fig. 2a), the slope of which changes continuously with time (Fig. 2b). It searches for the point with the correct slope: the 'Envelope Tracking (or 'Tag') Point' (avoiding the much earlier point with the same slope). The ECD is any discrepancy between the



(a)



(b)

Fig. 2 (a) Leading edge of envelope of ideal Loran-C pulse, and (b) slope of envelope

Envelope Tracking Point and the Standard Zero Crossing.

Ideally, the ECD is zero and the two points correspond precisely. However, the receiver can still distinguish the correct zero crossing from the adjacent positive-going ones, 10 μ s earlier and later, provided the ECD lies between -5 μ s and +5 μ s. Greater ECD values may cause TOA errors, in integral multiples of 10 μ s.

Receivers employ various techniques to measure the slope of the envelope leading edge. Since the

envelope is a line joining the peaks of the half cycles of the waveform, its slope is normally determined by measuring the amplitudes of the two half cycles which straddle the zero-crossing. The receiver measures the half-cycle peak ratio (HCPR) of pairs of adjacent peaks, choosing the pair whose HCPR is closest to the correct value.

Several factors cause non-zero ECD values to be measured. Atmospheric noise and non-synchronous carrier-wave interference (CWI) produce random ECD variations which may be reduced by averaging over time [2,3]. Transmitter mis-alignment or synchronous CWI can give systematic ECD errors which are minimised by transmitter adjustment and receiver front-end filtering, respectively. All these sources of apparent ECD change make measuring the real ECD exceptionally difficult, especially near the edge of coverage.

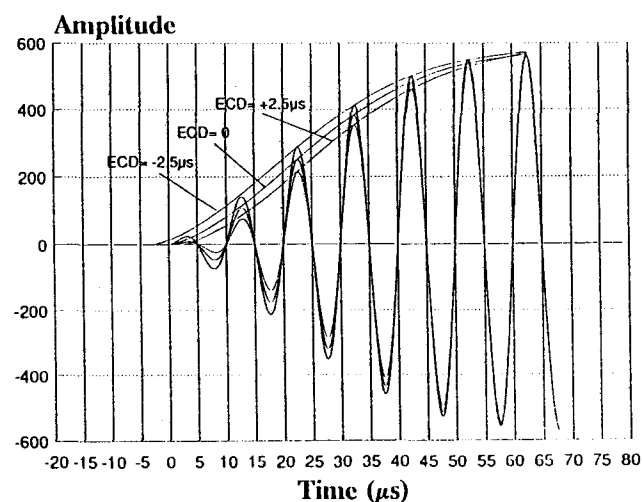


Fig. 3 Loran-C pulses - various ECD values

The principal remaining, irreducible, source of ECD is the propagation of the signal. As a Loran-C signal travels over sea or land the cycles of its carrier appear to lag its envelope progressively until an ECD change of some 2.5 μ s has been accumulated by the edge of the service area. This ECD change is in the negative sense (Fig. 3). Customarily transmitters radiate an ECD of +2.5 μ s (in the near far-field) so as

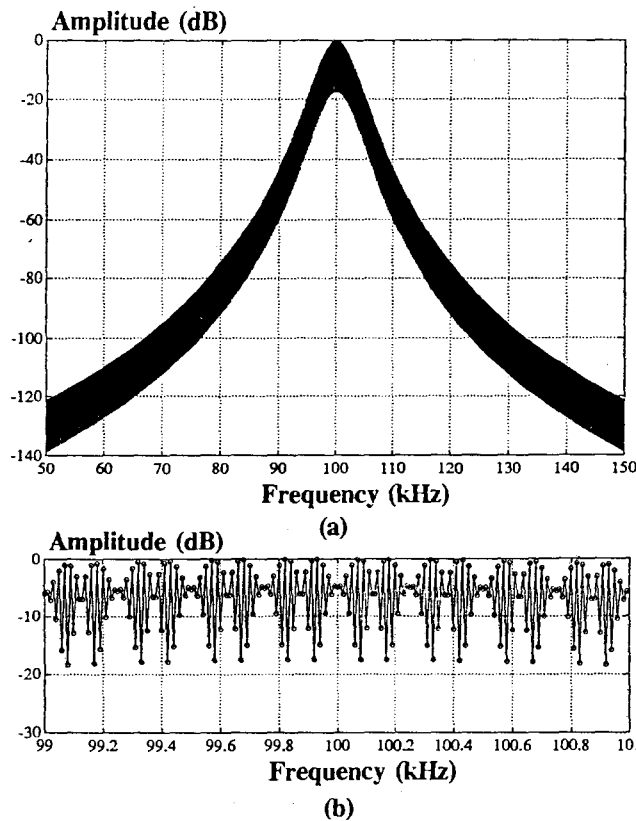


Fig. 4 Amplitudes of Loran-C spectral lines, (a) 50-150 kHz, (b) expanded view

to provide a nearly-ideal zero ECD at the edge of coverage to assist receivers suffering from noise and interference.

The change of ECD as the signals propagate is a consequence of the broad line spectrum of the pulsed Loran-C transmission, which extends from below 80 kHz to above 120 kHz (Fig. 4). Since both the attenuation and the phase delay of signals vary with frequency across this band, the phase velocity (that of the Loran-C cycles) of the received pulse is different from the group velocity of the envelope. Moreover, because the frequency-dependence of these parameters is slightly non-linear, the envelope of the pulse becomes a little distorted, again changing the HCPR and ECD. The degree of ECD shift is a function of range from the transmitter and the lower the conductivity of the path, the more rapidly the ECD falls.

These factors have long been known to those

with a deep understanding of Loran-C matters. A US Coast Guard (USCG) paper in 1961 [4] identified the mechanism of ECD change and estimated its magnitude over a 1000 nm sea-water path as 3 μ s. A measurement programme in 1977 and 1978 provided abundant experimental confirmation of the phenomenon. Jones [5] claimed that regression analysis of the data showed that ECD values fitted (within $\pm 1\mu$ s) the formula

$$\text{ECD} = 2.5 - 0.0025D \text{ (}\mu\text{s)}$$

where D is the range in nautical miles. The '2.5 μ s' results from the quadrature relationship between the signal phase in the near far-field and the zero-ECD antenna current.

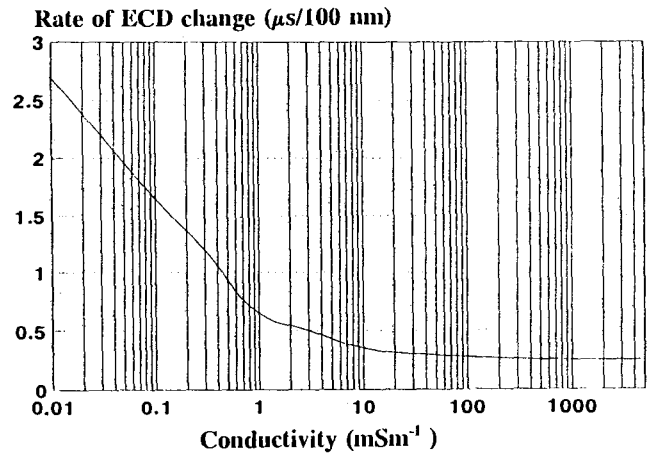


Fig. 5 Sherman's curve, relating rate of change of ECD to path conductivity

These trials also revealed substantial scattering of measured values, especially in the mountains of the western US. Dean [6] further analysed the data there and identified terrain-dependent ECD spreads of up to 4 μ s and extremely rapid localised changes of value. ECDs which 'sharply decreased by passage over rugged terrain appeared frequently to "recover" in propagating over a subsequent valley'. The Department of Transportation adopted Jones' regression ECD-range relationship, substituting the value of

2.5 μ s at 1000 nm over seawater for the of the earlier 3 μ s figure [7].

Sherman analysed experimental data to produce Fig. 5 [8]. Campbell & Wenzel used his results to explain ECD-related phenomena [9] and they also formed the basis of the ECD-estimating technique developed by Last *et al* for planning the new North-West European Loran-C system [10].

However, more recent airborne test results analysed by Peterson & Dewalt [11] have not agreed with Sherman's curve. These discrepancies have led us to re-examine the change of ECD with range, especially the influence of ground conductivity. Several questions concern us: Sherman and Peterson were obliged to extract ECD-range rates from signals arriving over paths of inhomogeneous conductivity; neither analysis allowed for possible non-linearity of the ECD-range relationship; the effects of topography, and ECD disturbances at conductivity boundaries, were ignored; and there is no demonstrated justification for applying the results to paths along which the conductivity value changes. These shortcomings result from the inherent difficulty of deriving such curves from data taken over inhomogeneous paths of irregular topography.

A NOVEL APPROACH TO ECD ESTIMATION

In recent years it has become standard practice to estimate the strength of Loran-C signals by computer modelling, employing curves of attenuation with range from the transmitter, as a function of ground conductivity values taken from conductivity maps. Paths of inhomogeneous conductivity are broken into sections of uniform conductivity and Millington's method employed to calculate the total attenuation. This relatively simple technique, recommended by the CCIR [12,13], has been implemented in computer programs which map the Loran field strength point-by-point across large areas.

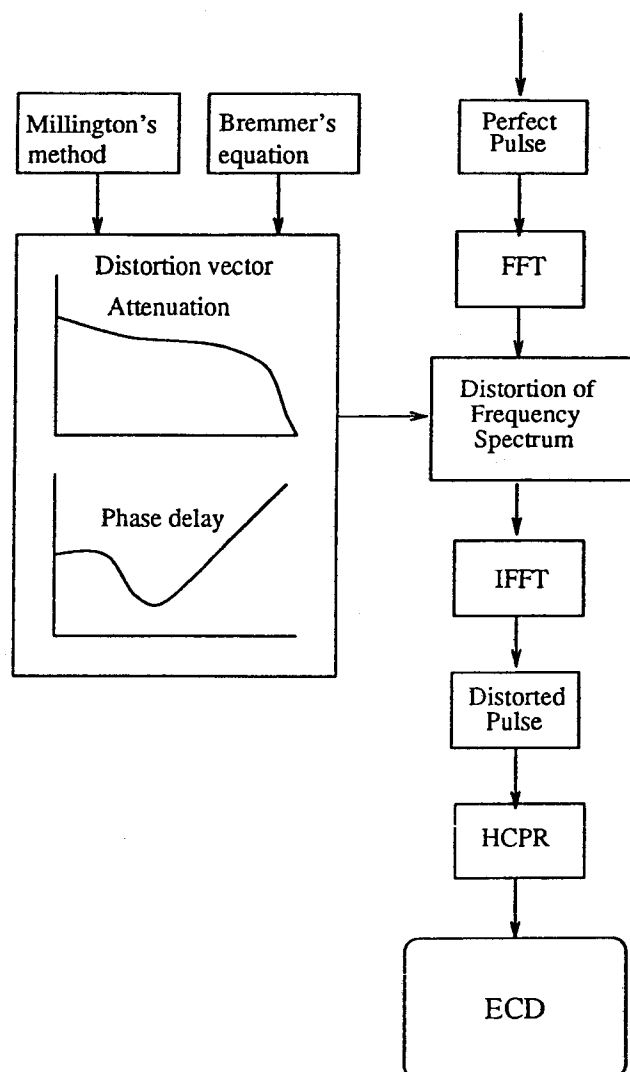


Fig. 6 Method of estimating ECD change due to propagation

More recently a similar approach has been developed for mapping the ground conductivity-dependent phase delay known in Loran-speak as the 'Additional Secondary Factor (ASF)'. The computer uses the ground conductivity map and a set of delay-range curves for various conductivity values. Paths of inhomogeneous conductivity are analysed by applying Millington's method to the delay values: this is the 'Millington-Presssey' technique [14].

Since the change of ECD with range is due to the effects of both attenuation and phase delay, it should be possible to map it by using these

two techniques (Fig. 6). However, since ECD change is due to the *variations* of these factors with frequency, it will be necessary to derive sets of curves which cover the band encompassed by the Loran-C signal. We can then take each frequency component of the transmitted signal, estimate the attenuation and phase delay it experiences in travelling to the receiver (the 'distortion vector'), and reassemble the distorted pulse from the individual components. The ECD of the received pulses may then be calculated from the appropriate half-cycle peak ratio.

PATHS OF UNIFORM CONDUCTIVITY

It is neither feasible, nor necessary, to derive attenuation and phase curves for each of the large number of individual components of the Loran-C signal (spaced at 5-12.5 Hz). These propagation parameters change slowly with frequency so one may interpolate between values calculated at frequency intervals. The spectrum of the Loran-C pulse is analysed at 1 kHz intervals over the range 50-150 kHz; curves of attenuation and phase delay have been computed at 5 kHz intervals between 80 and 120 kHz (where the Loran-C energy is concentrated) and at 10 kHz intervals elsewhere.

The attenuation and phase delay curves are derived from Bremmer's equation [15]:

$$F_r = \left[2\pi\alpha^{\frac{2}{3}} (k_1 a)^{\frac{1}{3}} \left(\frac{d}{a} \right)^{\frac{1}{2}} \sum_{s=0}^{\infty} \frac{f_s(h_1) f_s(h_2)}{\left[2\tau_s - \frac{1}{\delta_e^2} \right]} \right. \\ \left. \times \exp \left\{ i \left[(k_1 a)^{\frac{1}{3}} \tau_s \alpha^{\frac{2}{3}} \frac{d}{a} + \frac{\alpha d}{2a} + \frac{\pi}{4} \right] \right\} \right.$$

This somewhat complex equation, a sum of rainbow terms, has been solved on a Sun Workstation using the *Mathematica* language [16]. The magnitude of the signal may be computed

from:

$$H_c \propto \frac{|F_r|}{d}$$

where d is distance, and its phase from:

$$\phi_c = \arg F_r \text{ (radians).}$$

Thus we generate families of curves at each frequency interval for each of the CCIR-specified standard values of ground conductivity used in our conductivity maps. For maximum computational speed, an array of results is stored and interpolations calculated at the 1 kHz intervals. As an example, the curves which describe propagation over land of $3 \times 10^{-3} \text{ Sm}^{-1}$ are shown in Fig. 7; the individual lines represent the values at the 5 and 10 kHz frequency intervals specified above.

A standard, zero-ECD, Loran-C pulse has been generated from equation (1) using the Matlab package [17], on a Sun Workstation. It has been analysed into its frequency-domain components by the Matlab Fast Fourier Transform (FFT) and is reassembled after propagation by the corresponding Inverse FFT.

This analysis has been applied to sea-water paths and to land paths of conductivities down to $1 \times 10^{-3} \text{ Sm}^{-1}$. Fig. 8 shows the build-up of ECD change with range. The curves are not, in fact, linear, as had previously been assumed. However, at ranges in excess of about 600 miles their slopes are sufficiently nearly constant to let us compare the results with Sherman's and Peterson's empirical data (Fig. 9). At high conductivities our curve lies between their two. At low conductivities the agreement with Peterson's results is good, ignoring the bump which he ascribes to insufficient data. Particularly interesting is that, contrary to Sherman's curve, both our calculations and Peterson's observations [11] show a slight fall in

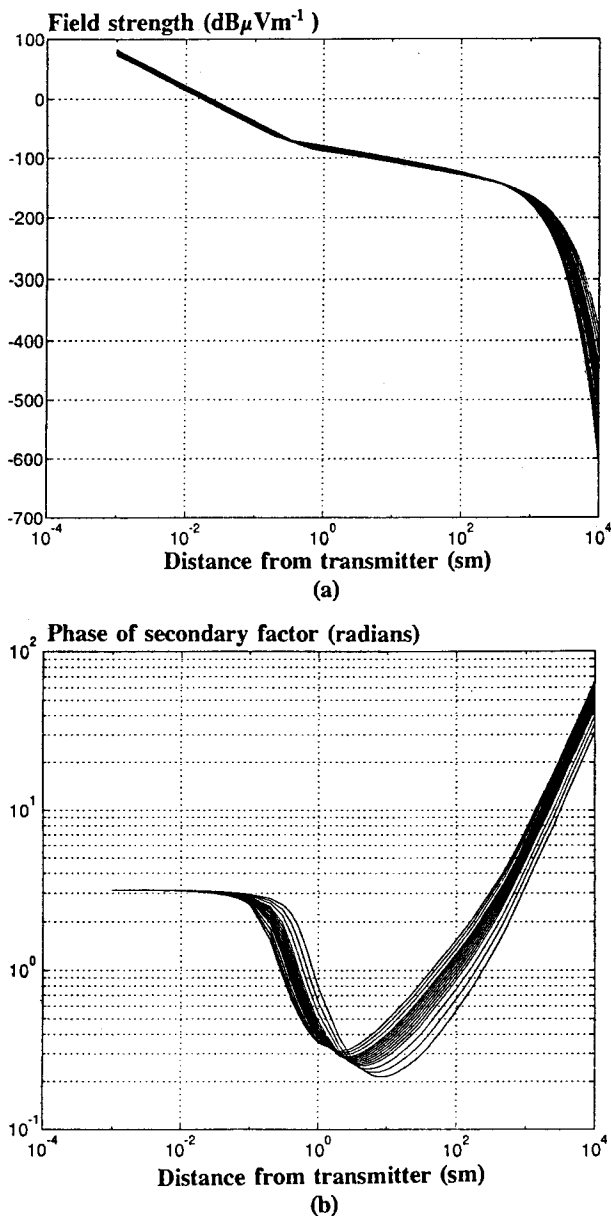


Fig. 7 (a) field strength (1 kW), (b) phase, from 50-150 kHz over land ($3 \times 10^{-3} \text{ Sm}^{-1}$)

the ECD rate with falling conductivity. The minimum rate is reached at about $8 \times 10^{-3} \text{ Sm}^{-1}$. At conductivities below $3 \times 10^{-3} \text{ Sm}^{-1}$ the rate increases steeply.

However, regions of conductivity such low below are relatively uncommon. Thus, for sea-

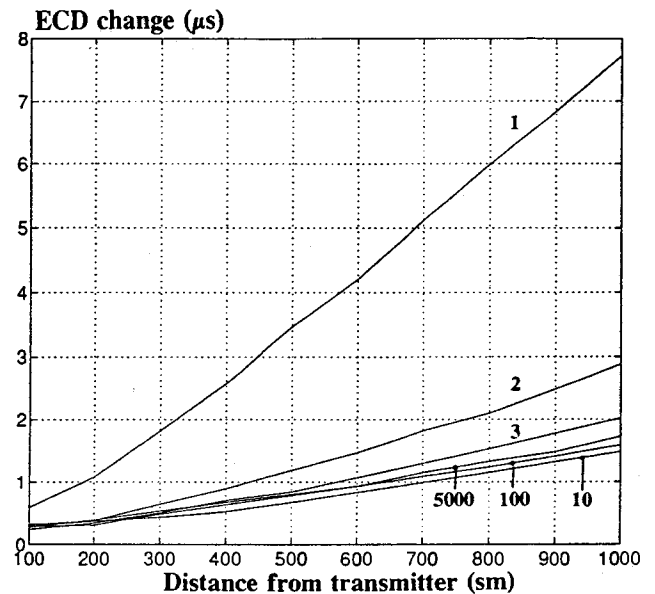


Fig. 8 Build-up of ECD with range (conductivity values in mSm^{-1})

water and most land paths, the ECD rate may be considered to about $0.15 \mu\text{s}/100 \text{ mile}$. It should be possible to use this rate to estimate ECD values in receivers from knowledge of range and so minimise cycle identification errors due to ECD.

INHOMOGENEOUS PATHS

The analytical method we have adopted may also be applied to paths along which the conductivity changes. We break the path up into sections, each of uniform conductivity. The total attenuation is calculated using Millington's method, the total phase delay using the Millington-Pressey technique. In both methods the incremental attenuation (or phase change) of each section is computed, then the increments are totalled along the path. This is done first from the transmitter to the receiver, then from receiver to transmitter, and the two results averaged.

Field strength and phase delay are both known to change sharply close to boundaries between regions of substantially different conductivity. Most striking are 'coastal recovery effects'; for

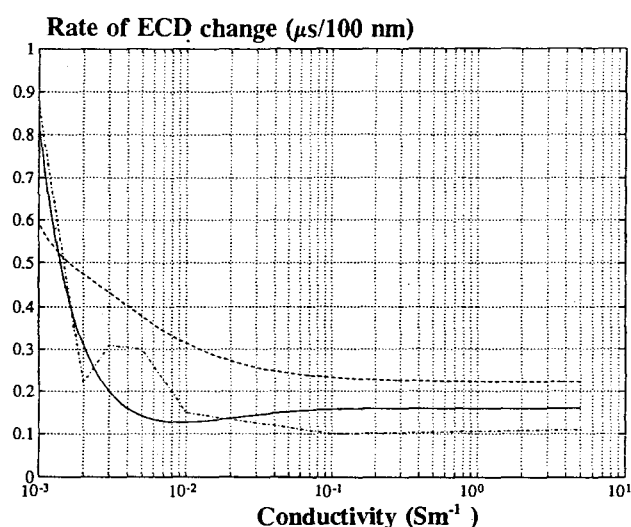


Fig. 9 Comparison of computed ECD rate (solid) with Sherman (dashed) and Peterson (chained)

instance, the phase delay accumulated over land of low conductivity falls sharply after the signal has passed out to sea over a coastline.

We have applied the analytical technique to a path consisting of 500 miles of land of a very low conductivity, $1 \times 10^{-3} \text{ Sm}^{-1}$, followed by 500 miles of seawater. The result is shown in Fig. 10 which illustrates the change of ECD as the signal propagates. Unexpectedly, very little coastal recovery effect is to be seen. Analysis of the reason for this is under way, but the situation is far from straightforward: ECD is due to subtle differences between the group and phase velocities of these complex signals due to non-linearly frequency-dependent, propagation factors. The behaviour of ECD at coast-lines and other conductivity boundaries clearly deserves further detailed study.

CONCLUSIONS

Empirical methods for describing the ECD change of Loran-C signals as they propagate may now be replaced by more scientifically-rigorous analytical techniques. These allow the

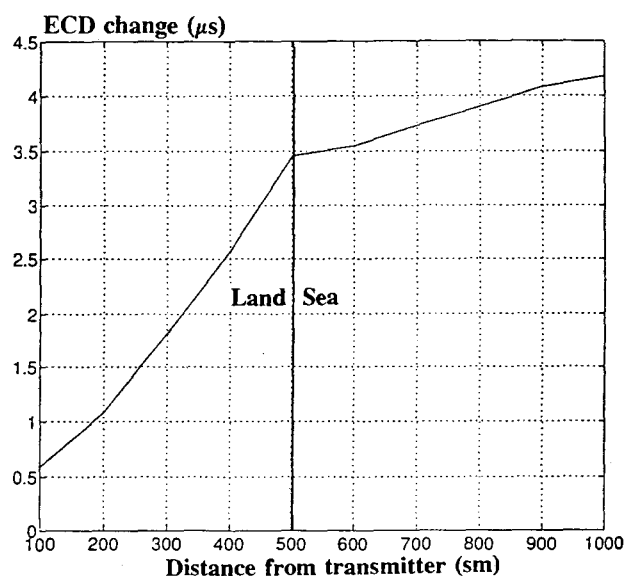


Fig. 10 Magnitude of ECD changes over inhomogeneous (land/sea) path

ECD to be computed from knowledge of the conductivity along the propagation path. The values which result agree well with the most recent measurements. Sherman's simplifying assumption, that the rate of increase of ECD with distance is independent of range, is shown not to be strictly valid. The analysis, first applied to paths of uniform conductivity, has been extended to more complex paths along which the ground conductivity changes, by applying Millington's method to the attenuation of the components and the Millington-Pressey techniques to their phase delay.

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BIOGRAPHIES

Dr. David Last - see other papers in this Symposium for Biography

Dr. Mark Searle was awarded the degrees of BSc, MSc and PhD by the University of Manchester, England in 1985, 1986 and 1989, respectively. From 1989-1992 he was a Postdoctoral Research Fellow working on Loran-C activities, especially coverage and ASF mapping techniques, at the University of Wales, Bangor. He is currently undertaking research in optical communications.

James McCulloch was awarded the degree of BEng by the University of Wales, Bangor in 1993. He is currently working for the United Kingdom Defence Research Agency.

LORAN-C UPGRADING AND RE-STRUCTURING CANADIAN EAST COAST

John J. Butler
Regional Manager, Telecommunications & Electronics

Edward B. Goudie
Co-ordinator of Chain Operations

CANADIAN COAST GUARD - NEWFOUNDLAND REGION

ABSTRACT

This paper describes the activities of the Canadian Coast Guard in upgrading and restructuring the Loran-C facilities on the Canadian East Coast. It addresses the issues surrounding the refurbishment of the Cape Race Loran-C station, the change in plans resulting from the collapse of the Cape Race 1350' antenna, the restoration of interim service using a 320' antenna, and the provision of full Loran-C coverage using an 850' antenna.

It also discusses the development of the *new* Newfoundland East Coast Chain with the construction of a new station at Comfort Cove, Newfoundland, to replace some of the coverage lost with the forthcoming closure of Angissoq, Greenland.

INTRODUCTION

Loran-C Station Cape Race was built by the United States Coast Guard (USCG) in 1963/64 and became operational in 1965 as part of the North Atlantic chain and the U.S. East Coast chain. Chain configuration changes occurred on April 1, 1980, when Cape Race became the Yankee secondary for the new Canadian East Coast chain and in December 1983, when it became the Whiskey secondary for the Labrador Sea chain. Figure 1 shows the coverage originally achieved by the Canadian East Coast and Labrador Sea Chains. As of April 1, 1983, the Canadian Coast Guard (CCG) assumed the total cost of operation and maintenance for the Cape Race Loran-C station, from the USCG.

CAPE RACE REFURBISHMENT

Cape Race transmitted approximately 1 MW of power using the FPN-45 tube-type transmitter into a 1350' antenna. The station was comprised of an operations building and a transmitter building. In 1988, a total review of the station operation and maintenance cost was

undertaken. After much evaluation, it was decided to completely refurbish the station. This would result in a guaranteed service to the user until the year 2015, increased safety to our personnel due to the refurbishment of the antenna, reduced operational and maintenance costs and reduced staffing requirements.

A Treasury Board submission was proposed in March 1990 requesting project approval for the restoration of the equipment and facilities at Cape Race. Funding approval was granted in February 1991.

A working group was established at the onset of the project and frequent meetings have been held throughout the project progression. The group consisted of the Cape Race station manager, the Chain Co-ordinator, staff from our Regional Engineering and Maintenance sections, Marine Navigation Services section and Telecom Headquarters in Ottawa. John Butler, Regional Manager, Telecommunications and Electronics, Newfoundland Region, was the Project Manager. One of the major factors in the success of this project has been the effectiveness of the project team, combined with the continued support from personnel with the USCG, Public Works, the building contractor, the antenna contractors, Megapulse Inc., etc.

The building design for Cape Race is basically a modified version of the station we built in Fox Harbour in 1982 and is sized at 40' x 220'. Modifications to the operations room and diesel generator room have been incorporated. The operations room is larger than conventional standards. The transmitter room and the operations room are sized to allow room for the possibility of future expansion. The air conditioning units are floor-mounted and allow full access for maintenance. The two 250 kW diesel generator units are not prime power; they provide an emergency standby function only.

Cape Race previously transmitted approximately 1 MW of power and provided coverage from Greenland in the north, to the Georges Banks, off the Maine/Nova Scotia coast in

the south, as well as the east and northeast coasts of Newfoundland. We felt that any substantial reduction in output power would negatively effect the Loran-C users in our service area.

With the assistance of our structural consultant, Don Harrison of Ronald H. Harrison and Associates Ltd., and our electrical consultant, Bill DeGeorge of Navigation Systems Specialists, we considered changing the 1350' antenna with 6 top loading elements (TLEs) to a 720' antenna with 12 TLEs. A 56 HCG Solid State Transmitter (SSX) was required with this design to produce the desired coverage.

The purpose of the modifications was to satisfy revised Canadian Standards Association (CSA) standards for wind and ice loading experienced at Cape Race, which the 1350' antenna did not meet. This would increase the level of safety for station staff and reduce the high cost of maintaining the antenna.

The 720' antenna design met all structural standards but provided only fair electrical performance. The structural configuration, required to satisfy heavy ice loading, was the major limiting factor of the design.[1]

Alternative antenna structures were considered. Preliminary electrical analyses were conducted on antenna height combinations between 720' and 860'. It was determined that an 850' antenna with 6 TLEs was the best choice for structural and electrical requirements.[1]

The larger 850' antenna allowed a size reduction of the transmitter from a 56 HCG set to a 32 HCG set. The 850' antenna and the 32 HCG SSX combination is capable of producing 805 kW of output power.[1] Although the output power is reduced, the signal coverage reduction is negligible.

As this is the first Loran-C 850' antenna in the Western Hemisphere, a number of conservative measures were included in the design to provide a margin of safety:

- ¹ The antenna input capacitance reactance was adjusted toward the high end of the transmitter tuning range. This allowed selection and installation of a small coil of up to $+j4\Omega$ in the transmitter output to allow the range of the autotuner to be used more effectively.

- ² A 25' quick change link was placed on each side of the primary insulators at the end of each TLE active section. This allowed shortening or lengthening of the TLEs to produce an antenna input reactance of $+j7\Omega$ and $-j9\Omega$ respectively.[1]

CAPE RACE ANTENNA COLLAPSE

At 2224 Z on February 2, 1993, our original antenna refurbishment plans were drastically changed - the Cape Race Loran-C 1350' antenna collapsed. There was no loss of life; all station staff were off shift at 1930 Z, since the station operated remotely via the ROS equipment from Control Station St. Anthony. Extensive damage to the old transmitter building and equipment resulted; 600 feet of antenna plunged into the old transmitter building. Although the new transmitter building was slightly damaged, no structural damage was incurred. At the time of the incident, there were no adverse weather conditions; winds were approximately 20 km/hr and there was no indication of ice accumulation on the antenna.

Investigation into the antenna collapse was conducted by Don Harrison of Ronald H. Harrison Associates Ltd. The preliminary report indicates that the tension failure of the 4th or 5th insulator in the 490' level assembly on structural guy line #2 induced failure of other insulator elements in the same and other assemblies, initiating collapse of the antenna. Tension failure occurred in three or more insulator assemblies prior to contacting the ground. (See Figure 2) In addition, a number of insulators which broke on impact with the ground exposed discontinuities and voids at the lines of failure.[2]

Mr. Harrison concluded that in the absence of wind and ice loading, it was unlikely that the collapse was initiated by the failure of a structural member or connection. Similarly, the good condition of strand observed in guy assemblies indicated that it was unlikely that failure occurred at one of a number of noted guy strand break points.[2]

The CCG conducts annual tower inspections on all of its Loran-C antennas. The Cape Race tower was inspected in September 1992 with only minor maintenance recommended. This maintenance was carried out immediately by the tower inspection crew.[3]

SERVICE RESTORATION

The CCG considered a number of options to restore the Loran-C service in the most timely manner. These options included the immediate construction of a permanent 400' antenna with an additional 450' to be added during the summer, the erection of the permanent 850' antenna as soon as possible and the erection of a temporary antenna supplied by the USCG with the permanent structure being erected during the scheduled off-air in July/August of 1993. The latter option was chosen and an emergency 700' antenna was borrowed from the USCG and was

returned in August 1993 when the permanent antenna was erected. The height of this antenna was reduced to 320' to meet CSA standards for ice and wind loading. The benefits of this option were availability, lower cost and compatibility with the SSX.

An inductive coil was required to match the short antenna to the SSX. The coil consisted of 25 turns of 3/4" copper spaced 2 1/8" apart (center to center) with a 4' diameter. The coil was rolled on site and then baked with a Class H VPI (vacuum pressure impregnation) polyester resin at Westinghouse Canada in St. John's, Newfoundland. Bakelite spacers were placed between turns, every 90°, to maintain the coil shape. The coil was placed between the antenna and the antenna feedline from the SSX. It was secured in a fiberglass housing for protection against the elements and ice falling from the antenna. A non-conductive material was required for the housing and spacers because of the high voltage of the short antenna in the vicinity of the antenna base.

The installation of the new SSX and Timing and Control Equipment (TCE) was accelerated. In addition, a new Primary Control Monitor Site (PCMS) was established at Red Head, Newfoundland. This site is closer to Cape Race than St. Anthony (the normal control site) and was required to ensure monitoring and control of the reduced signal from Cape Race. Again the USCG came to our assistance and provided us with the equipment for an entire PCMS.

On March 22, 1993, at 1630 Z, Cape Race became operational again, after waiting 6 days due to bad weather before the antenna was completed. Don Meyers of Megapulse Inc., tuned the SSX into the antenna using only 16 HCGs; the full 32 HCGs caused over-voltage problems at the transmitter output. The radiated power from Cape Race was drastically reduced, to approximately 40 kW. The predicted coverage diagram, shown in Figure 3, indicates that a major portion of our service area was served, however, a number of complaints were still received.

The time frame in which the Loran-C service was restored, considering the nature of the work and the environment, was outstanding. It required a substantial effort from Cape Race Station staff, Telecom & Electronics both Regionally and Nationally, Marine Navigation Services, USCG, Megapulse and the antenna contractor. The coordination of all elements of the work was carried out in a professional and efficient manner.

Throughout the entire ordeal, the CCG continued to notify the users as to what was happening. We issued Notships and press releases, and immediately responded to

individual enquiries. Once the temporary antenna was in operation, the most difficult news we had to deliver to the users was that after all the recent events we were still planning to go off-air again for approximately 25 days starting 0830Z July 19, 1993. This off-air time was required to install the new 850' antenna.

The construction and installation of the new antenna completed the Cape Race refurbishment project. Even with the antenna collapse, the project came in within budget. The station was certified during the week of September 13, 1993, and is now fully operational. Many thanks go out to everyone involved with this refurbishment on both sides of the border.

COMFORT COVE LORAN-C STATION

The USCG is planning to cease operation of all Loran-C stations not serving the Continental U.S.A. in December of 1994. Due to failure of the Loran-C Policy Group to achieve an acceptable cost sharing arrangement for the combined operation of the Loran-C station at Angissoq, Greenland, it became apparent that the Labrador Sea Chain, Rate 7930, would cease operation.

A Treasury Board submission was prepared in June 1992, to construct a new station at Comfort Cove, Newfoundland, to replace coverage lost with the forthcoming closure of Angissoq. Approval to proceed with this aspect of the project was received from Treasury Board in July 1992.

At this time the Cape Race portion of the project was scaled down; significant savings were realized as a result of lower than estimated costs for the building and site work and a reduction in the transmitter size. The transmitter size reduction, 56 HCG to 32 HCG, is a consequence of both the newer design and more efficient, 850' antenna. As well, the planned closure of the Angissoq transmitting station reduced the range requirements for the Cape Race signal. The smaller transmitter also permitted the use of smaller diesel generator sets, yielding another saving. And finally, the USCG provided the loan of TCE and ROS equipment which resulted in further savings.

Comfort Cove station will be significantly less expensive to operate and most importantly will, for the area that it will cover, provide an improved service to the mariner. It will not be affected by skywave interference as experienced by the users of the Angissoq baseline. A secondary benefit includes the stimulation of the local economy.

For Comfort Cove this project will involve the construction of a complete Loran-C transmitting station. This includes a 82' x 28' transmitter building, a single 16 HCG solid-state transmitter, a 625' transmitting antenna, two 100 kW diesel generator units and the provision of timing and remote control equipment.

A low-powered, 16 HCG, solid-state transmitter was chosen for Comfort Cove because of the short baseline distances involved and the constraints imposed by geometry/geography.

Originally, the CCG considered a 720' antenna with 12 TLEs for Comfort Cove, which would produce 283 kW of output power.[4] However, due to the reasonable performance of the 320' temporary antenna at Cape Race, shorter antennas were considered. Navigation System Specialists conducted preliminary electrical analyses on antenna height combinations between 320' and 720'. It was determined that a 625' antenna with 6 TLEs was the best choice for electrical/cost performance, transmitting approximately 203 kW output power.[5] This reduced height translates into negligible change in coverage and has the potential to save approximately \$340K.

Comfort Cove will be the master station of the *new* Newfoundland East Coast chain, rate 7270, with secondaries at the two existing stations at Cape Race and Fox Harbour (W & X respectively), shown in Figure 4. This new chain is expected to be operational by early November 1994. The parameters of the new chain are shown in Figure 5.

The Canadian Coast Guard is committed to providing a Loran-C service to the marine industry well into the next century.

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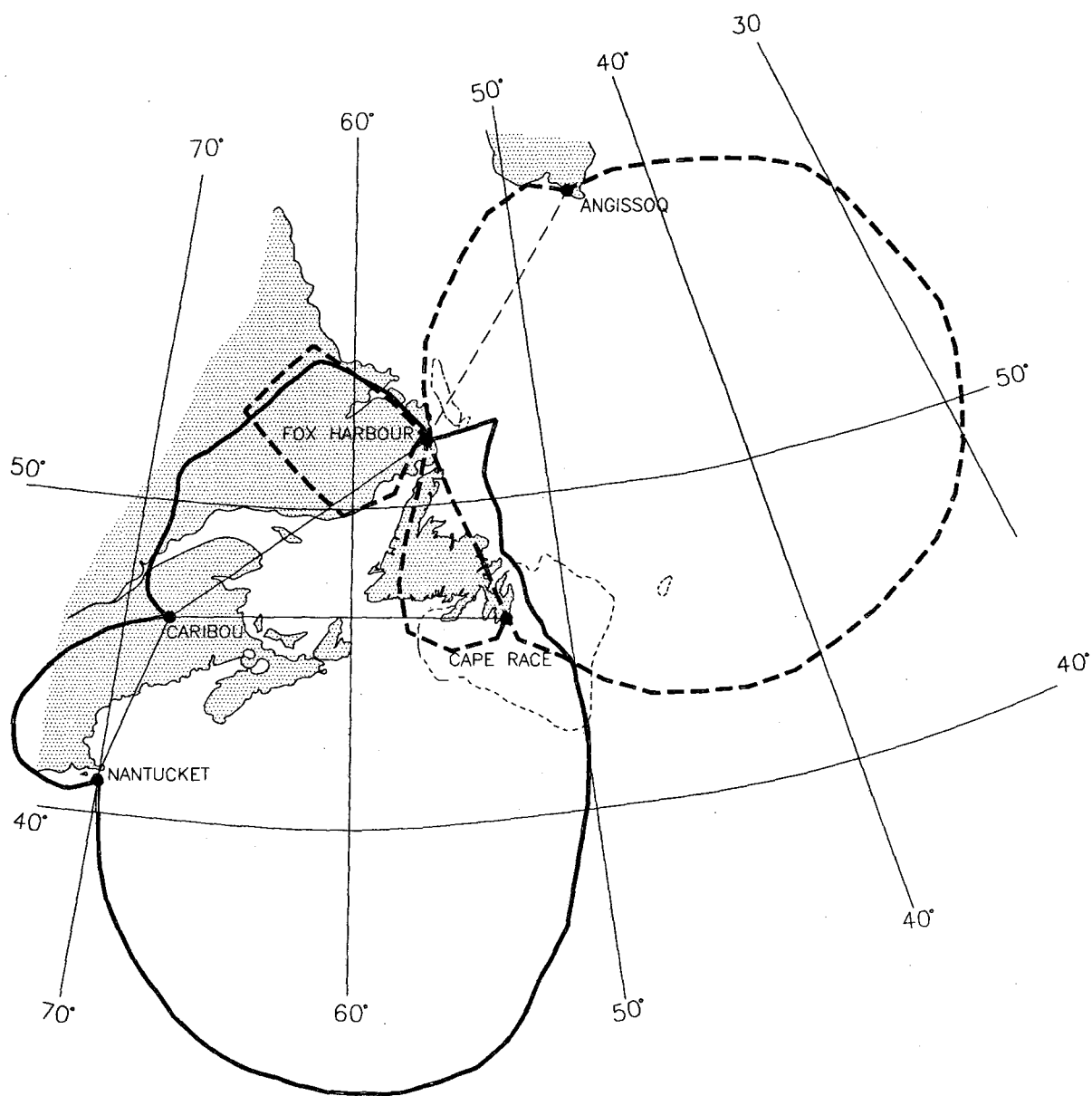
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BIOGRAPHY

John J. Butler received his Bachelor of Engineering in 1979 from Memorial University of Newfoundland. He received the designation of Professional Engineer in 1981 and completed his Masters of Business Administration in 1988. Prior to his employment with the Canadian Coast Guard in 1982, John worked with various communications and hydro electric companies in England, Norway, British Columbia and Newfoundland. In 1985, John was promoted to Regional Superintendent, Engineering Services and effective August 22, 1990, he was promoted to his current position of Regional Manager, Telecommunications and Electronics.

Edward B. Goudie received his high school education in Springdale, Newfoundland, and completed an Electronic Technologist course from the Cabot Technical Institute in St. John's, Newfoundland, in 1965. He commenced employment with Transport Canada after graduation and served in many capacities before taking the position of Coordinator of Chain Operations in 1981, which he currently occupies.



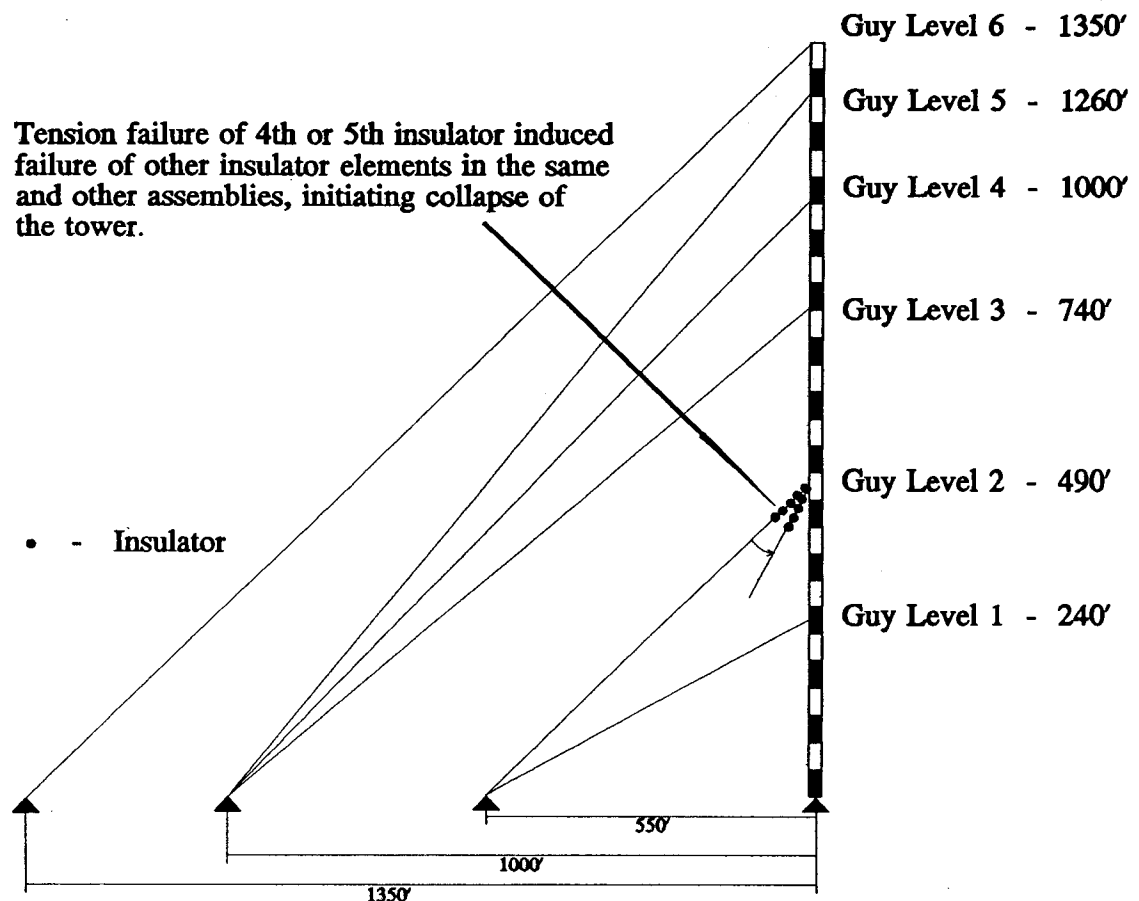
LEGEND:

- INDICATES CANADIAN EAST COAST CHAIN (5930)
- - - INDICATES LABRADOR SEA CHAIN (7930)

ORIGINAL LORAN-C COVERAGE
CANADIAN EAST COAST

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Figure 1



**DEPICTION OF CAPE RACE LORAN-C 1350' TOWER
SHOWING SUSPECT INSULATOR FAILURE**

Figure 2

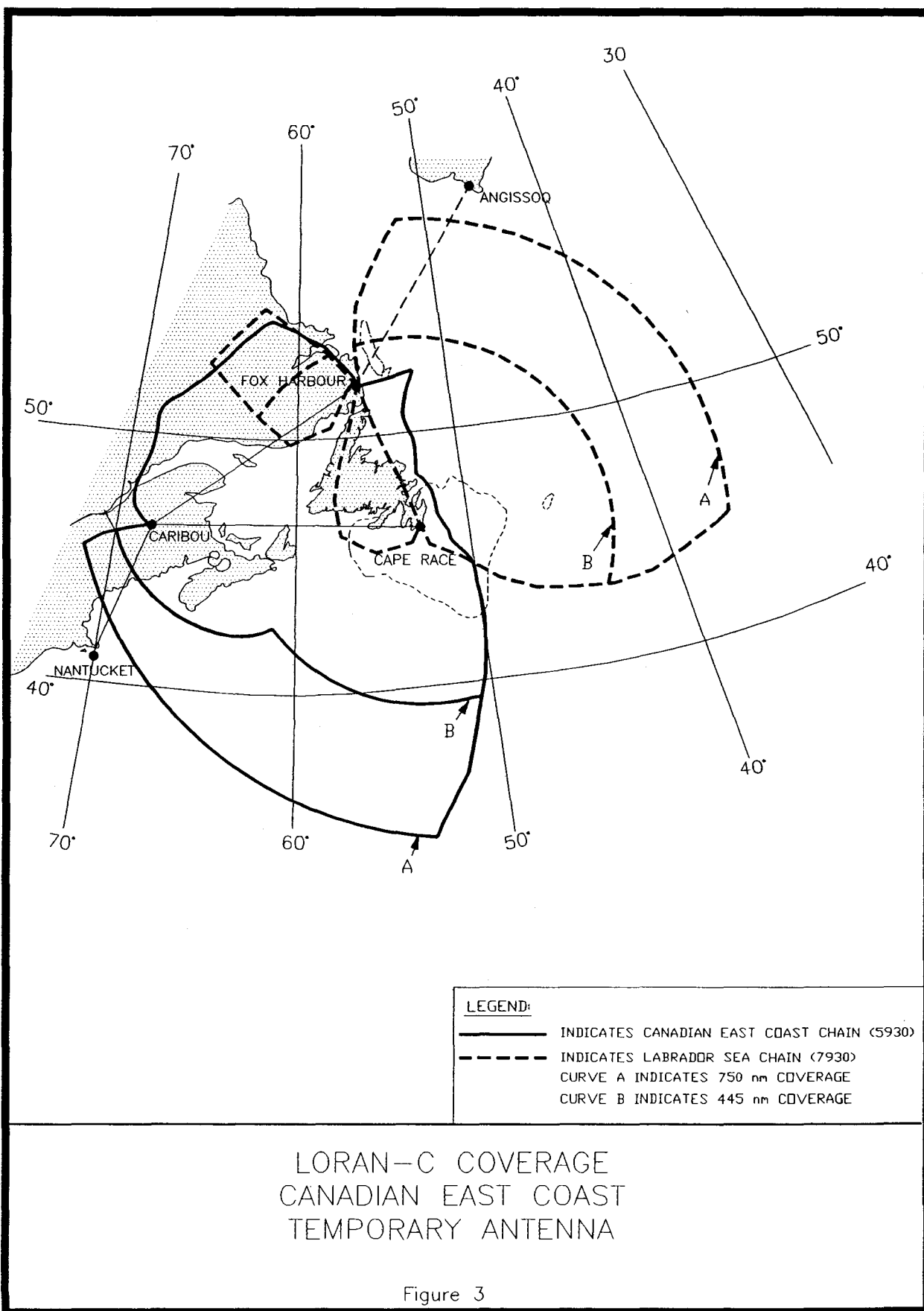


Figure 3

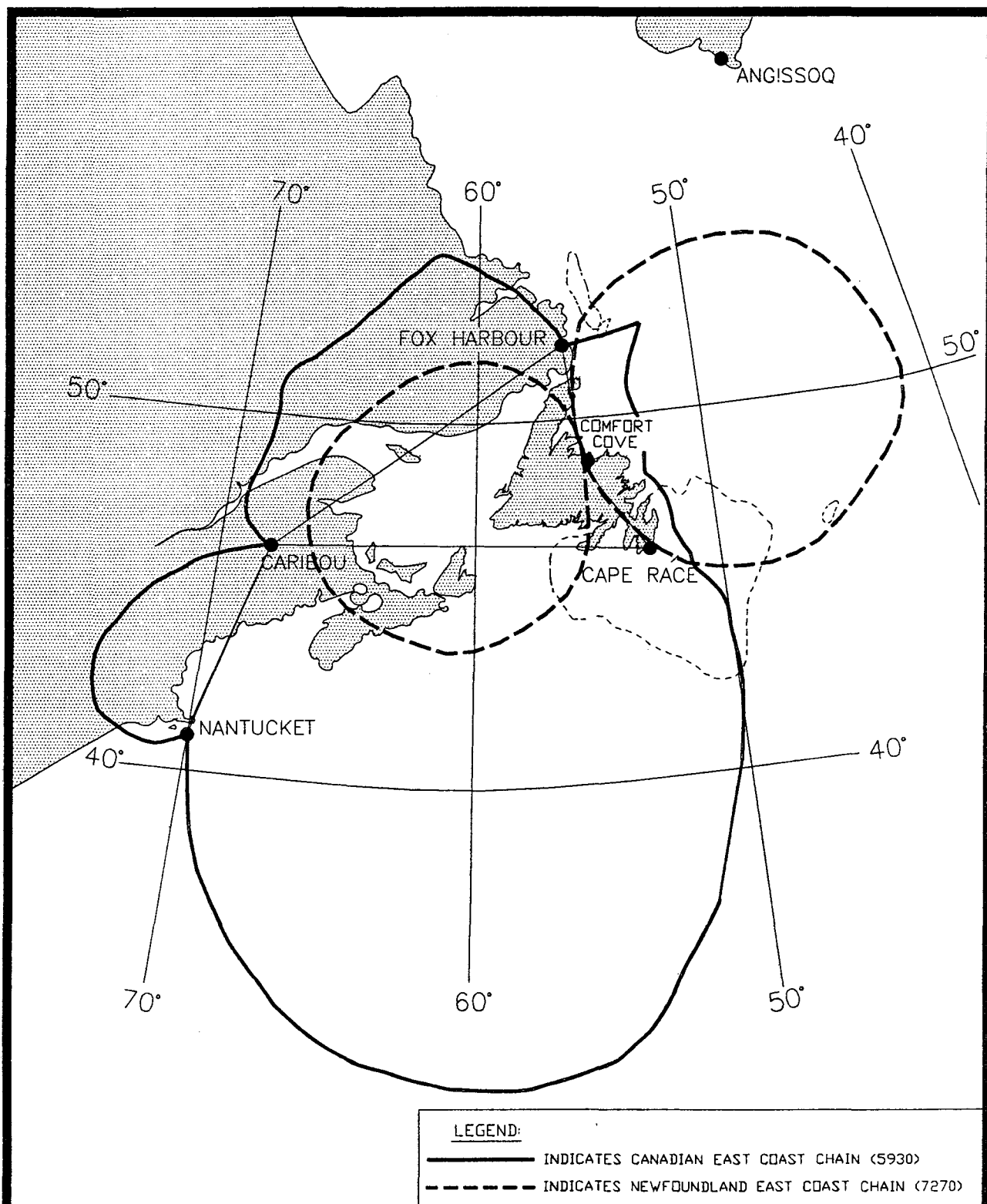
Explanation of Figure 3

LORAN-C COVERAGE CANADIAN EAST COAST TEMPORARY ANTENNA

The predicted Loran-C coverage on the Canadian East Coast, using the Cape Race temporary 320' antenna, was based on two different methods of calculation and are depicted by Curve A and Curve B.

Curve A indicates the theoretical range that we should have obtained from Cape Race. It is based on a 40 kW output power, a 50 dB above 1 μ /m atmospheric noise level, and a receiver capable of handling a 1/3 SNR. Using a pure seawater path, the Loran-C propagation chart indicates that the signal should have been usable to a distance of 750 nautical miles.

A second way of determining coverage is based on the previous performance of the original transmitter. Using the pessimistic assumption that the previous Cape Race signal (1350' antenna, FPN-45 tube-type transmitter) could only travel as far as Angissoq (we know it travelled farther), it would cover a distance of 840 nm. Fox Harbour, St. Anthony and Angissoq measured signal level drops of 14, 16 and 18 dB respectively on their Austron receivers after Cape Race came back on air at reduced power. The propagation chart indicates this average of 16 dB drop would lower the conservative range of 840 nm down to 445 nm, over a pure seawater path. Curve B show this 445 nm range limit.



LORAN-C COVERAGE
CANADIAN EAST COAST CHAIN
& NEWFOUNDLAND EAST COAST CHAIN

STATION	LOCATION (NAD83)	FUNCTION	EMISSION DELAY	THEORETICAL BASELINE TRAVEL TIME	RADIATED PEAK POWER
Comfort Cove, Newfoundland	49 19 53.57 N 54 51 42.57 W	Master	—	—	203 kW
Cape Race, Newfoundland	46 46 32.29 N 53 10 27.61 W	Whiskey Secondary	12,037.49 μ s	1037.49 μ s	805 kW
Fox Harbour, Labrador	52 22 35.25 N 55 42 27.86 W	Xray Secondary	26,148.01 μ s	1148.01 μ s	800 kW

**NEWFOUNDLAND EAST COAST LORAN-C CHAIN
PARAMETERS, RATE 7270**

Figure 5

Geographic Information System Loran-C Coverage Modeling

Peter H. Dana

Consultant

P. O. Box 1297 Georgetown, Texas 78627

Abstract

Geographic information system (GIS) technologies can offer significant advantages over conventional computer programs designed to predict Loran-C coverage. While newer conventional coverage prediction programs offer sophisticated propagation and interference modeling, flexibility in the specification of positioning techniques, and improved mapping quality, geographic information systems offer the potential for a more adaptive, flexible, and interactive approach. GIS technologies permit the acquisition, management, analysis, and display of spatially related information in a single integrated system. GIS modeling also offers the ability to perform interactive spatial analysis based on requirements unique to the user not included in the design of a conventional computer program. In addition, the geographic operators provided by GIS packages facilitate the transfer of Loran-C modeling concepts to various hardware and software platforms, making coverage prediction technologies available to independent agencies worldwide.

Introduction

Loran-C is a ground-based, long-range, 100 kHz, radio-navigation system. The coverage of the Loran-C system is defined by the geographic areas within which a receiver can reliably acquire and track the Loran-C pulses from a set of transmitters that can provide adequate measurements to meet the needs of the user.

The original Loran-C system was used primarily for marine navigation in a three transmitter, hyperbolic mode. Early receivers were designed to track a set of three transmitters consisting of a Master station and two Secondary stations (a chain) transmitting pulses at a common group repetition rate (GRI). The arrival times of the Secondary stations were measured with respect to the arrival time of the Master station to provide two time differences (TDs). The user located these hyperbolic lines of position (LOPs) on marine charts to obtain a position estimate.

Current Loran-C receivers track three or more transmitters to provide a position fix usually computed by the receiver and displayed as latitude and longitude. Some receivers contain accurate clocks, enabling them to use only two signals to provide position. Time and frequency receivers may need to track only one transmitted signal to control a timing pulse or oscillator signal with respect to the Loran-C system clocks. Some receivers operate in hostile interference environments while others are used in vehicles capable of high-dynamic maneuvers. Modern

avionics receivers may track as many as eight transmitters from up to four different chains. Some use individual transmitted signals as pseudo-range measurements in combination with Global Positioning System (GPS) satellite measurements to provide interoperable navigation service. Differential Loran-C service is available in some areas, where system bias errors are broadcast to users requiring high accuracy position fixes.

As used today, effective coverage for the Loran-C system is a function of transmitter power, the position of the receiver with respect to the tracked transmitters, the 100 kHz propagation environment, the capabilities of the receiver, and the requirements of the user. Early coverage charts assumed a user community with single chain receivers operating in the hyperbolic mode and are not adequate descriptors of coverage for the new generation of Loran-C receivers and the variety of user requirements.

GIS technologies can be used to model transmitters, propagation paths, interference sources, receiver capabilities, and unique user requirements in a flexible, interactive environment. Using the capabilities of GIS to manage, analyze, and display information in a single system, new coverage charts can be produced that can combine Loran-C modeling with other user information such as transportation routes, land use boundaries, fishing areas, or other interoperable navigation system service areas.

Geographic Information System Fundamentals

Geographic information systems are hardware and software systems that provide for the creation, management, analysis, and display of spatial information. Evolving from CAD packages, map display systems, and data base and spreadsheet software, GIS processes allow the user to perform complex spatial analysis difficult to achieve with any of the original systems that gave rise to GIS.

GIS software is available for a variety of platforms, from mainframes to personal computers. GIS prices range from a few hundred dollars for simple thematic mapping packages to hundreds of thousands of dollars for implementation of complete vehicle tracking and optimal routing dispatch systems for cities with populations in the millions.

Current users include private businesses as well as local, departmental, and national governmental agencies around the world. Applications include facilities management, natural resource inventory, land record maintenance, and site location analysis.

GIS software packages use a variety of approaches to the management of spatial information, but most model information as points, lines, and areas with associated attributes. While there are some successful raster-based GIS products, most are vector-based (with some capable of handling both). Modeling in GIS applications is often dependent on the way in which a specific GIS organizes data. Database management techniques range from simple spreadsheets to complex data structures. Relational databases and object-oriented methods are very different in their internal structure, but both methods have proven successful in similar applications.

One attribute of most GIS approaches is the use of a common coordinate system to represent information. In many GIS implementations real-world coordinates in the form of latitude and longitude are used, while in others an arbitrary graphic unit is used. Some systems model height and some can be configured to represent time as a fourth dimension. Data for GIS use must be georeferenced, or registered with the common coordinate system, to be useful. The accuracy of georeferencing has a significant impact on the validity of the GIS analysis to be performed. Some GIS packages can perform geocoding, an operation that matches attribute data in one data base with similar attributes in a georeferenced data base, resulting in automatic georeferencing of the original data base. The matching of customer addresses in one data base with the georeferenced street and street numbering representations in another data base is a common use of geocoding.

Data acquisition may be accomplished through the digitization of existing maps, keyboard entry of attribute data, or by the importation of existing data files. Many GIS packages allow for dynamic file sharing with data from spreadsheet or data base management packages. Data storage and management is an important task that may involve data transformations, preprocessing, error checking, and the manipulation of mass storage devices.

In most vector-based systems, points or nodes represent geographic entities with a single position in the common coordinate system. Utility poles, radio transmitters, and customer addresses are examples of point entities. Points are also used to represent those entities so small as to make their actual spatial extent insignificant at the scale required for GIS analysis. Points are also commonly used to represent area centroids, to arbitrarily locate an entity such as a label, or to position aggregate data within an area.

Lines, polylines, arcs, and spans are terms associated with groups of line segments that are used to represent transportation routes, pipelines, or other entities that link points within a GIS database.

Zones, polygons, and regions are GIS terms for groups of lines that enclose areas such as state boundaries, property lines, and soil type delineations. Complex

polygons may contain islands consisting of other polygons or unmodeled areas.

Layers, tables, overlays, and coverages represent ensembles of information related by common attribute types. Layers are often thought of as similar to individual overhead transparencies that can be stacked to show spatial relationships between them. A layer containing soil-type regions can be paired with a layer containing vegetation zones for analysis and display by a GIS.

GIS analysis often requires many kinds of data manipulation. Most GIS packages allow for statistical operations such as regression and correlation; measurement capability for distance, direction, area, and perimeter computation; and geometric operations such as rotation, translation, and scaling. Other capabilities may include a high level macro-language or the ability to call user supplied functions written in some other software language.

At the heart of GIS modeling are geographic operators. A wide variety of operators is available in different GIS packages for spatial analysis. Spatial operators may include the ability to determine connectivity of line segments and the relationships of those line segments to common attributes. The ability to determine topology is also an important capability found in more sophisticated GIS packages.

Other geographic operators commonly available in GIS packages are intersection, point in polygon, area in area, and other expressions of interrelationships between geographic entities that can be used to select, reject, merge, or query spatial data bases. Many GIS packages provide line thinning and smoothing operators. Contouring and the graphic representation of three dimensional surfaces are desirable features.

One of the most powerful geographic operations is the creation of new entities from existing ones through proximity analysis. Buffering is the creation of a polygon around some existing entity or group of entities. The creation of a polygon that represents the area within ten kilometers of a hazardous materials transportation route is an example.

GIS mapping capabilities often include the ability to handle different earth shapes, geodetic datums, and map projections. These capabilities are required by many users for the digitization of existing maps, and for the production of useful output. The most useful GIS mapping systems support many different scanners, digitizers, plotters, printers, and video output devices.

Loran-C Coverage Predictions and Charts

Many approaches have been taken to predict and chart Loran-C coverage. Important parameters for coverage limit determination are the signal to noise ratio (SNR) and the size and shape of the position error distribution for a given SNR. This geometric dilution of

precision (GDOP) is determined by the position of the receiver with respect to the selected transmitters. In the 1960s nomograms for computing contours of constant geometric accuracy were combined with graphs of field strength for various ranges and conductivities to produce hand drafted charts for early Loran-C users [1]. In the 1974 version of the *Loran-C User Handbook* a simple heuristic was suggested for geometric coverage limits. Secondaries were picked by selecting LOPs that crossed at more than 20 degrees at the estimated position on a Loran-C navigation chart. Coverage charts were still based on manually computed predictions and hand drafted contours [2]. During the 1970s a series of *Loran-C Repeatability Diagrams* were published by the Defense Mapping Agency (DMA). These charts provided contours of repeatable accuracies for each chain service area. DMA produced the *Loran-C Coverage Diagram*, chart 5130, showing worldwide groundwave coverage for 1500 foot 2drms ($2 \cdot \text{distance root-mean-squared}$) repeatable accuracies and skywave coverage for two nautical mile accuracies.

By 1980, the Loran-C User Handbooks provided separate charts of coverage for each chain based on geometry, noise, and signal strength. These charts assumed a three station, Master-Secondary-Secondary receiver. Manual Secondary selection was based on both crossing angles and gradient, the change in position resulting from a change in TD [3]. Increased use of Loran-C by ships, aircraft, and land-based vehicle tracking systems required additional coverage charts. The 1981 *Specification of the Transmitted Loran-C Signal* contained charts of GDOP contours for each triad in each chain allowing the navigator to select appropriate Master-Secondary pairs as the receiver location changed. Conventional two LOP, hyperbolic, single-chain navigation (triad navigation) was still assumed [4].

The increasing complexity of the Loran-C system and the increased use of Loran-C for avionics in the 1980s made more elaborate coverage generation methods necessary. The Federal Aviation Administration (FAA) sponsored a coverage generation software package, *The Airport Screening Model* [5]. This program allowed the user to compute TDs, gradients, SNRs, and GDOP for a selected triad from a selected chain, using transmitter and chain data, ground conductivity estimates, and noise estimates. Written specifically for FAA prediction purposes, the program allowed predictions for specific locations and for traditional hyperbolic triad operation. The program was modified by the Transportation Systems Center for use in predicting potential coverage improvements in the United States [6]. This new program incorporated receiver models and modern navigation techniques, including the use of TDs developed between Secondaries in a Master-independent mode. The output

consisted of GDOP or SNR grids that were used to help plan the Mid-Continent chains.

In 1986 the U.S. Coast Guard produced a coverage generator, *Coverage*, written in Basic and implemented on HP9836C computers [7]. This program generated coverage limit boundaries for output to plotters. Knowledgeable operator interaction was required to combine the result of SNR and GDOP computations. In 1989 a new coverage generator was produced by the Synetics Corporation and the U.S. Coast Guard for the U.S. Department of Transportation. This program was designed to run on IBM PC compatible computers and to be used by "an operator not knowledgeable in the field of Loran" [8]. The program was based on techniques from the FAA Airport Screening Model. Changes included new atmospheric noise models, an implementation of mixed conductivity path phase delay prediction, mapping capabilities, and a boundary-following algorithm. The output of the program consisted of charts in a form similar to those provided in earlier User Handbooks. The use of triad geometry as a criteria continues in such publications as the newest User Handbook [9] and the FAA *Advisory Circular 90-92*, where the Loran-C oceanic and national air space coverage diagrams are based on three station hyperbolic positioning techniques [10].

The newest generation of coverage prediction programs has been developed by the Radio-Navigation Group at the University of Wales. The first of these programs was a menu-driven program that used an existing Computer-Aided-Design (CAD) package for output [7]. The program modeled man-made interference sources that have long caused problems for Loran-C in Europe. This program was based on single triad navigation and used a three station GDOP model. The 1992 version of the Radio-Navigation Group program incorporated more sophisticated receiver models, including the ability to model cross-chain and master independent positioning modes [11]. Future versions of this program will no doubt incorporate even more complex receiver modeling.

GIS Case Study

To explore the potential for GIS modeling of Loran-C coverage a case study was conducted. Loran-C coverage prediction and graphic display of coverage limits are well suited to GIS modeling. Points can represent the locations of Loran-C transmitters and receivers. Transmitter power and chain relationship data can be stored as point attributes. The ray paths of groundwave signals can be modeled by arcs or polylines. Ground impedance or conductivity regions can be represented by areas or polygons. Noise values can be represented by regions, and interference sources can be modeled as points.

GIS packages can be used to acquire, manage, and store system data bases, conductivity maps, noise

contours, and interference lists. Spatial analysis techniques using geographic operators can determine the impedance segments of a ray path, and mathematical operators can model field strength attenuation, ECD shifts, and GDOP.

GIS mapping capabilities can be used to digitize existing conductivity maps, noise contours, or service area maps. High quality output of coverage diagrams can be produced in the chart projection and local datum of the user.

MapInfo

To examine the potential for GIS modeling of Loran-C coverage, MapInfo, a relatively low-cost, multi-platform GIS-desktop mapping product was chosen. MapInfo is a product of the MapInfo Corporation of Troy, New York. MapInfo has a minimal set of geographic operators, a macro language, MapBasic, and the ability to handle dozens of predefined map projections, any number of user-defined projections, and over a hundred geodetic datums.

Because the system runs under Microsoft Windows, any hardware system from a PC to a mainframe that supports Windows can serve as a MapInfo platform. Any input or output device supported by Windows can be used to digitize, plot, or print maps. MapInfo is also available in a Macintosh version and MapBasic scripts can be transferred between PCs and Macintosh computers.

MapInfo represents geographic entities as *objects*. Associated data is stored along with objects in *tables*, the MapInfo equivalent of GIS coverages or layers. Attribute information can be in character or numeric form. Objects include *points*, *polylines*, and *regions*. Geographic operators include *Contains*, *Contains Entire*, *Contains Part*, *Within*, *Entirely Within*, *Partly Within*, and *Intersects*. These operators, in conjunction with buffering, merging, joining, and a full array of structured query language (SQL) commands, allow the modeling of complex spatial relationships.

Many other GIS packages can be used to model Loran-C coverage. MapInfo was selected for its low cost, its availability, and the simplicity of use in the Windows environment.

The LCModel Program

The case study project resulted in a MapBasic program, LCModel, that runs under the MapInfo system. The program consists of less than 800 lines of comment and code and provides four menu functions. *Initialize* presents a world map from which the user selects an area in which coverage is desired. *Transmitters* allows the user to deselect transmitters, modify transmitter parameters or add new ones. *Receiver* provides for redefining the nominal receiver model. *DoMap* computes coverage contours and provides a coverage map. Once completed,

the map can be projected, labeled, and printed using the full array of GIS mapping capabilities of the MapInfo package.

Transmitter Data Base

Loran-C system parameters were imported into MapInfo as an ASCII text file. Included were transmitter names, latitude, longitude, transmitter power, transmitted ECD, and GRI designators. The GIS package was used to convert the data to a MapInfo table. Transmitter locations are modeled as points and are contained in the XMITER table with their associated transmitter parameters. The user can add, modify, or delete transmitters in the XMITER table.

Impedance Data Bases

While conductivity data bases in a variety of forms can be used, in this case study a computer file of conductivity data was used. The *FCC M3 Map Data File* supplied by the FCC through NTIS [12] contains two different sets of data files describing ground conductivity boundaries. The *FCC M3* files, covering Canada, the United States, and Mexico are topologically organized, with conductivities defined for the west and east sides of the line segments. The *WHEM* files, used in this case study, cover the entire Western Hemisphere. This data set is not organized topologically. A MapBasic program was used to convert the data into a sequence of line segments, each described by two sets of longitude and latitude coordinates and the two conductivity values on either side of the line segment. Conductivity values in mhos per meter were aggregated into eight discrete levels. This data base is stored in the WHEMSEGS table. Figure 1 shows the extent of this Western Hemisphere conductivity data base.

Noise and Interference

Acquisition and tracking are primarily functions of received signal strength with respect to atmospheric noise and man-made interfering signals. SNR is a function of transmitter power, the range and effective impedance of the propagation path, and the combination of noise and interference at the receiver location.

For this case study noise values were computed from CCIR noise values [13] and stored as regions with noise value attributes in rms noise levels in decibels above one microvolt per meter in the NOISE table. No modeling of individual man-made interferers was included.

Receiver Model

The user can specify a number of receiver modes. With the ease of programming the MapBasic script language, almost any conceivable receiver model can be accommodated. The maximum number of tracked signals and chains, minimum SNRs for acquisition and tracking,

and different positioning algorithms can be easily selected or reprogrammed. The basic model is an n-chain, n-station model with user selectable minimum SNR. The user defines the position accuracy requirement for the coverage chart.



Figure 1. WHEM Conductivity Data Base

Coverage Grid

After initialization the user is presented with a world map showing the currently defined Loran-C transmitters. Using zoom tools the user selects an area for coverage prediction. When *DoMap* is activated a grid of points is produced by the MAKEGRID module. Grid points are produced at equal distances over the selected area. By using equal distance for grid points, rather than equal increments of degrees, the grid remains representative at higher latitudes [Figure 2].

A new impedance table, SEGMENTS, is produced containing the line segments within a defined range limit of the grid. This is done using buffering commands and SQL selections.

Ray Path Modeling

At each grid position used in the model, a ray path is computed from transmitter to receiver. This path is modeled as a polyline following the geodetic groundwave path over the earth and is stored in the table RAYPATH. Simplified paths following a great circle route can be computed, or more complex models, describing the path over an ellipsoidal earth can be used.

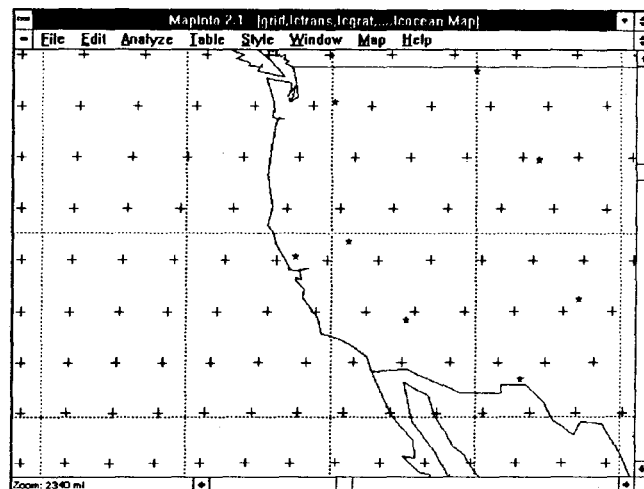


Figure 2. Selected Coverage Area (with Grid Points)

Transmitter Site Conductivity Level

The *WHEM* conductivity data base is not topologically organized. The two conductivity values in the data base are those on either side of the boundary line, but there is no east-west (as there is in the *FCC M3* files), left-right, or other fixed order to the two values. Because MapInfo has limited capabilities for building topological relationships (as do other GIS products such as ARC/INFO), the conductivity level at each transmitter site is computed whenever the transmitter data base is changed.

This is accomplished by the use of a table of known positions outside of the land conductivity boundaries. These known points at sea, stored in the SEAPOINTS table, are assumed to have a conductivity of 5.0 mhos per meter. A line from each transmitter to the nearest of these points is computed. An SQL query determines the list of line segments intersected by this line. The same SQL statement orders the intersections by range from the known sea point.

Starting from the known conductivity level of the sea point, each intersection is examined and the level on each side of the intersection determined, until the conductivity level at the transmitter site is resolved. This transmitter site conductivity level is stored in the XMITRS table.

Path Impedance

The ray path polyline and the conductivity SEGMENTS table are used in an SQL query to select the conductivity boundary segments and their associated conductivity level numbers. The SQL query [Figure 3] orders the segments by distance from the transmitter:

Using the computed conductivity level at the transmitter the program computes the topological relationships for each intersecting line segment, resolving the conductivity of each path segment. Given the list of ranges and conductivities stored in the SEGLIST table, any method, from full integral solutions to Millington's

method, can be employed for ray path field strength attenuation.

```

' get raypath from transmitter to grid point
raypath=CreateLine(tx,ty,gridx,gridy)

' compute list of conductivity segments, order them by
range
Select Distance (tx, ty, Centroidx (segments.obj),
Centroidy (segments.obj), "m"), segments.col1,
segments.col1
From
segments
Where
segments.obj Intersects raypath
Into
seglst
Order By
COL1

```

Figure 3. SQL to Select Ray Path Conductivity Segments

This case study uses an average impedance method that has been used for prediction of both field strength and phase delay computations [14]. Conductivity levels are converted to impedance values:

$$\nabla_1 = \sqrt{\frac{n^2}{\frac{\sigma}{\omega \cdot \epsilon_0} + \epsilon_2}}$$

where:

∇_1 = real impedance

n = index of refraction of air = 1.000338

ϵ_0 = permittivity of free space = 8.85×10^{-12}

ϵ_2 = permittivity of path (80 sea, 15 land)

σ = conductivity in mhos/meter

$\omega = 2\pi f$

For each SEGLIST table, the effective path impedance is computed:

$$\nabla_{2,mean} = \frac{\sum_{i=1}^n \nabla_{2i} \cdot range_i}{\sum_{i=1}^n range_i}$$

Field Strength

Field strength is a function of range, path impedance, and transmitter power. At each grid point field strength is computed for each transmitter. A field strength value is interpolated from a table of field strength attenuation at selected ranges and impedances. That value is adjusted for transmitter power and converted to dB above one microvolt per meter.

Noise and SNR

The noise level is computed from the NOISE table as the nearest modeled noise value. SNR in decibels is

computed for each transmitter by subtracting the noise level region from the field strength.

Bias Errors

Estimates for the magnitude of chain and transmitter timing bias were used in position error estimates. Values of 25ns for chain, and 20ns for transmitter errors were used in the case study. For this study of repeatable accuracies, no propagation model error bias was included.

ECD and Skywave

Pulse shape distortions may affect the probability of acquisition and the correct cycle identification required by Loran-C receivers to resolve ten microsecond arrival-time ambiguities. Variations in the impedance and terrain of the ground-wave path result in envelope to cycle distortion (ECD), and interference from sky-wave signals can further distort the ground-wave pulse shape. In the case study no ECD or skywave modeling was implemented, but for users requiring coverage at high geomagnetic latitudes or at long ranges, such modeling would be useful.

TOA Variance

If the SNR for a transmitter is above the minimum required for acquisition and tracking by the receiver model, a time of arrival variance is computed. The TOA variance is based on SNR, the GRI, and values for chain and transmitter timing and receiver servo bandwidth (ten second averages in the nominal model) [15].

$$TOA \sigma = C \cdot \frac{10}{2\pi} \cdot \frac{N}{S} \cdot \sqrt{\frac{B_s}{F_s}} + t_1 + t_2$$

where:

$C = 299.69 \text{ m} / \mu\text{s}$

$\frac{N}{S}$ = noise to signal ratio

B_s = servo bandwidth in radians per second

F_s = samples per second

t_1 = chain timing error = 25ns

t_2 = transmitter timing = 20ns

The resulting TOA variance is used as a weight in the position error computation:

$$W = \frac{toa\sigma_1^2}{toa\sigma_1^2 + toa\sigma_2^2 + toa\sigma_n^2}$$

Directional Derivatives

At each grid location the geodetic azimuth from the receiver position to each tracked transmitter is used to form the directional derivatives of range errors with respect to easting, northing, and clock errors. The resulting matrix for n-stations is:

$$\begin{matrix} \sin(\text{azimuth}_1) & \cos(\text{azimuth}_1) & 1.0 \\ A = \sin(\text{azimuth}_2) & \cos(\text{azimuth}_2) & 1.0 \\ \sin(\text{azimuth}_n) & \cos(\text{azimuth}_n) & 1.0 \end{matrix}$$

Position Error

Position error at a given location is computed using the following operations where the weight matrix is formed from a column of TOA variances.

$$\text{Error} = \sqrt{\text{trace}(\mathbf{A}'\mathbf{W}^{-1}\mathbf{A})^{-1}}$$

GDOP

For GDOP coverage charts, the weights containing TOA variances are not used and the directional derivatives compute GDOP from:

$$\text{GDOP} = \sqrt{\text{trace}(\mathbf{A}'\mathbf{A})^{-1}}$$

Coverage Contours

To compute error contours a new grid is produced with four times the number of points as in the original grid. Grid points between original points are interpolated from neighboring points. Coverage contours are computed by selecting those grid points from the new grid with error estimates below the required user position accuracy. Using an SQL statement [Figure 4] a buffer is created around the ensemble of selected grid points. The resulting polygon is used as a contour line representing the limits of coverage for the specified position error.

```
Select * From Grid
Where position_error < level
Create Object As Buffer
From Selection
Into Variable contour
Width gridincx*30*1.852 Units "km"
Resolution 12
```

Figure 4. SQL to Create a Position Error Contour Buffer

Coverage Map Creation

The coverage contour is added as a layer on the user defined coverage map. The user can then select any projection and datum and prepare the map for output using the MapInfo *Layout* commands. Maps can be colored and annotated in a variety of ways. The resulting map can be printed, plotted, transferred to a word processor or other Windows program, or stored for later use.

Problems

MapInfo is not a highly sophisticated GIS package. The design of the LCMModel program was hampered by the limited ability of MapInfo to build topological

relationships from boundary lines and attributes. Currently no capability exists in MapInfo for the conversion of connected polylines into regions. While distances are computed over great circle paths, lines created between two geodetic positions are modeled as lines in an orthogonal system of latitude and longitude coordinates, rather than as great circle or ellipsoidal paths. The lack of built-in contouring functions hampered the creation of smoothed coverage limit lines in the LCMModel program.

Sample Coverage Chart

To demonstrate the capabilities of the GIS approach to modeling Loran-C coverage, the U.S. West Coast Chain, GRI 9940, was modeled. The receiver model used is a single chain, four station receiver capable of tracking at -9 dB SNR. The differences between this and published coverage maps using the same coverage criteria are minimal.

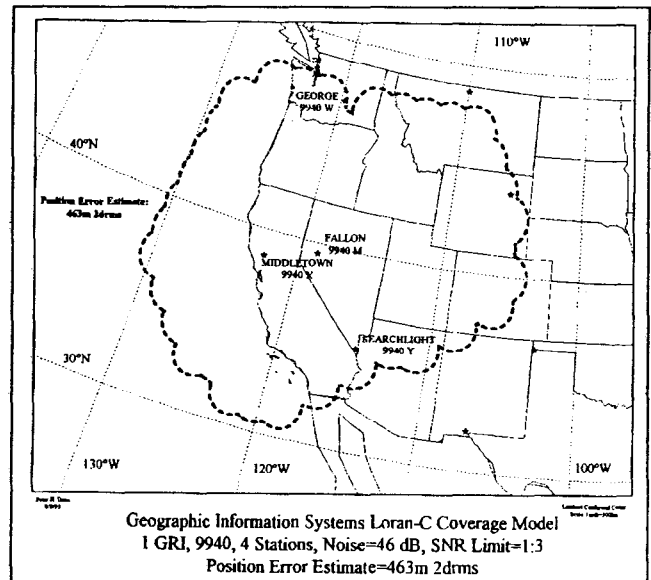


Figure 5. Sample Coverage Map

GIS Spatial Analysis

The primary advantage of GIS modeling is the ability to combine layers of data and investigate interrelationships between them. To provide a simple example, a table containing U.S. Interstate Highways was imported into MapInfo. A SQL statement using the *Sum* and *ObjectLen* functions, computed the length of the highway system [Figure 6]. A 100 meter coverage contour was produced for a single chain receiver operating on the 9940 chain. An SQL selection was performed on the contour table and the highway table, resulting in a new table containing the highways within the contour region. Another query computed the total length of the highways within the 100 meter, 2drms, coverage region [Figure 7].

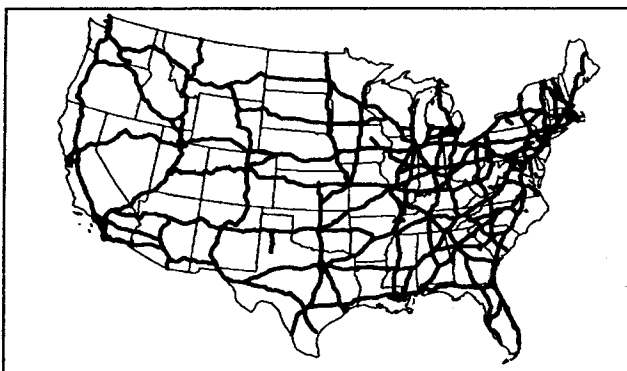


Figure 6. 65,369 Kilometers of U. S. Interstate Highway

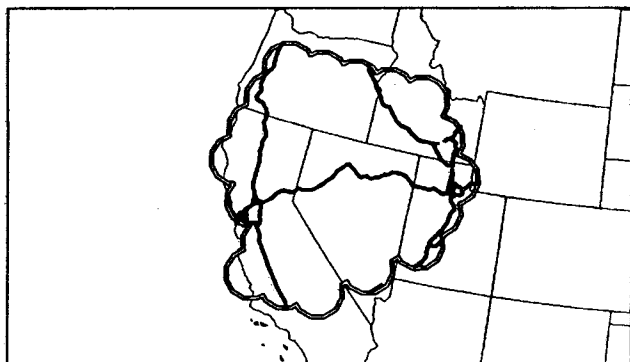


Figure 7. 4,678 Kilometers of Interstate Highways Within a 100 Meter (2drms), GRI 9940, Coverage Contour

Conclusion

Geographic information systems can provide a flexible, interactive, and adaptable means of providing Loran-C coverage estimates based on the specific requirements of independent users around the world. Providing a means of acquisition, management, analysis, and display of Loran-C system data, modern GIS packages are available for a variety of hardware platforms. Drivers are available for hundreds of input and output devices. GIS can produce high quality output of coverage charts in map projections and geodetic datums required by a variety of users.

Of particular significance is capability of GIS to model interoperable navigation systems. GIS techniques offers the potential for modeling differential GPS (DGPS) coverage and Loran-C concurrently, enabling independent users to experiment with DGPS beacon placement within existing and proposed Loran-C transmitter coverage. A fundamental advantage of GIS methods is the ability to use Loran-C coverage predictions in conjunction with other layers of spatial information. Rapid advances in GIS technologies will provide additional Loran-C coverage modeling capabilities in the future.

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Computer Networking and C3I Systems for Emergency Services: How Radionavigation fits in

Rex A Buddenberg

Buddenberg Consulting
budden@shell.portal.com

Abstract

Radionavigation systems have an important role to play as components within a community's emergency services C3I system. This paper examines how that role should be played.

When considering radionavigation as part of the emergency services C3I situation, the perspective shifts. The positioning inputs provided by the radionavigation system are often most needed by the command center. The vehicle operators usually have a pretty good idea where they are — after all, they are driving around their home territory. Consequently, the radionavigation receiver is only valuable when it can communicate its position data over a network to the command center. And the positioning data is only valuable when it can be integrated with the rest of the information in the command center.

This shift in perspective means that radionavigation receivers and the underlying radionavigation providing system need to be conscious of new uses and markets.

Community Emergency Services

Information gleaned from a variety of sources and integrated into a comprehensive tactical picture is becoming increasingly important in the community emergency services where the price of brute force continues to escalate. Communities are finding it necessary to cut the numbers of ambulances, fire departments and crews. Like the military, the neighborhood police are increasingly required to 'fight smarter'. This places an increasing burden on the decision making infrastructure. We need a shared vision of the community's C3I¹ system and the role of radionavigation systems within this C3I system.

Fire departments must work hand in hand both with other city

¹A C3I (Command, Control, Communications & Intelligence) System is an information system consisting of sensors (data collection), communications networks, decision support systems and a means for effecting decisions. In this context, 24 hour operations and presence of vehicles in the system distinguish a C3I system from a garden variety MIS.

services such as police and water departments and with neighboring communities' fire departments in order to gain the synergism and resilience that offsets a tight budget.

Order of Business

In the rest of this paper, we'll discuss these topics:

- Requirements of a typical emergency services C3I system.
- Network — the underlying communications substrate that communicates a variety of data and information ... including, but far more than, the radionavigation data.
- Decision support systems that fuse data into information and provide the command center personnel with their vital support in keeping the community's street forces working coherently.
- The implications that these requirements impose on the radionavigation system.

Requirements Synthesis

Regardless of local variables, every C3I system has these requirements:

- a high availability communications network with backups (altroutes),
- an open systems communications network that can support applications such as position reporting and secure electronic mail,
- a communications network that is interoperable with other entities,
- a responsive network

management capability to limit damage when it occurs and to speed restoral,

- interoperability with other parts of your community's government and with the public,
- a decision support system that reduces dispatcher workload by relieving the watch of data handling chores.

High Availability through Redundancy

When planning a C3I system, the elements need to meet three criteria on order to yield the 24 hour/365day availability we need:

1. Independence of mode of failure. When one component or communications route fails, the backups do not also fail by the same means.
2. Failures detected upon occurrence. This includes failures in the backup systems.
3. Reliable changeover from primary to backup. This cannot be allowed to become the weak link.

In order to meet the high availability needs of a C3I system these three criteria need to be applied to the network, to the decision support system and — germane to this audience — to the radionavigation system.

The Network — an Internet 'cloud'

To the user the network can be pictured as simply a 'cloud' to which

one attaches the sensors, decision support systems and other *end system*² building blocks necessary to build a complete function. This is the view that the network should expose to the decision support and sensor components. The underlying connectivity issues are effectively hidden.

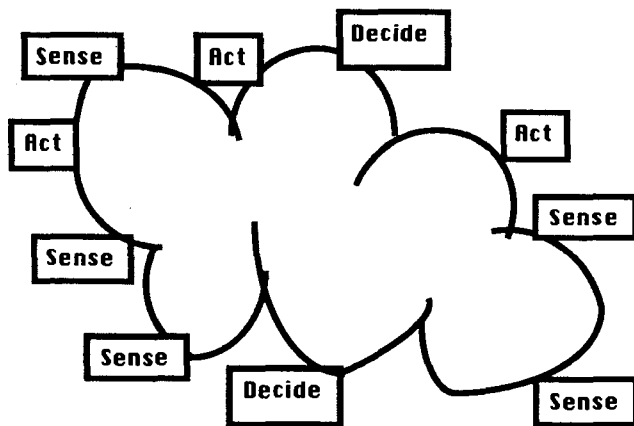


Figure 1 External View of an Internetwork

But before we attach end systems to this internetwork, we have to do some stage setting. First, electronic messaging is one of the interfaces we expose to the user. Secondly, some explanation of how internetworks are built and operated is appropriate as a technology survey.

Electronic messaging

Electronic messaging is the part of the

²End systems are data sources and sinks that attach to the network. By contrast intermediate systems are the network components including bridges, routers, and connectivity that do not generate or consume data (except overhead) but rather make up the communications substrate.

network that is exposed to the user and the applications developers. Electronic messaging is more than just text messages passed between human writers and readers — it offers a great potential in our C3I environment to automate a great deal of routine data passing as well.

Electronic messaging is changing the way organizations do business in some very interesting ways. In particular, e-mail has enabled a flattening and greater distribution of many organizations. Since most emergency services rely heavily on the judgement of on-scene personnel, e-mail is simply a reinforcing agent.

Electronic messaging will be one of the most powerful tools in your C3I system — it is the means of effective, secure communication both within your community services domain and also with the public — the community served.

The language of electronic messaging

Much of the electronic messaging terminology parallels the conventional post office language which makes understanding of the conceptual problems easier. For instance, when a chunk of data (e.g. a Loran position sentence) is encapsulated, it is said to be inserted into an electronic *envelope*. This payload is known as the *message body*. The *header* information can be visualized as being on the outside of the envelope — it contains the From: and To: addresses.

The User Agent is the part of

the electronic messaging system you, the user or your radionavigation receiver, interact with. It helps you compose your messages, affix the proper addresses, stuff the envelopes and so on.

User Agents can be of the programmable UA type — one which interacts with a radionavigation receiver or a database, for example, instead of a human users. Programmable User Agents are key to achieving the kind of automation that relieves humans of some of the tedium of data handling.

Developing a network

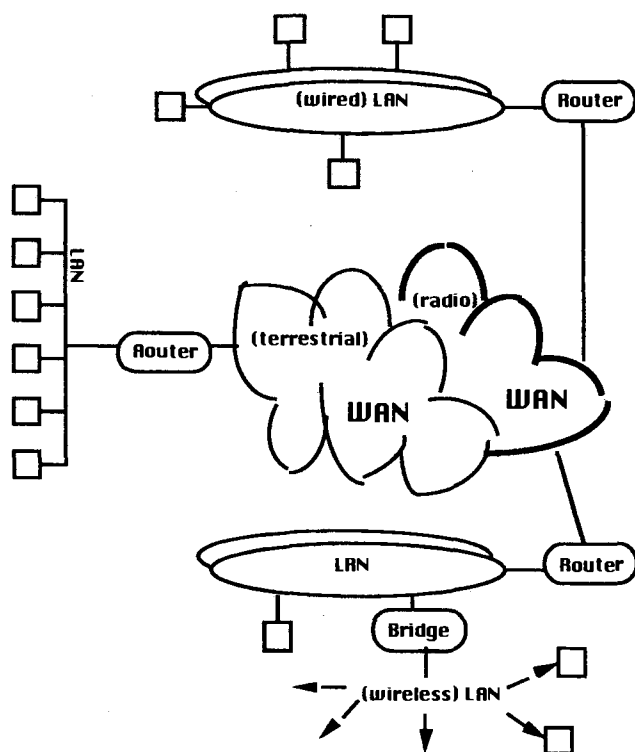


Figure 2 A Complex Internet

A level of detail down into the internet cloud, the network architecture is an internet — a

network of networks consisting of:

- Local Area Networks (LANs),
- Wide Area Networks (terrestrial WANs),
- radio-based wide area networks (radio-WANs), all tied together with
- routers.

These are the intermediate systems that provide the connectivity and underlying protocol support. They are not normally visible to the end user. These components are configured, controlled and monitored by a network management system of some kind.

Network management

Network management includes the following:

- network fault notification and isolation. For our C3I system, this is the most important part as it targets the maintenance activity critical to keeping the system operating.
- managing security. With high levels of interoperability that we need in our C3I systems, we also offer an easier means for the wrong people to get into it and for the right people to get into it for the wrong purposes. The network management system must be able to identify and control intrusions.
- understanding and configuring network performance.

For C3I systems, fault detection, isolation and repair is by far the most critical problem — keeping the network in a functioning state.

Fault tolerant LAN

Operation centers with 24 hour/365 day up time requirements can meet that requirement with a LAN patterned after the Navy's SAFENET standard to eliminate single points of failure that cause downtime. SAFENET uses the Fiber Data Distributed Interface (FDDI)³ which provides several attributes that we need:

- two, counter-rotating, rings.
- This meets our initial high availability principle of redundant connectivity
- ability for each node to detect downstream failures. When this happens, the node 'wraps' the data back onto the second ring. This isolates a failure allowing the network to continue functioning.
- Because the data is present on both rings, the surviving nodes can use either connection. This makes the crossover action reliable, meeting another high availability principle.

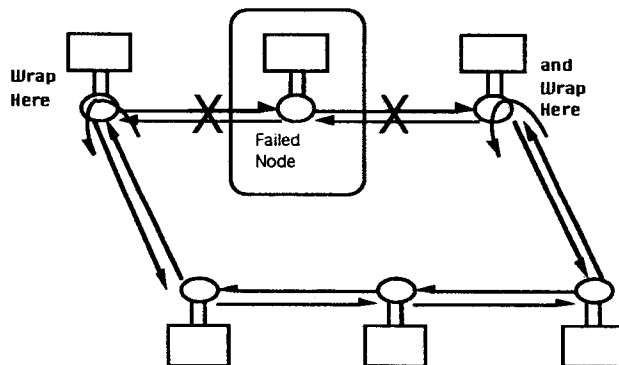


Figure 3 FDDI Ring Wrap

- the FDDI standards include a strong station management protocol allowing a network manager to detect

³ANSI Committee X3T9.5

failures and direct maintenance activity effectively.

Wide Area Networks

Terrestrial wide area network connectivity is purchased directly from a connectivity provider such as a phone or cable television company or indirectly from an Internet services provider which also includes several additional integration services and support. The only real trick in the community C3I problem is to get adequate alternate routing to satisfy the high availability requirements. Recall that central offices have been incapacitated by fires and earthquakes.

Radio-WANs

The coming decade will witness the mushrooming growth in radio-based connectivity. All of the services described below can use small antennae ranging in size from a car radio antenna to a handheld one attached to a handset⁴.

The first growth area is in terrestrial radio-WAN service. These services already offer electronic mail to handheld personal messaging units using a mesh of low-power transceivers in urban areas. One company plans reuse of its cellular telephone infrastructure to provide radio-WAN connectivity.

⁴A Low Earth Orbit satellite (altitude 400-700 km) has a 25 db improvement in system power over an equivalent geosynchronous satellite.

The second growth area is in the low earth orbit satellite based connectivity. This industry can be sorted into three stages:

- Little LEOs which orbit one to a dozen satellites, usually in polar orbits offering both bent-pipe and store-and-forward service. Two of the half dozen companies here are commercializing formerly Soviet technology. Limited service is available now with operational constellations to be available within the next year.

- Big LEOs which orbit one to six dozen satellites in order to provide near-continuous satellite visibility anywhere on the earth's surface. The half dozen companies in this market plan to offer satellite-based cellular telephone service and expect to be operational in the latter half of the 1990s⁵.

Most of the LEOs offer an RDSS⁶ service as well, although this is incidental to the communications offerings.

- Mega-LEO, currently one company, which consists of nearly a thousand satellites in polar orbits offering at least two satellites 40 degrees or higher in elevation to any user anywhere on the earth's surface. The company plans to offer ATM⁷ inter-satellite switching that brings

megabit WAN capacity to any structure ashore, afloat, or aloft. The company plans a 1999 operational capability.

Decision Support Systems

The decision support system problem is much more than simply display of vehicle tracking data. It is the fusion of many different pieces of data from multiple sources.

The open systems approach outlined here is expressly intended to lower the consequences of errors in the conception and analysis of requirements. Make it affordable to be wrong, so mistakes are easily recovered. Use the tactic of isolating the requirements unknowns into modules that can be changed and updated easily without affecting the rest of the C3I system.

A secondary benefit of this modularization approach is that our C3I system is maintainable over time — different components can be updated as new products appear without requiring a re-engineering of the entire system.

The first step to this isolation of unknowns is to examine the anatomy of decision support systems.

Figure 4 illustrates our building-block anatomy.

- Layer 1. All decision support systems have a means of communications in order to receive incoming data and to transmit the decision maker's orders. The networking interface foundation above describes this layer.

⁵The pacing factor is the spectrum allocation process before the FCC which is clearly contentious.

⁶Radio Determination Satellite System, a positioning capability.

⁷Asynchronous Transfer Mode, a cell-switching technology at the data link layer of the ISO Reference Model that permits the circuits to handle integrated voice, video and binary data in a single substrate.

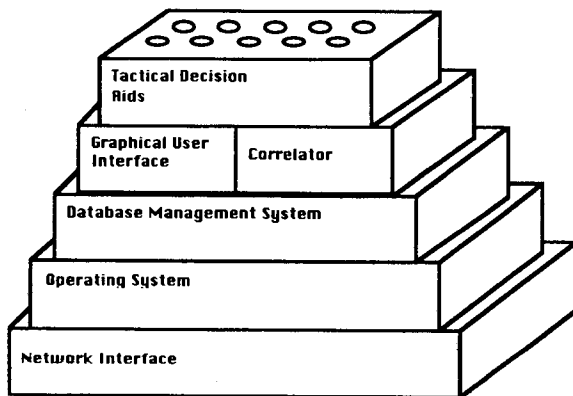


Figure 4 Anatomy of Decision Support Systems

- Layer 2. Computer systems require an operating system which schedules tasks for the central processing unit, organizes and maintains a file system, and controls communications input/output.

- Layer 3. The central function of a decision support system is to file data in a database and then extract appropriate views of the database for the user. In our anatomy illustration, the layers under the database management system are concerned with feeding data into the database. Those layers over the database management system are tasked with preparing the data and presenting a picture to the decision maker.

- Layer 4. The Graphical User Interface (GUI) is the means for making bits into graphics. When creating a tactical picture in the mind of a decision maker, graphics are far more effective at human communications than the written word so a powerful GUI is a pretty essential requirement in nearly all C3I decision support systems.

The correlator is the process that fuses, or links, chunks of data in the database to each other. This is

the essential process of transforming data into information.

- Layer 5. Finally, the tactical decision aids are those processes that help the decision maker operate on the information and produce decisions. Tactical decision aids are those which suggest resources to dispatch to a certain incident based on knowledge of resources, their capabilities and positions, probabilities of incidents and other factors.

Development of decision support systems is an evolutionary process highly dependent on users as they actually use the system. Given the prospect of many software releases in the process of maturing a product, a careful modularization and specification of the interfaces is both essential and complex.

Recommendations — radionavigation receivers

Now that we've built some information system context, we can lay out some recommendations for radionavigation receivers so that they can play their proper role.

Receivers will be providing data to multiple users, not just one. Therefore a network interface should be provided (not just a point-to-point serial interface). This interface should contain the following components.

1. A hardware interface for LANs, perhaps a wireless LAN one⁸,

⁸IEEE committee 802.11 is working on a wireless LAN interface standards.

2. To the network, the radionavigation receiver should appear as a managed object. This means it should contain a management interface that conforms to the SNMP MIB, particularly RMON⁹,

3. An application layer interface, either through an electronic mail user agent or the network management system¹⁰.

4. A publicized data definition in order to support integration of the positioning data into the decision support system's database.

Radionavigation receivers need to be built not as standalone devices, but with easy means of integration. Allow:

1. multiple receivers such as GPS, Loran, and RDSS to offset system deficiencies in urban environments.

2. Integration into the vehicle's overall control and information system.

Recommendations — underlying radionavigation systems

Both Loran and GPS have known problems in urban environments, a

⁹Simple Network Management Protocol, Management Information Base, Remote MONitoring protocol. All Internet protocols both documented in the Request for Comments (RFCs) and supported by multiple vendors.

¹⁰SNMP management consists of the network manager polling devices for information (gets), configuring devices (sets) and managed devices initiating messages (traps). It's entirely practical to include the positioning sentence from a radionav receiver as part of a get message.

good share of which can be blamed on the unalterable multipath present. Each radionavigation system tends to offset the other. Further, differential service improves both. View the radionavigation system as an amalgamation of Loran, GPS and differential service, not as separate components. And build your products accordingly.

Since community emergency services need the underlying network connectivity anyway, adding differential service on a local basis becomes quite practical.

Vehicles

View the vehicular information system as a whole. The user messaging interface, the positioning and navigation system, and the vehicle monitoring and control system all need to be thought of as components integrated into the complete automobile. Wireless LAN connectivity may be a convenient means, particularly with the advent of palmtop computers.

Conclusion

The information content of emergency services will continue to rise. Radionavigation systems properly play a role in the community's C3I system. Effective integration through standardized interfaces is the key to building a comprehensive, scalable and supportable information system.

Bio for Rex A Buddenberg

Mr Buddenberg teaches networking at the postgraduate level and consults on networking and C3I issues and programs. Current work includes writing the program plan to extend the Internet to the oceanographic fleet at sea.

Mr Buddenberg is a retired USCG officer. While on active duty he:

- served aboard two cutters,
- commanded a Loran station,
- managed lifeboat stations at a coastal group, and
- served in USCG Headquarters in technical billets relating to
 - cutter CIC modernization,
 - radionavigation, and
 - engineering planning.

His concluding job prior to 20 year retirement was as the C3I Architect of the Coast Guard.

Mr Buddenberg holds

- a masters degree in communications from the Naval Postgraduate School,
- a completion certificate from the Naval War College and
- a bachelors degree from the US Coast Guard Academy.

Been a member of Wild Goose Association since 1989.

AUTOMATIC PULSE SHAPING WITH THE AN/FPN-42 AND AN/FPN-44B LORAN-C TRANSMITTERS

LT Dean C. Bruckner, U.S. Coast Guard Electronics Engineering Center,
Wildwood, New Jersey, USA

Dr. Murali Tummala, Associate Professor, Naval Postgraduate School,
Monterey, California, USA

ABSTRACT

Automatic pulse shape control is simulated for the AN/FPN-42 and AN/FPN-44B Loran-C transmitters using a MATLAB computer program developed by the authors. The simulation program is very briefly reviewed and the approach to Loran pulse shape control is presented. A control algorithm based on the method of steepest descent is then implemented. In a variety of realistic tests the control algorithm successfully shapes the Loran-C pulse, except that zero-crossing times are not always in tolerance and the algorithm shows a sensitivity to noise. The algorithm controls Envelope-to-Cycle Difference, produces an entire Phase Code Interval of pulses while compensating for power supply droop and phase code bounce, and produces a near-optimal transmitter drive waveform for the transmitter/antenna system using the dummy load.

INTRODUCTION

The U.S. Coast Guard Electronics Engineering Center is incorporating the new VXIbus standard into a prototype replacement for its Loran-C Timing and Control Equipment suite. One of the goals of this project is to replace the manually-controlled pulse generators used for tube-type transmitters with automatically-controlled VXIbus arbitrary function generators (AFGs). Before this can be implemented, however, an algorithm to shape the Loran pulse automatically must be developed and tested.

THE MATLAB SIMULATION PROGRAM

A MATLAB computer program which simulates pulse shape control of the AN/FPN-42 and AN/FPN-44B Loran-C transmitters is developed in a companion paper [1]. Based on a nonlinear, time-varying model of each transmitter, the program includes all the details of each transmitter which affect pulse shape. Accordingly, the simulation results are realistic and are directly applicable to the Coast Guard's pulse-shaping work with the new VXIbus system. The user may set many of the simulation

parameters, as shown by the program's main menu in Figure 1.

THE PULSE SHAPE CONTROL APPROACH

The VXIbus system uses a batch processing approach to monitor and control the Loran-C pulse shape, as in Figure 2. The digital storage oscilloscope (DSO) captures and stores in memory an entire RF pulse. The control algorithm receives a parameterized form of the pulse and compares these parameters to those of the ideal pulse defined in the Coast Guard's Loran-C Signal Specification [2]. The algorithm then produces a new parameterized transmitter drive waveform (TDW), which is expanded into a digital data vector and then converted by the AFG to an analog TDW. This operation constitutes one iteration of the Loran-C pulse shape control loop.

The control algorithm uses a simple parameterization of 16 TDW half-cycle peak amplitudes

$$\mathbf{x}_p = [x_p(1), x_p(2), \dots, x_p(16)]' \quad (1)$$

and 16 RF pulse half-cycle peak amplitudes:

$$\mathbf{y}_p = [y_p(1), y_p(2), \dots, y_p(16)]' \quad (2)$$

The algorithm tracks these in successive control iterations; Figures 3 and 4 show this for $x_p(3)$ and $y_p(3)$. The ideal pulse's half-cycle peak amplitudes are

$$\mathbf{y}_{op} = [y_{op}(1), y_{op}(2), \dots, y_{op}(16)]' \quad (3)$$

and the output error vector is

$$\mathbf{e}_y = \mathbf{y}_p - \mathbf{y}_{op} = [e_y(1), e_y(2), \dots, e_y(16)]' \quad (4)$$

Thus, the Loran-C pulse shape control problem is essentially a 16-dimensional regulator problem where $\mathbf{y}_p$ is kept as close as possible to $\mathbf{y}_{op}$ [3].

LORAN-C TUBE TRANSMITTER SIMULATION
(c) Dean C. Bruckner & Murali Tummala, 1992

1. Transmitter:	AN/FPN-42	2. Xmtr load:	Dummy Load
3. Sampling freq:	10.00 MHz	4. Local ECD:	0.00 us
5. Resolution:	8 bits	6. Imbalance:	0.00
7. W. Noise pct:	0.39	8. Reset Xmtr	
9. Pulses to control:	[1]		
10. Pulses to analyze:	[1]		
11. Number of iterations:	100 (1st pulse), 20 (following pulses)		
12. Xmtr parameter drift occurs every	0 iterations w/ norm mag. 1		
13. Xmtr switch occurs every	0 iterations (1st pulse w/ drift on)		
14. Display method:	plot		
15. Control algorithm:	Steepest Descent		
16. Display/change current algorithm parameters			
17. Access keyboard		18. Exit	

Enter number(s) to change parameters or <Enter> to begin:

(e.g., 1 or [1 7 8]) ==>

Figure 1: Simulation Program's Main Menu

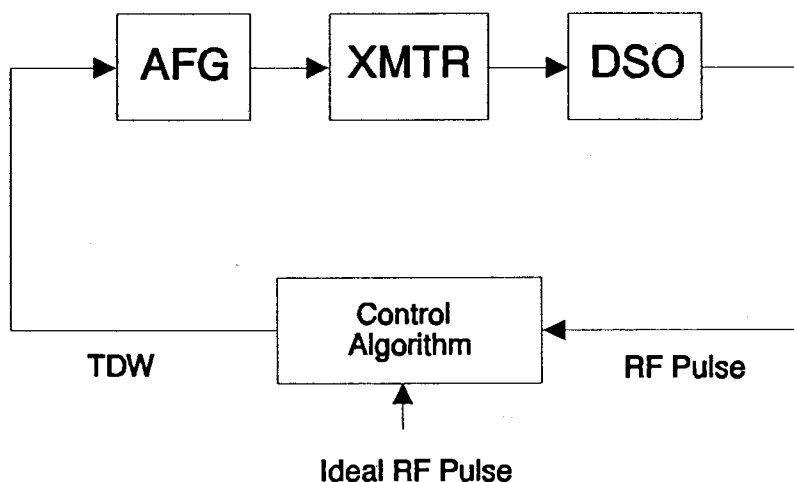


Figure 2: Pulse Shape Control Block Diagram

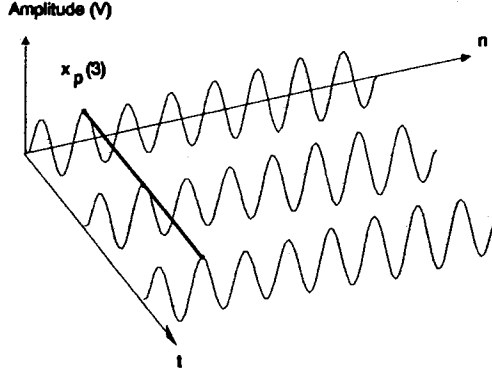


Figure 3: TDW in Successive Iterations

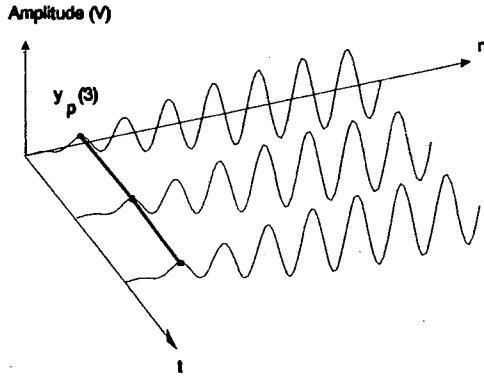


Figure 4: RF Pulse in Successive Iterations

THE STEEPEST DESCENT ALGORITHM

Derivation

A linear closed loop control algorithm based on the steepest descent approach effectively shapes the Loran-C pulse by minimizing the quadratic error $\mathbf{e}_y^T \mathbf{W} \mathbf{e}_y$, where $\mathbf{W}$ is a weighting matrix. This algorithm, developed by Peterson [4] and successfully implemented in a limited hardware simulation by Steinvorth [5], is derived as follows:

The transmitter is modeled as a linear system

$$\mathbf{A}_0 \mathbf{x}_p = \mathbf{y}_p, \quad (5)$$

where $\mathbf{A}_0$ is the matrix of impulse response samples (half-cycle peak amplitudes are used here):

$$\mathbf{A}_0 = \begin{bmatrix} h_p(0) & 0 & \dots & 0 \\ h_p(1) & h_p(0) & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ h_p(16) & h_p(15) & \dots & h_p(0) \end{bmatrix}. \quad (6)$$

Vector $\mathbf{x}_{0p}$ contains the optimum TDW half-cycle peak amplitudes. The ideal pulse peaks are produced by multiplying $\mathbf{x}_{0p}$ by the true (but unknown) system matrix $\mathbf{A}_0$:

$$\mathbf{A}_0 \mathbf{x}_{0p} = \mathbf{y}_{0p}. \quad (7)$$

The vector of errors in the TDW half-cycle peak amplitudes is

$$\mathbf{e}_x = \mathbf{x}_p - \mathbf{x}_{0p}. \quad (8)$$

Beginning with $\mathbf{A}$, the best estimate of $\mathbf{A}_0$, the initial vector (i.e., at $t=1$) of TDW half-cycle peak amplitudes is

$$\mathbf{x}_{0p} = \mathbf{A}_0^+ \mathbf{y}_{0p}. \quad (9)$$

At each iteration t , vector $\Delta \mathbf{x}_p$ updates $\mathbf{x}_p$ in the direction of steepest descent on the quadratic error surface defined by $\mathbf{e}_y^T \mathbf{W} \mathbf{e}_y$:

$$\Delta \mathbf{x}_p = -\frac{\mu}{2} \nabla_{\mathbf{e}_x} [\mathbf{e}_y^T \mathbf{W} \mathbf{e}_y]. \quad (10)$$

Here μ is a small constant greater than zero and $\nabla_{\mathbf{e}_x}[\kappa]$ is the vector of partial derivatives of scalar κ with respect to the elements of $\mathbf{e}_x$.

Equation 10 may be expanded to

$$\Delta \mathbf{x}_p = -\frac{\mu}{2} \nabla_{\mathbf{e}_x} [\mathbf{e}_x^T \mathbf{A}_0^T \mathbf{W} \mathbf{A}_0 \mathbf{e}_x]. \quad (11)$$

Diagonal matrix $\mathbf{W}$ weights the elements of $\mathbf{e}_x$ and $\mathbf{e}_y$. Setting $\mathbf{W} = \mathbf{I}$ weights the errors equally throughout the pulse, while using a $\mathbf{W}$ whose diagonal elements decrease in size from upper left to lower right implements a tighter tolerance in the first part of the pulse. Equation (11) becomes

$$\Delta \mathbf{x}_p = -\mu \mathbf{A}_0^T \mathbf{W} \mathbf{A}_0 \mathbf{e}_x, \quad (12)$$

then

$$\Delta \mathbf{x}_p = -\mu \mathbf{A}_0^T \mathbf{W} \mathbf{e}_y. \quad (13)$$

Known matrix $\mathbf{A}$ now takes the place of unknown $\mathbf{A}_0$, and the steepest descent algorithm results:

$$\mathbf{x}_{new} = \mathbf{x}_{old} - \mu \mathbf{A}^T \mathbf{W} \mathbf{e}_y. \quad (14)$$

The sign of $\Delta \mathbf{x}_p$ is reversed for negatively phase coded pulses. Finally, if $[\mathbf{A}^T \mathbf{W} \mathbf{A}_0]^{-1}$ is positive definite and

$$0 < \mu < \frac{2}{\text{largest eigenvalue of } [\mathbf{A}^T \mathbf{W} \mathbf{A}_0]}, \quad (15)$$

the steepest descent algorithm has a steady-state solution.

Advantages and Limitations

This algorithm works well and is simple, requiring only two (16 X 16) matrix multiplications per iteration. However, the algorithm is based on the assumption of an overall linear system and is unable to control zero-crossing times. Fortunately, these two limitations are not serious ones. By using small values of μ and a "standard" 16-half-cycle TDW, the controller keeps the transmitter confined to an approximately linear region. Zero-crossing times are adjusted as they have always been: by keeping the transmitters well-maintained and tuned to exactly 100 kHz. Having an algorithm that adjusts zero-crossing times automatically would be advantageous, but automatic pulse shaping can be successfully performed without one.

PULSE SHAPE CONTROL OF PULSE #1

Ideal Conditions ('42 Transmitter)

The steepest descent algorithm controls the shape of a single pulse of the '42 transmitter effectively in ideal conditions, as Figures 5 through 8 demonstrate. No noise has been added, quantization is set to the numerical precision of the computer, no amplifier imbalance is present and the station is single-rated. This case shows the best performance that can be expected of the algorithm. All half-cycle peak amplitudes of the initial TDW (at iteration $t=1$) are set to 0.4 volts, removing any *a priori* knowledge from the algorithm. Figure 5 shows the smooth convergence of the mean squared error $\mathbf{e}_y^T \mathbf{e}_y$, for 100 iterations, and Figure 6 presents the convergence of three measures of Loran-C error for the same 100 iterations. These are the half-cycle peak amplitudes (ensemble tolerance) and the half-cycle peak amplitudes (individual

tolerance) for half-cycles 1-8 and for half-cycles 9-13. The temporary rise in mean squared error between iterations 10 through 18 in Figure 6 results from linearly controlling a nonlinear system. Figures 7 and 8 show the ideal and synthetic RF pulses after 100 iterations and the optimum TDW that produces the synthetic pulse. In these plots, the normalized adaptation constant

$$\mu_n = \mu \frac{\text{largest eigenvalue of } [\mathbf{A}^T \mathbf{W} \mathbf{A}_0]}{2} \quad (16)$$

is set to 0.7.

Realistic Conditions ('42 and '44B Transmitters)

Next, a more realistic simulation is performed with the '42 transmitter. Noise and quantization are set to actual values and the program now simulates a dual-rated station. The steepest descent algorithm shapes pulse number one effectively and maintains the half-cycle peaks in tolerance for 78.3 percent of the control iterations examined. The program begins shaping the pulse using the dummy load, switches to the antenna at iteration 26, and brings the pulse into tolerance in four iterations. Also, other plots of this run (not shown here) reveal that transient errors due to dual-rating occur at iterations 11 and 24, without significantly affecting the algorithm's convergence. The half-cycle peaks, zero-crossings and Envelope-to-Cycle Difference (ECD) of the final RF pulse are in tolerance [2]. During convergence, however, the system noise repeatedly drives the pulse half-cycle peaks out-of-tolerance. This condition would probably not require blink, but these out-of-tolerance iterations are undesirable. They reveal, in any case, the algorithm's sensitivity to noise. Figures 9 through 12 show the plots for this run.

Similarly, in a realistic simulation of the '44B transmitter, the steepest descent algorithm successfully shapes pulse number one and maintains the half-cycle peaks in tolerance for 97.1 percent of the control iterations examined. The half-cycle peaks and ECD of the final RF pulse are in tolerance, but the first three zero-crossings of the pulse are not in tolerance. The '44B transmitter has a cleaner RF pulse than the '42 transmitter, and the algorithm performs much better as a result. The program switches from the dummy load to the antenna at iteration 38, and the transmitter comes on air in tolerance. Figures 13 and 14 are the error convergence plots for this run.

Other tests

In three other test cases the algorithm performs successfully. First, slow drifts are introduced and the

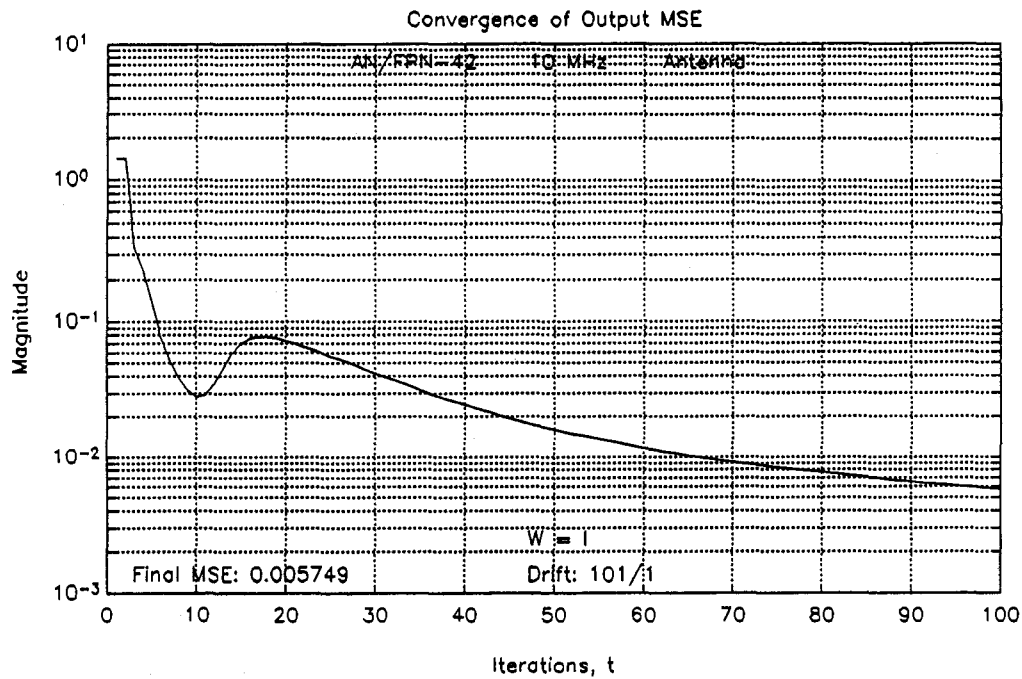


Figure 5: Convergence of Mean Squared Error, '42 Transmitter in Ideal Conditions

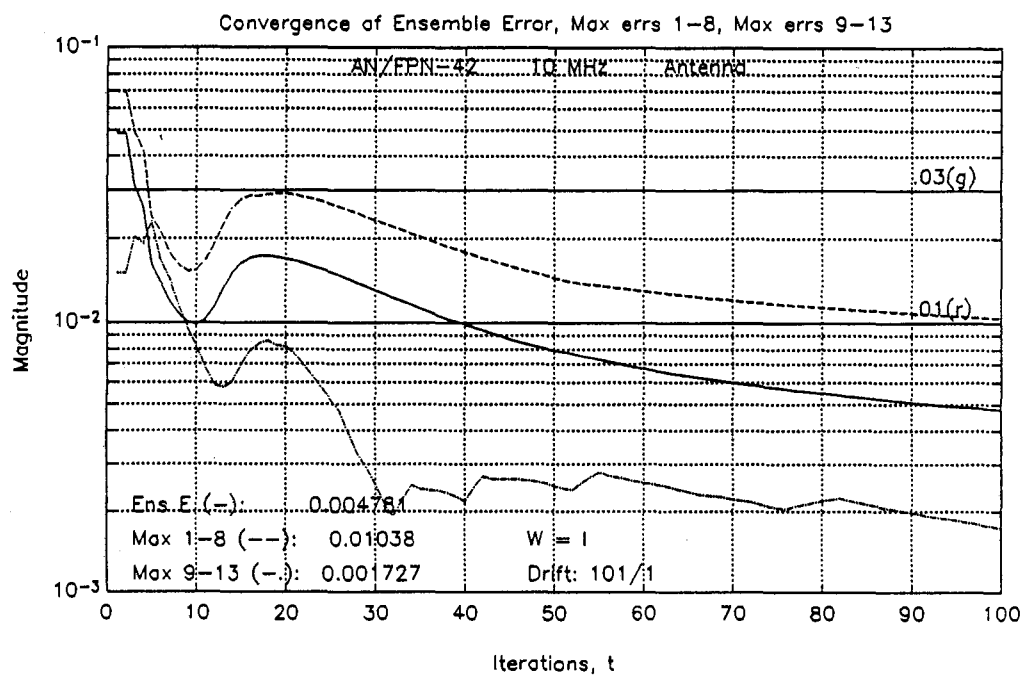


Figure 6: Convergence of Three Measures of Loran-C Error, '42 Transmitter in Ideal Conditions

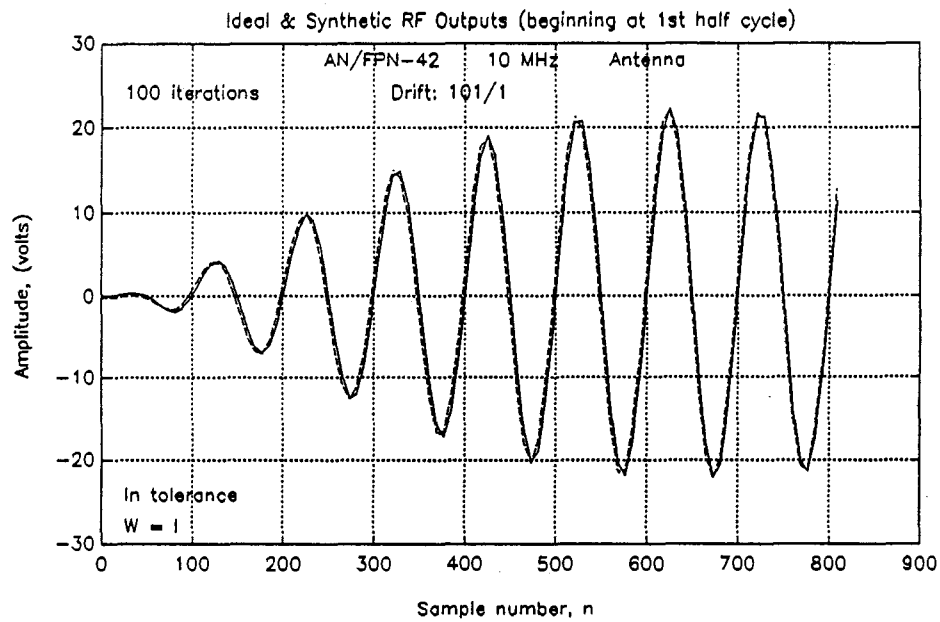


Figure 7: Ideal and Synthetic RF Pulses, '42 Transmitter in Ideal Conditions

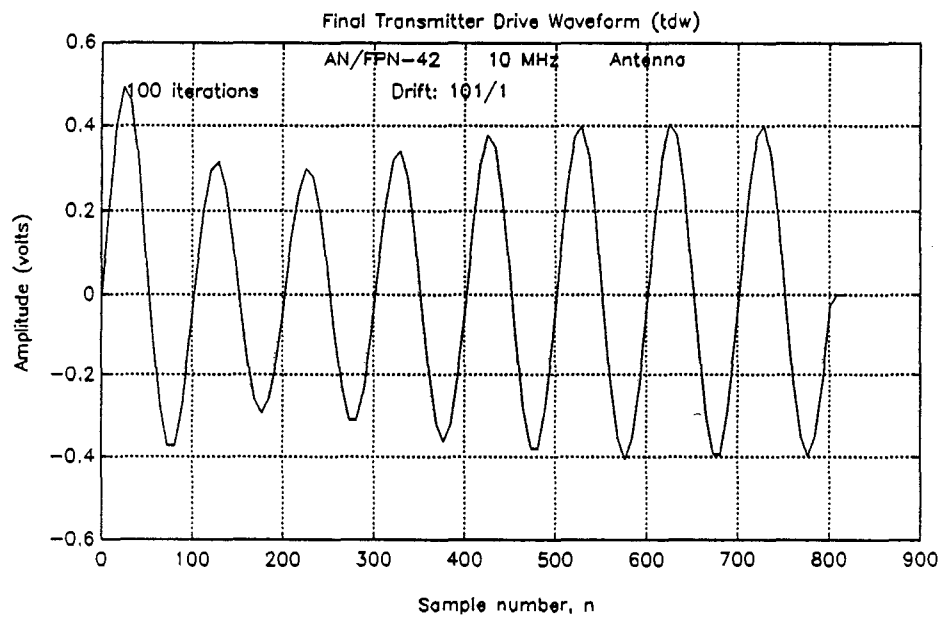


Figure 8: Optimum TDW, '42 Transmitter in Ideal Conditions

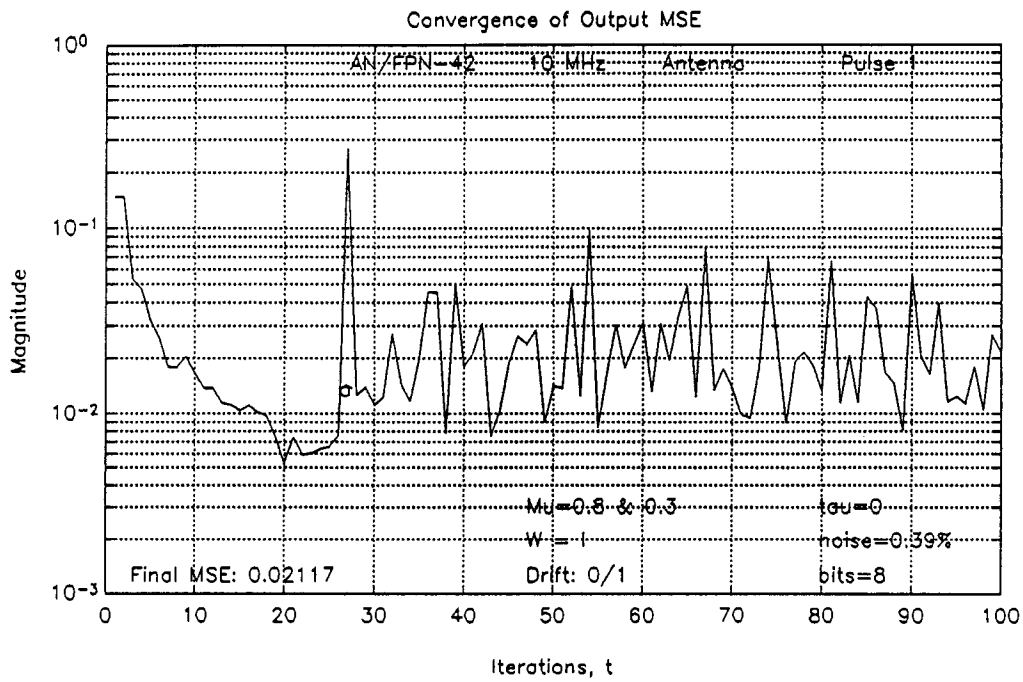


Figure 9: Convergence of Mean Squared Error, '42 Transmitter in Realistic Conditions

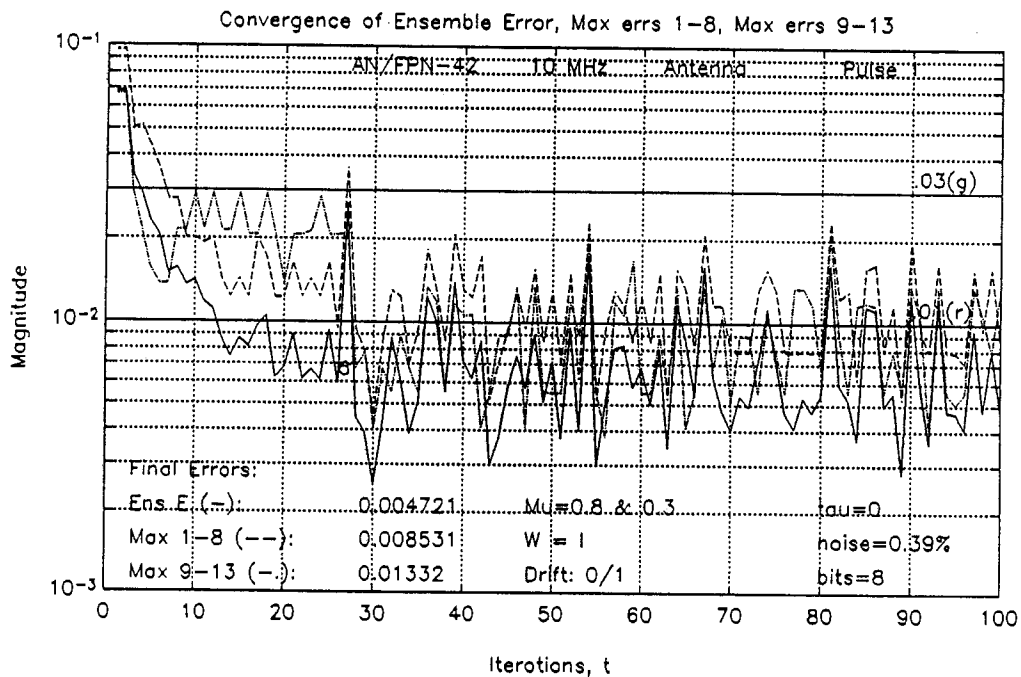


Figure 10: Convergence of Three Measures of Loran-C Error, '42 Transmitter in Realistic Conditions

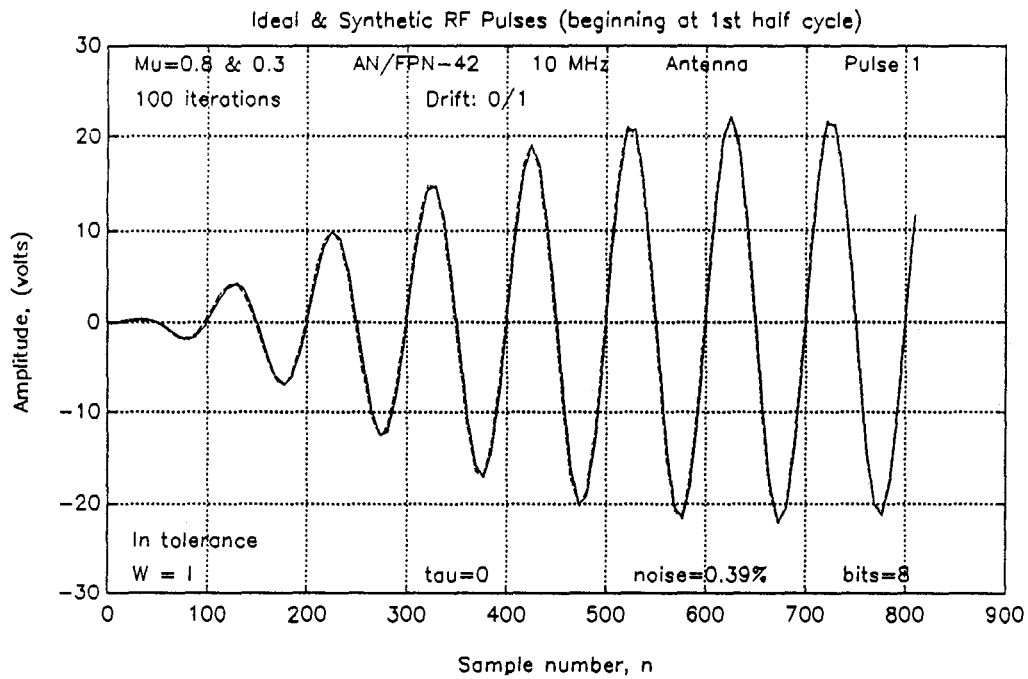


Figure 11: Ideal and Synthetic RF Pulses, '42 Transmitter in Realistic Conditions

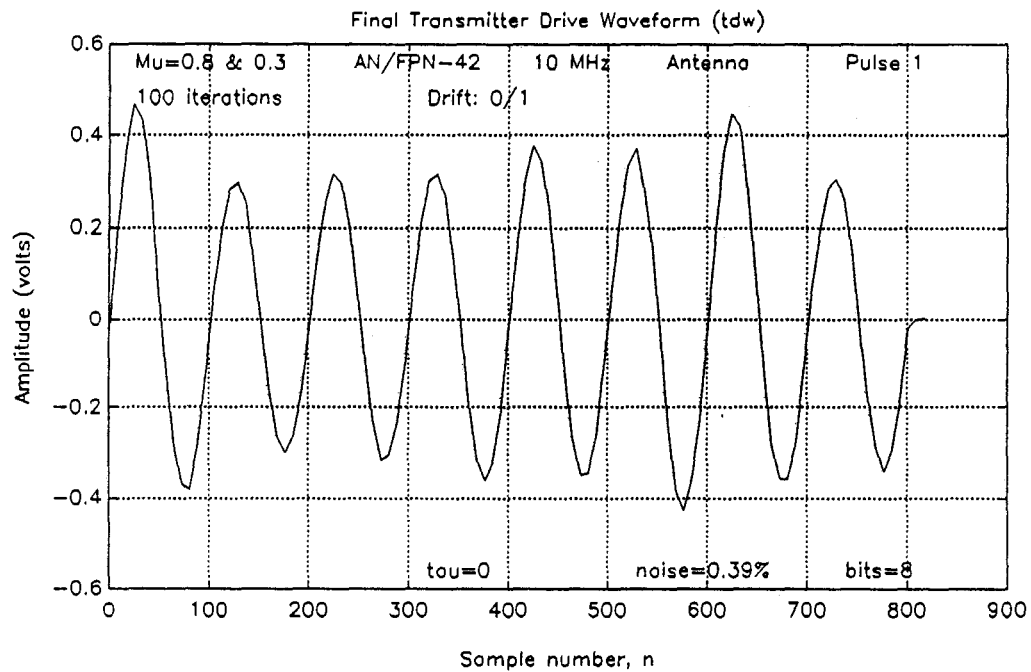


Figure 12: Optimum TDW, '42 Transmitter in Realistic Conditions

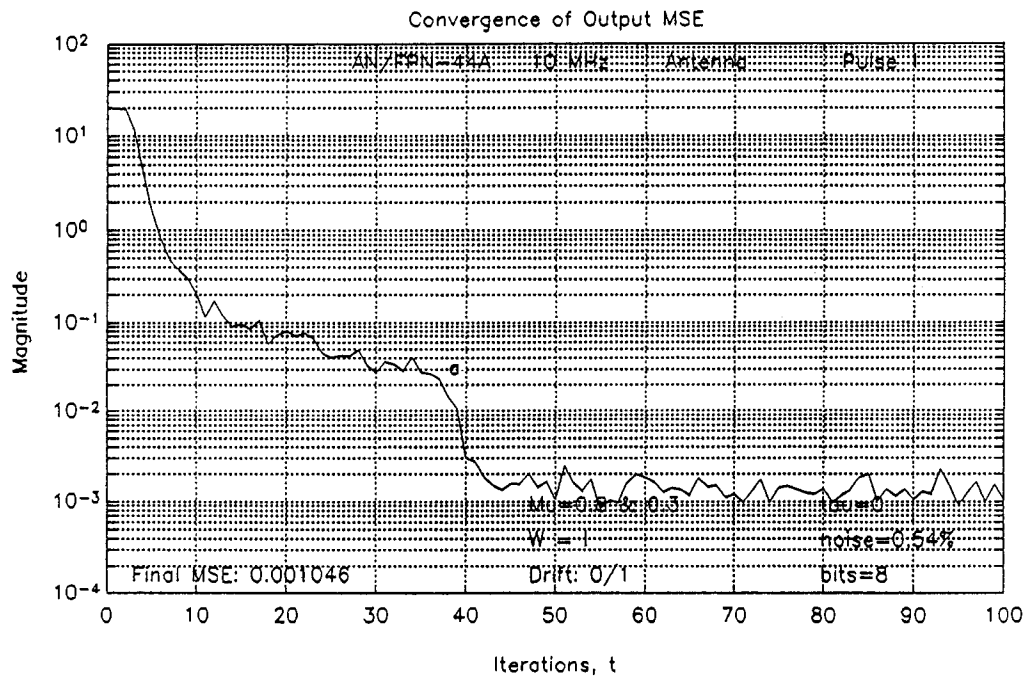


Figure 13: Convergence of Mean Squared Error, '44B Transmitter in Realistic Conditions

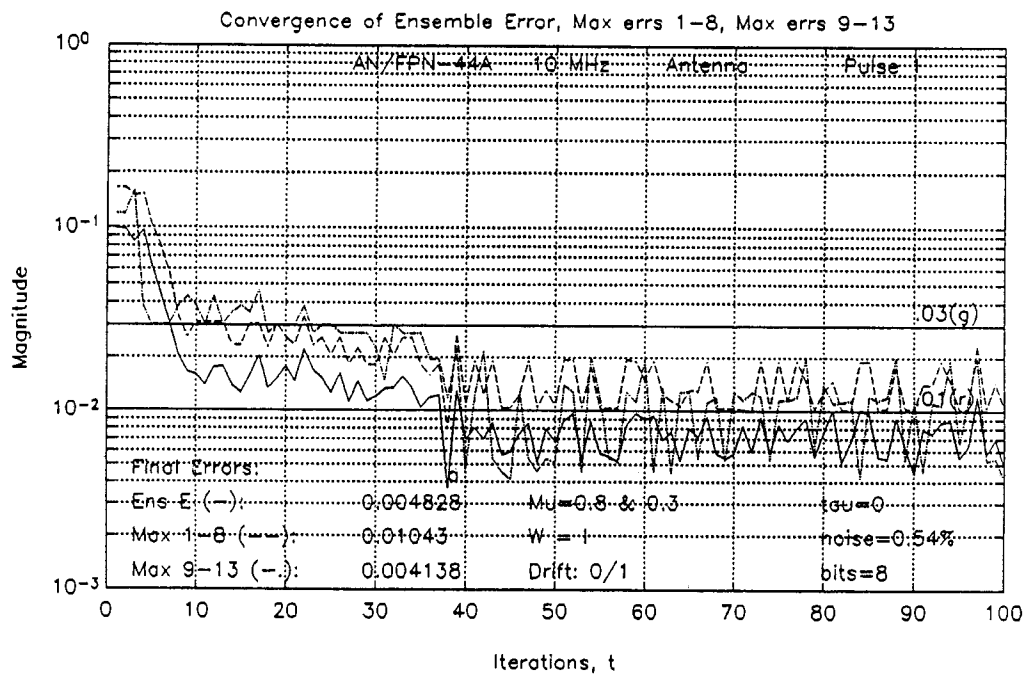


Figure 14: Convergence of Three Measures of Loran-C Error, '44B Transmitter in Realistic Conditions

errors are monitored over a simulated 24-hour period. The algorithm compensates for these time variations in the transmitter. Second, after a simulated transmitter switch the algorithm quickly brings the pulse shape back into tolerance in less than five iterations. Third, transient errors due to dual rating are introduced during and after the algorithm's convergence, with $\mu_n = 0.7$. In these iterations, droop reduces the pulse amplitude by one percent. In each case, the algorithm recovers in less than four iterations.

PULSE SHAPE CONTROL OF THE PCI

The steepest descent algorithm also effectively controls a whole PCI in a realistic simulation, with an added transmitter amplifier imbalance of 3.0 percent. The pulse-to-pulse ECD and pulse-to-pulse amplitude tolerances from the Signal Specification are easily met [2]. The algorithm is still sensitive to noise in pulses two through sixteen, but the features of the program designed to control those pulses work successfully. The program controls ECD without using an Envelope Timing Adjustment, keeps all pulse amplitudes the same without a separate droop correction circuit, and compensates for amplifier imbalance without a separate phase-code balance adjustment.

CONCLUSIONS

Three conclusions can be drawn. First, the steepest descent algorithm automatically shapes the pulse effectively in realistic simulations of both the '42 and '44B transmitters, with two shortcomings. The zero-crossing tolerances are exceeded sometimes with the '42 transmitter and always with the '44B transmitter, and the algorithm shows a sensitivity to system noise. This noise causes the pulse peaks to go out of tolerance frequently. Nevertheless, the algorithm maintains the ECD of pulse one in tolerance and quickly produces an entire PCI which meets the pulse group tolerances for amplitude and ECD, even with an added transmitter imbalance. The algorithm also restores proper pulse shape after transmitter switches within a few iterations.

Neither of these two shortcomings necessarily disqualify the algorithm even as presently implemented, for two reasons: the ability to control zero-crossing times is not an absolute requirement for a pulse-shaping algorithm; and the acceptable level of error for the VXIbus control strategy has not yet been defined. The Signal Specification's error tolerances should be interpreted as applying in steady state to an average of measurements; no tolerances for individual iterations have been established. In any case, improvements in these two areas will make the algorithm even more useful.

Second, the errors introduced into the algorithm's convergence by power supply droop at dual-rated stations are only transient. They cause the controller no significant problem.

Third, a near-optimum TDW for the transmitter with the antenna can be obtained successfully off-line using the dummy load. In this way, when switching to the antenna, a transmitter comes on-line in tolerance or nearly in tolerance.

REFERENCES

- [1] D. Bruckner, M. Tummala and G. Kmiecik, "A Computer Simulation for Pulse Shape Control of the AN/FPN-42 and AN/FPN-44B Loran-C Transmitters," *Proceedings of the Wild Goose Association Symposium*, October 1993.
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- [4] B. Peterson, "Closed Loop Control of Loran-C Pulse Shape for Tube Type Transmitters," Derivation, USCG Academy, 1988.
- [5] R. Steinvorth, "An Adaptive, Digital Loran-C Pulse Generator," Course Report, USCG Academy, 1989.

ABOUT THE AUTHORS

LT Dean Bruckner graduated from the Coast Guard Academy with a B.S.E.E. in 1985 and from the Naval Postgraduate School with an M.S.E.E. in 1992. He is an Engineering Project Manager in the Loran-C Branch at the Coast Guard Electronics Engineering Center.

Dr. Murali Tummala received a Ph.D. in Electrical Engineering from the Indian Institute of Technology in Bombay, India. He is an associate professor in the Department of Electrical and Computer Engineering at the Naval Postgraduate School, where he conducts research in adaptive signal processing and modeling of random processes and fields.

A COMPUTER SIMULATION FOR PULSE SHAPE CONTROL OF THE AN/FPN-42 AND AN/FPN-44B LORAN-C TRANSMITTERS

LT Dean C. Bruckner, U.S. Coast Guard Electronics Engineering Center,
Wildwood, New Jersey, USA

Dr. Murali Tummala, Associate Professor, Naval Postgraduate School,
Monterey, California, USA

LCDR Gregory A. Kmiecik, U.S. Coast Guard Electronics Engineering Center,
Wildwood, New Jersey, USA

ABSTRACT

A MATLAB computer program which simulates pulse shape control of the AN/FPN-42 and AN/FPN-44B Loran-C transmitters is developed in two stages. In the first stage, a dynamic model of each transmitter is obtained. The vacuum tube-type transmitter is assumed to be linear, time invariant (LTI) at a typical operating point. Using frequency-domain deconvolution and median smoothing, a unit sample response sequence is obtained at this operating point. An LTI pole-zero model for this sequence, obtained from the least-squares modified Yule-Walker method and Shank's method, is presented. Similar LTI models for a range of operating points and an extended period of time are catenated to represent observed nonlinear and time-varying behavior. In the second stage, the catenated models and transmitter system characteristics such as power supply droop, dual rating and noise are incorporated into a MATLAB pulse shape simulation program.

INTRODUCTION

The U.S. Coast Guard Electronics Engineering Center (EECEN), in cooperation with the Naval Postgraduate School, has recently initiated research to develop techniques for automatic pulse shape control of two classes of tube-type Loran-C transmitters, the AN/FPN-42 and the AN/FPN-44B. The VXibus Timing and Control Equipment suite should be able to perform the tedious task of shaping the transmitted pulse to fit the ideal pulse [1, 2]. A proven algorithm, however, is required. Because development work with these high-powered transmitters is best carried out in simulation, a dynamic computer model is needed to complete this work. In order for the results of the simulation to be valid, all of the details of the transmitter system that affect pulse shape must be included. The transmitter models presented here, and the simulation program in which they operate, meet these requirements.

MATLAB, a high-performance numeric computation program, is ideal for this development work. It easily handles the vectors and matrices used in this simulation and provides many useful signal processing tools. Because each statement is interpreted, MATLAB programs do not require compiling or linking as do programs in traditional computer languages.

DISCRETE-TIME MODELS OF THE '42 AND '44B VACUUM TUBE-TYPE TRANSMITTERS

Data

EECEN provided the paired input and output data sequences for this project. The Transmitter Drive Waveform (TDW) and Radio Frequency (RF) output voltages were simultaneously sampled at 10 MHz by a LeCroy 9410 digital oscilloscope with eight bits of resolution. The relatively high sample frequency preserves detailed zero-crossing information. The eight bits correspond to the amplitude resolution of the VXibus prototype's high-performance digitizer, the Tektronix VX5260A. The data includes a number of different TDW shapes, and each sequence has 4096 points.

Assumptions and Modeling Approach

A fundamental assumption was made that a tube transmitter is a nonlinear, time-varying system but behaves as a linear, time invariant (LTI) system at a given operating point and within a limited time interval [3]. This assumption is reasonable, since the '42 and '44B transmitters were designed to act as linear amplifiers and were originally driven by an ideal pulse input. The data also supports it, in that a synthetic output produced when a typical TDW and the transmitter's response to a test input are linearly convolved almost perfectly matches that TDW's actual output. Accordingly, a tube transmitter's

behavior at each operating point and within a limited time interval can be modeled as a single discrete-time unit sample response.

The transmitter's overall nonlinear behavior can be accurately represented by a number of these LTI models catenated as a function of some parameter of the transmitter's operating point. An examination of the data indicates that the shape of the TDW, particularly its length, is closely associated with these operating points. The energy of the TDW, with its maximum positive value normalized to one, quantifies this effectively and is easy to calculate.

Typical time variations of a transmitter can likewise be represented by moving from one LTI model to another, in this case as a function of elapsed time. Gradual time variations in tube transmitters occur over hours, days, and weeks due to weather, component aging and other factors. Step changes may occur when components are replaced or when transmitter station equipment is brought on-line or off-line. In the absence of severe weather conditions or component failure, the transmitter may be considered essentially time invariant for a period of several hours. Both gradual changes and step changes may be represented by using LTI models which differ from each other by varying degrees.

Estimating the Unit Sample Response ('42 Transmitter)

Building on the LTI assumption, frequency-domain linear deconvolution using the Discrete Fourier Transform (DFT) is adapted to estimate the unit sample response. In this operation, the DFT of the zero-padded output sequence is divided, sample by sample, by the DFT of the zero-padded input sequence. The resulting complex sequence $H(k)$ in the frequency domain may be interpreted as the DFT of the time-domain unit sample response $h(n)$. This sequence $h(n)$ is real and is calculated directly from $H(k)$ using the Inverse DFT (IDFT). Fast Fourier Transform (FFT) techniques are used to compute the DFT.

Spurious peaks in the frequency domain, however, are a significant problem in this approach. These occur when output DFT samples are divided by near-zero input DFT samples. Most of this numerical noise is removed by an ideal filter which zeroes the elements of $H(k)$ outside the 50 kHz (sample 40) to 150 kHz (sample 123) band. Sample 82 is at 100 kHz. However, spurious peaks also occur inside this band, as in Figure 1. If not removed, they produce significant distortion in $h(n)$. However, setting frequencies in this range to zero also distorts $h(n)$. A more sophisticated filter is needed.

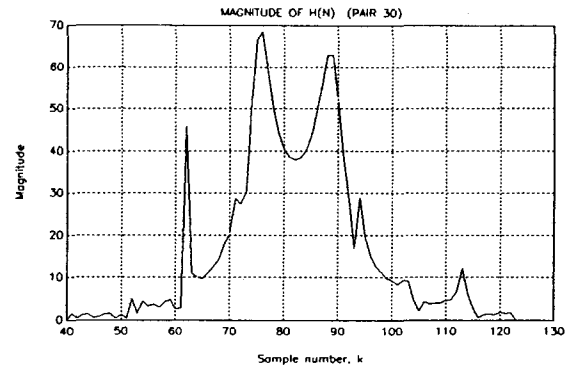


Figure 1: $H(k)$ with Spurious Peaks

The combination of median smoothing and lowpass linear filtering can remove the spurious peaks in $H(k)$ [4]. In this nonlinear technique, the signal is considered to be the sum of rough and smooth parts $R[H(k)]$ and $S[H(k)]$:

$$H(k) = R[H(k)] + S[H(k)]. \quad (1)$$

The running median $M_U[H(k)]$, simply the median of the U -point sequence $H(k-M+1), \dots, H(k-1), H(k), H(k+1), \dots, H(k+M-1)$, is used in place of sample $H(k)$. Here U is an odd integer and $M = (U+1)/2$. By removing single samples with large errors, this smoother separates the rough and smooth parts of the signal. Its output effectively follows a low-order polynomial curve without distorting the surrounding samples to the same degree as a linear filter would. A succession of a five-point median smoother and a three-point median smoother proved effective in this application. To soften the sharp discontinuities preserved by the smoothers, a three-point lowpass hanning filter follows them:

$$\begin{aligned} h(n) &= 1/4, & n &= -1 \\ &1/2, & n &= 0 \\ &1/4, & n &= 1. \end{aligned} \quad (2)$$

The three-stage smoother/filter is applied twice each to the frequencies 50-90 kHz (samples 41-74) and 110-150 kHz (samples 91-122) in $H(k)$. It is not applied to the Loran-C frequency band, 90-110 kHz, since no spurious peaks appear there.

This technique works well, as shown in Figure 2. The estimated unit sample response of Figure 3 represents the

$$y(n) + a_1 y(n-1) + \dots + a_P y(n-P) = b_0 x(n) + b_1 x(n-1) + \dots + b_Q x(n-Q). \quad (3)$$

Here $y(n)$ is the n th sample of the output sequence and $x(n)$ is the n th sample of the input sequence. Coefficients $\mathbf{a} = [1, a_1, \dots, a_P]$ and $\mathbf{b} = [b_0, \dots, b_Q]$ are real and constant. This representation is more efficient than the FIR sequence, because there are far fewer parameters; and more useful, because the roots of the IIR parameters have physical significance. Complex pole pairs represent the natural or resonant frequencies of the system while zeros represent the system's delays, gains, losses and initial conditions [5].

The least squares modified Yule-Walker method yields the $\mathbf{a}$ parameters of the IIR model of $h(n)$ while Shank's method is used to estimate the $\mathbf{b}$ parameters. [5, 6, 7]. These methods are selected because of their proven performance in modeling transient signals in the time domain. Model order $P=4$, $Q=3$ balances the competing needs for accuracy and model simplicity. Vectors $\mathbf{a}$ and $\mathbf{b}$ model $h(n)$ of Figure 3 with the minimum mean squared error:

$$\mathbf{a} = \begin{bmatrix} 1.00000000 \\ -3.98522848 \\ 5.96373738 \\ -3.97173137 \\ 0.99323802 \end{bmatrix} \quad \mathbf{b} = \begin{bmatrix} 0.03984064 \\ -0.12702893 \\ 0.13499076 \\ -0.04782358 \end{bmatrix}. \quad (4)$$

These may be factored into poles and zeros:

$$\text{poles} = \begin{bmatrix} 0.9982 e^{+j0.0683} \\ 0.9982 e^{-j0.0683} \\ 0.9984 e^{+j0.0578} \\ 0.9984 e^{-j0.0578} \end{bmatrix} \quad (5)$$

$$\text{zeros} = \begin{bmatrix} 1.0296 e^{+j0.0551} \\ 1.0296 e^{-j0.0551} \\ 1.1324 e^{j0} \end{bmatrix}.$$

relatively low-order system dynamics virtually free of random noise and of the numerical errors inherent in the frequency-domain deconvolution technique. This $h(n)$ is tested satisfactorily using linear convolution as before, with a similar TDW and RF output pair.

A Pole-Zero Model of the Unit Sample Response ('42 Transmitter)

This finite impulse response (FIR) sequence is now modeled as an infinite impulse response (IIR) system, according to the constant-coefficient difference equation

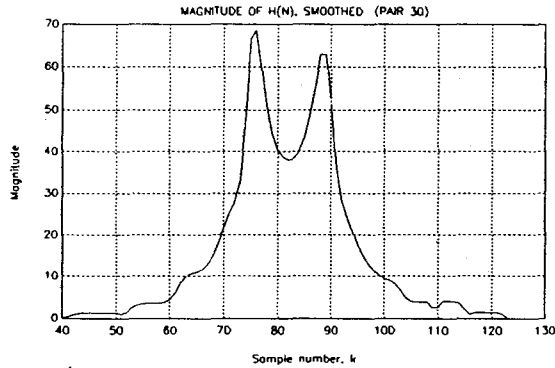


Figure 2: Smoothed and Filtered $H(k)$

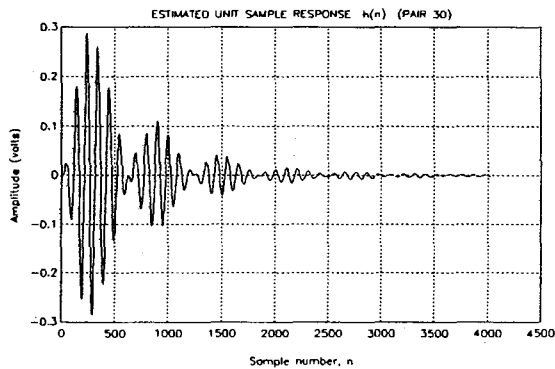


Figure 3: Unit Sample Response $h(n)$

Because the poles are so close to the unit circle, coefficient vectors $\mathbf{a}$ and $\mathbf{b}$ require the additional numerical precision shown in (4) to ensure stability. When $\mathbf{a}$ and $\mathbf{b}$ are substituted into Equation (3), a unit sample input yields the model sequence $h_{AB}(n)$. Figure 4 contains a z-plane plot of these poles and zeros while Figure 5 is a time-domain plot of $h(n)$ and $h_{AB}(n)$. A synthetic RF output pulse is also produced by convolving a typical TDW with $h_{AB}(n)$; the actual and synthetic outputs appear in Figure 6.

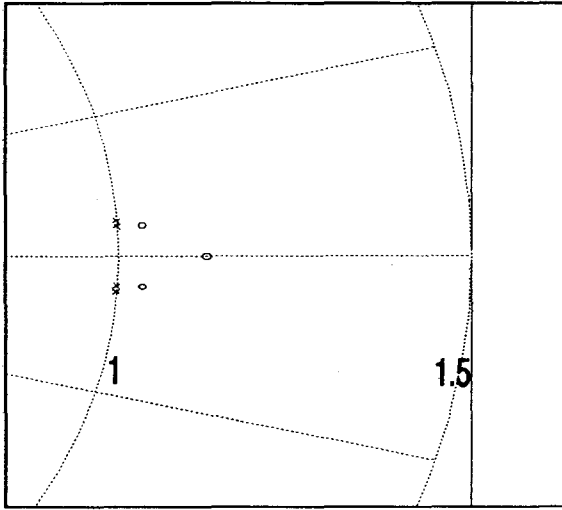


Figure 4: Z-plane Plot of Poles and Zeros

The excellent time-domain matches in Figures 5 and 6 indicate that the pole-zero modeling algorithm has performed well. This model further identifies the tube transmitter as a non-minimum phase system which cannot be inverted, as that would result in an unstable system. Controlling this system using certain algorithms is potentially more difficult than controlling minimum phase systems.

Catenating the LTI Models ('42 Transmitter)

The catenated model may be expressed as a linear difference equation with *non-constant* coefficients:

$$y(n) + a_1(t, E)y(n-1) + \dots + a_p(t, E)y(n-P) = b_0(t, E)x(n) + b_1(t, E)x(n-1) + \dots + b_q(t, E)x(n-Q) \quad (6)$$

Here each coefficient is a function of TDW energy E , which accounts for the transmitter's nonlinear behavior; and of elapsed time, t , which indexes time variations. Both n and t are integer indices of discrete time, but they are used differently. Index n , a multiple of the uniform 100 ns sampling interval, appears in equations which represent transmitter dynamics within a period of 409.6 μ s. This period is too short to experience the time variations described above. Index t , on the other hand, is a multiple of the interval at which a pulse shape controller samples and stores specified Loran pulses. A reasonable value for this interval is 3 seconds. Every t_d iterations of t ,

coefficients $a(t, E)$ and $b(t, E)$ are incrementally changed. Using a realistic value of $t_d = 300$, the parameters change incrementally every 15 minutes; after a few hours these changes may become noticeable. For analysis and testing, the rate of the time variations may be increased by lowering t_d , in effect compressing the time scale along t .

This catenated model may be constructed by gathering TDW and RF output data pairs for a range of t and E and estimating the unit sample response, and then the poles and zeros, for each pair. Each pole and zero can be further divided into magnitude and phase. This results in $2P + 2Q$ data sets, each a function of t and E . A three-dimensional polynomial surface can then be fit to each data set. The eighty-six data pairs provided do not cover the domain of t and E sufficiently to form these surfaces, so the surfaces are generated synthetically in two steps. First, polynomial curves are fit to each set as a function of E , as in Figure 7:

$$P(E) = c_k(E)^k + c_{k-1}(E)^{k-1} + \dots + c_1 E + c_0 \quad (7)$$

Next, the polynomial's constant term c_0 is made to vary with t according to a double-pole random process which generates slow drifts:

$$c_0(t) - 2(0.996)c_0(t-1) + (0.996)^2 c_0(t-2) = w(t) \quad (8)$$

where $w(t)$ is one sample of a white noise sequence with variance 6.25×10^{-8} . The surface in Figure 8 is generated in this way.

Given a TDW and the time index t_0 , the model produces a synthetic RF output sequence. The energy of this TDW, E_0 , is computed and each surface then is evaluated at (t_0, E_0) . This yields the magnitude and phase of each pole and zero, which together form an LTI model. The TDW is linearly convolved with the model's unit sample response to produce the synthetic RF output sequence.

The catenated model thus meets the need for which it is designed: it simulates all the observed nonlinear and time-varying behaviors of the transmitter during the convergence of a pulse-shape control algorithm. As the control algorithm changes the TDW shape, the model's transfer function changes also, just as the real transmitter's transfer function does. This dynamic feature allows pulse shape control algorithms to be tested realistically in simulation.

A Pole-Zero Model of the '44B Transmitter

A catenated model for the '44B transmitter, with order $P=6, Q=5$, is also found. A typical LTI model is

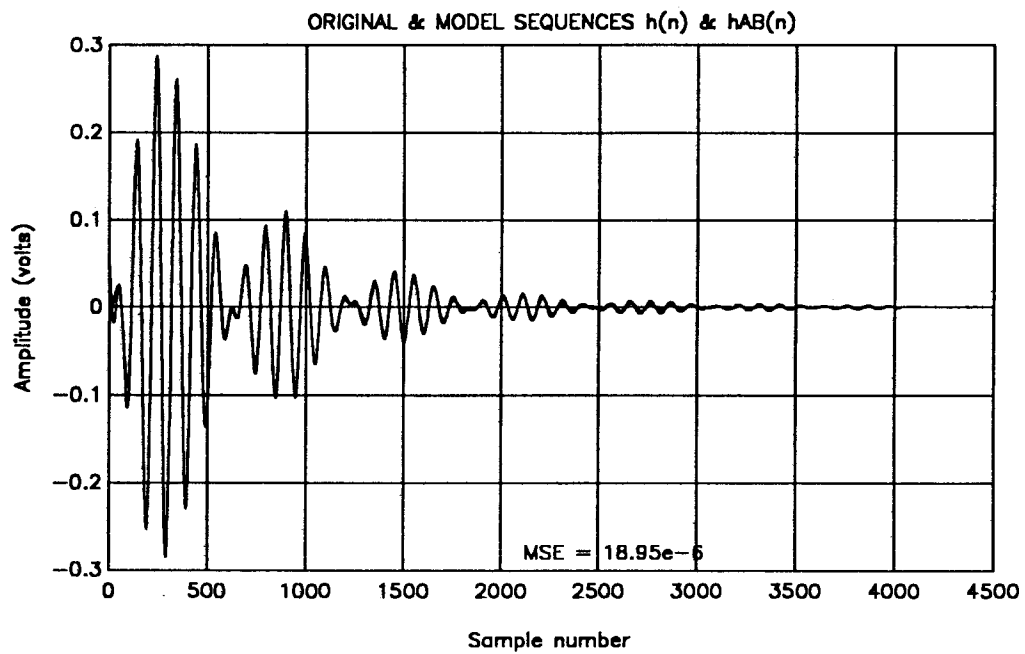


Figure 5: Original and Model Sequences $h(n)$ and $h_{AB}(n)$

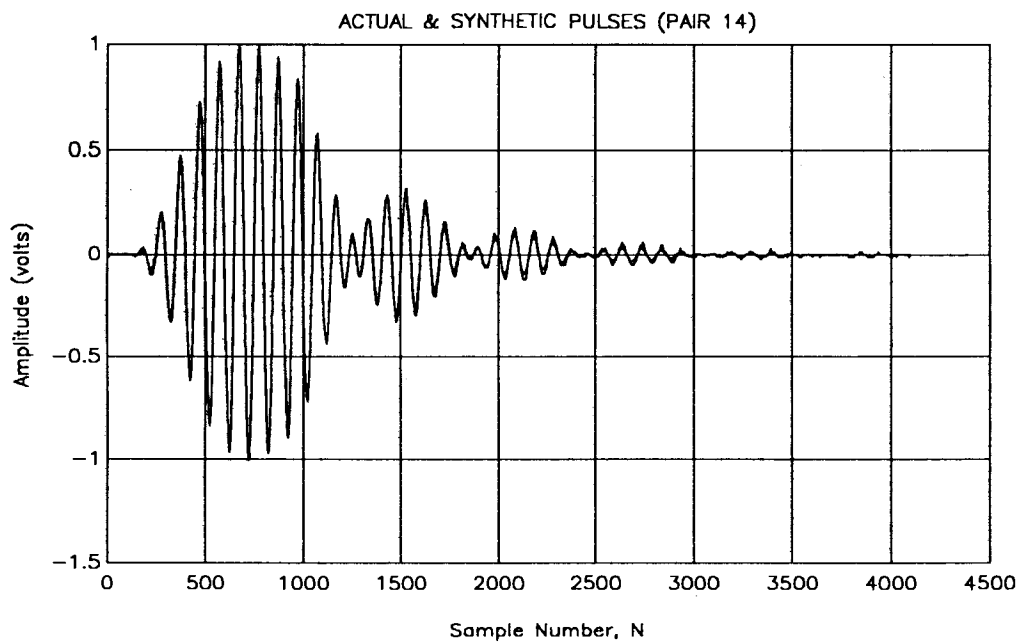


Figure 6: Actual and Synthetic RF Output Pulses

$$\mathbf{a} = \begin{bmatrix} 1.0000000000 \\ -5.9647497664 \\ 14.8366513380 \\ -19.6988259169 \\ 14.7241150625 \\ -5.8746083767 \\ 0.9774177080 \end{bmatrix} \quad \mathbf{b} = \begin{bmatrix} -0.0055248619 \\ 0.0277593170 \\ -0.0558484324 \\ 0.0562397791 \\ -0.0283473184 \\ 0.0057215159 \end{bmatrix} \quad (9)$$

The poles and zeros are

$$\text{poles} = \begin{bmatrix} 0.9950 e^{+j0.0820} \\ 0.9950 e^{-j0.0820} \\ 0.9986 e^{+j0.0632} \\ 0.9986 e^{-j0.0632} \\ 0.9950 e^{+j0.0423} \\ 0.9950 e^{-j0.0423} \end{bmatrix} \quad (10)$$

$$\text{zeros} = \begin{bmatrix} 0.9980 e^{+j0.0974} \\ 0.9980 e^{-j0.0974} \\ 1.0229 e^{+j0.0399} \\ 1.0229 e^{-j0.0399} \\ 0.9937 e^{j0} \end{bmatrix}$$

All the data vectors for the '44B transmitter were obtained on the same day, so typical time variations of this transmitter model are inferred from the '42 data.

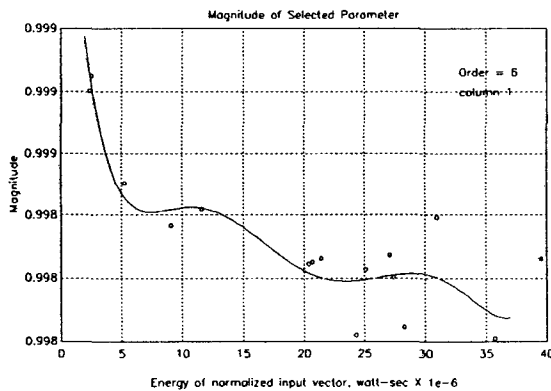


Figure 7: Polynomial Curve (Outer Pole Pair)

Dummy Load Models of the '42 and '44B Transmitters

Each tube-type transmitter is outfitted with a resistive dummy load to test the transmitter off-air at full power.

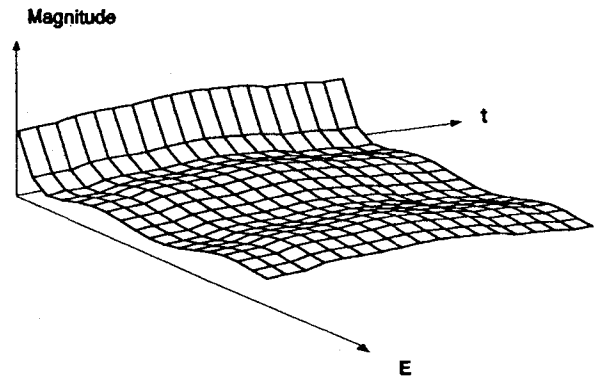


Figure 8: Polynomial Surface (Outer Pole Magnitude)

Pole-zero models of the '42 and '44B transmitters connected to the dummy load are useful for simulating pulse shape control off-air, as the next section describes. The '42 transmitter at a typical operating point with dummy load is modeled as

$$\text{poles} = \begin{bmatrix} 0.9959 e^{+j0.0633} \\ 0.9959 e^{-j0.0633} \end{bmatrix} \quad (11)$$

$$\text{zeros} = [1.0345]$$

The dummy load model for the '44B transmitter is

$$\text{poles} = \begin{bmatrix} 0.9974 e^{+j0.0586} \\ 0.9974 e^{-j0.0586} \\ 0.9691 e^{+j0.0667} \\ 0.9691 e^{-j0.0667} \end{bmatrix} \quad (12)$$

$$\text{zeros} = \begin{bmatrix} 0.9886 e^{+j0.0667} \\ 0.9886 e^{-j0.0667} \\ 0.9871 e^{j0} \end{bmatrix}$$

The purely resistive load produces fewer system resonances than does the antenna, so it requires fewer model parameters.

THE MATLAB SIMULATION PROGRAM

Program Structure

The catenated model is placed into a pulse shape control loop to form the key part of the MATLAB simulation program. The transmitter model is the feedforward part of

User-selectable features

The simulation program's main menu, shown in Figure 10, lists the user's options. Each feature tests a different aspect of a pulse shape control algorithm. Both the '42 and '44B transmitters are available, either with the dummy load or antenna. The program is designed to be able to shape the pulse on the dummy load; that is, it uses the dummy load to produce a near-optimum TDW for the antenna. If the program begins on the dummy load, it switches automatically to the antenna when the output errors fall below a threshold. After switching, the RF output pulse should be in tolerance or nearly in tolerance as defined in [2]. Once a control algorithm is added to this program, the "ideal" dummy load RF output pulse used in this process may be obtained by allowing the algorithm to converge on the antenna, switching to the dummy load and recording the output of this TDW.

Sampling frequencies of 1.25 MHz, 2.5 MHz and 5 MHz are available as well as the 10 MHz described above. At the lower sampling frequencies the program runs faster but is more susceptible to oscillations in the control loop. The user may also set Envelope-to-Cycle Difference (ECD) to any desired value in the interval $-2.5 \mu s < \tau < 2.5 \mu s$. An ideal pulse with this ECD is then provided to the control program.

Neither of the discrete-time models in this program simulates solely the analog transmitter; rather, each simulates the combination of an arbitrary function generator, the transmitter, and a digital storage oscilloscope. The amplitude resolution of the function generator and the oscilloscope, in bits, may be set by the user. With regard to system noise, the program incorporates the noise model shown in Figure 11. The noise present in the data pairs may be duplicated in simulation by selecting 8-bit quantization and adding white noise to the synthetic TDW and synthetic RF pulse until the SNRs of both match the average SNRs of the actual data.

Imbalance in the two amplifier banks of the transmitter causes the negative and positive pulses in a PCI to have different amplitudes. This appears as phase code "bounce" when the two Group Repetition Intervals (GRIs) in a PCI are superimposed on an oscilloscope. The program allows the user to introduce up to a five percent amplitude difference between positive and negative pulses.

The program sequentially controls any or all of the pulses in a PCI; a detailed analysis of each pulse is also available after the algorithm has finished shaping it. The rate and

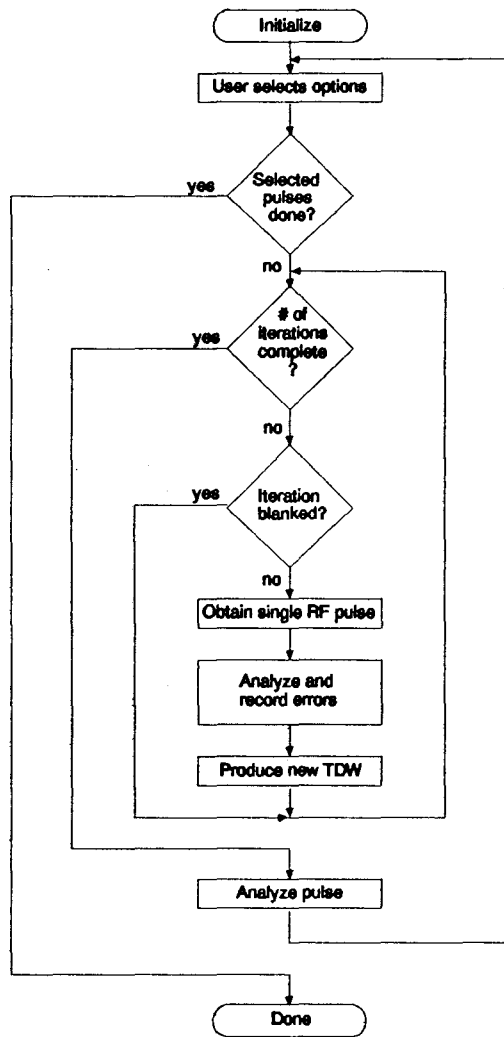


Figure 9: Simulation Program's Basic Structure

the loop; a pulse-shape control algorithm (not specified in this paper) is the feedback part. The simulation program's basic structure appears in Figure 9. The user selects which pulses of the Phase Code Interval (PCI) are to be controlled sequentially, and the number of control iterations desired for the first and following pulses. Other options are also available and are described in the next section. Beginning with the first selected pulse, the program executes the pulse shape control loop the specified number of times, skipping over any PCIs that have been blanked due to dual rating. Pulse shape errors are computed and recorded in each iteration so the user may review the algorithm's convergence.

LORAN-C TUBE TRANSMITTER SIMULATION
Dean C. Bruckner & Murali Tummala, 1992

1. Transmitter: AN/FPN-42	2. Xmtr load: Dummy Load
3. Sampling freq: 10.00 MHz	4. Local ECD: 0.00 us
5. Resolution: 8 bits	6. Imbalance: 0.00
7. W. Noise pct: 0.39	8. Reset Xmtr
9. Pulses to control: [1]	
10. Pulses to analyze: [1]	
11. Number of iterations: 100 (1st pulse), 20 (following pulses)	
12. Xmtr parameter drift occurs every 0 iterations w/ norm mag. 1	
13. Xmtr switch occurs every 0 iterations (1st pulse w/ drift on)	
14. Display method: plot	
15. Control algorithm: Steepest Descent	
16. Display/change current algorithm parameters	
17. Access keyboard	18. Exit

Enter number(s) to change parameters or <Enter> to begin:

(e.g., 1 or [1 7 8]) ==>

Figure 10: Simulation Program's Main Menu

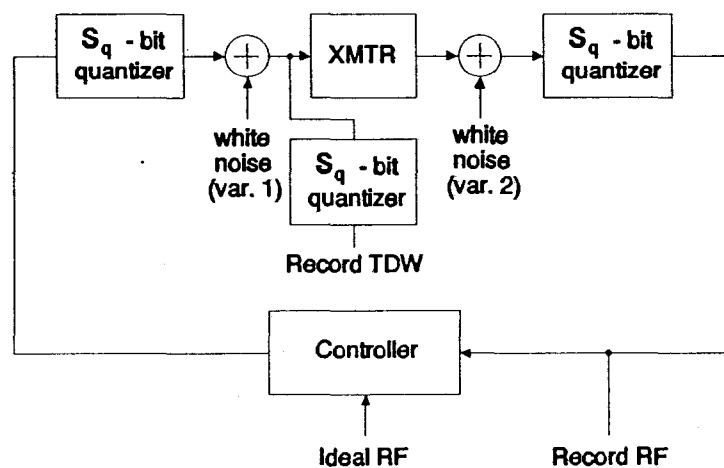


Figure 11: Simulation Program's Noise Model

magnitude of the transmitter parameter drifts described in Equation (8) can also be set by user. By introducing a random step change into the $c_d(t)$ parameter for the magnitude and phase of each pole and zero, the program simulates a transmitter switch at regular intervals set by the user. In this way, an algorithm may be tested with an infinite number of different '42 and '44B transmitter models, as no two random settings of the $c_d(t)$ parameters are exactly alike. The user may monitor the convergence errors of an algorithm with a graph or rows of text.

Other features

Power supply droop creates a problem for a closed-loop pulse shape control system. When the transmitter's power supply does not recover fully between pulses, the amplitude of the next pulse will be slightly smaller. The transmitter's power supply is modeled here as an energy-storing circuit which discharges instantaneously when a pulse is transmitted and then recharges exponentially afterwards. Various droop characteristics can be simulated by changing the amount of energy discharged or the rate at which it is recharged.

At a dual-rated station, the pulse group of one rate may closely follow the pulse group of the other. This accentuates the power supply droop problem. A pulse in the second group, when sampled by a pulse shape controller, will be noticeably smaller than those obtained in previous or subsequent iterations. This introduces into the control loop a transient disturbance, one which an algorithm must be able to handle. The program includes a sophisticated dual-rate timing function to simulate realistically the time interval preceding the sampled GRIs, and to blank the sampled rate appropriately. The user may choose any two rates by modifying the setup routine.

CONCLUSIONS

Based on all the data available, the MATLAB simulation program and the nonlinear, time-varying models it contains accurately represent the behavior of the '42 and '44B transmitter systems over the range of operating points used. The assumption of LTI behavior at each operating point is valid, and the model reproduces this behavior faithfully. The details of Loran operation included in the program make the simulation a realistic one. Therefore, the program is a useful tool for developing pulse shape control algorithms, and its results are directly applicable to the Coast Guard's work with the new VXibus system. This new Timing and Control Equipment suite will provide the transmitter drive for the Loran-C system of the twenty-first century.

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ABOUT THE AUTHORS

LT Dean Bruckner graduated from the Coast Guard Academy with a B.S.E.E. in 1985 and from the Naval Postgraduate School with an M.S.E.E. in 1992. He is an Engineering Project Manager in the Loran-C Branch at the Coast Guard Electronics Engineering Center.

Dr. Murali Tummala received a Ph.D. in Electrical Engineering from the Indian Institute of Technology in Bombay, India. He is an associate professor in the Department of Electrical and Computer Engineering at the Naval Postgraduate School, where he conducts research in adaptive signal processing and modeling of random processes and fields.

LCDR Greg Kmiecik completed a B.S.E.E. at the Coast Guard Academy in 1979 and an M.S.E. in Computer Engineering at the University of Michigan in 1983. He is the Assistant Chief of the Loran-C Branch at the Coast Guard Electronics Engineering Center.

The Future of Radionavigation Framing the Debate

Rex A Buddenberg

Buddenberg Consulting
budden@shell.portal.com

Abstract

The business of provision of radionavigation services is changing dramatically. The technology will change more radically in the coming decade than it has in the past one. The economic barriers to entry for service providers have decreased; provision of services will effectively cease being a government monopoly. And the user base is changing. All sorts of users are joining the traditional maritime and aviation user community ... with a set of requirements of a slightly different color -- the nature of radiopositioning use is altering. Often the purpose that radionavigation is used for is less that of telling a vehicle where it is and more telling the vehicle's dispatcher where the vehicle is.

While systems engineers seek ways to avoid reinventing wheels, the politicians are reinventing government with abandon. The budget drills associated with trying to save a few taxpayer dollars frequently tend to get shrill and religious, closing the window on sober policy discussions. Let's attempt to set out a framework for those sober policy discussions before the political

process overtakes us. We do not attempt to here answer the questions, only to suggest the ones that belong on the national and international agendas.

The Changing Technology of Radionavigation

For years, when one spoke of radionavigation, the topic revolved almost wholly around Loran and Omega with the non-US players chiming in about Decca and a few other government-operated systems. Then GPS started to become more than just a DoD program as the satellites began launching. During most of the 1980s, the discussion has been between Loran/Omega and GPS. And too often, the term 'versus' rather than 'with' was used as the conjunction (also rather shrilly on occasion). In time, GLONASS got added to the suite. But throughout this continuing discussion, a tacit assumption was that radionavigation was a service that government, on either the national or international level, provided.

Further technological advance is occurring which makes this 'which system' discussion almost moot. First,

we see the Loran vs GPS is a discussion now overtaken by dGPS. Secondly, that discussion will soon be overtaken by the advent of commercial (i.e. non-governmental, taxable, for-profit) providers. These changes threaten to occur with greater rapidity than successive editions of the Federal Radionavigation Plan.

Differential GPS

The first piece of heresy is the practical addition of dGPS to the pantheon of radionavigation technology. Because the US Coast Guard is developing a dGPS deployment, this tends to mask the

commercial aspects of the problem, but it certainly calls into question some of the existing radionavigation structure.

Given a dGPS deployment, what does Loran bring to the table? If the discussion revolves wholly around the question of accuracy and precision, then the answer may well be 'nothing'. If, however, the discussion is framed on the high availability and integrity requirements, and if we have compunctions about placing all our radionavigation eggs in space-based baskets, then there may well be a continuing role. Here, we must take a look at the prospective user base -- somewhat more than just the maritime and aviation users.

Questions:

- Is GPS + dGPS a complement or replacement for Loran (and, for you Europeans, for Decca)? What attributes does Loran bring to the overall capability that are not met or exceeded by the GPS + dGPS suite?

This is an interesting question in itself. But it also dangles several follow-on questions to an investigator.

Commercial providers

The economics of radionavigation provision have been such that the service has historically been a government monopoly. There is nothing that says that this is the way it always has to be -- there just haven't been economically feasible alternatives.

This too is changing radically.

dGPS has low barriers to entry, particularly for several niche markets that have appeared. This has led to the commercial availability of dGPS products and service -- wholly outside the government domain. But wait, there's more!

Low Earth Orbit Satellites and RadioDetermination

Over the next half decade, we will see a proliferation of Low Earth Orbit (LEO) satellites placed in service by commercial companies. The first half dozen companies, known as the Little

LEOs, each plan to orbit between two and 36 satellites, mostly in polar orbits of 700 - 1400 km altitude. Three of the companies are US based; two Russian; one with a Latin American focus. Whatever the market focus, orbital dynamics tend to make service availability global.

While the primary intent of these satellite systems is communications, five of the six also advertise Radio Determination Satellite System (RDSS) services. The exact nature of these services seems to shift periodically, but the typical RDSS services from a Little LEO are:

- doppler, which will provide a positioning with an error ellipse of 1000M at a frequency of perhaps once per hour. Most system designs provide the data to some central dispatching site rather than the vehicle itself. This service is designed to support the trucking company that needs to know which city the truck is in, not which side of the road it's on. Note that this version of service is self-contained -- it does not use GPS, Loran or any other external positioning source.

- GPS backhaul where a GPS receiver is contained within the truck's communications terminal assembly. The GPS data is then relayed to the dispatcher via the communications link which is the bread and butter of the vendor.

- The sixth vendor intends to offer dGPS service. Indeed, it is technically easy for all of the vendors to do so if the demand exists.

- An additional RDSS vendor, GeoStar, is now bankrupt. GeoStar had planned to offer a ranging RDSS

as its primary product with the ability to communicate the positioning data as a secondary service. This company chose this particular path because the spectrum it wished to use was chartered by the FCC primarily for radiopositioning and only secondarily for communications. It is instructive that only one company chose this route and that company is now out of business.

Most of the satellite vendors are immersed in the space segment and few are attending to the information systems problems. For example, none of the satellite vendors are interoperable with each other in their communications aspects. There is no evidence that they are interoperable in their RDSS services either. The market is likely to develop as a grab-bag of niches rather than an integrated, universal service¹. While all the vendors advertise connection into the public service switched (aka telephone) network, none have explained how they intend to interconnect to the Internet. The positioning service is viewed as a secondary service, auxiliary to the communications function.

Both Loran and GPS have known problems in urban environments, a good share of which can be blamed on the multipath and shading. The US-based Little LEOs will communicate in the VHF band; the Russians in the UHF band. The next generation, known as the Big LEOs, will work in a frequency band

¹This is likely to lead to some market fallout too. I doubt if we will see all 6 Little LEOs and all 5 Big LEOs yet in business at the end of the decade.

above 1 GHz so their multipath problems are likely to be similar to those in GPS. Will these same problems reappear with RDSS services?

The impending ubiquity of commercial radiopositioning capability raises some questions that

we really haven't faced since the dawn of radionavigation. Suggest that these questions should be thought through by those in the radionavigation business before politically-driven answers are forced upon us.

Questions:

- How should commercial RDSS systems be treated in the overall navigation picture? Would our attitude be RDSS vs GPS vs Loran or RDSS *with* GPS *with* Loran?
- How does government mandate use of a commercially provided service?
- When use is mandated, how does government ensure the public's legitimate quality control requirements for radionavigation services without owning and operating the system?
- Given several commercial alternatives, should government require interoperability in the interest of best service for the user? If so, how? Interoperability with respect to what?
- Should government simply ignore the commercial service providers, allowing the market to develop? Or should the government reappraise its role as a service provider and promote an orderly migration to a commercial radionavigation service base?
- Assuming the advent of large scale commercially operated radionavigation service providers, should we choose not to fight, but to join and place existing government-operated systems on a similar basis?

Changing User Base

Historically, the maritime and aviation users used radionavigation systems to determine where they were. To a degree, this persists in the various terrestrial uses, but there is a basic change.

The maritime and aviation user

is the pilot or navigator who is colocated on the same vessel with the radionavigation receiver asking the question: "*Where am I?*"

The terrestrial question is more often being asked by a supervisor remote from the receiver: "*Where are my vehicles?*" For instance, in an emergency services environment, most police and fire engine drivers know the neighborhood in which they

operate so they don't need a radionavigation device. On the other hand, their supervisors and dispatchers do have a continuing need to know where those police cruisers and fire engines are so radionavigation inputs are quite useful (but only if the position and

timestamp data can be communicated).

This changing set of requirements will be evident in the marketplace soon enough. The set also needs to be reflected in public policy.

Questions:

- Should radionavigation systems continue to be treated separately from communications systems in the spectrum allocation and other regulatory processes?
- Should the RDSS vendors specialize in the terrestrial market while traditional government-supplied services provide for the maritime/aviation markets? Or should an interoperable, integrated market be developed?
- What differences in navigation services exist between prospective terrestrial users and the better understood maritime and aviation ones? In terms of availability, integrity, and receiver noise environments.

Summary questions

We have two sets of questions that need to be addressed in the public forum.

Service mix and integration

The first are those dealing with competing radionavigation technologies. Too often the problems have been dealt with with compability in mind; not often enough with interoperability and synergism as goals.

Commercial service

The second set of questions have to do with some rather core questions about who provides radionavigation services of the future: government or private commercial enterprises?

It's fairly obvious that the commercial service providers are on the way. It is not obvious how they are integrated into the radionavigation regime.

Wild Goose Association and Institute of Navigation both have expertise and corporate memory to lead the discussions. My opinion is that the discussions will publicly emerge soon; you can either drive the issues or let them drive you.

THE OMEGA NAVIGATION SYSTEM CENTER -- MORE THAN THE NAME IMPLIES

by

**CDR Tom Gunther, CDR Clyde Watanabe, LCDR Gene Schlechte, and
LT Luann Barndt, USCG OMEGA Navigation System Center**

BIOGRAPHY

Commander Tom Gunther is the Commanding Officer of the Omega Navigation System Center, Alexandria, Virginia. He has over 17 years experience with the engineering, operations, support, and national/international policy related aspects of Omega, LORAN-C, GPS, DGPS, and other radionavigation systems.

Commander Clyde Watanabe is the Atlantic Area LORAN-C Regional Manager. He has over 14 years experience in the engineering, operations, support, and policy aspects of LORAN-C and Omega. He was the initial Project Officer for the G-N reorganization efforts discussed in this paper.

Lieutenant Commander Gene Schlechte is Chief of the Differential Global Positioning System (DGPS) Section at the Omega Navigation System Center. Prior to this assignment, he served at the Electronics Engineering Center in Wildwood, NJ as a Project Officer, then as Commanding Officer of the LORAN-C Detachment in Iceland.

Lieutenant Luann Barndt is Chief of the Global Positioning System Information Center (GPSIC) Branch at the Omega Navigation System Center. She is a 1984 graduate of the United States Coast Guard Academy with a Bachelor of Science in Management. She recently earned a Master of Science Degree in Information Management from the George Washington University School of Engineering and Applied Science.

DISCLAIMER

The views expressed herein are those of the authors and are not to be construed as official or reflecting the views of the Commandant of the U.S. Coast Guard.

ABSTRACT

The Omega Navigation System Center (ONSCEN) is evolving into the U.S. Coast

Guard's central point for radionavigation management, operation, and coordination of information dissemination. Originally formed to coordinate operation of the Omega Navigation System, ONSCEN's missions now include the GPS Information Center (GPSIC), the U.S. Coast Guard Differential GPS (DGPS) project, and administrative support of the Atlantic Area LORAN-C Regional Manager staff. Recent changes that impact the radionavigation user includes a watchstander that responds to radionavigation user inquiries 24 hours a day, seven days a week; provisions to disseminate general information on GPS, DGPS, Omega, LORAN-C, and Radiobeacons through various mediums; and the coordination and management of the Civil GPS Service Interface Committee (CGSIC). Current plans indicate that the Precise Positioning Signal Program Office (PPSPO) will also be located at ONSCEN. In addition, ONSCEN is part of the maritime DGPS project team and the site designated for the East Coast DGPS Control Center. With this and the transfer of LORAN-C operational oversight, we will provide one-stop-shopping to the Radionavigation users worldwide. The Omega Navigation System Center will be a key element in the radionavigation services provided by the U.S.

INTRODUCTION -- THE SAGA BEGINS

In November 1989, the Chief, Office of Navigation Safety and Waterway Services, the Program Director for the U.S. Coast Guard's radionavigation efforts, initiated an effort "...to consolidate Operational Control (OPCON), management, ...of radionavigation systems and to centralize user access to system information." [G-N 1991] These systems include Omega, LORAN-C, radiobeacons, civil interface for the Global Positioning System (GPS), and Differential GPS (DGPS). The overall goal of the project is to ensure, through existing and anticipated resources, the U.S.

Coast Guard can:

- Meet our current operational radionavigation mandates identified in SOLAS Chapters IV and V and Title 14 U.S.C. 81;
- Maintain our international lead in radionavigation; and
- Posture ourselves strategically for effective and efficient development of, and transition to, the future radionavigation systems identified in the 1992 Federal Radionavigation Plan [FRP 1992].

This project was undertaken by elements from U.S. Coast Guard Headquarters, U.S. Coast Guard Atlantic and Pacific Areas, and the Omega Navigation System Center (ONSCEN). The project, implemented in phases, is ongoing. As evidenced by the discussion that follows, significant progress has been made.

BACKGROUND -- THE LONG TERM STRATEGY AND USER'S NEED

The need for this project is evident when you consider the potential applications for radionavigation systems and their impact on the world. An integrated navigation system's approach is essential as it is becoming increasingly apparent that worldwide radionavigation (RA) is a critical element in the transportation and commerce infrastructure -- the catalyst, the enabler, for future enhancements in safety, traffic management, surveillance, surveying, etc. The incredible growth in technology (microprocessors, software, PCs, video displays, etc.) has enabled the use of RA far beyond what was deemed possible ten years ago. Today, the use of RA systems to provide position, time, and frequency information for data collection networks and information systems is as commonplace as its use for navigation. As technology continues to forge ahead, new applications will continue to emerge. Growth trends in the user community are increasing dramatically, with no decrease, or even leveling,

for the foreseeable future. Rapid growth in GPS and DGPS technology is leading towards Federal laws requiring carriage of GPS/DGPS equipment. The U.S. Coast Guard, as one of the primary providers of navigation services, must be ready and able to meet the growing and expanding demands on radionavigation services.

ONSCEN -- THE ORGANIZATION

The paper is divided into sections which explain the current and planned efforts related to the various navigation systems and ONSCEN's organization. To begin the discussion and to show where ONSCEN is in the hierarchy of the radionavigation efforts, please refer to Figure 1. Although ONSCEN is not at the top of the diagram, it is a major element and in fact, is the senior operational Command level for the Omega system and the anticipated senior most operational level for LORAN-C (currently this resides with the Regional Managers at the two U.S. Coast Guard Area commands). It is also planned to be Control Center for the U.S. Maritime DGPS service. In addition, and of primary interest to the user, is the fact that ONSCEN, through the GPS Information Center, is the source for operational status and general information on all radionavigation systems with which the U.S. Coast Guard is involved.

Going back in history, ONSCEN's mission, prior to February 1989, was solely to provide operational oversight and support the Omega Navigation System. ONSCEN has its roots, dated back to 1971, when its predecessor, the Omega Navigation System Operations Detail, was formed to manage the U.S. Coast Guard's development and subsequent operations of the Omega Navigation System. Today, ONSCEN, located outside of Washington, D.C. in Alexandria, Virginia, provides all technical support, station operator and technician training, signal analysis, and operational control required to sustain operation of the Omega system. It is a strong foundation from which to build this new organization.

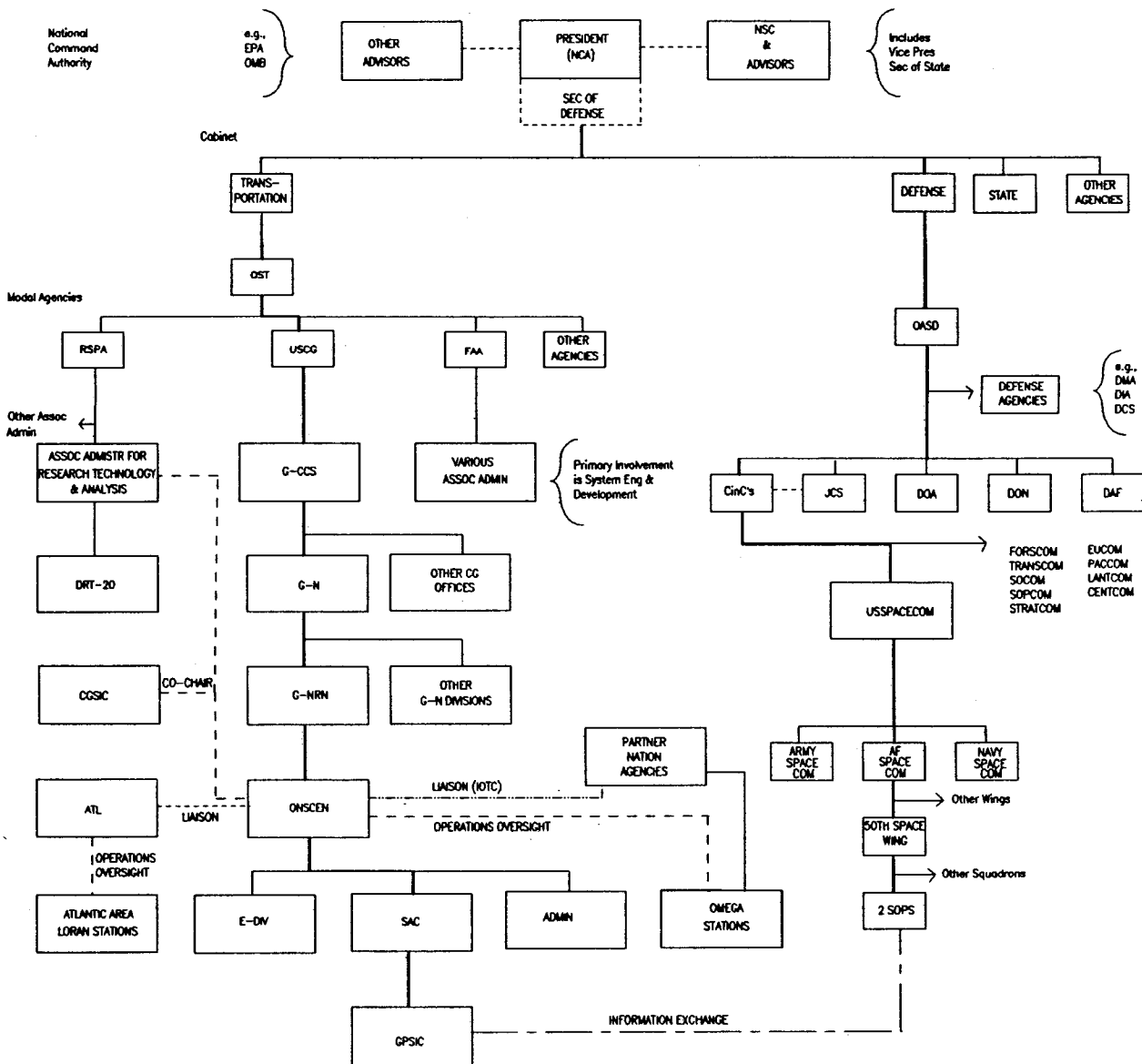


FIGURE 1.

The organization of ONSCEN is relatively simple (see Figure 2). There is basically three divisions: one responsible for engineering (primarily electronics), one responsible for operations and one responsible for management and administration. There are currently 67 people assigned, including the LORAN Regional Manager detachment. The Command is responsible for:

a. Worldwide coordination and electronics support of the Omega navigation system;

b. Operational control and management of the LORAN-C, Omega, DGPS, and radiobeacon navigation systems;

c. Assisting in the electronics and civil engineering support of the LORAN-C, Omega, DGPS, and radiobeacon navigation systems;

d. Operational information support to users of the GPS, DGPS, LORAN-C, Omega, and radiobeacons systems.

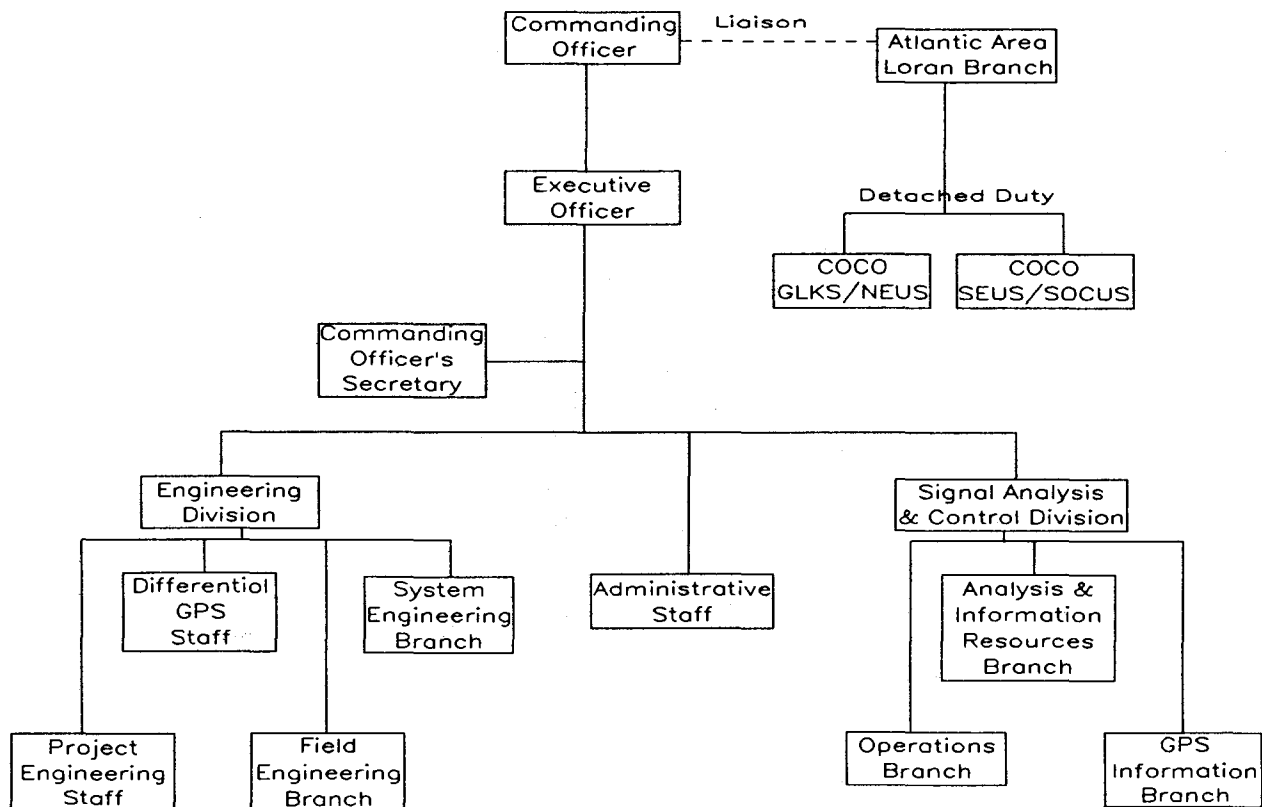


FIGURE 2. ONSCEN's Current Organization

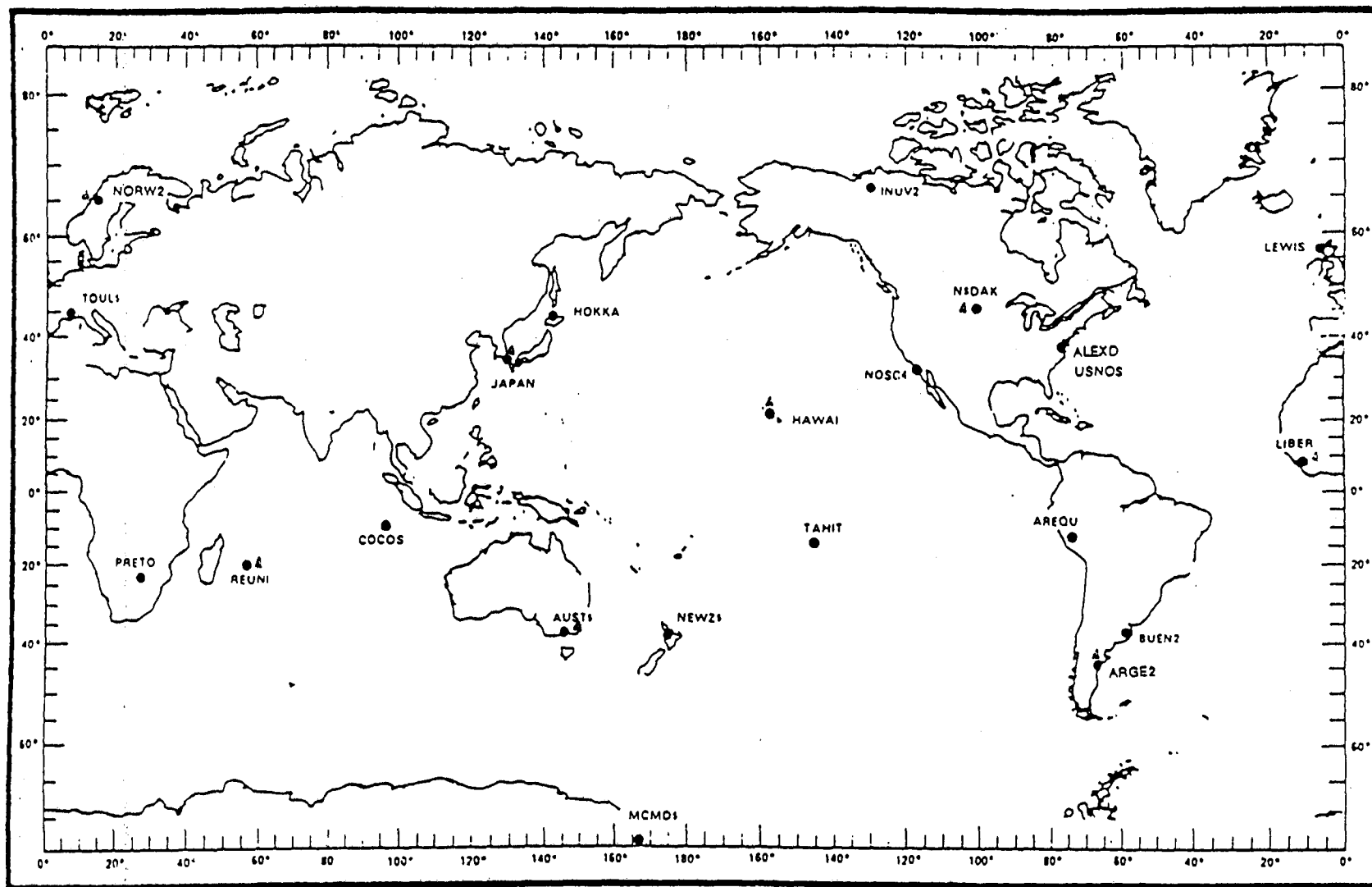
OMEGA -- THE FOUNDATION

The Omega Navigation System is truly an international radionavigation system run in partnership by seven nations. It is also the only operational worldwide radionavigation system. Omega consists of a network of eight very-low-frequency (VLF) transmitting stations located in Norway, Liberia, two in the U.S. (Hawaii and North Dakota), Isle of La Reunion (France), Argentina, Australia, and Japan. There is also a worldwide monitor system composed of 22 sites located in fourteen different countries (see Figure 3). Omega, a hyperbolic navigation system provides worldwide coverage specified with a least 99% system availability at a predictable 2D accuracy of 2-4 nautical miles (nm) [O'Brien 1984]. The navigation users of the system are primarily aviation and marine; with user numbers decreasing as newer more accurate systems come on-line. However, a large non-navigation user community exists and is expected to continue to use Omega -- the Weather forecasting community. Their application is worldwide and uses Omega because it is available, meets their requirements and is coast effective (over 220,000 radiosondes [Stratton 1990] are used annually

at a cost of \$8-14 for the Omega portion of the sonde. [Sakaran 1993]). Other uses of Omega stem from the unique VLF signal propagation characteristics that are not matched or surpassed by any existing or planned system.

Because of the international character of the system and international user acceptance, operational decisions regarding the system are coordinated with the Partner Nations. Thus, any disestablishment of the Omega system would be conditional upon international acceptance of the replacement system, and in accordance with the applicable sections of the agreements between the U.S. and each of the Partner Nations. Additionally, the needs of domestic U. S. agencies and the U.S. DOD must be considered. Coordination of these considerations was begun in 1987 with the review of the 1988 FRP and discussions with the International Omega Technical Commission (IOTC), the Partner Nation governing body; the dialogue continues today. [Gunther 1992]

Further information on the Omega system is found in the "Omega Navigation System User's Guide" [Omega 1990] and in the 1992 Federal Radionavigation Plan.



- ▲ Omega transmitting stations
- Omega monitor sites

Figure 3.

LORAN-C -- THE NEXT ADDITION

Although LORAN has been a U.S. Coast Guard mission since World War II, there was never an effort to combine resources with any other radionavigation system. In fact, LORAN (both A and C) was the U.S. Coast Guard's primary radionavigation system through the 1970's. The implementation of GPS gradually reduced DOD's reliance on LORAN-C to the point of having stated that they will have no further overseas requirement for LORAN-C after 31 December 1994.

This has created the mistaken impression that the U.S. Coast Guard is closing down its LORAN-C operations, since most of the publicity surrounding LORAN-C has been the closure of the overseas stations and the impending declaration that the GPS is operational.

This could not be further from the truth. Although the U.S. Coast Guard's presence at overseas stations will cease, the U. S. and other countries have taken steps to turnover the overseas stations, expand LORAN-C coverage, and refine LORAN-C operations. [Thompson 1992]

In the 1970's, there arose a need by various user groups to expand LORAN-C coverage in the midcontinental U. S., as well as in Alaska. The U.S. Coast Guard, working with the Federal Aviation Administration (FAA), embarked on two projects to provide the LORAN-C coverage. By early 1991, most of Alaska was covered by LORAN-C and the midcontinent "gap" was closed.

In addition to these efforts, projects are underway to update the technology of the equipment, improve synchronization, and reduce unusable time. [Taggart 1990]

With all LORAN-C resources being planned to be within U. S. boundaries, the present economic policies, and improved technology, the present operational, management, and information dissemination policies and practices maybe outdated. There is definitely no further need for Regional and Chain Managers. And in fact, operation and management can be consolidated to a single point, conserving resources while providing training for the next generation of operators and managers.

GPS -- THE NEW MISSION

Although GPS is a Department of Defense system, the U.S. Coast Guard assumed the civil interface responsibilities after GPS became available to the public. In 1983, a Presidential statement announced that the United States would make GPS available to all the world to

increase the safety of navigation. Citing direction from both the President and Congress to make the Standard Positioning Service (SPS) of GPS available to the civil community, a 1987 letter from the Deputy Secretary of Defense to the Deputy Secretary of Transportation requested that DOT provide the government interface to the civil community on behalf of the DOD. This request was made based on DOT's responsibilities as the positioning and navigation representative of the civil community. After organizational and implementation planning by various DOT and DOD agency staffs, a 1989 letter from the Deputy Secretary of Transportation to the Deputy Secretary of Defense named the U.S. Coast Guard as the lead DOT agency for Civil GPS Service operations [Dawson 1989]. Also mentioned were the Research and Special Programs Administration (RSPA), which was to manage intermodal issues, and the Federal Aviation Administration (FAA), which was to address aviation specific issues. The U.S. Coast Guard's responsibilities of meeting civil requirements for GPS status reporting, use of the Precise Positioning Service (PPS), distributing precise GPS satellite ephemerides, and a recent project developing a DGPS maritime service are all included in ONSCEN's current or evolving missions.

ONSCEN has been working with the GPS even before the move of the LORAN detachment in July 1992. This is due largely to the existing ONSCEN infrastructure and the desire for consolidation and integration. Also, the Omega system was using GPS as a check on system synchronization (n.b. the Omega is synchronized to Universal Coordinated Time (UTC) to within 500 nanosecs [Thompson 1989] and there are numerous Omega timing users). Involvement in GPS has now permeated, throughout ONSCEN, to the point where ONSCEN is seen internationally as the civil source of GPS information.

The Civil GPS Service is composed of four major areas. These are the GPS Information Center, the Civil GPS Interface Committee, the Precise Positioning System Program Office, and the Differential GPS Service for U. S. maritime areas. ONSCEN is involved in all of the areas.

Let's look at each of these areas:

GPSIC -- THE DIRECT LINK TO ALL USERS

ONSCEN operates the Global Positioning System Information Center (GPSIC) as the key element of our responsibilities as the government's civil GPS interface. The GPSIC's activities are based on our regulatory and international requirements to make navigation information on systems operated by the U. S. available to users. The GPSIC's primary

function is to serve as an information link between the United States Department of Defense, which operates the Global Positioning System (GPS), and civil users of the system. A link we have expanded to include all RA systems.

The GPSIC sends GPS status information to civil users through Operational Advisory Broadcasts (OAB). These broadcasts contain the following general categories of GPS performance data:

- Current constellation status
- Recent (past) outages
- Scheduled (future) outages
- Almanac data

The Operational Advisory Broadcast (OAB) consists of textual matter containing the GPS performance data listed above. Conditions that impair the GPS for navigational purposes receive special attention and wide distribution.

The Operational Advisory Broadcast is updated by the GPSIC staff at a minimum of once per day. OABs are updated more frequently if information on changes in the constellation is received. The Operational Advisory Broadcast is disseminated through the following media:

- GPSIC Computer Bulletin Board System (BBS)
- GPSIC 24-Hour Status Recording
- WWW/WWVH worldwide high-frequency radio broadcasts
- U.S. Coast Guard Marine Information Broadcasts (MIB)
- DMAHTC Broadcast Warnings
- DMAHTC Weekly Notice to Mariners
- DMA Navigation Information Network (NAVINFONET)
- NAVTEX Data Broadcast

Some of these services have limited time or space available for GPS information.

In addition to updating the OAB, the GPSIC watchstander responds to individual user inquiries, comments, and concerns about radionavigation systems. The GPSIC now has watchstanders on duty 24 hours a day, seven days a week, so this service is available anytime. Most inquiries can be answered immediately over the phone. Some technical questions or requests are referred to a more authoritative source.

CGSIC -- INTERFACE TO THE WORLD

The Civil GPS Service Interface Committee (CGSIC) was established to identify civil GPS user technical information needs in support of the Civil GPS (CGS) program. To effectively identify information needs that relate to the civil

use of GPS, the CGSIC interfaces between civil GPS users, the Civil GPS Program Office, and the GPS operators (Department of Defense).

The current CGSIC evolved from DOD preliminary planning for a GPS civil user interface function in 1986. As part of the effort, an oversight committee led by the USAF Joint Program Office, with representatives from government, industry and the user community, was established to provide a GPS Information and Data System for the civil community. This committee became known as the Civil GPS Service Steering Committee and became jointly chaired by DOD and DOT after DOT accepted responsibility for the civil interface in 1987. In 1988, DOT assumed the sole Chairmanship of the CGSIC, but with continued DOD representation on the committee. In early 1991, the Committee's name was changed to the Civil GPS Service Interface Committee (CGSIC) and its charter revised to more accurately reflect its mission of establishing a forum for technical information exchange.

ROLES OF THE CGSIC

The roles of the CGSIC, as defined in the new charter, are to:

- provide a forum for exchanging technical information in the civil GPS user community regarding GPS information needs,
- identify types of information and methods of distribution to the civil GPS user community, and
- identify any issues that may need resolution by the CGS Program Office.

CGSIC ORGANIZATION

The current CGSIC is jointly chaired by the U.S. Coast Guard and the Research and Special Programs Administration and consists of a general committee and three subcommittees.

Membership in the Committee is intended to represent the widest possible coverage of the civil community. About 100 participants from relevant private, government, and industry user groups, both U. S. and international, attend each meeting.

Three subcommittees have been created to identify specific areas of general GPS user information needs and facilitate technical information exchange. These are for:

- Timing Information
- International Information
- Reference Station, Technology, and Applications

PPSPO -- FOR THOSE THAT CAN JUSTIFY THE NEED FOR MORE ACCURACY

The Precise Positioning Service Program Office (PPSPO) will administer civil applications and collect fees for access to encoded Precise Positioning Service (PPS) capabilities.

The Government will publish detailed guidance, for users interested in requesting access to PPS, once policy is established for the following:

- Submitting applications
- Granting approval for user access
- Establishing operational procedures and compliance requirements for accessing data from the GPS PPS

The Federal Radionavigation Plan (FRP) contains general criteria for qualified civil use of PPS. Access determination will be made on a case by case basis. The following criteria may be refined as a government policy is developed:

- Access is in the U.S. national interest
- Security requirements can be met
- There are no other means reasonably available to the civil user to obtain a capability equivalent to that provided by the GPS PPS

DGPS -- WHAT'S ON THE HORIZON

Current U.S. Coast Guard Differential GPS (DGPS) Project work is aimed at providing an operational DGPS system covering U. S. harbors and harbor approaches by 1996. Under present plans, this means designing, procuring and installing a DGPS System consisting of about 45 Monitor Stations, 45 Reference/Broadcast Stations, and two Control Stations.

To accomplish this vast undertaking, the project has been divided between three U.S. Coast Guard Engineering Units: The Research & Development Center (R&DC) in Groton, CT; the Electronics Engineering Center (EECEN) in Wildwood, NJ; and the Omega Navigation System Center (ONSCEN) in Alexandria, VA. The Office of Navigation Safety & Waterway Services of U.S. Coast Guard Headquarters is managing the Project.

ONSCEN has responsibility for developing the DGPS operation doctrine to ensure System integrity, the Control Station Design, and keeping future DGPS users informed of Project progress.

ONSCEN expects to complete the System operational requirements in late 1993. Work will then focus on building a prototype Control Station based on requirements, architecture, and the experience gained from the present test

broadcast sites; this will start in December 1993. The Control Station, with the GPSIC 24 hour live watch, will provide continuous, computer aided monitoring of the DGPS signals. The DGPS system status will be provided directly from the Control Station to the U.S. Coast Guard GPS Information Center (GPSIC) to ensure timely user notification.

There is still a considerable amount of work to be done to implement the service and ongoing research is required. The USCG will continue to investigate and develop methods and technologies that increase the areas covered by a single DGPS reference station while maintaining the required level of accuracy, allow the combination of measurements by several DGPS reference stations to develop wide area corrections, and provide broadcast coverage over a wider area than is possible using a single radiobeacon. As the accuracy range of the correction increases, a broadcast method with extended range may be desirable. However, at the present time, there is a good correlation between the range of the high power radiobeacon broadcast and the accuracy range of the DGPS correction. Radiobeacons are very cost-effective and their use will allow the USCG to deploy a working DGPS service by 1996 with an accepted technology. It is important to note that there is nothing about this architecture that precludes its use by aviation users with similar accuracy and integrity requirements, or adding other types of differential corrections to the broadcasts, e.g., LORAN.

ONSCEN'S FUTURE -- INTEGRATION OF SYSTEMS

GPS or satellite systems are a boon to the world, however, people don't always realize there are limitations of GPS, e.g., integrity and the cost associated with the system. The potential for improvement to navigation when the satellite systems are mixed with existing navigation systems is something that should be further explored, vice the abandonment of existing systems. This latter philosophy is gaining acceptance and centers on integration of systems. The concept can be equated to other transportation infrastructures. For example, when a new highway or expressway is constructed, the existing roadway infrastructure is not abandoned. It is maintained and used, for it provides alternative routing, i.e., everyone is not dependent on one and only one path. All Radionavigation systems should be considered a national and/or international infrastructure. The terrestrial based systems exists, are maintainable, and cost considerably less than the satellite system (The entire cost of Omega system is estimated at \$12 million per year, whereas, GPS for one satellite and launch vehicle, on the pad is conservatively estimated at \$100M+ ... operations are

estimated in 100's millions of dollars annually [Beuker 1992]). There are also savings to be gained from integration of systems from the system provider perspective and more importantly, increased safety to the user. This is fertile ground that needs to be exploited.

The U.S. Coast Guard and specifically ONSCEN has a major part in the future integration of these navigation systems. Changes are in the making. Some are technical; some are political; some are in name only. ONSCEN is the foundation for what will ultimately be the U.S. Coast Guard's Center of Excellence for navigation services. A Center for Navigation Services to be used by people all over the world.

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ON THE RUSSIAN RADIONAVIGATION PLAN

Yuri Nikulin

Internavigation Research & Technical Centre
Moscow, Russia

INTRODUCTION

Radionavigation support of economic activities and national security is a state-level mission.

Departmental approach to establishing and exploitation of national radionavigation aids with defense priority that was formed in the previous years has led to poor utilization of the existing national radionavigation systems (RNS) and unreasonably high RNS development, operation and control costs.

This situation has caused the necessity of elaborating the state policy of radionavigation user support for all concerned departments and as a result the Russian Government commissioned the Internavigation RTC to draw the Russian Radionavigation Plan (RRP).

The RRP project has been developed in accordance with the general state policy of Russia directed towards improving the efficiency of the national economy, developing international relations on the basis of mutual understanding, eliminating opposition, cooperation in the field of resolving global problems, one of which is establishing the radionavigation support structure for users irrespective of their state membership.

The RRP outlines:

- missions requiring employing radionavigation information;
- radionavigation support requirements of various groups of users;
- technical nav aids, their future usage, improvements and development;
- forms of cooperation among the member states of the CIS and foreign countries in

radionavigation support;

- efforts for realizing the RRP.

The Russian Radionavigation Plan possesses the status of the State research and technical programme for up to 2000.

THE PRINCIPLES OF THE STATE POLICY FOR USER RADIONAVIGATION SUPPORT

The Russian state policy in the area of radionavigation support is elaborated in accordance with the following mission:

- creation of guaranteed conditions for world-wide and near
- space real-time supply of radionavigation information adequate for resolving problems at minimum costs.

This policy is based on the following principles:

- support of economic activity (with priority on traffic safety for all kinds of transport - air, marine, land) on the entire territory of Russia;
- provision of national defense missions;
- cooperation with the members of the CIS and other countries in establishing united radionavigation support structures in the CIS, Europe and the World.

Realization of the state policy is planned in the following directions:

- improving operational efficiency of the existing national radionavigation systems meeting user requirements;
- providing receivers of various modifications and applications which meet user requirements and international standards in their performances;
- introducing novel radionavigation systems

and aids with higher specifications;
-establishing joint national and foreign RNS and systems in joint operation;
-establishing user radionavigation support structure in Russia interfacing with the European and world systems.
The above principles of the state policy and their means of realization are laid the basis of the Russian Radionavigation Plan.

THE PURPOSE AND THE PRIMARY TASKS OF THE PLAN

It is impossible to create anything of use without a clear answer to the questions "What should be created?", "Why?" and "Is this document needed?". Only a positive answer to these questions can justify the efforts and provide the expected results.

Therefore when proceeding to the Plan we formulated its goal as specifying and authorization of the state policy of Russia in radionavigation support of economic and defense missions.

To achieve the above goal the Plan should resolve the following issues:

- to specify requirements for radionavigation support of the main user groups (air, marine, land);
- to analyze the capabilities of the operational radionavigation systems and the degree of meeting user requirements with the existing means;
- to define the directions of improving and development of radionavigation systems and their optimal series, satisfying all user group demands;
- to elaborate measures to improve user radionavigation support structure;
- to define directions of interstate cooperation in radionavigation support;
- to develop the programme of primary activities providing implementation of the RRP.

When resolving the above issues two conditions should be met: maximum satisfying

user demands and eliminating groundless costs. Necessary provisions of the traffic safety require a special approach to radionavigation support of transportation. Due to different dynamics and traffic environment the Plan differentiates requirements of air, marine and land users with due account of the ICAO and IMO recommendations.

The Plan describes radionavigation aids both existing and those under development, their performances, status and user applications. 17 system types are presently in operation, 4 of which are satellite-based and 13 are ground-based systems. Those systems of common use (for all user groups) are of most interest: the GLONASS global navigation satellite system and the Chayka and Alpha long-range radionavigation systems.

The GLONASS system most fully responds the user demands. However it is not yet fully deployed, and it is therefore of limited use for civil users and does not meet the availability and integrity requirements. The system is scheduled for full deployment in 1996.

The Alpha system meets air and marine user requirements for en-route flights and open-sea navigation, except availability. The system is under test in its present status of 3 operational and 3 additional stations and will be in operation up to 2000. Issues of its future exploitation will be resolved after 2000.

High performance, positive operational experience and considerable number of users make the Chayka the primary system among the other RNS. It meets the requirements of air, marine and land users of long- and short-range navigation and it can improve its coverage and accuracies due to introducing range-measuring and differential positioning techniques; it easily integrates into the Loran-C system and permits to extend coverage areas due to establishing joint chains. The economical aspect is also a strong point of the Chayka system - its equipment, receiver and operation costs are much lower (as compared to the cost of the satellite RNS).

These considerations predetermined its operation beyond 2015 which is appointed in the Plan.

The other systems are exploited by individual user groups and resolve special problems (these are short-range, landing systems etc.). The Plan outlines their further operation, modernization and replacement.

NAVIGATION USER SUPPORT IMPROVEMENTS AND THEIR IMPLEMENTATION

In this situation one of the primary problems for the nearest future is improving the operational efficiency of the existing systems. It is to be resolved in both technological and institutional aspects.

The technological aspect calls for making efforts in improving general-purpose RNS performances in accuracy, availability and integrity due to introducing the differential subsystem; integrating the existing systems and establishing a combined radionavigation field; developing and providing user receivers for the above mentioned operating techniques of the existing systems.

The accumulated results show that the GLONASS differential subsystem introduction will provide absolute positioning accuracy of 3-5 m and relative accuracy of the order of 1 m. In geodetic surveys when using carrier phase measurements and dedicated processing techniques it is possible to achieve higher accuracies of relative positioning in centimeter range.

One of possible versions of a differential subsystem is implementation of a reference station as a "pseudo-satellite" broadcasting corrections simultaneously with navigation signals similar to navigation satellite transmissions.

The differential corrections are planned to be transmitted in the recommended RTCM SC-104 standard format.

The Alpha RNS differential mode of

operation will improve positional accuracy to 0,6-2,5 km in areas of 500 km radius around the reference station. However its implementation requires considerable expenses without any appreciable benefit in positional accuracy as compared to other navigation systems. Therefore the differential subsystem of the Alpha RNS is not planned.

The Chayka RNS differential subsystem will provide positional accuracy improvement up to 10-15 m for areas of 200 km radius around the reference station. Besides the commonly used differential mode we consider another version of the differential mode for this system, that is combining the functions of the existing monitor stations and the reference stations. Such a combined station apart from monitoring and control will simultaneously specify via the communication channel the differential corrections for the stations in the chain through which the corrections are transmitted to the users via the navigation channel. Also the Chayka RNS navigation channel can be used for transmitting the GLONASS differential corrections.

The Plan puts forward the necessity to pursue efforts in the above directions.

As was mentioned before, none of the existing radionavigation systems fully meets user requirements, and implementation of new systems demands considerable investments and time, thus the solution to the problem of maximum radionavigation support improvement will be in integrating general-purpose systems, and the GLONASS system with the Chayka and Alpha systems as supplementary systems. Realization of this concept for the national systems will primarily lie in the plane of integrating the user receiver equipment.

However a more prominent effect can be gained by integrating national and foreign RNS systems. This task is feasible and can be embodied through referencing all the stations generating the integrated radionavigation field with the UTC and united coordinate systems,

as well as developing integrated user equipment in compliance with the established international standards. This work is being done now and we do not experience any prominent technical problems. More sound are institutional difficulties - these are legal security for user access to exploitation of general-purpose national systems on the international basis and establishing united European and World infrastructure for radionavigation support of all user groups irrespective of their state membership.

The Commonwealth of Independent States has done the first step in this direction. In January 1993 the Radionavigation Intergovernmental Council was established to coordinate the efforts for the CIS user radionavigation support which decided to elaborate the CIS Radionavigation Plan.

In compliance with the authorized principles and trends of the state and technological policy and judging from the real status of the user radionavigation support and economical situation in Russia the Radionavigation Plan is proposed to be implemented in two phases:

- Phase 1 - up to 1996 - to conduct works and make arrangements for improving operational efficiency of the existing general-purpose radionavigation systems.

This requires:

- full deployment of the GLONASS global navigation satellite system;

- development of reference station equipment and the

corresponding user equipment for the differential GLONASS and Chayka subsystems;

- establishing the combined user radionavigation support in the country;

- establishing the Alpha/Omega system for common use;

- developing the integrated user equipment for common operation of the GLONASS/GPS/Chayka/Loran-

C/Alpha/Omega national and foreign

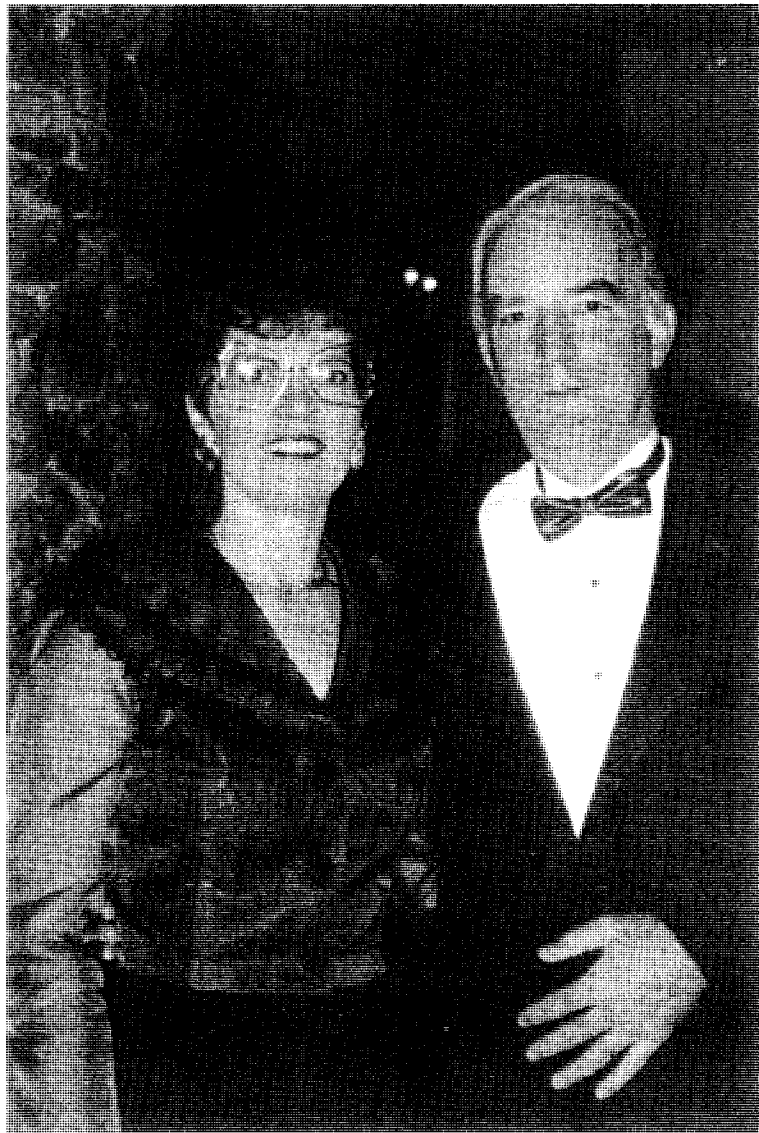
radionavigation systems (in versions satisfying user demands).

- Phase 2 - 1996-2000 - to conduct works for integrating national and foreign general-purpose radionavigation aids, to introduce the differential subsystems and provide integrating the CIS radionavigation structure into the European and World structures.

In 1995 the Radionavigation Plan will be updated in accordance with the results accumulated during Phase 1.

In July 1993 the Russian Radionavigation Plan was submitted to the Government of the Russian Federation.

Social Programs



Kindly referred to as "Mother Goose" (Ellen Lilley - Executive Director for the WGA) pictured with Bob Lilley. Ellen provided the 1993 convention with super support!



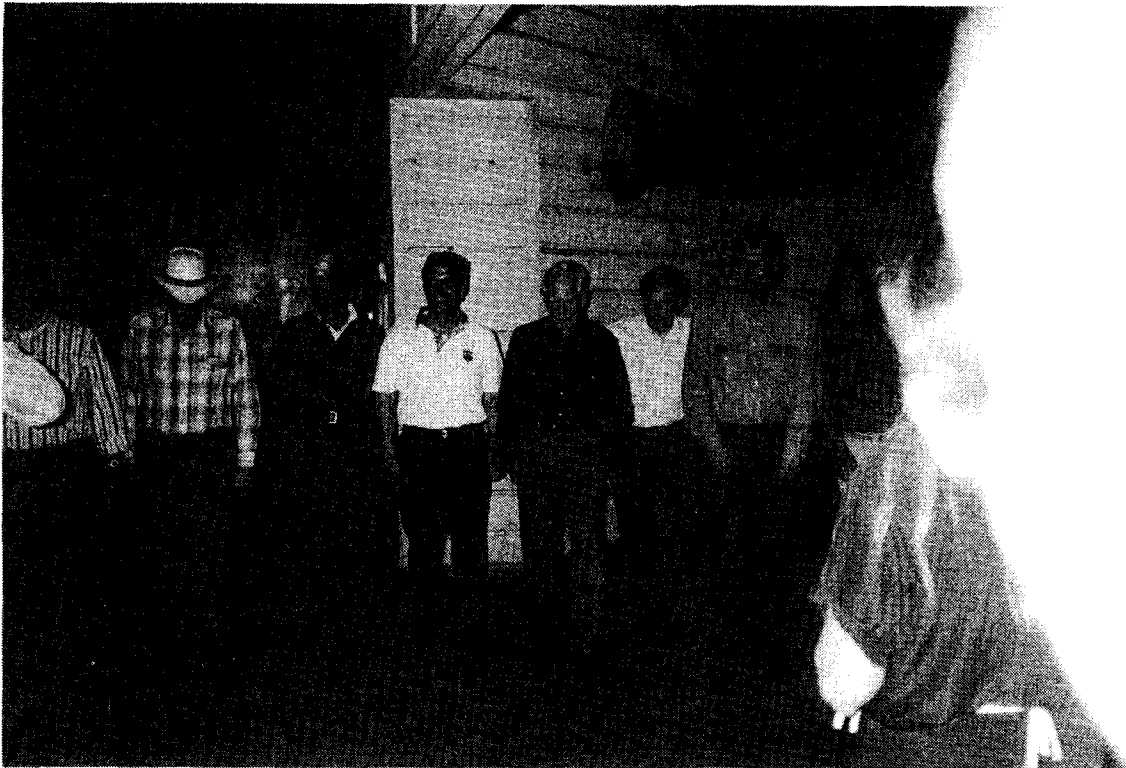
**Bob Erickson, FAA Tech Center, Receives President's Award
for Outstanding Contributions to Loran-C**



Carolyn McDonald (NAVTECH Seminars) provided outstanding support in planning and operating technical equipment. Carolyn's professional support unquestionably is a major WGA asset.



Mike Moroney gives Dave Amos (Synetics) a hand for rushing off to Boston to prepare for the 1994 WGA Convention to be held in Rhode Island



**Walt Dean leads WGA members in a western dance lesson
at the Red Dog Saloon**



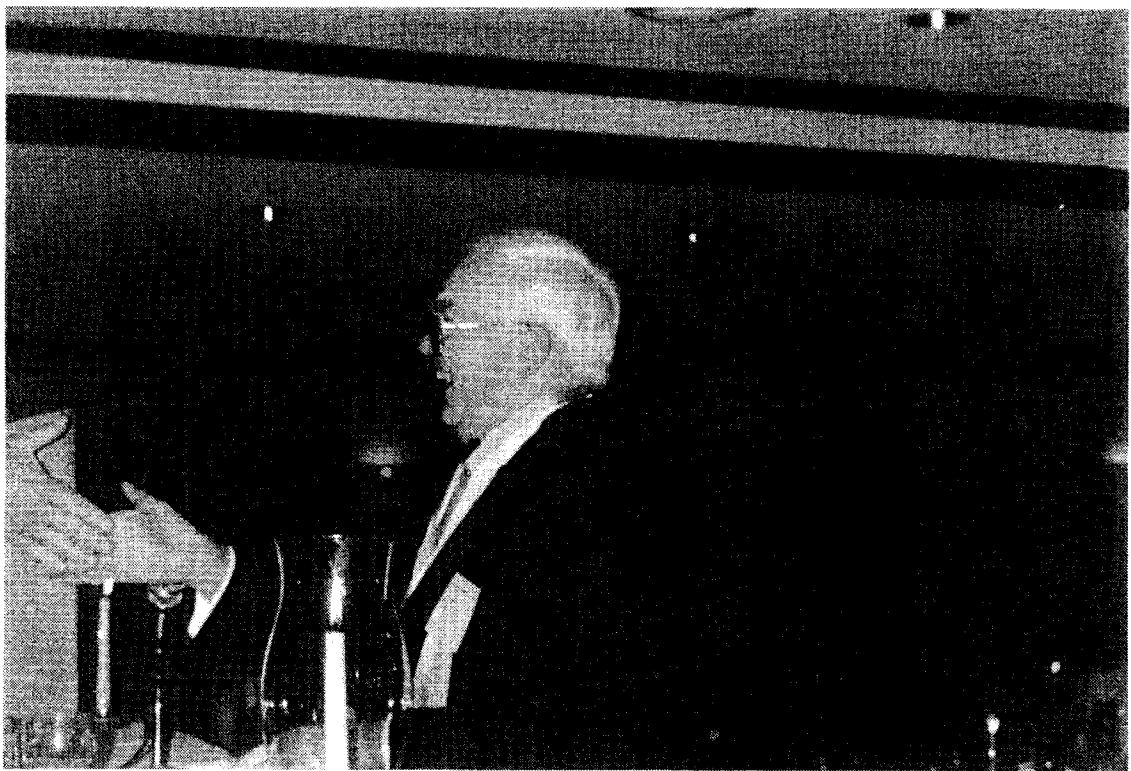
**Mike Moroney, Chairman of the 1993 Panel Discussion and Director of Navigation at the Volpe
National Transportation Systems Center, led one of the best ever panel discussions.
Congratulations to Mike and his panel members for a job well done.**



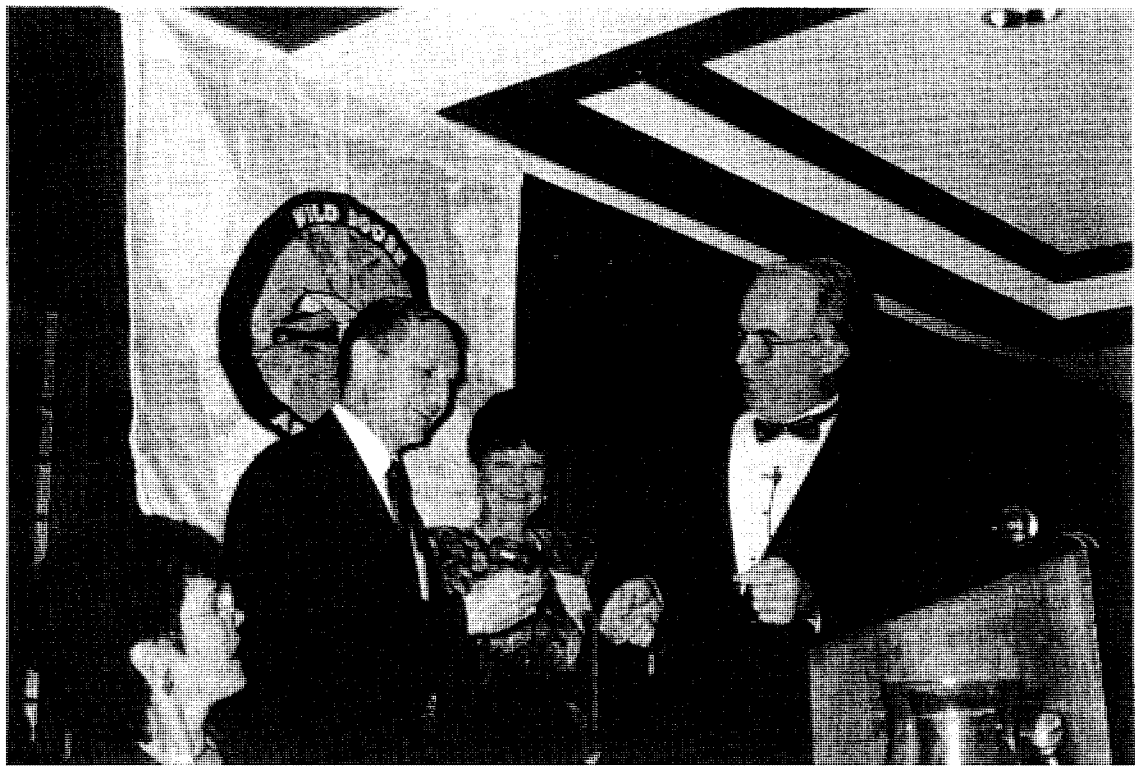
**Dr. David Last, Dr. Yi Bian (University of Wales), Andre Nieuwland (Delft University).
Congratulations to Best Paper Award recipients.**



Jim Van Etten (Awards Chairman) reading the Meritorious Medal citation for Leo Fehlner who made outstanding contributions to the art of Loran-C (1993 Medal of Merit Recipient). Bob Lilley (WGA President) speaks with Leo (who was unable to attend) over the telephone.



**Capt. Jim Culbertson (USCG Retired) receives the Medal of Merit
for Outstanding Loran-C Contributions**



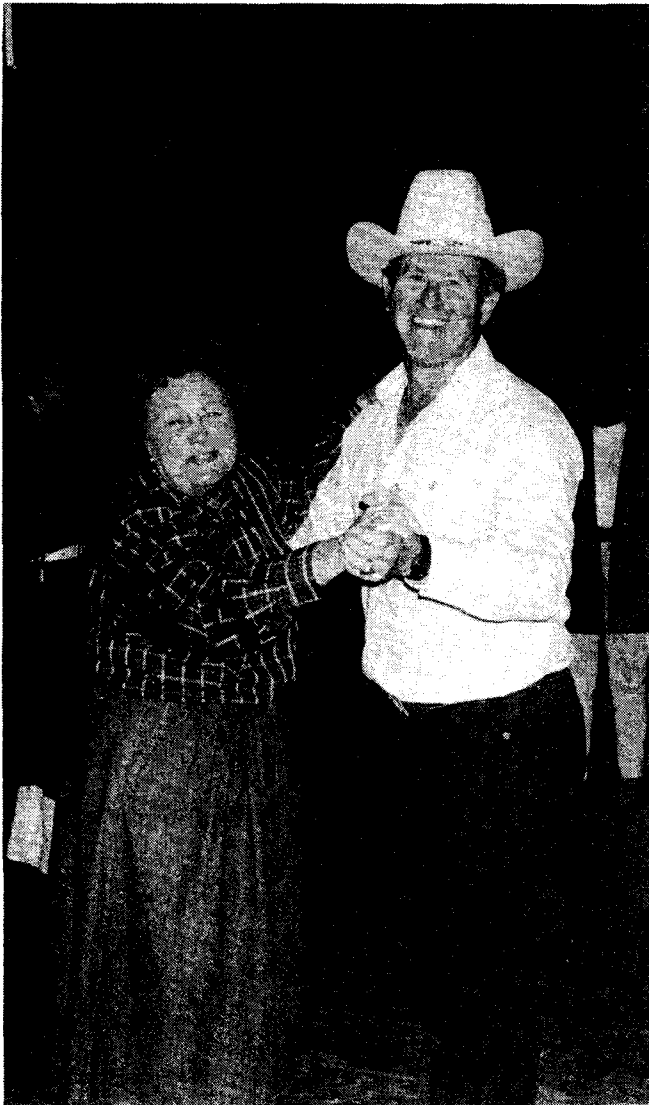
**Dale Johnson (President, 1993-1994) receives the gavel from Past President Dr. Bob Lilley. Bob,
Thank you for a job well done. Dale, we look forward to your leadership.**



John Beukers, David Last, and Steve Ruttle enjoy a lighter moment at the banquet reception. Steve put on quite a show singing ballads at the Red Dog Saloon.



Dr. Charlie Jarvis, an American humorist, was the featured banquet speaker.



**Ruth Scull does the two-step with a cowboy
in the Red Dog Saloon**



**John and Marilyn Beukers. We will not forget
the outstanding symposium held in
Birmingham, UK, in 1992.**

The Wild Goose Association
P.O. Box 556
Bedford, Massachusettes 01730